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The influence of bottom currents on the Zambezi Valley morphology (Mozambique Channel, SW Indian Ocean): In situ current observations and hydrodynamic modelling

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1 **The influence of bottom currents on the Zambezi Valley morphology (Mozambique**
2 **Channel, SW Indian Ocean): *in situ* current observations and hydrodynamic modelling**

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14

15 **Abstract**

16 Mixed turbidite-contourite systems can be found in oceans where bottom currents and turbidity
17 currents interact. The Zambezi turbidite system, located in the Mozambique Channel (SW Indian
18 Ocean), is one of the largest sedimentary systems in the world in length and area of the related
19 catchments. The oceanic circulation in the Mozambique Channel is intense and complex, dominated
20 by eddies flowing southwards and deep currents flowing northwards along the Mozambican margin.
21 Current measurements obtained from moorings at 3400-4050 m water depth in the Zambezi and
22 Tsiribihina valleys show periods of intense currents at the seafloor with peaks of 40-50 cm s⁻¹ that last
23 up to one month and are not related to turbidity currents. These strong bottom-current events are
24 correlated with a change in current direction and an increase in temperature. The periods of current
25 intensification may be related to eddies, since they present similar frequencies (around 7 per year).
26 Moreover, modelling results show that during periods of intense deep circulation an anticyclonic

27 eddy is present between the Mozambican slope and the centre of the Mozambique Channel, which
28 may block the northward transport of the deep water mass and thus enhance the southward
29 transport along the western slope of Madagascar. According to our hydrodynamic modelling of the
30 circulation near the seafloor, intense currents are often present along the Zambezi Valley, especially
31 along the valley flanks. Multi-channel seismic reflection data show that the Zambezi turbidite system
32 does not show the typical characteristics of turbidite systems, being dominated by erosional
33 processes, which mainly affect the valley flanks. Levees associated with the valley are absent in the
34 main axis of the system. The effect of bottom currents on sedimentation in the basin is evidenced by
35 the low sedimentation rates that witness winnowing in the basin, the presence of contouritic sand in
36 the Zambezi Valley flanks and the abundance of current-related bedforms observed in multibeam
37 bathymetry and seismic data. The intense oceanic processes observed in the Mozambique Channel
38 may transport a large part of the fine sediment out of the basin and erode the seafloor even at great
39 depths. Therefore, the Zambezi turbidite system could at present be considered as a mixed turbidite-
40 contourite system, with important implications for source-to-sink studies.

41

42 **Keywords**

43 Contourite; Turbidity current; Mixed system; Oceanic circulation; Mooring; ADCP; ROMS model;
44 Bedform

45

46 **1. Introduction**

47 The effect of oceanic currents on sediment transfer from the continent to the deep sea has been
48 widely recognised on the continental shelves (e.g., Sømme et al., 2009; Covault et al., 2011).
49 However, in source-to-sink studies, the effect of bottom currents in deep-sea settings has not often
50 been taken into consideration (Calvès et al., 2013). The source-to-sink system is commonly divided
51 into different segments: catchment, continental shelf, slope and basin floor (Sømme et al., 2009;
52 Helland-Hansen et al., 2016; Romans et al., 2016). This vision of the continent-basin transition as a

53 continuum does not take into account the complexity and intensity of the oceanic circulation.
54 Bottom currents can generate, for instance, erosion on the slope with the formation of contouritic
55 terraces dominated by erosional processes and coarse-grained sediment (Hernández-Molina et al.,
56 2016; 2017), or alongslope redistribution of the sediment carried by turbidity currents (Mulder et al.,
57 2008). Therefore, in order to take the effect of oceanic circulation on basin sedimentation into
58 account, it is necessary to perform 3D studies of the sedimentary processes acting across- and
59 alongslope.

60 All turbidite systems can potentially be affected by geostrophic currents because these occur along
61 continental margins worldwide. However, when the energy of sediment gravity flows is high, the
62 influence of bottom currents may become insignificant. Mixed contourite-turbidite systems are
63 developed where bottom currents and gravity-driven processes occur in the same area and have
64 similar energy, resulting in modifications of the sediment body morphology or in alternations of
65 contourites and turbidites (Mulder et al., 2008).

66 Bottom currents are often considered as permanent steady flows, in contrast to the more episodic
67 nature of gravity-flows (Rebesco et al., 2014). Nevertheless, both short-term and seasonal variations
68 may also be involved in controlling the formation of sediment drifts (Zhang et al., 2016; Thran et al.,
69 2018). More studies based on *in situ* current measurements and hydrodynamic modelling are needed
70 to better understand the intensity and variability of bottom currents and their effect on deep-sea
71 sedimentation. In order to provide new insights on this topic, we aim to: (i) analyse intensity and
72 temporal variability of the bottom circulation in the Mozambique Channel; and (ii) decipher the
73 impact of such circulation on the development of the Zambezi turbidite system, by comparing the
74 observed and modeled current patterns with the resulting morphology. We used a multidisciplinary
75 approach that integrates multibeam bathymetry, seismic reflection data, sediment cores, mooring
76 data (current velocity, temperature and sediment trap) and hydrodynamic modelling.

77

78

79 **2. Regional setting**

80 *2.1. Geological setting*

81 The Mozambique Channel is an elongate, north-south oriented basin, located in the Southwest
82 Indian Ocean between the African continent and Madagascar. Its depth ranges between 2700 m in
83 the north at the narrowest part of the channel and 5000 m in the southern part of the channel (Fig.
84 1A). The Mozambique Channel developed during the breakup of Gondwana in the Early Jurassic-Early
85 Cretaceous (Mahanjane, 2014; and references therein). A group of modern isolated carbonate
86 platforms is located in the middle of the channel, which includes Bassas da India and Europa (Jorry et
87 al., 2016; Fig. 1B). The study of seamounts at the vicinity of the modern reef has shown that
88 carbonates started to settle on volcanic edifices during Oligocene-Miocene times (Courgeon et al.,
89 2016).

90 The sedimentary deposits in the Mozambique Channel are bounded in the north and west by the
91 Mozambican margin, and in the east by the Madagascar margin and the Davie Ridge (Castelino et al.,
92 2017). The Zambezi is the main river delivering sediment to the basin, which, with a catchment area
93 of $1.4 \cdot 10^6$ km² (Walford et al., 2005), is one of the largest fluvial systems in SE Africa. However, some
94 sediment is also supplied from Madagascar, for instance from the Tsiribihina river (Fig. 1B). The
95 modern Zambezi turbidite system started to develop at the beginning of the Oligocene (Droz and
96 Mougnot, 1987). It is composed of two main valleys, the Zambezi Valley originating from the
97 Mozambican margin and the Tsiribihina Valley, which is a tributary originating from the Madagascar
98 margin (Figs. 1B and 2). At present the Zambezi submarine system is not directly connected to the
99 river system (Schulz et al., 2011). The sediment is mainly dispersed by alongshore currents on the
100 continental shelf during sea level high-stands (Schulz et al., 2011; Wiles et al., 2017a).

101

102 *2.2. Oceanographic setting*

103 The oceanic circulation in the Mozambique Channel is very complex and intense. It forms part of the
104 greater Agulhas Current system that extends from north of Madagascar to South Africa (Fig. 1A;

105 Lutjeharms, 2006). The Agulhas Current is the strongest western-boundary current in the southern
106 hemisphere, and it is an important link in the heat and salt exchange between the Indian and the
107 Atlantic Oceans (Gordon, 1986; Weijer et al., 1999). Currents in the Mozambique Channel comprise a
108 southward-bound, western boundary current (Mozambique Current, MC) (DiMarco et al., 2002;
109 Quartly et al., 2013; Flemming and Kudrass, 2018) and anticyclonic eddies with diameters of ≥ 300
110 km, that flow southwards and can affect the whole water column (Fig. 1A; de Ruijter et al., 2002;
111 Halo et al., 2014). The frequency of the eddy passage is about four to seven per year (Schouten et al.,
112 2003). Eddies trap anomalous water masses with higher nutrient and lower oxygen concentrations
113 (Swart et al., 2010), advect coastal waters with high phytoplankton biomass into the offshore oceanic
114 environment (Tew-Kai and Marsac, 2009), and may also transport sediment in suspension as
115 observed in the South China Sea (Zhang et al., 2014). The formation of eddies in the Mozambique
116 Channel is related to the South Equatorial Current (SEC) (Fig. 1A; Schott et al., 2009). The SEC splits
117 near 17°S into two branches, the Northeast and Southeast Madagascar Currents (NEMC and SEMC)
118 (Fig. 1A; Schott et al., 2009).

119 The upper layers of the Mozambique Channel are composed of the Tropical Surface Water (TSW) at
120 the surface and the Subtropical Surface Water (STSW) in the subsurface. The permanent thermocline
121 is mainly composed of South Indian Central Water (SICW) (Figs. 1C, D). Intermediate waters in the
122 Mozambique Channel are composed of Red Sea Water (RSW), that enters into the Mozambique
123 Channel from the north, and Antarctic Intermediate Water (AAIW), that enters from the south as
124 part of the Mozambique Undercurrent (MUC) (Fig. 1; Ullgren et al., 2012). The deep waters in the
125 Mozambique Channel contain North Atlantic Deep Water (NADW) and Antarctic Bottom Water
126 (AABW) (Figs. 1C, D; van Aken et al., 2004; Ullgren et al., 2012). The NADW is found between about
127 2000 and 3500 m water depth (wd) and the AABW at more than 3500 m wd (Figs. 1C, D). The NADW
128 is characterised by a relative maximum in salinity and oxygen at about 2500 m wd (Fig. 1D; Mantyla
129 and Reid, 1995). The upper portions of the NADW and the AAIW flow, as the Mozambique
130 Undercurrent (MUC), northwards along the western margin of the basin through the sill of the

131 Mozambique Channel (Fig. 1A; van Aken et al., 2004; Ullgren et al., 2012). The deep portion of the
132 NADW and the AABW (characterised by an absolute minimum of temperature and a relative
133 minimum of salinity; Fig. 1D) are constrained by the bathymetry, flowing northwards along the
134 Mozambican margin and back southwards along the eastern part (along Madagascar) (Fig. 1A; van
135 Aken et al., 2004).

