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# Foraminiferal sandy contourite of the Limpopo Corridor (Mozambique margin): Facies characterization and paleoceanographic record

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## Highlights:

- Continuous and homogenous foraminiferal sandy contourite facies.
- Very low sedimentation rate of 0.26 cm.kyr<sup>-1</sup>.
- This sedimentary facies results from the action of strong bottom currents related to the AAIW/NADW interface.
- Bottom current speed increases during glacial stages and decreases during interglacial stages.

## Abstract:

Contourites encompass a wide variety of sedimentary facies. Some of them show common facies with others deep-water deposits, such as turbidites and hemipelagites. Sedimentological characterization at macro- and microscales is valuable to discriminate those close facies but the distinction is not always clear. Contourites are increasingly used in paleoceanographic and paleoclimatic reconstructions. Improving their characterization is therefore essential to their interpretations.

This study aims at characterizing a foraminiferal sandy contourite facies from a sediment core collected on top of a contourite drift under the influence of the Antarctic Intermediate Water/North

29 Atlantic Deep-Water interface located in the Limpopo Corridor (Mozambique margin, Indian Ocean) at  
30 2000 meters depth. This work is based on a detailed analysis of the sedimentary record using physical  
31 properties (gamma density and magnetic susceptibility) as well as laser grain size and X-Ray  
32 Fluorescence core scanning data.

33 Our results show that: (1) the foraminiferal sand is vertically continuous and homogenous over  
34 633 kyr with an average sedimentation rate of 0.26 cm.kyr<sup>-1</sup>; (2) this contourite facies results from  
35 sedimentation with low terrigenous inputs under stable hydrodynamic conditions over time, with  
36 relatively strong bottom currents for this water depth (~16 cm.s<sup>-1</sup>); (3) during glacial stages,  
37 sedimentation rates are lower and bottom current speed is higher than during interglacial stages. We  
38 also propose the concept of “Contourite Graphical Chart” which summaries the theoretical distribution  
39 of contourite endmembers from cross-plot of “sorting versus grain-size median D<sub>50</sub>” and their related  
40 sedimentary processes.

41 This study highlights the relevance of condensed foraminiferal sandy contourites as long time-  
42 scale paleoceanographic archives and provides new insights for studies related to paleoclimatology and  
43 paleoecology.

44  
45 **Keywords:** bottom current; contourite; foraminiferal sand; paleoceanography; Mozambique Channel;  
46 Indian Ocean; Quaternary.

## 47 1. INTRODUCTION

48 Contourites are sediments deposited or significantly affected by the action of bottom currents  
49 (Stow et al., 2002; Rebesco, 2005; Stow and Faugères, 2008). Their accumulations, i.e., contourite drifts  
50 and related erosional features, i.e., contourite channels, moats and furrows, form large sedimentary  
51 structures on continental margins called contourite depositional systems (Hernández-Molina et al.,  
52 2003). Since their discovery in the 1960s (Heezen and Hollister, 1964; Hollister, 1967), contourite drifts  
53 have raised a growing interest for their applications in the petroleum industry as potential reservoir  
54 (e.g., Viana and Rebesco, 2007; Sansom, 2018; Fonnesu et al., 2020; Yu et al., 2020), paleoclimatic and  
55 paleoceanographic studies as high resolution sedimentary records (e.g., Knutz, 2008; Miramontes et al.,

56 2016; Tallobre et al., 2017; Gruetzner et al., 2019; Martorelli et al., 2021), sequence stratigraphy and  
57 slope instability for their influence on continental margin morphologies (e.g., Brackenridge et al., 2011;  
58 Mosher et al., 2017; Miramontes et al., 2018). At large scale, morphological features and internal  
59 structures of contourite drifts are well recognized from seismic profiles and bathymetric data, but at  
60 macro- and microscale, discrimination of contourites from other deep-water sedimentary deposits is  
61 still challenging.

62 Contourites are part of a sedimentary continuum from continental shelves to deep-sea basins  
63 (summarized in Stow and Smillie, 2020). Therefore, contourites are often associated or mixed with  
64 other sedimentary deposits like turbidites, hemipelagites or debrites (Rebesco et al., 2008). To establish  
65 clear criteria to distinguish contourites, most of the recent studies highlight the usefulness of sediment  
66 characterization according to their grain-size parameters (i.e., grain-size indicators such as  $D_{50}$ , sorting,  
67 skewness, kurtosis), principal component analysis and their microstructural features (Brackenridge et  
68 al., 2018; Bankole et al., 2021; de Castro et al., 2020, 2021a, b; Rodrigues et al., 2022). These studies  
69 provided useful tools to discriminate contourites from other deep-water deposits, and need to be  
70 complemented by further work on lesser-known contourites to obtain a comprehensive understanding.

71 The Atlantic-Indian Ocean gateway is a key element of the global ocean thermohaline circulation  
72 (de Ruijter et al., 1999; Sloyan and Rintoul, 2001). It constitutes an exchange area where warm Indian  
73 Ocean surface waters enter the Atlantic Ocean and with the volume lost are compensated at depth by  
74 the influx of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW). The seismic study  
75 of Gruetzner et al. (2019) on a contourite drift from the Agulhas Plateau (South Africa, Fig.1) has  
76 shown that the most important global climate and oceanographic changes of the last 7 Ma can be  
77 recorded in contourite drift sedimentation and used to understand the regional bottom current paleo-  
78 variability. In that study area, only two studies have explored the behavior of bottom currents over the  
79 last 200 kyr (Molyneux et al., 2007; Krueger et al., 2012) and suggest an increase of NADW during glacial  
80 stages.

81 To the north-east of the Agulhas Plateau, the Mozambique Channel hosts a huge diversity of  
82 contourite systems and provides a good area for the study of contourite deposits and bottom current

83 behavior over the Plio-Quaternary (Breitzke et al., 2017; Counts et al., 2018; Thiéblemont et al., 2019,  
84 2020; de Castro et al., 2021b; Evain et al., 2021; Miramontes et al., 2019, 2020, 2021; Babonneau et al.,  
85 2022). In the scope of the Passive Margins Exploration Laboratories project (PAMELA), the PAMELA-  
86 MOZ3 cruise (Moulin and Aslanian, 2016) has acquired five piston cores (MOZ3-CS03, CS02, CS07, CS06  
87 and CS05) in a contourite system located in the Limpopo Corridor (Figs. 1 and 2). Recent results of  
88 Babonneau et al. (2022) on this contourite system have highlighted the existence of a contourite facies  
89 composed of foraminiferal sand covering the 11.47 m length of core MOZ3-CS07. Based on two  
90 strontium dating at 6 and 11 m, the foraminiferal sand seems to be continuous and condensed over 5  
91 Ma with very low sedimentation rate about  $0.3 \text{ cm.kyr}^{-1}$  and without influence of gravity deposits or  
92 erosional features (Fig. 3). Therefore, this sedimentary succession could provide a good record for  
93 Plio-Quaternary paleoceanographic/paleoclimatic reconstructions and contourite characterization.

94 Bioclastic contourite, and in particular foraminiferal sandy facies, are very poorly known. Some  
95 studies mention their existence within contourite systems (Lonsdale and Malfait, 1974; Huizhang and  
96 McCave, 1990; Robinson and McCave, 1994; Mulder et al., 2019), but none of them has really studied  
97 their characteristics and their depositional processes in depth. However, it is frequently observed in  
98 outcrops within fossilized contourites (Schiller et al., 1994; Carter, 2007; Hüneke et al., 2021;  
99 Hernández-Molina et al., 2022).

100 This study is a continuation of the work of Babonneau et al. (2022) with three objectives: (1)  
101 improve the knowledge on foraminiferal sandy contourite using physical, geochemical and grain-size  
102 analyses on core MOZ3-CS07; (2) compare characteristics of the foraminiferal sandy contourite facies  
103 with other sandy facies found in the same contourite system; and (3) explore its potential as  
104 sedimentary record of paleoceanographic changes.

## 105 2. REGIONAL SETTING

### 106 2.1. Geodynamic setting

107 The Mozambique Basin is located in the south-west of the Indian Ocean, between Africa and  
108 Madagascar (Fig. 1). Its formation results from the breakup of Gondwana and the southwards  
109 movement of eastern Gondwana (i.e., Madagascar, India, Australia and Antarctica) in respect to the

110 western Gondwana (South America and Africa) during the Jurassic (Thompson et al., 2019). The  
111 Mozambique Basin is fringed to the east by the Davie Fracture Zone (DFZ), which marks the dextral  
112 southward movement of Madagascar in respect to Africa between 155 Ma and 120 Ma (Fig. 1). To the  
113 west, the Mozambique Fracture Zone (MFZ) marks the southward drift of the Antarctica plate  
114 (Watkeys and Sokoutis, 1998; Jokat et al., 2003; Gradstein et al., 2012; Leinweber et al., 2013; Thompson  
115 et al., 2019). The southern part of the Mozambique Channel hosts two major topographic highs (Fig. 1):  
116 the Mozambique Ridge to the West (MozR) and the Madagascar Ridge to the East (MadR).

117 The western part of the Mozambique Channel, the Limpopo Corridor, is marked by high positive  
118 gravity anomalies (e.g., Mueller and Jokat, 2017) but recent data acquired during the PAMELA project  
119 showed that these anomalies are related to large and thick contourite drifts above a thin continental  
120 intruded crust (Moulin et al., 2020; Evain et al., 2021; Li et al., 2021; Matsinhe et al., 2021).

121 The Limpopo Corridor corresponds to a strike-slip or slightly transtensional margin, where the MFZ  
122 marks the continent-ocean transition (Evain et al., 2021).

## 123 ***2.2. Oceanographic and morpho-sedimentary setting***

124 The ocean circulation within the Mozambique Channel is constrained by its complex and incised  
125 morphology. The warm and surface water masses (>1200 m) coming from the northern Indian Ocean  
126 and the Red Sea, constitute the Mozambique Current (MC) and flow preferentially southward along the  
127 African coast (Fig. 1). Conversely, the intermediate and deep-water masses from the Atlantic (North  
128 Atlantic Deep Water "NADW" 2200-3500 m) and Antarctic (Antarctic Intermediate Water "AAIW" 800-  
129 1500 m and Antarctic Bottom Water "AABW" >4000 m) flow northwards (de Ruijter et al., 2002; Ullgren  
130 et al., 2012; Miramontes et al., 2019). Bottom currents strongly interact with the seafloor and their  
131 circulation is impacted by the submarine reliefs. The AABW and part of the NADW are thus redirected  
132 in a southward rip current to meet the shoals of the Northern Mozambique Basin (Fig. 1; van Aken et al.,  
133 2004; Miramontes et al., 2019). The oceanographic circulation in the Mozambique Channel is also  
134 affected by large oceanic eddies coming from the north and the east, flowing southward along the  
135 African margin. These eddies are known to impact the seafloor until 3000 meters below the sea-level  
136 (mbsl; Fig. 1; Sætre and da Silva, 1984; Swart et al., 2010; Halo et al., 2014).

137 Thiéblemont et al. (2019) mapped the contourite depositional system of the Limpopo Corridor.  
138 Their results show four contourite terraces, and they propose as the main factors for the formation of  
139 these contourite terraces, the internal waves of tidal period generated at the transition zone between  
140 two water masses.

141 Gao et al. (2020) and Thiéblemont et al. (2020), confirmed the influence of water mass  
142 circulation and their interactions on the shaping of the African margin. Using seismic reflection data  
143 acquired in the northern Mozambique margin, their work shows the morpho-sedimentary evolution of  
144 the ridge since the Cretaceous in relation to changes in global ocean circulation. They defined four stages  
145 of sedimentary construction: (1) Lower Cretaceous, development of progradational clinoforms with  
146 hemipelagite drape after the initial break-up phase; (2) Upper Cretaceous, development of the first  
147 contourite system; (3) Paleocene-Eocene, sedimentation dominated by gravity processes; (4) Middle  
148 Miocene, re-establishment of contourite systems in the lower part of the continental slope with the  
149 formation of the various present contourite terraces.