136

137 **3. Material and methods**

138 The bathymetry used for this study (Figs. 1A, B and 2) is a compilation of GEBCO bathymetry
139 (GEBCO_08, version 2010-09-27, <http://www.gebco.net>), with a 30 arc-second resolution, and the
140 multibeam bathymetry of the PAMELA project surveys PTOLEMEE (2014, R/V L'Atalante; Jorry, 2014),
141 PAMELA-MOZ01 (2014, R/V L'Atalante; Olu, 2014), PAMELA-MOZ02 (2015, R/V L'Atalante, Robin and
142 Droz, 2014) and PAMELA-MOZ04 (2015, R/V Pourquoi pas?; Jouet and Deville, 2015), with a
143 horizontal resolution of 30-40 m.

144 In this study we used 24-channel mini GI-gun seismic reflection data acquired during the PTOLEMEE,
145 PAMELA-MOZ02 and PAMELA-MOZ04 surveys. We used two sediment piston cores (MOZ02-KS06
146 and MOZ02-KS07) to show the sedimentary facies of the current-controlled deposits, collected
147 during the PAMELA-MOZ02 survey. The age of core MOZ02-KS06 has been estimated using
148 biohorizons as defined by first and last occurrences of calcareous nannofossil species (Thierstein et
149 al., 1977; Sato et al., 1991; Reale and Monechi, 2005), as well as by dominance intervals within this
150 group of single species/taxonomical categories according to Pujos (1988), Weaver (1993), and
151 Giraudeau et al. (1998). The top of cores MOZ02-KS06 and MOZ02-KS07 were dated using
152 radiocarbon analyses on bulk planktonic foraminifera performed at Beta Analytic laboratories.
153 Radiocarbon ages were calibrated using the Marine13 calibration curve (Reimer et al., 2013). Average
154 sedimentation rates for the last 248-718 kyr were obtained from age models based on radiocarbon
155 dating and $\delta^{18}\text{O}$ isotope correlation (Fierens et al., 2017) of seven cores collected during cruises
156 PAMELA-MOZ01, PAMELA-MOZ02 and PAMELA-MOZ04. Further analysis of the split cores consisted

157 on the acquisition of real colour photographs, grain size measurements (every 5 cm) using a Malvern
158 136 Mastersizer 3000 laser diffraction particle size analyser, and analysis of the bulk sediment semi-
159 quantitative geochemical composition using an Avaatech X-ray fluorescence (XRF) core scanner.

160 Hydrographic data (Conductivity, Temperature and Depth, CTD profiles) were obtained from the
161 World Ocean Database 2013 (WOD13; <https://www.nodc.noaa.gov/OC5/WOD13/>) and the Coriolis
162 Database (<http://www.coriolis.eu.org/>), and used to identify the water masses present near the
163 Zambezi Valley.

164 During the PAMELA-MOZ01 survey, three moorings (MLP2, MLP3 and MLP5; Fig. 2) were deployed in
165 November 2014 in the Zambezi and Tsiribihina Valleys and were recovered in December 2015 during
166 the PAMELA-MOZ04 survey. At the same time, two more moorings (MLP8 and MLP10; Fig. 2) were
167 deployed in the Zambezi Valley and recovered in January 2017 during the PAMELA-MOZ08 survey
168 (R/V Antea; Khripounoff, 2017). The moorings were located at water depths that range between
169 3415 and 4054 m (Fig. 2). They were thus under the influence of the upper part of the AABW and of
170 the mixing zone with the NADW (Figs. 1C, D). With the exception of mooring MLP5, they all consisted
171 of a sediment trap located at 40 m above the seafloor, a HOBO temperature sensor and a downward
172 looking 307 kHz ADCP located 30 m above the seafloor. MLP5 consisted of a 614 kHz ADCP mounted
173 22 m above the seafloor.

174 The Regional Ocean Modelling System (ROMS, here the version CROCO: [https://www.croco-
175 ocean.org/](https://www.croco-ocean.org/)) was used to simulate the bottom circulation at a regional scale with a resolution of $1/36^\circ$
176 (~ 3 km). The simulations extended from 1993 to 2014. ROMS is a primitive equation model that can
177 realistically resolve basin-scale, regional and coastal oceanic processes at high resolution
178 (Shchepetkin and McWilliams, 2005). High resolution is here attained by three levels of nested grids,
179 communicating between each other (Debreu et al., 2012). ROMS has a free surface and uses a σ
180 topography following vertical grid. The model successfully resolves mesoscale eddies in the
181 Mozambique Channel (Halo et al., 2014). The bathymetry used in the model is GEBCO 2014
182 (Weatherall et al., 2015) smoothed for numerical constraints.

183 We used maps of Sea Level Anomalies (SLA) in order to link the observed changes in current velocity
184 with mesoscale features in the Mozambique Channel. The Ssalto/Duacs SLA heights (MSLA-H) were
185 produced and distributed by the Copernicus Marine and Environment Monitoring Service (CMEMS)
186 (<http://www.marine.copernicus.eu>).

187

188 **4. Results**

189 *4.1. Bottom currents in the Mozambique Channel*

190 *4.1.1. In situ current observations in the Zambezi and Tsiribihina Valleys*

191 Five moorings were deployed in the Zambezi system during two years: (i) from October 2014 to
192 December 2015 in the Zambezi Valley 80 km upstream and 210 km downstream of the confluence
193 with the Tsiribihina Valley (MLP2 and MLP5, respectively), and in the Tsiribihina valley 95 km
194 upstream of the confluence (MLP3); (ii) from December 2015 to January 2017 close to the valley
195 confluence (MLP8) and 210 km downstream of the confluence (MLP10) (Figs. 2 and 3). Currents near
196 the seafloor show different directions depending on their location, but they often follow a direction
197 similar to the valley axis (Fig. 4). South of the confluence, moorings MLP5 and MLP10 mainly
198 recorded northward currents (Fig. 4). The other three sites, by contrast, show mainly southward
199 currents, with large inversions towards the N-NE, which are particularly remarkable at sites MLP2
200 and MLP8 (Fig. 4). The periods of S-SSW direction correspond to periods of higher current speed (Fig.
201 4). Rose diagrams of sites MLP5 and MLP10 show a wider range of current direction than sites MLP3,
202 MLP2 and MLP8 (Fig. 4). Currents at sites MLP5 and MLP10 are less constrained by the valley
203 morphology. In this area, the Zambezi U-shaped thalweg is lower, resulting in a less confined valley
204 and hence a lower impact on the bottom circulation (Fig. 3).

205 Current speed near the seafloor is very intense at all the studied sites (Fig. 5), reaching up to 53 cm s⁻¹.
206 Upstream and close to the confluence, sites MLP2 and MLP8 registered mean speeds of the
207 available data set of 13 and 15 cm s⁻¹, and maximum speeds of 51 cm s⁻¹; while at site MLP3 in the
208 Tsiribihina Valley a mean speed of 9 cm s⁻¹ and a maximum speed of 38 cm s⁻¹ were registered.

209 Downstream of the confluence, moorings MLP5 and MLP10 registered mean speeds of 7 and 11 cm s⁻¹,
210 and maximum speeds of 37 and 53 cm s⁻¹, respectively (Fig. 5). The currents show periods of
211 intensified circulation, especially at sites MLP2 and MLP8, that can last up to one month (Fig. 5).
212 These periods of intense bottom currents are coincident with a change in current direction and an
213 increase in temperature (Fig. 6). The high frequency variability observed in the current data (Figs. 5
214 and 6) is related to tides. At site MLP8, the current direction is generally NNE when the currents are
215 weaker, while during the periods of intense circulation the direction reverses to SSW (Figs. 5 and 6).
216 These events of intense circulation are not related to turbidity currents because there is no
217 correlation between the current speed and the sediment flux obtained from a sediment trap (Fig. 6).
218 The measured sediment flux is usually low during the periods of strong currents, for instance during
219 December 2015-January 2016, April-May 2016 or August 2016. Miramontes et al. (accepted) also
220 observed reduced sedimentation from turbidity measurements during periods of intense currents on
221 the Hall seamount located in the centre of the Mozambique Channel (Fig. 1B).

222

223 *4.1.2. Simulated bottom currents*

224 The circulation near the seafloor obtained from the ROMS hydrodynamic model successfully
225 simulates the main currents that are known in the Mozambique Channel: surface currents flowing
226 southwards along the African continental margin at the surface and intermediate depths
227 (Mozambique Current), and deep currents flowing northwards along the same margin (Mozambique
228 Undercurrent) and back southwards along the western Madagascar margin (Fig. 7). The group of
229 seamounts and islands present in the centre of the Mozambique Channel generate multiple
230 topographic changes that result in a complex bottom circulation, forming gyres within small basins
231 and around topographic highs (Fig. 7).

232 Hydrodynamic modelling results show strong currents flowing southwards along the western part of
233 the Davie Ridge with mean speeds of 10-15 cm s⁻¹ and maximum speeds of 30-55 cm s⁻¹ (Fig. 7). The
234 model also simulates intense currents along the Zambezi Valley, especially along the eastern flank,

235 with maximum velocities of 40-60 cm s⁻¹, and mean velocities of 8-18 cm s⁻¹ (Fig. 8), in agreement
236 with the *in situ* measurements (Fig. 5). On the basin seafloor outside the valleys, simulated bottom
237 currents are more intense to the west of the Zambezi Valley than to the east (towards the
238 Madagascar margin). West of the Zambezi Valley mean velocities oscillate between 5 and 14 cm s⁻¹
239 and maximum velocities between 15 and 50 cm s⁻¹, while east of the Zambezi Valley, mean velocities
240 are often around 3-5 cm s⁻¹ (reaching locally 13 cm s⁻¹) and maximum velocities of about 15 cm s⁻¹
241 (reaching locally 40 cm s⁻¹) (Fig. 8). Modelling results also show intense bottom circulation around
242 Europa Island, especially on the western and southern sides of the island, with mean velocities that
243 can reach up to 18 cm s⁻¹ and maximum velocities up to 70 cm s⁻¹ (Fig. 8).