### 150 ***2.3. Contourite system studied***

151 The study area is characterized by the presence of a contourite system located in the Limpopo  
152 Corridor between 1800 and 2200 mbsl (Fig. 1). It is 75 km long and 50 km wide, with a NNE-SSW  
153 orientation. The system is divided into two mounded drifts, surrounded by two main channels on the  
154 eastern and western edges, separated by an intermediate channel (Fig. 2A). According to the closest  
155 water mass depths measurement from our study area (Thiéblemont et al., 2019; Gao et al., 2020), the  
156 present contourite system is located at the transition zone between the base of the AAIW (1500 mbsl)  
157 and the top of the NADW (2200 mbsl; both flowing northward) corresponding to a progressive change  
158 in seawater density about 700 m thick (Thiéblemont et al., 2019).

159 Babonneau et al. (2022) studied the sedimentary architecture of the contourite system since the  
160 Cretaceous based on seismic profile and its recent behavior through stratigraphic correlations from  
161 sediment cores. The contourite drift evolution shows three stages of construction (Fig. 3): (1) initiation  
162 and development of the drift/channel system from the Cretaceous to the Miocene; (2) an intermediate  
163 stage with successive incisions/aggradations, and; (3) channel infill and drift erosion since the Plio-

164 Quaternary. The depositional process of the contourite system during the stage 3 is explained by the  
165 lateral and vertical change in the area of high current speed and by the morphological evolution of the  
166 system itself. This stage of channel filling is also recognized by Thiéblemont et al. (2020) and interpreted  
167 as resulting from the onset of NADW and AAIW in the Southern Hemisphere during the middle Miocene,  
168 which significantly changed the water circulation along the Mozambique margin.

169 Since the Plio-Quaternary, the drift growth has stopped. Low sedimentation rates of 3 to 1.9  
170 cm.kyr<sup>-1</sup> are recorded in the western channel, and about 0.3 cm.kyr<sup>-1</sup> on the western flank of the drift.  
171 The top and the eastern flank of the drift are in erosion. The sedimentary facies vary from the western  
172 to the eastern part of the contourite system, with mixed siliciclastic-bioclastic sediments (clay to  
173 fine-sand in grain size) in the western channel, transitioning into pelagic-sourced bioclastic sands  
174 (foraminifers dominated) near the top of the drift (Fig. 3).

### 175 3. MATERIALS AND METHODS

#### 176 3.1. *Bathymetry and sediment cores*

177 Five Calypso piston cores (Figs. 2 and 3) were collected on the contourite system during the  
178 PAMELA-MOZ3 oceanographic cruise aboard the R/V "Pourquoi pas?" (Moulin and Aslanian, 2016) at  
179 water depths ranging from 1853 to 2125 mbsl (Table 1 and Fig. 2). All<sup>[ul5]</sup><sup>[ul6]</sup> the data acquired on the  
180 piston cores are summarized in Table 2.

181 The regional bathymetric map (Fig. 1) is the "General Bathymetric Chart of the Ocean"  
182 (GEBCO\_08, version 2010-09-27, <http://www.gebco.net>). The detailed bathymetry (Figs. 2A and 2B) is  
183 acquired with a multibeam echosounder (SMF) ©RESON-Seabat 7150 bi-frequency 12/24 kHz, allowing  
184 the acquisition of reflectivity images and the bathymetry of the seafloor with 20x20m resolution grid.  
185 The MOZ3-SDS-0038 seismic profile (Fig. 2C) was acquired with a CHIRP sediment echosounder with a  
186 signal frequency varying between 5300 and 1800 Hz, allowing for ~80 m penetration into the sediment  
187 with an average resolution of 0.75 m.



### 188 **3.2. X-Ray Fluorescence (XRF) core scanner and Multi-Sensor Core Logger (MSCL) data**

189 X-Ray Fluorescence (XRF) measurements are used to analyze the variations of the geochemical  
190 composition of the sediment. XRF measurements were performed at a 1 cm interval with the Avaatech  
191 X-Ray Core Scanner from Ifremer on split cores. Two energy sources were used (10 and 30 kv at 0.6 mA  
192 and 1 mA) to measure the semi-quantitative value (in count per second) of more than 25 elements  
193 having an atomic mass between aluminum and uranium. Among them, we use the log-normalized ratios  
194  $\ln(\text{Ca/Fe})$  and  $\ln(\text{Zr/Rb})$  as a respective indicator of the terrigenous versus biogenic sediment  
195 proportion and as an indicator of the bottom current intensity (Weltje and Tjallingii, 2008; Vandorpe et  
196 al., 2019; Wu et al., 2020).

197 Physical parameters (gamma-density and magnetic susceptibility) were acquired with a Multi-  
198 Sensor Core-Logger (MSCL Geotek Ltd) at Ifremer (Brest), with a sampling interval of 1 cm. X-ray  
199 radiography (CT scan, Geotek Ltd) was also acquired on the core half-sections at Ifremer (Brest).

### 200 **3.3. Grain-size analysis**

201 Laser grain-size measurements were performed on bulk sediment with the ©Malvern 2000G  
202 from UMR Geo-Ocean (Brest) giving an accurate measurement of particles with a size from 0.02 to 2000  
203  $\mu\text{m}$ . A total of 907 measurements were performed on cores MOZ3-CS03, MOZ3-CS02, MOZ3-CS07 and  
204 MOZ3-CS06. On the cores MOZ3-CS03, MOZ3-CS02 and MOZ3-CS06, measurements were performed on  
205 selected parts (most frequently on coarser intervals), whereas on MOZ3-CS07, sampling resolution  
206 ranges from 1 to 3 cm and is defined according to the  $\ln(\text{Ca/Fe})$  and  $\ln(\text{Zr/Rb})$  curves. For all core  
207 samples, ~10 mg of sediment was collected over a 5 mm width, placed in distilled water for 24 hours  
208 and vibrated during 4 minutes to deflocculate the particles before laser grain-size measurement.

209 The grain-size data were processed with the GRADISTAT program (Blott and Pye, 2001). The  
210 grain-size indicators (sorting, skewness and  $D_{50}$ ) were calculated using the method of Folk and Ward  
211 (1957). The grain-size fractions used are those defined by Friedman and Sanders (1978). The use of  
212 cross-plots "skewness versus  $D_{50}$ " and "sorting versus  $D_{50}$ " provides the characterization of the grain-  
213 size sorting evolution and grain-size distribution trend as a function of the increase of the  $D_{50}$  for each  
214 sample (Blott and Pye, 2001).

215 **3.4. Microfacies**

216 Microfacies analyses were performed at TotalEnergies Scientific and Technical Center (Pau)  
217 with Qemscan ® technology, which allows inventory, mapping and particle count on the sections. A total  
218 of twelve thin sections were analyzed and collected for the core MOZ3-CS07 (Table 3). For each section,  
219 the proportion of quartz, feldspar, carbonate, clay and mica, as well as unidentified elements (“Others”),  
220 is given. Bulk quantitative mineralogy (BQM) analysis, including elementary composition by DX, density,  
221 insoluble residue, loss on ignition (LOI) and cation exchange capacity (CEC) measurements were carried  
222 out in addition on 4 of these samples for calibration. Qemscan ® and BQM analysis diverge slightly in a  
223 few cases (heavy minerals, quartz content).

224 **3.5. Isotopic stratigraphy**

225 Oxygen isotope ( $\delta^{18}\text{O}$ ) measurements were performed on planktonic foraminifers,  
226 *Globigerinoides ruber*. On core MOZ3-CS07, 233 samples were collected from 1 to 4.93 meters below the  
227 seafloor (mbsf) with the same resolution as grain-size measurements (Table 2). On average, for each  
228 sample, 12 specimens were picked (representing 60-120  $\mu\text{g}$ ) in the fraction  $>250 \mu\text{m}$  and analyzed using  
229 the MAT253-KIEL IV isotope ratio mass spectrometer at the IUEM (Brest). Samples are normalized with  
230 a standard routine MNHN (V-PDB=-1.93 and std=0.03) and with the international carbonate standards  
231 NBS-18=-23.20 and NBS-19=-2.20. The analytical precision is  $< 0.05\%$ .

232 To complete the oxygen isotope measurements, 38 new strontium isotope measurements were  
233 performed between 3.51 and 11.45 mbsf (Table 2 and 4) using the Sr Isotope Stratigraphy method (SIS;  
234 Elderfield, 1968; McArthur, 1994). Samples (foraminifer tests or bulk material) are dissolved in weak  
235 acetic acid. After centrifugation and evaporation to dryness, dry residues are taken up into 1 ml of  $\text{HNO}_3$   
236 1M and centrifuged before loading on Biorad® columns using Triskem® Sr resin (Pin and Santos  
237 Zalduegui, 1997). Sr is eluted in 2 ml of hot ultrapure  $\text{H}_2\text{O}$ . Samples are loaded on W filaments for  
238 thermal ionization mass spectrometry (TIMS) measurements. Sr isotope compositions were measured  
239 in static mode on a Thermo TRITON at the PSO (Pôle de Spectrométrie Océan) in Brest, France. All  
240 measured ratios are normalized to  $^{86}\text{Sr}/^{88}\text{Sr}=0.1194$  and the Sr isotope compositions of standard  
241 solution NBS987 is routinely measured with a frequency of one full analysis each five samples. Six

242 measurements were made on bulk sediment and 34 measurements were made on the fraction >250  $\mu\text{m}$   
243 (Table 4) to remove as much as possible the detrital sediments and keep exclusively the carbonates,  
244 composed mainly of foraminiferal tests.

## 245 4. RESULTS

### 246 4.1. *Facies and sedimentological characteristics*

#### 247 4.1.1. *Facies*

248 Core MOZ3-CS07 presents a single homogenous sedimentary facies, beige, composed of 76.5%  
249 fine sand (mostly foraminifers), 19.9% silt and 3.6% clay (Fig. 4). The facies is slightly bioturbated,  
250 lamination is difficult to discern (Fig. 5). On the X-ray images, pseudo-cross-bedding can be seen in the  
251 lower part of the core (at 9 and 10 mbsf, Fig. 4). Despite being mainly homogenous, the facies of core  
252 MOZ3-CS07 shows two variations: (1) foraminiferal pockets, corresponding to lighter intervals with  
253 coarser sediments, low content of fine particles and present mainly in the upper part of the core; (2)  
254 very fine mottled sand, corresponding to darker intervals with finer sediments, characterized by the  
255 presence of black spots (reduced organic matter) and a higher proportion of clay (Figs. 4 and 5).

256 The magnetic susceptibility and gamma density curves indicate similar trends, with values  
257 ranging respectively from 5 to 22  $\text{SI}^{-1}$  and from 1.4 to 1.8  $\text{g}\cdot\text{cm}^{-3}$  (Fig. 4). Magnetic susceptibility shows  
258 an increase from the base of the core to 7.5 mbsf, then a progressive decrease to the top of the core with  
259 higher variations. Gamma density shows a progressive decrease from the bottom to the top of the core  
260 that appears to be related to the increase in grain size indicated by a decrease in clays and silts and an  
261 increase in sands and  $D_{50}$  (Fig. 4).

262 The  $\ln(\text{Ca}/\text{Fe})$  ratio reveals an increase in the amount of terrigenous sediment from the base to  
263 8 mbsf, followed by a progressive increase in the amount of biogenic sediment to the top of the core.  
264 The  $\ln(\text{Zr}/\text{Rb})$  ratio indicates a slight increase in current intensity during deposition according to the  
265 increase in grain size described above. In general, an increase in the proportion of biogenic sediments  
266 and current intensity is observed during the facies formation.

267 *4.1.2. Composition and microfacies*

268 Based on microfacies analyses, the sediment is defined as a foraminiferal calcarenite with a small  
269 proportion of silty-clayey mud. The proportion of carbonates varies between 60 and 76%, and the  
270 proportion of clay and mica between 6 and 12% (Table 3). The other minerals (i.e., quartz and feldspar)  
271 are less abundant and represent between 1.8 and 10% of the sediment.

272 The detailed description of section 3 (Fig. 5) illustrates the general sedimentary facies  
273 composition of core MOZ3-CS07. The X-ray images and photography show a homogenous sediment with  
274 no or unclear erosional structures and bioturbation traces. The very fine mottled sands are  
275 systematically marked by an increase in gamma density, magnetic susceptibility, clays and silts  
276 (corresponding to silty-clayey mud) and by a decrease in  $D_{50}$ , and conversely for the foraminiferal  
277 pockets. The proportion of silty-clayey mud varies between 10 and 40%. The sample taken at 2.36 mbsf  
278 is composed of 62.8% carbonates, 24.5% clay and mica, 7.8% feldspar and 3.7% quartz (Fig. 5B).