244 In order to better understand the observed changes in current direction and intensity at mooring
245 sites, we calculated a composite of the Sea Level Anomaly (SLA), the bottom currents and the
246 barotropic currents from the ROMS model for the periods of time during which currents at the
247 mooring site MLP2 were above 25 cm s⁻¹ (Fig. 9). The results show that during the periods of intense
248 southward flow along the Zambezi Valley, the Mozambique Undercurrent is less intense, and there is
249 an intensification of bottom currents flowing eastwards north and south of the group of islands and
250 seamounts, and southwards along the Zambezi Valley (Fig. 9B). The composite of the SLA shows the
251 presence of a large anticyclonic eddy (positive SLA) located between 21-24°S and 36-41°E. The
252 composite of barotropic currents (i.e. average of the currents in the whole water column) follows the
253 eddy field, thus demonstrating that eddies are affecting the whole water column (Fig. 9C). The
254 bottom current direction and zone of high intensity are generally coincident with the barotropic
255 currents. However, the model results show a focusing of bottom currents along topographic reliefs
256 such as the islands and seamounts, and the Zambezi Valley (Fig. 9).

257

258 *4.2. Evidence of contouritic sedimentation in the Zambezi turbidite system*

259 The Zambezi turbidite system is mainly composed of two valleys: the Zambezi Valley (U-shaped
260 thalweg and V-shaped valley; Fierens et al., accepted) originating from the Mozambican continental

261 slope, and the Tsiribihina Valley originating from the western Madagascar slope (Figs. 1 and 2). Both
262 valleys converge at about 22°S, and the combined valley extends with a N-S orientation until about
263 26°S, where the depositional fan system starts to develop. Levees are absent along the main axis of
264 the recent valleys and the flanks are often eroded (Fig. 3). The Zambezi Valley flanks are asymmetric,
265 with more sediment accumulation east of the valley. The Tsiribihina Valley is more sinuous and
266 narrower than the Zambezi Valley (Figs. 2 and 3). The flanks of the Zambezi Valley are covered by
267 bedforms (Fig. 3). Sediment architectures similar to the Zambezi Valley flanks are observed in a
268 purely contourite depositional system associated with a seamount near the Madagascar Ridge (Fig.
269 10). Elongated separated mounded drifts covered with large bedforms are separated from the
270 seamounts by moats characterised by a flat homogeneous bottom (Fig. 10). The Serpa Pinto Valley
271 used to act as the main conduit for terrigenous sediments in the Mozambique Channel until the Early
272 Miocene (Droz and Mougenot, 1987). Despite being inactive, its relief can still be recognised on the
273 present seafloor, and its sedimentary geometry shows similarities with the Zambezi Valley (Fig. 11).
274 West of this valley the seafloor is dominated by an erosional surface and by large bedforms (Fig. 11).
275 Further evidence of bottom-current related features was obtained from two sediment piston cores
276 (MOZ02-KS06 and MOZ02-KS07) collected on the Zambezi Valley flanks about 60 km south of the
277 confluence with the Tsiribihina Valley (Fig. 12), in areas with strong bottom currents according to the
278 hydrodynamic modelling results (Fig. 8). The upper 0.80 (MOZ02-KS07) and 1.75 metres (MOZ02-
279 KS06) of the sediment records are composed of foraminiferal sand (planktonic and benthic
280 foraminifers), without clear lamination (Fig. 13). This area adjacent to the valley is characterised by
281 high backscatter (Fig. 12C), in agreement with the sand sampled in cores (Fig. 13). The first
282 centimetres of core MOZ02-KS06 have been dated at $25,350 \pm 240$ cal yr BP, and of core MOZ02-
283 KS07 at $11,648 \pm 284$ cal yr BP. According to the analysis of nannofossil assemblages of core MOZ02-
284 KS06, the foraminiferal sand began to be deposited 600-830 kyr ago (zone NN19-CN14a, absence of
285 *R. asanoi*, at 1.69-1.70 m) (Fig. 13A). This allows the sedimentation rate to be estimated at about 0.2-
286 0.3 cm kyr⁻¹. Low sedimentation rates have also been observed in hemipelagic sediment in the

287 vicinity of the Zambezi turbidite system. Sedimentation rates obtained by Fierens et al. (2017) at
288 seven different sites for the last 248-718 kyr range between 0.5 and 2.4 cm kyr⁻¹ (Fig. 1B). The mud-
289 sand transition in core MOZ02-KS06 is characterised by a hiatus. The age of the top of the mud unit
290 (1.80-1.81 m) was estimated at 2.5-5 Ma (zones NN16-NN14). The foraminiferal sand layers display
291 coarsening-up sequences, which are more marked in core MOZ02-KS06. The volume of sand in these
292 layers ranges between 54 and 89% in core MOZ02-KS06 and between 45 and 70% in core MOZ02-
293 KS07 (Fig. 12). The increasing amount of carbonate sand in these layers is consistent with an increase
294 in the XRF Ca/Fe ratio (due to a higher concentration of foraminifers) and in the XRF ln(Zr/Rb) ratio
295 (due to the more energetic conditions and coarser grain size). Heavy minerals such as zircon can be
296 accumulated due to winnowing under intense bottom currents (Bahr et al., 2014). The upper part of
297 the muddy sequence in core MOZ02-KS07 is characterised by burrows infilled with foraminifera sand
298 from the upper sandy layer (Fig. 13B). This observation suggests that the sand could be contouritic.
299 Contourites exhibit continuous and homogeneous bioturbation, while turbidites are mainly
300 bioturbated from the top (Rodríguez-Tovar and Hernández-Molina, 2018). This interpretation is also
301 supported by the observed inverse grading sequence (Fig. 13), which is typical of contourites
302 (Rebesco et al., 2014, and references therein).

303

304 **5. Discussion**

305 *5.1. Modelled, observed and inferred circulation near the seafloor of the Mozambique Channel*

306 The ROMS hydrodynamic model successfully simulated bottom circulation in the Mozambique
307 Channel in terms of speed and direction. The modelling results are in agreement with *in situ*
308 measurements and directions inferred from morpho-sedimentary features recorded in previous
309 studies.

310 The Agulhas Undercurrent (AUC) carries AAIW and NADW northwards below 700 m water depth
311 along the southeast African continental slope, with speeds between 30 and 40 cm s⁻¹ (Donohue et al.,
312 2000). The Mozambique Undercurrent (MUC) is the continuation of the AUC (Fig. 1A; Beal and

313 Bryden, 1997). Ullgren et al. (2012) measured the MUC flowing northwards at 1500-2500 m water
314 depth in a section at 37°S, with mean speed below 4 cm s⁻¹ and maximum values of 35 cm s⁻¹. De
315 Ruijter et al. (2002) reported that the MUC attains speeds ranging from 10 to 20 cm s⁻¹. In the area
316 studied by Ullgren et al. (2012) (~ 17°S) our model results show mean bottom currents of about 10
317 cm s⁻¹ and maximum speeds of 33-40 cm s⁻¹ (Fig. 7), which is in agreement with *in situ*
318 measurements. The modelling results show a southwards flow west of the Davie Ridge (Fig. 7) that
319 has also been observed in the *in situ* measurements published by Ullgren et al. (2012).

320 Morpho-sedimentary features related to bottom currents also support the modelling results in the
321 central and southern part of the Mozambique Channel in the depth range of the NADW (2000-3500
322 m water depth) and the AABW (below 3500 m) (Fig. 1). An erosional surface and large bedforms
323 were observed in the area of strong currents flowing southwards near the Davie Ridge (Figs. 7 and
324 11). This southward setting bottom current continues along the Zambezi Valley (Fig. 7), inducing the
325 erosion of the V-shaped valley flank described by Fierens et al. (accepted) (Figs. 3 and 12) and the
326 deposition of contouritic sand (Fig. 13). Kolla et al. (1980) inferred current directions towards the
327 south in the northern part of the Zambezi Valley and towards the north in the southern part of the
328 valley, as observed in the *in situ* measurements described in the present study (Fig. 4). Kolla et al.
329 (1980), Breitzke et al. (2017) and Wiles et al. (2017b) showed that bedforms are more abundant on
330 the basin floor west of the Zambezi Valley than east of the valley. This asymmetric distribution of the
331 bedforms is in agreement with the modelling results, which show stronger bottom currents on the
332 basin floor west of the Zambezi Valley (Figs. 7 and 8). Moreover, the strong currents NW of Europa
333 Island (Fig. 8) may explain the observed asymmetry of a carbonate levee system originating from the
334 island, as documented by Counts et al. (2018).

335 The central part of the Mozambique Channel is characterised by the presence of multiple
336 topographic highs and small basins (Fig. 1B). This bathymetric heterogeneity induces local changes in
337 the bottom circulation, with the formation of gyres within the basins (e.g. in the basin southwest of
338 the main group of seamounts and islands) and currents flowing around the topographic highs (e.g.

339 northeast of the group of islands and seamounts) (Fig. 7). This bottom circulation pattern could be
340 the cause of the arcuate and sub-circular bedforms observed by Breitzke et al. (2017) in this area.
341 In the southernmost part of the Mozambique Channel, the AABW flows northwards east of the
342 Mozambique Ridge. It is then constrained to the north by the decreasing water depth, being forced
343 to return southwards along the Madagascar Ridge (Figs. 1 and 7). The modelled current direction is
344 once again in agreement with the inferred directions from morpho-sedimentary features and bottom
345 photography described by Kolla et al. (1980) and Breitzke et al. (2017).

346

347 *5.2. Origin of intense bottom currents in the Zambezi Valley*

348 Anticyclonic rings in the Mozambique Channel have a large barotropic component, affecting the
349 whole water column and reaching the bottom of the channel, as identified by velocity measurements
350 and water properties (de Ruijter et al., 2002; Swart et al., 2010). Halo et al. (2014) showed that these
351 large anticyclonic structures mainly propagate along the western edge of the Mozambique Channel.
352 Hence, they would not directly affect the deep part of the Zambezi Valley. However, the presence of
353 eddies may induce changes in the deep circulation pattern. Ullgren et al. (2012) correlated
354 hydrographic properties at intermediate and greater depths with changes in current direction.
355 Anticyclonic eddies passing through the narrowest part of the Mozambique Channel carry salty and
356 warm RSW southwards, and thereby reduce or even revert the northward transport related to the
357 Mozambique Undercurrent (Ullgren et al., 2012). They recognised that the meridional or vertical
358 displacement of the water-mass interfaces induces rapid changes in temperature and salinity at fixed
359 stations and that the end of the hydrographic changes (temperature and salinity) related to the
360 velocity of the Mozambique Undercurrent is more abrupt than its onset. Similar variations have been
361 observed in the mooring sites of the Zambezi Valley. The periods of intense currents are correlated
362 with a change in current direction (southwards) and an increase in temperature (Fig. 6). The end of
363 the warm water intrusion period is more abrupt than its onset. In some cases, such as in May 2016,
364 the end of the event lasts only a few hours (Fig. 6). Modelling results show that during periods of

365 intense southward currents at mooring site MLP2, a large anticyclonic ring is present at 21-24 °S
366 between the African continental slope and the group of islands and seamounts in the centre of the
367 Mozambique Channel (Fig. 9). Anticyclones can block the northward transport of the Mozambique
368 Undercurrent along the Mozambican slope (Fig. 9; Ullgren et al., 2012). When the northward
369 transport along the western part of the Mozambique Channel is limited, the southward NADW
370 transport may increase along the Zambezi Valley (Fig. 9). This may induce a deepening of the
371 interface between the NADW and the AABW at the Zambezi Valley (Fig. 14). The NADW-AABW
372 interface would thus move southwards, and the mooring sites would detect an increase in
373 temperature related to the warmer NADW compared to the AABW (Figs. 6 and 14). Intense
374 southward setting currents are related to these changes in the water-mass properties (Fig. 7).
375 Although the mooring duration is too short for a precise assessment, the occurrence of 7 events in a
376 year is consistent with the eddy variability obtained from satellite altimetry by Schouten et al. (2003)
377 and from the LOCO mooring by Harlander et al. (2009) and Ridderinkhof et al. (2010). This is also
378 consistent with the frequency of occurrence of Mozambique Channel Rings obtained by Halo et al.
379 (2014) from altimetry and two ocean models.