279 **4.2. Grain-size analysis of core MOZ3-CS07**

280 *4.2.1. Grain-size distribution*

281 Grain-size measurements on core MOZ3-CS07 provide an average grain-size distribution (Fig.  
282 6) that corresponds to a coarse silty sand sediment, very poorly sorted and finely skewed. On average,  
283 the mean grain size is 157  $\mu\text{m}$ , the  $D_{50}$  is at 344  $\mu\text{m}$ , and the grain-size distribution is unimodal with  
284 a mode at 598  $\mu\text{m}$ . Nevertheless, two other peaks not considered as modes are observable at 3 and 100  
285  $\mu\text{m}$ . The general shape of the grain-size distribution allows us to divide it into two major fractions: (1)  
286 the fraction  $>30 \mu\text{m}$ , corresponds to 80% of the sediment, it is composed mostly of foraminifer tests and  
287 in lesser proportion of quartz grains, feldspar and fragmented or juvenile foraminifer tests (Qemscan  
288 analysis, Fig. 6); (2) the fraction  $<30 \mu\text{m}$ , corresponds to 20% of the sediment, represented by a silty-  
289 clayey mud composed of clays and micas.

290 *4.2.2. Grain-size modes*

291 The grain-size distributions of the samples are characterized according to their number of  
292 modes. Four types of grain-size distributions are identified with the GRADISTAT program (Fig. 7):

293 -unimodal distributions, characterized by low variance and a major mode at 600  $\mu\text{m}$ . The curves  
294 also show two other peaks not considered as grain-size modes at 3 and 100  $\mu\text{m}$ .

295 -bimodal distributions, with mode 1 also located at 600  $\mu\text{m}$  and mode 2 between 2 and 3  $\mu\text{m}$ .  
296 Some distributions, such as the red curve in figure 7, show modes 1 and 2 in the fraction  $>30$   $\mu\text{m}$  at 500  
297 and 100  $\mu\text{m}$  respectively.

298 -trimodal distributions, with mode 1 around 500  $\mu\text{m}$ , modes 2 and 3 are located either in the  
299 fraction  $<30$   $\mu\text{m}$  or in the fraction  $>30$   $\mu\text{m}$ .

300 -quadrимodal distributions show a high diversity of grain-size distributions. On average, mode  
301 1 mostly corresponds to 500-600  $\mu\text{m}$ , mode 2 to 100  $\mu\text{m}$ , mode 3 to 3  $\mu\text{m}$  and the fourth mode to 20  $\mu\text{m}$ .

302 The unimodal and bimodal distributions are the most represented, with 230 and 216 samples,  
303 respectively. The proportion of the fraction  $<30$   $\mu\text{m}$  increases significantly between the unimodal and  
304 bimodal distributions from 12.9% to 25.3% and is approximately the same for the trimodal and  
305 quadrимodal distributions with respectively 27.5% and 27.2%. The frequency of occurrence of  
306 unimodal distributions increases towards the top of the core and is correlated with sand enrichment  
307 during deposition (Fig. 4). The other distributions are observed rather in the lower part of the core.

#### 308 *4.2.3. Sorting/Skewness versus $D_{50}$*

309 The cross-plot of "skewness versus  $D_{50}$ " shows two trends: (1) for bimodal, trimodal, and  
310 quadrимodal distributions, as  $D_{50}$  increases, skewness increases; (2) for unimodal distributions, as  $D_{50}$   
311 increases, skewness decreases. Thus, for bimodal, trimodal, and quadrимodal distributions, an increase  
312 in  $D_{50}$  results in a higher deviation of the distribution toward fine particles, and thus a larger proportion  
313 of the fraction  $<30$   $\mu\text{m}$ . Conversely, for unimodal distributions, the larger the grain size is, the more  
314 symmetrical the grain-size distribution is, and the lower the fraction  $<30$   $\mu\text{m}$  is.

315 Two trends in sorting are also observed: (1) for bimodal, trimodal, and quadrимodal  
316 distributions, there is no clear relationship between  $D_{50}$  and sorting; (2) for unimodal distributions,  
317 there is an increase in sorting as  $D_{50}$  increases. The most poorly sorted sediments are those with  
318 bimodal, trimodal and quadrимodal distributions. For unimodal distributions, there is a progressive

319 increase in sorting as  $D_{50}$  increases. A trend can be defined that the coarser the grain size is, the fewer  
320 the modes are and the better the sediment is sorted.

321 For both cross-plots shown in figure 8, the transition zone between the two trends for bimodal  
322 and unimodal distributions suggests that some bimodal distributions could be reinterpreted as  
323 unimodal and *vice versa*.

#### 324 **4.3. Grain-size comparison with the other cores**

325 To complete the characterization of the sedimentary facies from cores MOZ3-CS03, MOZ3-CS02,  
326 MOZ3-CS07 and MOZ3-CS06 performed by Babonneau et al. (2022), the grain-size samples are analyzed  
327 using a cross-plot of "sorting versus  $D_{50}$ " (Fig. 9).

328 The sediments of core MOZ3-CS07 (yellow points, Fig. 9) form a continuous point cloud ranging  
329 from a very poorly sorted sediment with a  $D_{50}$  of 70  $\mu\text{m}$  to a moderately well sorted sediment with a  $D_{50}$   
330 of 700  $\mu\text{m}$ . The sediments of core MOZ3-CS03 (green points) are more diffuse, but broadly divided  
331 between a point cloud showing very poorly sorted and very fine sediment with a  $D_{50}$  ranging from 7 to  
332 70  $\mu\text{m}$  and a second point cloud showing moderately sorted to moderately well sorted sediments with  
333 a  $D_{50}$  around 140  $\mu\text{m}$ . The sediments of core MOZ3-CS02 (blue points) mark the transition between the  
334 point clouds of MOZ3-CS03 and MOZ3-CS07. For moderately sorted to moderately well sorted  
335 sediments, the points of MOZ3-CS02 correspond to the sediments with the highest  $D_{50}$ , at 900  $\mu\text{m}$ .  
336 Finally, 12 laser grain-size measurements were performed in the foraminiferal sand and muddy  
337 sediments of core MOZ3-CS06 (red points in Fig. 9). These measurements belong to the best sorted and  
338 coarsest sediments for the foraminiferal sand and the worst sorted and finest points for the muddy  
339 sediments.