380 The effect of eddies on the seafloor may be direct: as in the Gulf of Cadiz, by generating sub-circular
381 depressions (García et al., 2016), and in the NW Atlantic Ocean, by generating benthic nepheloid
382 layers (Gardner et al., 2017); or indirect, as shown in the present study. Eddies can influence the
383 deep circulation and induce periods of strong bottom currents that may erode the seafloor, winnow
384 fine-grained sediment or generate furrows and large bedforms. Gardner et al. (2017) observed
385 benthic storms (i.e. events of strong currents capable of eroding the seafloor and generating benthic
386 nepheloid layers) in areas with high sea-surface eddy kinetic energy, related to the Gulf Stream or its
387 associated rings. The importance of eddies in controlling deep-sea sedimentation is also supported
388 by a global comparison of contourite distribution and hydrodynamic modelling, which showed that
389 contourites are located in areas with high simulated bottom eddy kinetic energy (Thran et al., 2018).

390 Shanmugam (2016) criticizes the use of the generic term contourite because of its broad sense that
391 covers all the sediment affected by any bottom current, and suggests the use of a classification
392 according to the different processes that generate the deposits: contourite for geostrophic currents,
393 bottom-current reworked sands for wind-driven bottom currents, tidalite for tide-driven bottom
394 currents, and baroclinite for internal waves or tide-driven baroclinic currents. But in the ocean,
395 different processes are superimposed with different daily, seasonal and interannual frequencies. For
396 instance, geostrophic currents in the Zambezi Valley are modulated in the frequency band of tides
397 and anticyclones. It is very hard or almost impossible to relate a pure oceanographic process to a
398 pure depositional facies. Therefore, we consider that the generic term contourite is appropriate for
399 any sediment affected by bottom currents, although in contrast to the common definition of Rebesco
400 et al. (2014) and references therein, bottom currents do not need to be persistent, their velocity may
401 strongly vary, as shown in this study.

402

403 *5.3. Implications for source-to-sink studies*

404 Mixed contourite-turbidite systems are often characterised by an alternation of contouritic and
405 turbiditic deposits, that result from variations in the dominant sedimentary process (Mulder et al.,
406 2008). The Zambezi system is a particular mixed system dominated by erosive processes related to
407 the oceanic circulation. The Zambezi Valley flanks are eroded (V-shaped), and levees are absent in
408 most part of the system. Another particularity of the Zambezi mixed system is the absence of
409 contourite drift-turbidite alternation, as observed in mixed systems of the southeastern Brazilian
410 margin (Viana et al., 1999) or of the South China Sea (Zhu et al., 2010; He et al., 2013). In addition, no
411 typical sediment drifts have been identified associated with the turbidite system, as described for
412 example in Antarctica (Rebesco et al., 2002). At present, the circulation in the Mozambique Channel
413 is probably too intense to allow the formation of large sediment drifts. The seafloor is characterised
414 by erosive features such as furrows and irregular large-scale bedforms, especially west of the
415 Zambezi Valley (Breitzke et al., 2017). Lower sediment accumulations west of the Zambezi Valley may

416 also be related to stronger bottom currents that could prevent or reduce sediment deposition in this
417 area, compared to the area east of the valley where weaker bottom currents would favour sediment
418 accumulation (Figs. 3 and 8). Most of the sediments carried by turbidity currents are probably re-
419 transported by bottom currents at all depths, thus little fine-grained sediments would arrive as a
420 gravity flow to the deep part of the basin.

421 Van Sebille et al. (2015) demonstrated that planktonic foraminifera shells could be transported off
422 South Africa hundreds of kilometres before being deposited on the seafloor. They considered for the
423 foraminifera shells a settling velocity of 0.23 cm s^{-1} , that is much higher than the settling velocity of
424 coarse silt (0.1 cm s^{-1}) or fine silt (0.01 cm s^{-1}) (Gibbs et al., 1971). Therefore, the fine-grained
425 sediments could be transported in suspension by the eddies travelling southwards and be finally
426 deposited outside the Mozambique Channel. Zhang et al. (2014) showed that surface-generated
427 mesoscale eddies of the South China Sea can trap and transport sediment in suspension, influencing
428 deep-water sedimentary processes.

429 The Zambezi Valley presents a low sinuosity (Wiles et al., 2017b), in contrast to most of the low-
430 latitude submarine channels that are characterised by high sinuosity due to a regular and stable
431 sediment supply, usually composed of fine-grained material (Mulder, 2011; Peakall et al., 2012). This
432 particularity of the Zambezi Valley may be caused by sediment sorting due to bottom currents before
433 the formation of the turbidity current or during its movement. The NAMOC (Northwest Atlantic Mid-
434 Ocean Channel) in the Labrador Sea and the Tanzania channel in the Southwest Indian Ocean show
435 similar characteristics to the Zambezi Valley: absence of well-developed aggradational levees, low
436 sinuosity and flat erosive thalwegs (Hesse et al., 1987; Klaucke et al., 1998; Bourget et al., 2008;
437 Wiles et al., 2017b). All these areas are under the influence of strong western boundary currents. For
438 instance, the Eirik and Gloria Drifts are located in close vicinity to the NAMOC turbidite system
439 (Klaucke et al., 1998), evidencing the effect of bottom currents in the area. The slope of North
440 Mozambique-Tanzania is also well known for the interaction of contouritic and turbiditic processes.
441 Palermo et al. (2014) interpreted the presence of channel and lobe complexes flanked by unilateral

442 drift mounds in the Lower Eocene depositional sequence of the Rovuma Basin as the effect of
443 bottom currents that would deviate the fine-grained suspension cloud of the turbidity currents. This
444 process would remove part of the fine-grained sediments from the turbidity current, increasing the
445 grain size composition of the turbidity current, and thus generating low sinuosity channels even at
446 low latitudes.

447

448 **6. Conclusion**

449 *In situ* current measurements, obtained from 5 mooring stations in the Zambezi and Tsiribihina
450 Valleys, and regional hydrodynamic modelling show that the circulation near the seafloor in the
451 Mozambique Channel is very intense and may have an important impact on deep-sea sedimentation.
452 The main conclusions of this study are:

453 (1) Measured mean bottom currents in the Zambezi and Tsiribihina Valleys at 3400-4050 m water
454 depth are about 9-15 cm s⁻¹, but bottom currents show a high variability, with periods of intense
455 circulation characterised by current speeds up to 53 cm s⁻¹. The results of the ROMS hydrodynamic
456 model show that bottom currents are accelerated along the V-shaped valley flanks, with velocities
457 similar to the mooring data, and in agreement with the flank erosion observed in seismic profiles.
458 The periods of intense current speed are correlated with a reversal of the current direction and with
459 an increase in temperature. These events seem to be related to the eddy activity, since they present
460 a similar frequency as the anticyclonic eddies (about 7 per year). Moreover, modelling results show
461 that during the identified periods of intense bottom currents, an anticyclonic ring was present
462 between the Mozambican slope and the centre of the Mozambique Channel. The anticyclone may
463 induce a reduction of the northward transport of the Mozambique Undercurrent along the
464 Mozambican margin. Therefore, the southward transport of North Atlantic Deep Water along the
465 eastern part of the Mozambique Channel could be enhanced, deepening the interface between the
466 North Atlantic Deep Water and the Antarctic Bottom Water, and generating increased bottom
467 currents and temperature at the mooring sites.

468 (2) Multibeam bathymetry and seismic reflection data show that the Zambezi turbidite system is
469 mainly dominated by erosive processes: the Zambezi Valley flanks are eroded and covered in some
470 areas by contouritic sand. Moreover, levees are absent in most of the system, and large zones with
471 furrows and large bedforms are found in the vicinity of the turbidite system. The morphological
472 characteristics of the Zambezi Valley (low sinuosity, absence of levees and a flat erosive U-shaped
473 thalweg) are not typical of low latitude systems, which are usually mud-rich systems. The strong
474 bottom currents present in the Mozambique Channel may transport away most of the fine-grained
475 sediment carried in suspension by the turbidity currents, generating coarser and probably better
476 sorted turbidity currents.