340 Figure 10 shows the mean grain-size distribution and the mineral composition for the four  
341 sedimentological poles of the figure 9 called; "Mainly terrigenous", "Mainly biogenic", "Siliciclastic sand"  
342 and "Foraminiferal sand" after interpretation. The mineral composition of each grain-size mode (Fig.  
343 10) is determined from Qemscan analysis.

344 -The pole "Mainly terrigenous" based on samples from the core MOZ3-CS03, shows a bimodal  
345 distribution with the mode 1 at 4  $\mu\text{m}$  composed of clay and mica, representing 50% of the sediment; the

346 mode 2 at 70  $\mu\text{m}$  composed of quartz and feldspar representing 40% of the sediment and a peak at 400  
347  $\mu\text{m}$  composed of foraminifer tests representing 10% of the sediment.

348 -The pole “Mainly biogenic” based on samples from the cores MOZ3-CS07 and MOZ3-CS02,  
349 reveals a bimodal distribution with the mode 1 at 400  $\mu\text{m}$  mainly composed of foraminifer tests and in  
350 lesser proportion of quartz and feldspar, representing 75% of the sediment and; the mode 2 at 3  $\mu\text{m}$   
351 composed of clay and mica, representing 25% of the sediment.

352 -The pole “Silicilastic sand” based on samples from the cores MOZ3-CS03 and MOZ3-CS02, shows  
353 an unimodal distribution with a mode at 140  $\mu\text{m}$  composed of quartz and feldspar, representing 95% of  
354 the sediment and; a peak at 20  $\mu\text{m}$  composed of mica, representing 5% of the sediment.

355 -The pole “Foraminiferal sand” based on samples from the cores MOZ3-CS07 and MOZ3-CS02,  
356 has an unimodal distribution with a mode at 750  $\mu\text{m}$  composed of foraminifer tests, representing 87%  
357 of the sediment; a peak at 100  $\mu\text{m}$  composed of quartz and feldspar, representing 5% of the sediment  
358 and; a large peak at 6  $\mu\text{m}$  composed of clay and mica, representing 8% of the sediment.

#### 359 ***4.4. Isotopic stratigraphy of core MOZ3-CS07***

360 The isotopic stratigraphy of core MOZ3-CS07 is based on  $\delta^{18}\text{O}$  measurements correlated with  
361 the reference  $\delta^{18}\text{O}$  curve LR04 (Lisiecki and Raymo, 2005, Fig. 11) over the first 5 mbsf. This stratigraphy  
362 is completed with strontium isotope measurements translated into ages using the global strontium  
363 variation reference curve (McArthur et al., 2012) from 3.51 to 11.45 mbsf. The obtained ages are  
364 grouped and fitted according to a power regression to better approximate a model of non-linear  
365 sedimentation rate evolution over time (Fig. 12).

##### 366 *4.4.1. Oxygen isotopic stratigraphy*

367 The  $\delta^{18}\text{O}$  measurements acquired along the first 5 mbsf of core MOZ3-CS07 vary from 0.1 to 1.5  
368 ‰. The  $\delta^{18}\text{O}$  curve can be divided into two parts (Fig. 11): (1) from 0 to 1.53 mbsf, the  $\delta^{18}\text{O}$  curve shows  
369 high-amplitude variations; (2) from 1.53 to 5 mbsf, the  $\delta^{18}\text{O}$  curve shows shorter wavelength and lower  
370 amplitude changes, with one major peak at 3.7 mbsf.

371 Over the first 1.53 m, the  $\delta^{18}\text{O}$  curve of MOZ3-CS07 correlates with the first 11.5 m of MOZ3-CS03  
372 (Babonneau et al., 2022) and corresponds to the LR04 reference curve to 100 kyr climate cycles (Lisiecki and

373 Raymo, 2005). Sixteen isotopic stages are identified along this part. The first 1.53 m of core MOZ3-CS07 and  
374 the 11.5 m of MOZ3-CS03 are estimated to cover the last 632 kyr, with average sedimentation rates  
375 respectively about 0.24 cm.kyr<sup>-1</sup> and 1.82 cm.kyr<sup>-1</sup>. Sedimentation rate of core MOZ3-CS07 is therefore  
376 calculated 7.6 times lower than that of MOZ3-CS03.

377 Given the sedimentary record resolutions of cores MOZ3-CS07 and MOZ3-CS03, interglacial  
378 phases of the last 800 kyr (Past Interglacials Working Group of PAGES, 2015) cannot be distinguished.  
379 Therefore, complete odd-numbered MIS (except MIS 3) are labelled as interglacial stages, being aware  
380 that they include more than the interglacial phases themselves. The  $\delta^{18}\text{O}$  curves of cores MOZ3-CS07  
381 and MOZ3-CS03 thus show interglacial stages that are expressed over thicker sedimentary intervals  
382 than glacial stages (in proportion to their actual duration). The  $\ln(\text{Ca}/\text{Fe})$  and  $\ln(\text{Zr}/\text{Rb})$  ratio of core  
383 MOZ3-CS07 reveal an increase in the amount of terrigenous sediment and a decrease in current speed  
384 during interglacial stages and conversely during glacial stages.

385 At 1.53 mbsf in core MOZ3-CS07, the change in the frequency of  $\delta^{18}\text{O}$  oscillations is interpreted  
386 to mark the end of the Mid-Pleistocene Transition (MPT). Below this level, grain-size proxies the  
387 sampling resolution is no longer adapted to the change in frequency and does not allow us to assign an  
388 isotopic stage with variations of the  $\delta^{18}\text{O}$  curve.

#### 389 *4.4.2. Strontium Isotopic Stratigraphy*

390 The strontium measurements at 3.51, 4 and 4.51 mbsf (green, purple and orange lines in Fig. 11)  
391 with uncertainties ranging from 50 to 150 kyr, give ages of 1.36, 1.46 and 1.74 Ma, respectively. A  
392 sedimentation rate about 0.26 cm.kyr<sup>-1</sup> can be estimated at 4.51 mbsf.

393 Figure 12 combines the estimated ages from oxygen and strontium measurements. The x-axis is  
394 the age in millions of years, and on the y-axis is the depth below the seafloor in meters.