477

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489

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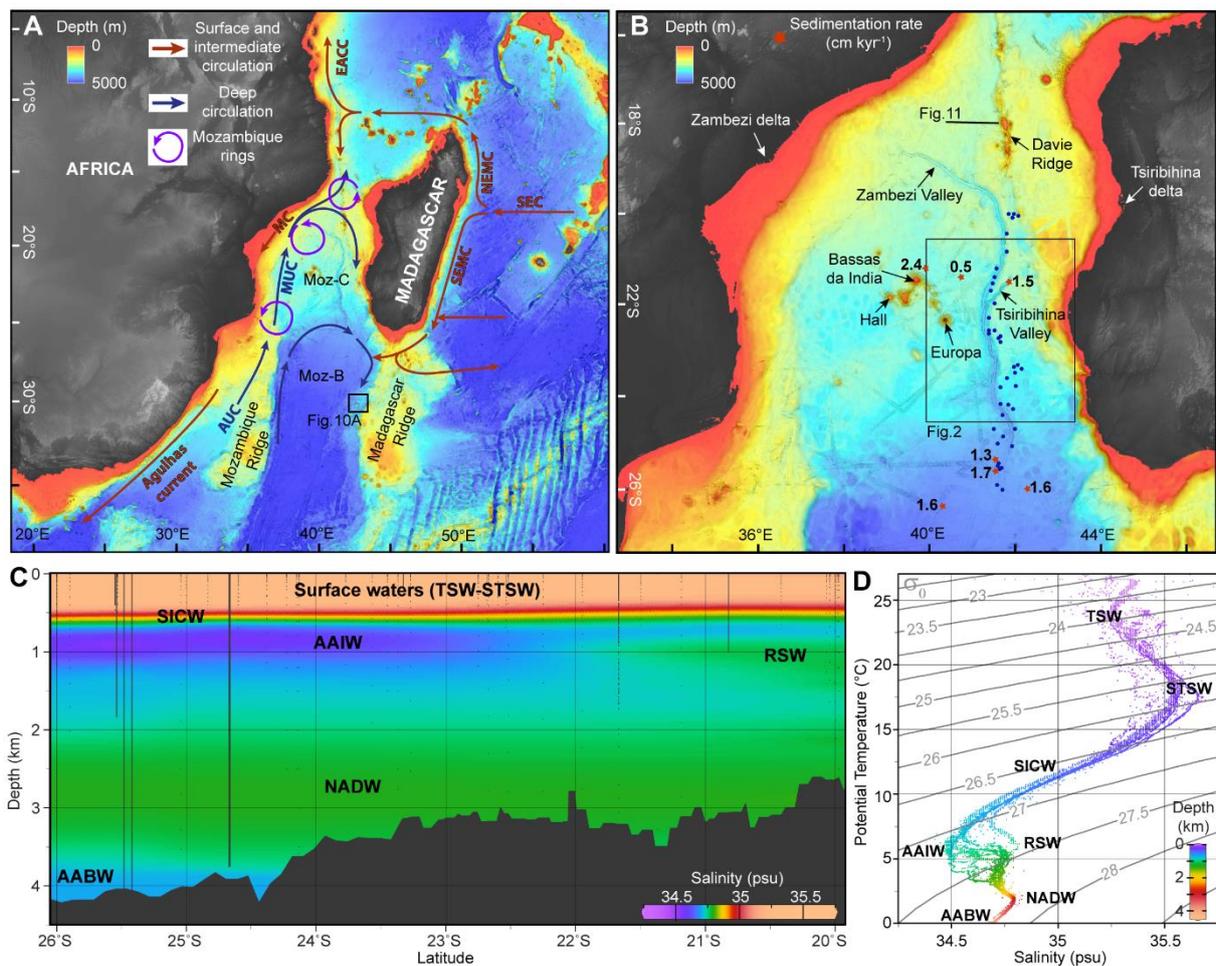
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FIGURES CAPTIONS

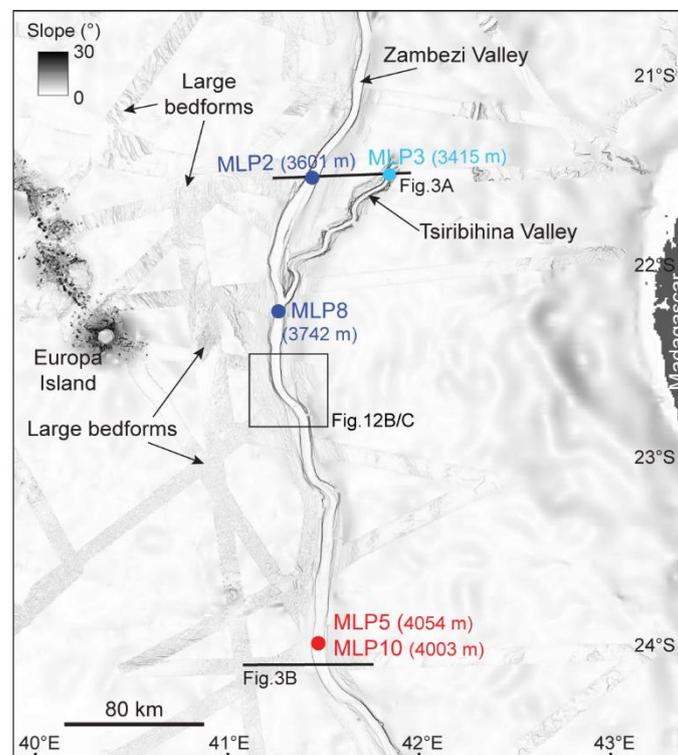


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727 **Fig. 1.** (A) Bathymetry of the South East Indian Ocean (GEBCO and PAMELA cruises) showing the main
728 circulation patterns (based on van Aken et al., 2004 and Schott et al., 2009). AUC: Agulhas
729 Undercurrent; MC: Mozambique Current; MUC: Mozambique Undercurrent; SEC: South Equatorial
730 Current; NEMC: Northeast Madagascar Current; SEMC: Southeast Madagascar Current; Moz-C:
731 Mozambique Channel; Moz-B: Mozambique Basin. (B) Zoom of the Mozambique Channel
732 bathymetry. The blue dots represent the Conductivity Temperature Depth (CTD) profiles used in Fig.

733 1C. The mean sedimentation rates (cm kyr^{-1}) over the last 248-718 kyr, obtained from the sediment
 734 cores and represented with red stars, are also indicated. (C) Salinity section along the Zambezi Valley
 735 showing the distribution of the main water masses present in the area, based on CTD profiles located
 736 in 1B. (D) Potential temperature-salinity diagram showing the different water masses present in the
 737 Mozambique Channel. σ_0 : potential density anomaly (kg m^{-3}); TSW: Tropical Surface Water; STSW:
 738 Sub-Tropical Surface Water; SICW: South Indian Central Water; AAIW: Antarctic Intermediate Water;
 739 RSW: Red Sea Water; NADW: North Atlantic Deep Water; AABW: Antarctic Bottom Water.

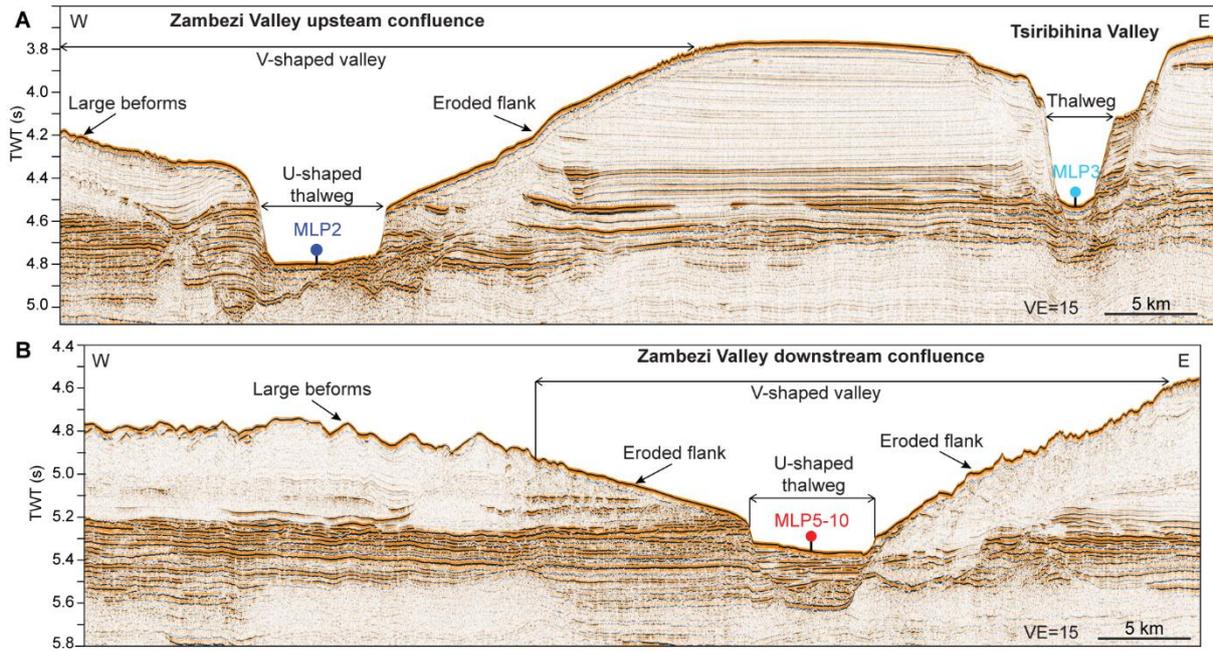
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742 **Fig. 2.** Slope map obtained from the PAMELA project multibeam bathymetry and GEBCO bathymetry
 743 showing the location (and depth) of the moorings. See location in Fig. 1B.

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Fig. 3. Multi-channel seismic reflection profiles (A) PTO-SR-785 and PTO-SR-685; (B) MOZ2-SR-13B;

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showing the location of the moorings MLP2, MLP3, MLP5 and MLP10. Moorings MLP5 and MLP10 are