395 The  $\delta^{18}\text{O}$  points (corresponding to the ages of the red lines in Fig. 11) line up along a straight  
396 axis and have very little dispersion (power regression,  $R^2=0.98$ ). Conversely, the strontium points are  
397 more scattered (power regression,  $R^2=0.71$ ). The sediment fraction chosen evolved according to the  
398 results obtained during the measurement of the sample series (Table 4). The points outside the grey  
399 area were not selected for the age model determination (discussed in section 5.3.2).



400 The power regression equation gives an age of 4.08 Ma at 11.45 mbsf. Nevertheless, the  
401 strontium ages dispersion and uncertainties related to SIS method (up to 1 Ma) do not allow to affirm  
402 this result.

## 403 5. DISCUSSION

### 404 *5.1. Foraminiferal sand accumulation in contourite system*

#### 405 *5.1.1. Atypical sedimentary facies*

406 The absence of erosional structures, clear bioturbation traces, and the homogeneity of the  
407 sedimentary facies observed in MOZ3-CS07 are characteristic and diverge from the current model of  
408 organization and classification of contourite sequences proposed by Stow and Faugères (2008).  
409 Composed of 70% foraminiferal sand, the sedimentary facies of MOZ3-CS07 is atypical for a  
410 homogenous deposit of several meters in thickness on a present-day contourite system. Contourite  
411 facies with a similar content of foraminifers are documented from outcrops (Schiller et al., 1994; Carter,  
412 2007; Hüneke et al., 2021) or correspond to sequences of a few tens of centimeters with a lower  
413 proportion of foraminifers (e.g., Viana et al., 1998; Brackenridge et al., 2018; de Castro et al., 2020;  
414 Hüneke et al., 2020).

415 In addition to its particular facies, core MOZ3-CS07 presents an extremely low sedimentation  
416 rate of about  $0.26 \text{ cm.kyr}^{-1}$  for the first 4.51 mbsf, corresponding to the lowest sedimentation rates  
417 measured on a contourite deposit. This condensed sedimentation appears to be continuous over 11.45  
418 meters and could provide one of the few contourite sedimentary records that allow accessing climate  
419 changes and its regional oceanographic impacts at the Plio-Quaternary scale. Nevertheless, the  
420 establishment of such a particular facies and its preservation over time raise some questions, which are  
421 discussed in the following sections.

#### 422 *5.1.2. Sedimentary processes inducing foraminiferal sandy contourite formation*

423 The sediments of core MOZ3-CS07 correspond to coarse sand, composed of 70% foraminifer  
424 tests and 30% clayey-silty mud. This high content of foraminifer tests is likely due to: (1) a depositional  
425 environment with low terrigenous inputs attested by the low sedimentation rates and the pelagic origin

426 of the particles; (2) significant bottom currents inducing the winnowing of fine particles shown by the  
427 grain-size results. This last point is supported by the presence of an erosional surface just above the  
428 core MOZ3-CS07 (Fig. 2B) indicating that the core is close to an area subject to strong bottom current  
429 influence. In these depositional conditions, the low content of fine particles results from their trapping  
430 in the interstices between foraminifer tests (Fig. 13). The sedimentation process can be divided into two  
431 steps: (1) the pelagic sedimentation, settling of foraminifer tests on the seafloor; (2) the interstitial  
432 sedimentation, when suspended particles are trapped in the interstices formed between tests (Fig. 13).  
433 This interpretation is supported by the gap observed in the grain-size distribution (Fig. 6) that  
434 corresponds to a natural break in the distribution of grain-size fractions that reflects a change of the  
435 sediment origin/processes (Smalley, 1966; Pettijohn, 1975). In this foraminiferal sandy contourite, the  
436 break separates biogenic (pelagic sedimentation) from terrigenous (interstitial sedimentation)  
437 sediments.

438 For the facies variations, observed along core MOZ3-CS07 (Figs. 4 and 5), it is assumed that:

439 -for very fine mottled sand, bottom currents are weaker, all the sizes of foraminifer tests can be  
440 deposited, increasing the potential of trapping fine particles.

441 -for foraminiferal pocket, bottom currents are stronger, only larger sized foraminifer tests are  
442 deposited. Under these conditions, the surface sediments are reworked, transport of foraminifer tests  
443 by saltation/traction allows to resuspend both the fine particles trapped and the small and medium-  
444 sized foraminifer tests (corresponds to tests <300  $\mu\text{m}$ ). Being transported on the seafloor, the tests are  
445 fragmented and concentrated, forming foraminiferal pockets.

446 One centimeter of deposition in core MOZ3-CS07 records about four thousand years of  
447 sedimentation. We assume that the preservation of fine particles (clays and silts) over such a long period  
448 results from stable hydrodynamic conditions over the time (more explanations in section 5.3.1) and it  
449 seems that once fine particles are trapped in interstices between foraminifer tests, the bottom currents  
450 are not strong enough to winnow them except in the case of the foraminiferal pockets.

451 This foraminiferal contourite facies does not show typical contourite sedimentary layers  
452 organized in bi-graded sequences (Gonthier et al., 1984). The only evidence for variations in bottom

453 current speed is the variations in geochemical and grain-size proxies (ln (Zr/Rb) and  
454 sorting/skewness). The two main diagnostic criteria for distinguishing contourite are based on the  
455 presence and abundance of bioturbation (e.g., Lovell and Stow, 1981; Gonthier et al., 1984; Wetzel et al.,  
456 2008) or on the presence of primary sedimentary structures (e.g., Shanmugan, 2000; Martín-Chivelet et  
457 al., 2008). The foraminiferal sandy contourite facies of core MOZ3-CS07 is interpreted slightly  
458 bioturbated because of the absence of sedimentary structures. Nevertheless, even on X-ray images, no  
459 clear bioturbation structures have been observed. This observation could be explained by a benthic  
460 community mainly composed of grazing animals that destroy pre-existing sedimentary structures and  
461 do not produce burrows as commonly observed in contourite deposits (summarized in Rodríguez-Tovar  
462 et al., 2022).