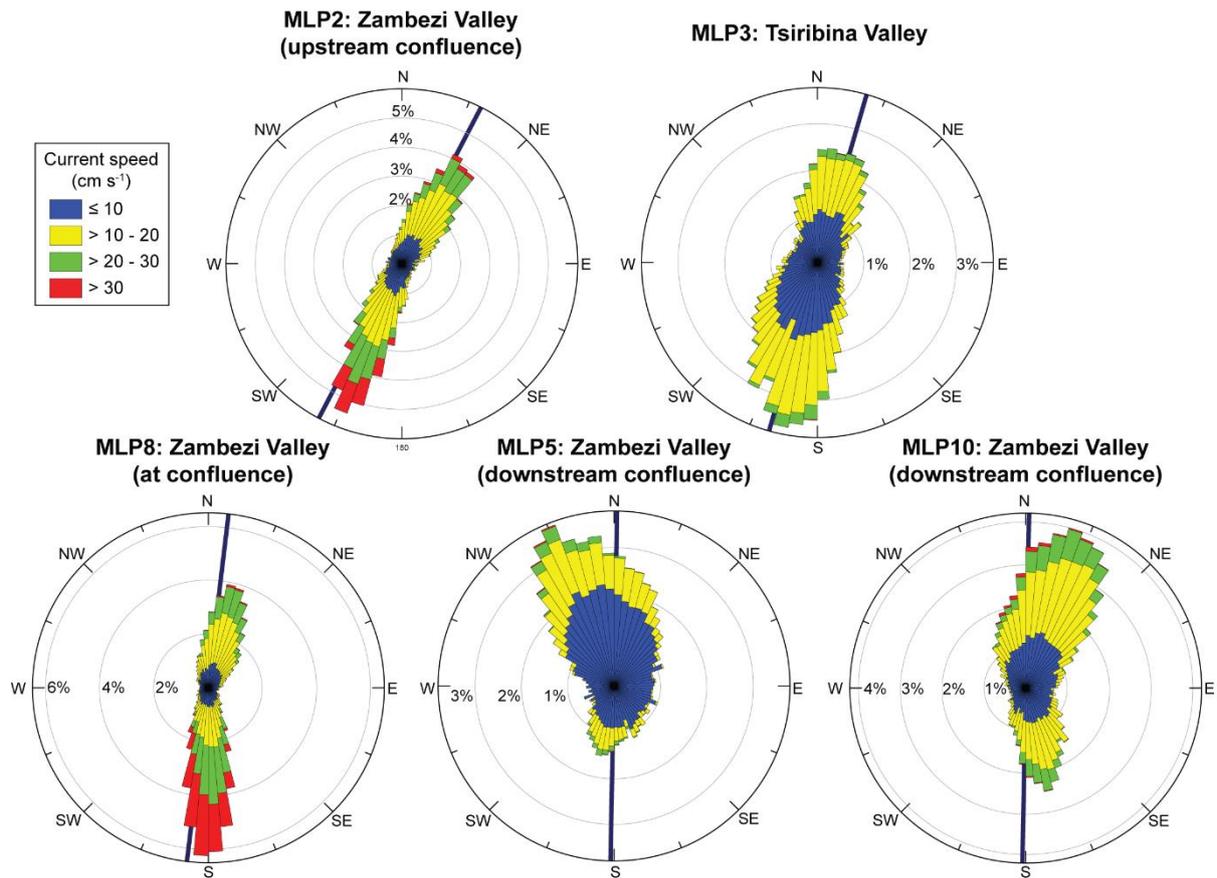
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projected on the seismic profile since they are located 13 km north of the profile. See location in Fig.

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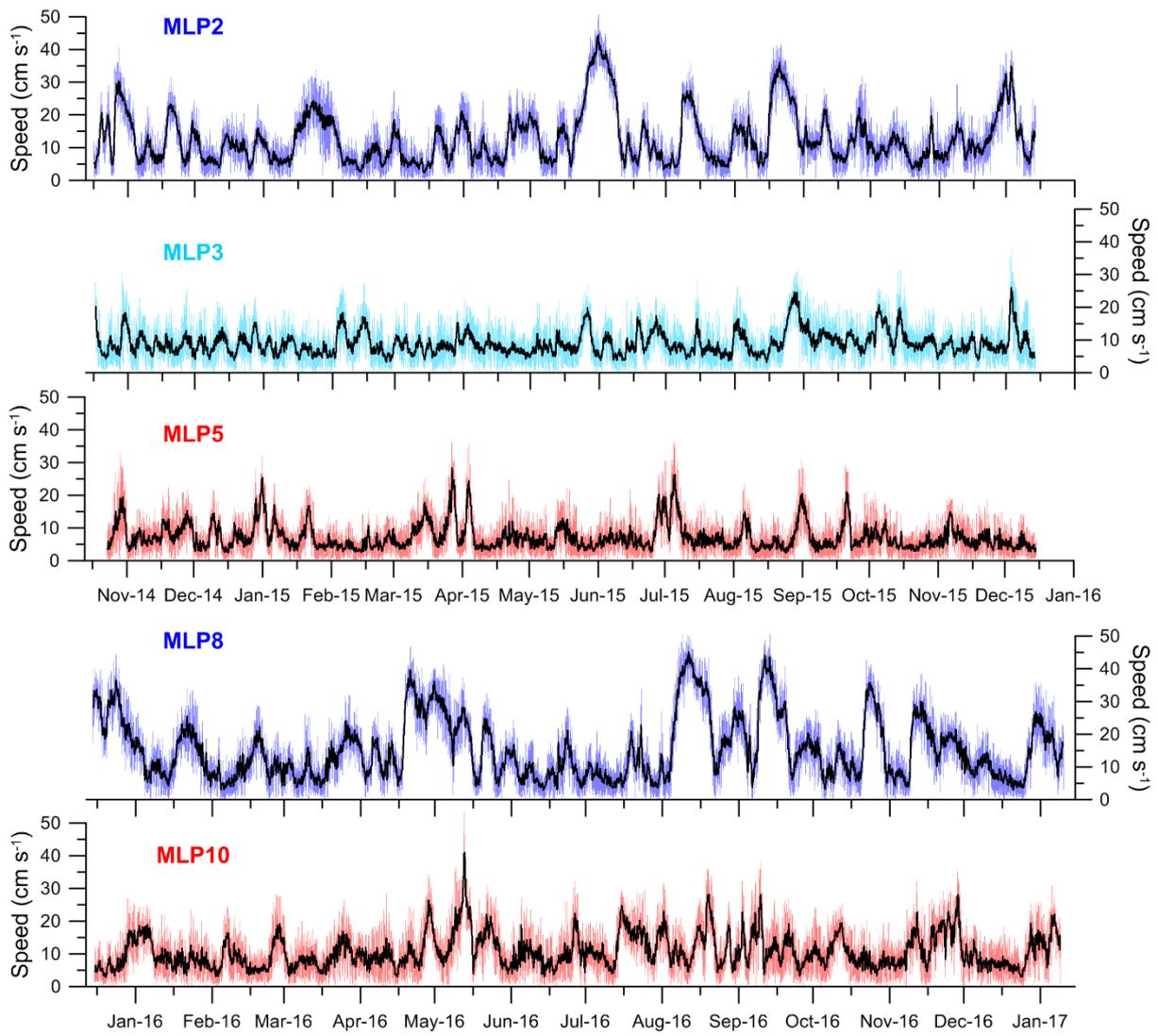
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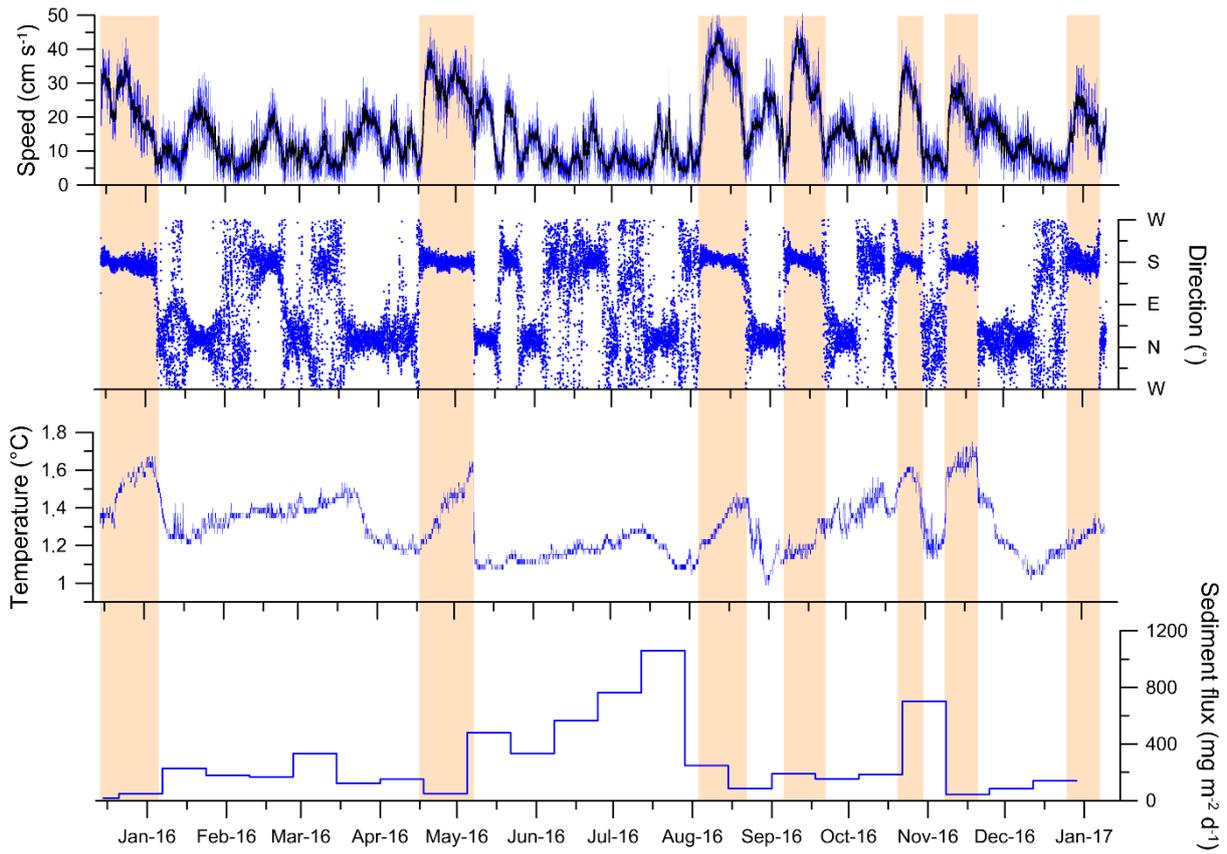
752 **Fig. 4.** Rose diagrams of current direction at 15 m above the seafloor at mooring sites MLP2, MLP3,
 753 MLP5, MLP8 and MLP10. The colours represent the current speed and the dark blue lines the
 754 orientation of the valley axis at the mooring sites. See Fig. 2 for mooring location.



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756 **Fig. 5.** Time series of the current speed at 15 m above the seafloor at mooring sites MLP2, MLP3,

757 MLP5, MLP8 and MLP10. See Fig. 2 for mooring location and colour codes.



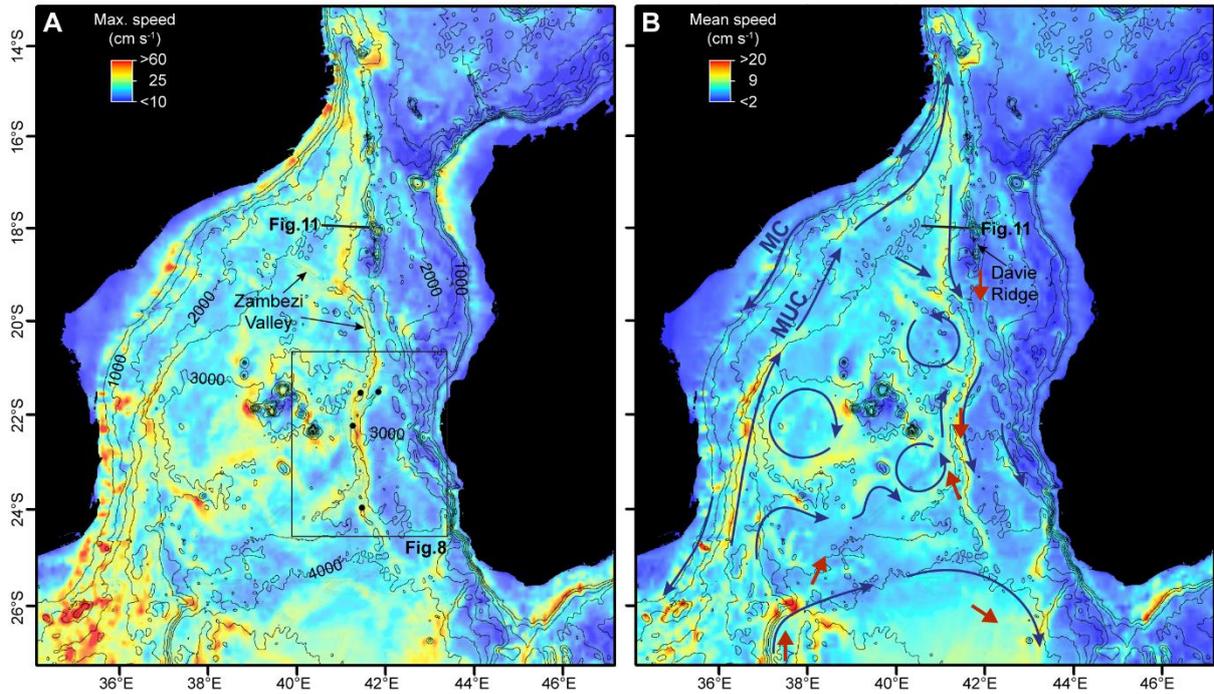
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Fig. 6. Time series of the current speed and current direction measured at mooring site MLP8 at 15 m above the seafloor, temperature measured at the same mooring at 30 m above the seafloor, and sediment flux from a sediment trap located at 40 m above the seafloor. See Fig. 2 for mooring location.

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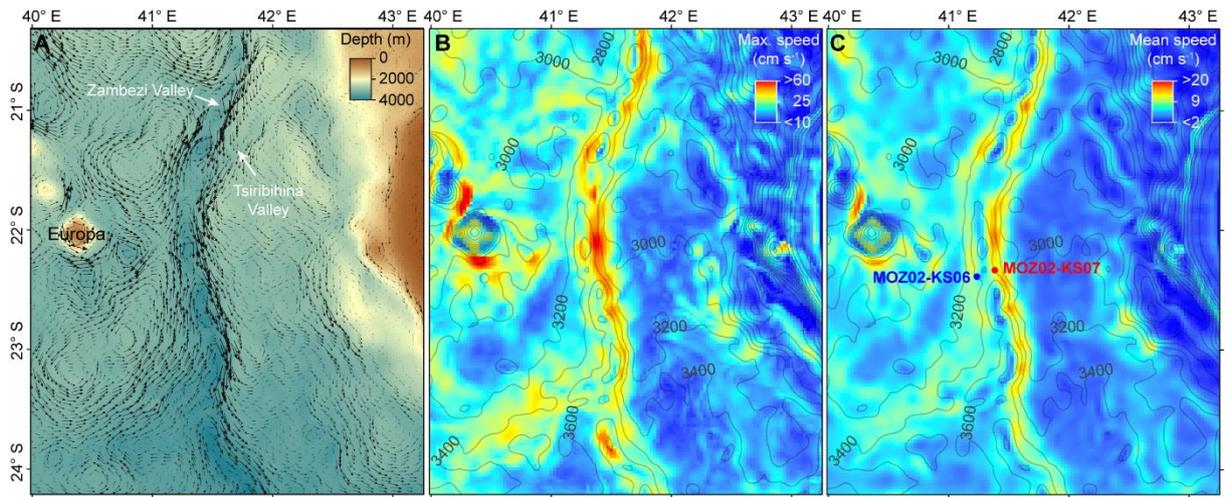
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765 **Fig. 7.** Bottom circulation in the Mozambique Channel simulated from 1993 to 2014 with the
 766 Regional Ocean Modelling System (ROMS) model: (A) Maximum speed. The black dots indicate the
 767 location of the mooring sites; (B) Mean speed. The schematic arrows represent the mean bottom
 768 current directions obtained from the hydrodynamic model. Depth contours are shown every 500 m.
 769 MC: Mozambique Current; MUC: Mozambique Undercurrent. The red arrows represent the current
 770 direction inferred from seafloor photographs by Kolla et al. (1980).

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775 **Fig. 8.** Zoom of the simulated bottom circulation at the Zambezi turbidite system: (A) Bathymetry and
 776 vectors of the mean bottom current velocity. The arrow size is proportional to the speed and the
 777 orientation to the current direction; (B) Maximum speed; (C) Mean speed. Contours of the model
 778 bathymetry are shown every 200 m. See Fig. 7 for location.

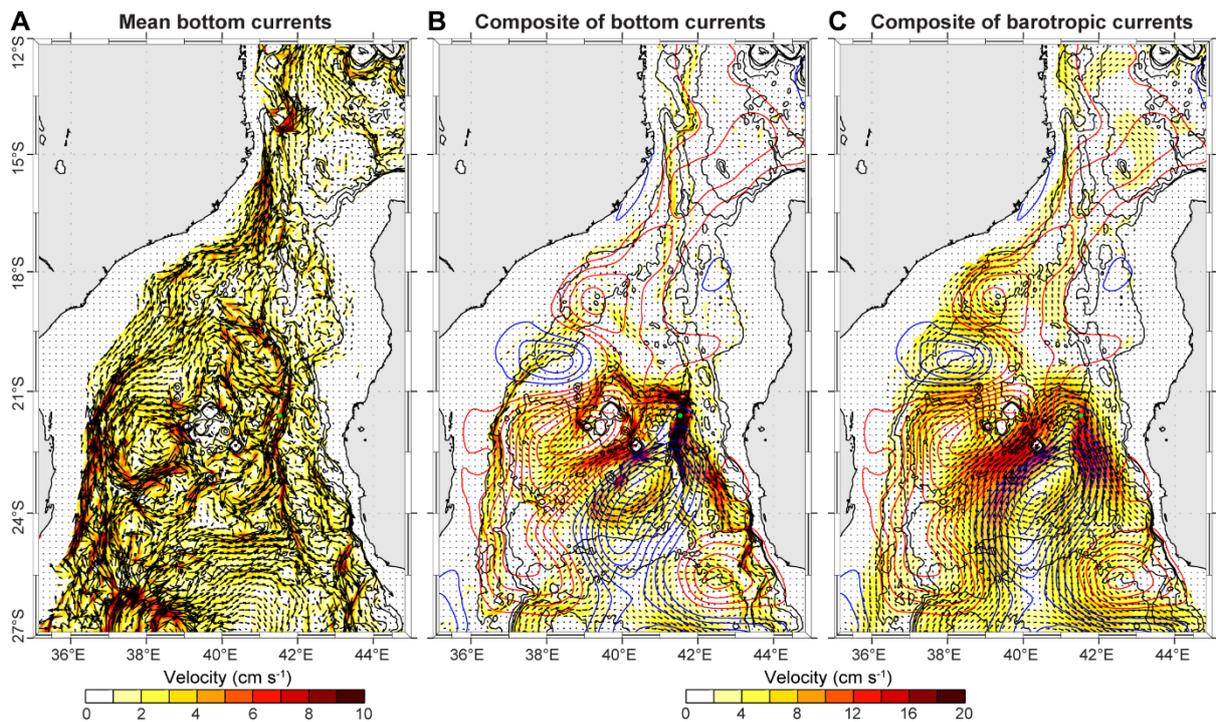
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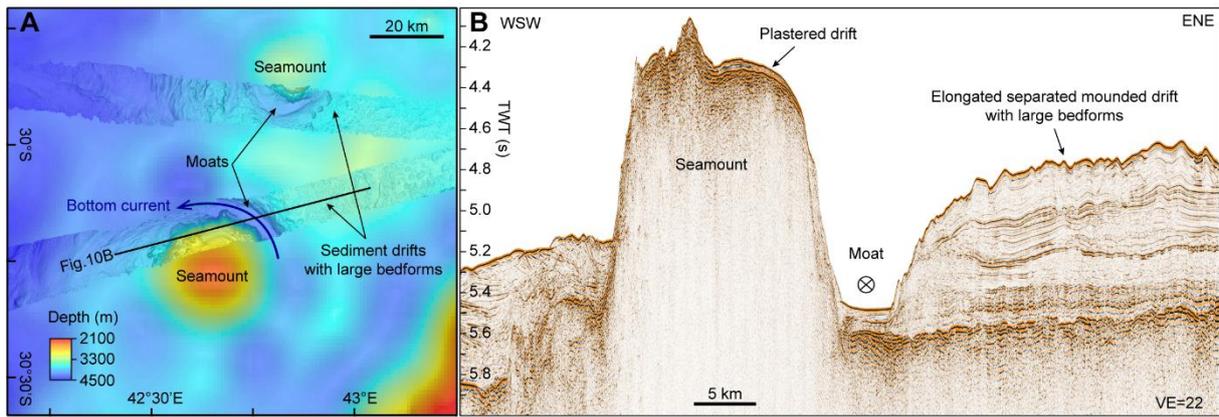


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785 **Fig. 9.** (A) Mean bottom currents obtained from the ROMS model for the period 1993-2014. (B)
 786 Composite of bottom currents obtained from the periods during which bottom currents at the
 787 mooring site MLP2 (indicated with a green dot) are above 25 cm s^{-1} , and composite of the Sea Level
 788 Anomaly (SLA) during these periods of time (red and blue contours). SLA contours (red and blue
 789 lines) for the same period of time are indicated every 1 cm. The blue contours indicate cyclones
 790 (SLA<0) and the red contours anticyclones (SLA>0). (C) Composite of barotropic currents (vertical
 791 average of the currents) during the same period of time as (B). SLA is also indicated. Bathymetric
 792 contours are indicated every 1000 m.

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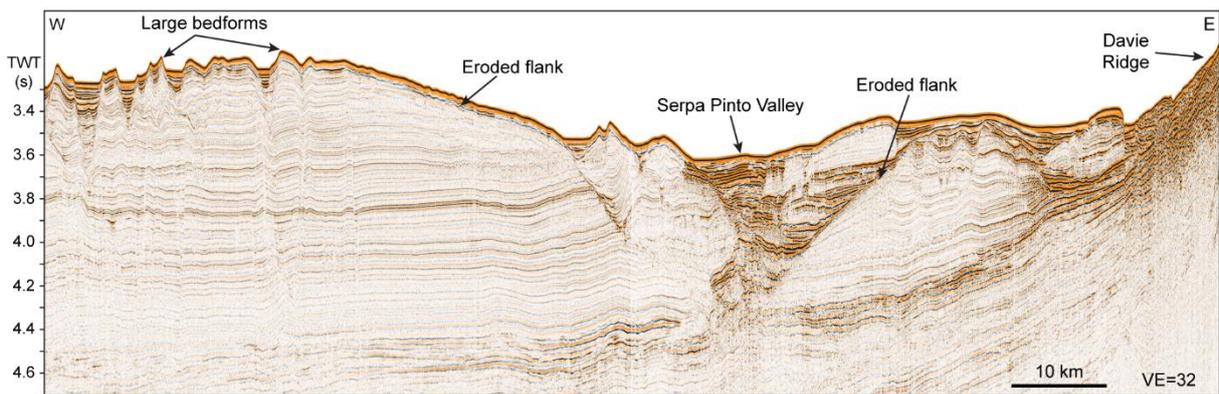
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796 **Fig. 10.** Moats and sediment drifts related to seamounts near the Madagascar Ridge. (A) Bathymetric
 797 map (Gebco 2008 and PAMELA multibeam bathymetric data). See Fig. 1A for location. (B) Multi-
 798 channel seismic reflection profile MOZ2-SR-21B (location in A).

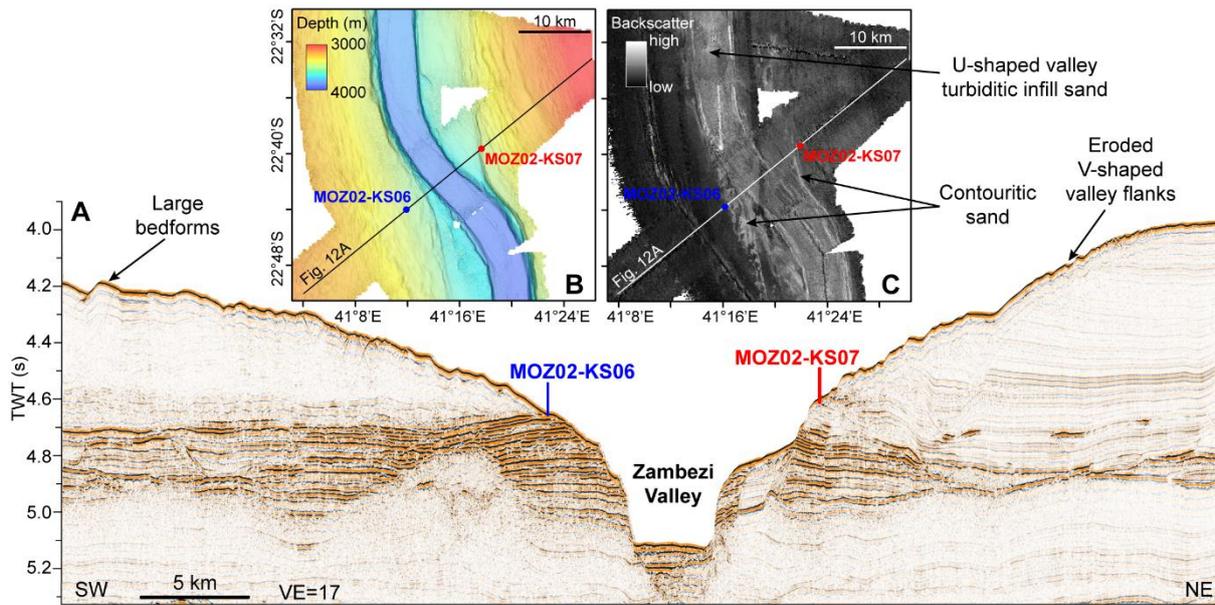
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801 **Fig. 11.** Multi-channel seismic reflection profile MOZ4-SR-024 showing current-related features such
 802 as large bedforms and erosional surfaces in the vicinity of the Serpa Pinto Valley. See Fig. 7 for
 803 location.

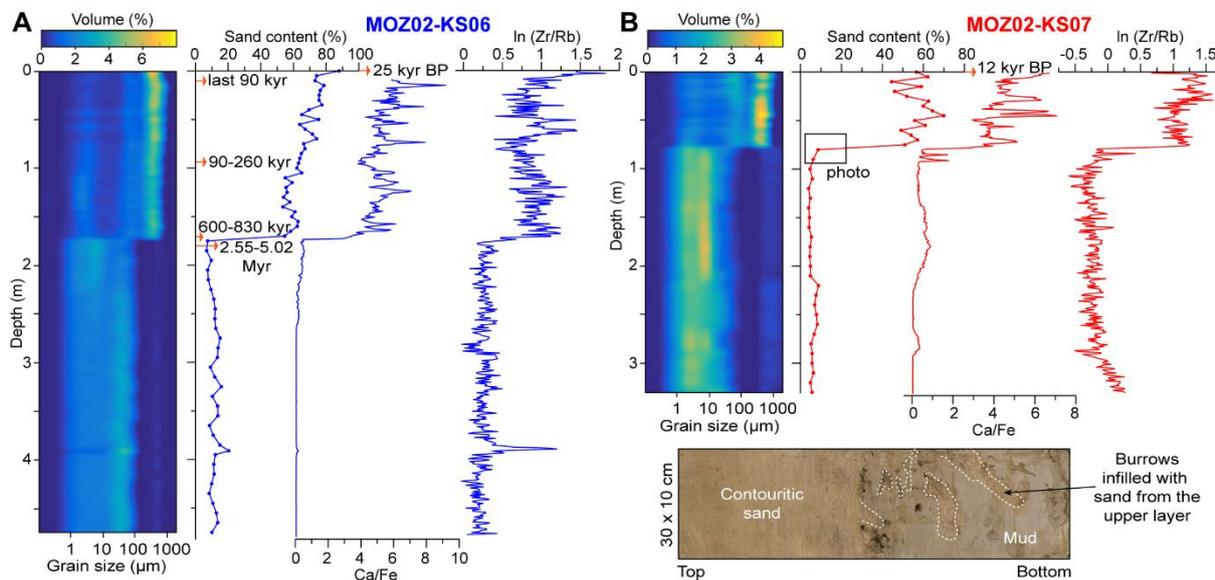
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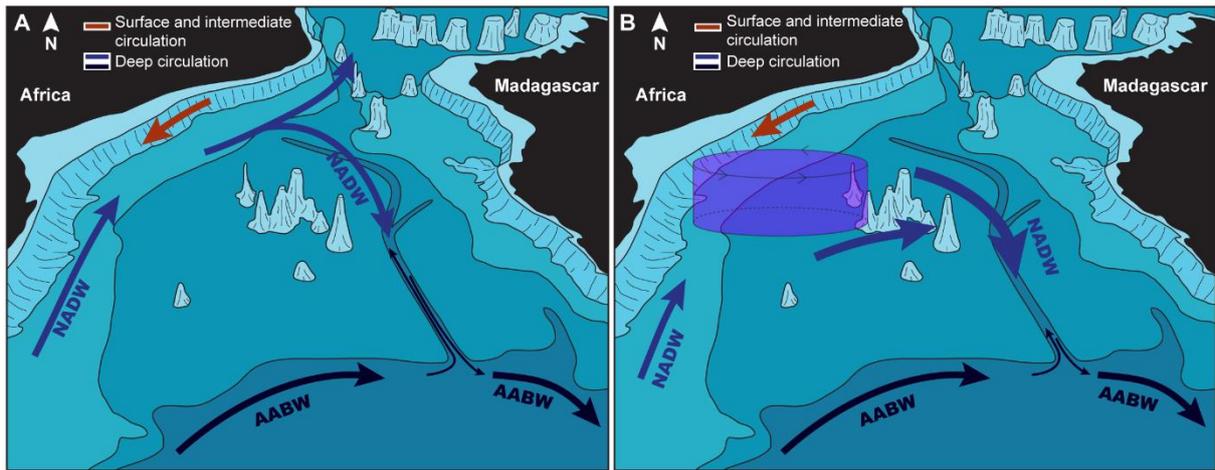
806 **Fig. 12.** Location of cores MOZ02-KS06 and MOZ02-KS07 on (A) multi-channel seismic reflection
 807 profile PTO-SR-002, (B) multibeam bathymetry and (C) backscatter image of the Zambezi Valley,
 808 showing high backscatter at the core sites. See Fig. 2 for location of B and C.

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811 **Fig. 13.** Grain size distribution, sand content, XRF Ca/Fe ratio and XRF nepierian logarithm of the
 812 Zr/Rb ratio of cores (A) MOZ02-KS06 and (B) MOZ02-KS07. The ages shown with red arrows were
 813 obtained from radiocarbon dating and from nannofossil assemblages. The photo shows in real colour
 814 the mud to contouritic sand transition in core MOZ02-KS07. See Fig. 12 for core location.



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816 **Fig. 14.** 3D sketch of the circulation in the Mozambique Channel. (A) Common circulation pattern
 817 with part of the North Atlantic Deep Water (NADW) flowing northwards along the Mozambican
 818 margin as part of the Mozambique Undercurrent, and part flowing back southwards along the
 819 eastern part of the basin. (B) Circulation pattern when an anticyclonic eddy is located between the
 820 Mozambican slope and the group of islands and seamounts in the centre of the Mozambique
 821 Channel, resulting in the intensification of the southward NADW transport, and deepening of the
 822 NADW and the Antarctic Bottom Water (AABW) interface.