### 463 *5.1.3. Estimation of bottom current speed*

464 The equation of McCave et al. (2017) on the value of the "Sortable Silt mean size" ( $\overline{SS}$ ,  
465 corresponds to the grain-size average of the classes between 10 and 63  $\mu\text{m}$ ) is applied on the bulk  
466 sediment to estimate the current speed according to the following equation:  $\overline{SS}=0.808U+15.46$  (with U:  
467 the current speed in  $\text{cm}\cdot\text{s}^{-1}$ ). Taking  $\overline{SS}=28.63 \mu\text{m}$  (corresponds to the average  $\overline{SS}$  of MOZ3-CS07), we  
468 obtain  $U=16.30 \text{ cm}\cdot\text{s}^{-1}$ . Without carbonate dissolution and deflocculating agent, this value is only an  
469 estimation of the average current speed (certainly overestimated due to the flocculation process of the  
470 finest particles). Nevertheless, the latest work by Miramontes et al. (2021), using the Regional Ocean  
471 Modelling System (ROMS, CROCO version: <https://www.croco-ocean.org/>), shows a similar bottom  
472 current speeds at the location of the contourite drift where the core MOZ3-CS07 was collected.

473 Taking the smallest value of  $\overline{SS}$  (19.27  $\mu\text{m}$  at 7.29 mbsf), a speed of  $4.72 \text{ cm}\cdot\text{s}^{-1}$  is obtained. The  
474 maximum current speed is not calculable because in this case no sediment smaller than 63  $\mu\text{m}$  is  
475 deposited (at 0.84 mbsf). According to the work of Lonsdale et al. (1972), foraminiferal sand motion  
476 threshold is at  $17 \text{ cm}\cdot\text{s}^{-1}$ . Miller and Komar (1977) and McCave and Hall (2006), also calculated the  
477 critical speed for the movement of foraminifers with sizes between 200 and 300  $\mu\text{m}$  and found 20-25  
478  $\text{cm}\cdot\text{s}^{-1}$ . Following these estimations, sediments of core MOZ3-CS07 seem to have been deposited under  
479 the action of a bottom current speed ranging from 4.72 to 17-20  $\text{cm}\cdot\text{s}^{-1}$ .

480 **5.2. Contourite system of the Mozambique Ridge**

481 The results of Babonneau et al. (2022) suggest that the entire contourite system is almost  
482 disconnected from continental inputs, fed by hemipelagic/pelagic sediments and sediment transfer  
483 processes within the contourite channels. This contourite depositional system provides a perfect study  
484 area to investigate contourite without the impact of gravity-driven processes.

485 *5.2.1. Evolution of the sedimentary processes from the channel to the drift*

486 Three major sedimentary sources are identified in figure 10, according to the grain-size modes:  
487 (1) suspended particles forming the clayey and fine silty modes composed of clay and mica; (2) biogenic  
488 inputs, mainly foraminifer tests forming the coarse sand mode and (3) the along-slope transfer of  
489 siliciclastic material (i.e., quartz and feldspars) into the channel creating the fine sand mode. Depending  
490 on the location in the contourite system, these sedimentary sources are found in different proportions  
491 in the sediment and reflect changes in bottom currents speed creating unimodal or bimodal grain-size  
492 distributions. These distributions (Fig. 10) can be divided into two contourite sedimentary processes  
493 proposed by Miramontes et al. (2021): (1) contourites dominated by depositional processes and; (2)  
494 contourites dominated by winnowing/reworking processes. For each sedimentary process, two  
495 sedimentological poles are defined from the cross-plot of “sorting versus  $D_{50}$ ” (Fig. 9).

496 **Contourites dominated by depositional processes** show a bimodal grain-size distribution  
497 developed under weak bottom currents allowing the deposition of fine and coarse particles. For the  
498 “mainly terrigenous” pole, corresponding to sediments close to the channel, fine particles are composed  
499 of clay and micas, and; coarse particles are composed of quartz and feldspars. For the “mainly biogenic”  
500 pole, corresponding to sediments from the drift, fine particles consist of clay and micas, and coarse  
501 particles are composed of foraminifer tests and in lesser proportion of quartz and feldspars.

502 **Contourites dominated by winnowing/reworking processes** show an unimodal grain-size  
503 distribution, which is set up under strong bottom currents where fine particles are winnowed, and only  
504 coarse particles can be deposited. For the “siliciclastic sand” pole, corresponding to sediments close to  
505 the channel, coarse particles are composed of quartz and feldspar. For the “foraminiferal sand” pole,  
506 corresponding to sediments from the drift, the coarse particles are composed of foraminifer tests.

507 If the bottom current speed increases, contourites dominated by depositional processes will  
508 evolve into contourites dominated by winnowing/reworking processes adopting a siliciclastic or  
509 foraminiferal sand depending on the location in the system and thus the composition of the sediment  
510 (Fig. 9 and 10).

#### 511 *5.2.2. Contourite endmembers and their relationships*

512 Sorting and size of contourite sediments are controlled by the bottom current speed and  
513 sediment sources. Using cross-plots of "sorting versus  $D_{50}$ " provide a better characterization of these  
514 deposits (Branckenridge et al., 2018; de Castro et al., 2020, 2021a, 2021b; Bankole et al., 2021;  
515 Rodrigues et al., 2022). Nevertheless, the continuity and the possible interplay between contourite,  
516 hemipelagite and turbidite processes, make it difficult to distinguish clearly these deposits from this  
517 type of graph.

518 The contourite system studied here is disconnected from gravity driven continental inputs, thus  
519 only two types of sedimentary deposits are present in this system, contourites and hemipelagites. Based  
520 on our results (Fig. 9) and on previous studies (Brackenridge et al., 2018; de Castro et al., 2020, 2021a,  
521 2021b; Bankole et al., 2021) using cross-plots of "sorting versus  $D_{50}$ ", two contourite trends can be  
522 defined: (1) siliciclastic trend (already shown by de Castro et al., 2021), mainly represented by the  
523 sediments of core MOZ3-CS03 and partly by those of MOZ3-CS02; (2) foraminiferal trend, mainly  
524 represented by the sediments of core MOZ3-CS07 and partly by those of CS02. Both trends illustrate an  
525 increase in current speed from contourites dominated by depositional processes to contourites  
526 dominated by winnowing/reworking processes. As foraminifer tests have a lower density than  
527 siliciclastic particles (i.e., quartz), for the same given current speed, they will therefore be larger than  
528 siliciclastic particles, thus explaining the size difference between a foraminiferal sand and a siliciclastic  
529 sand. These results conducted us to propose the "Contourite Graphical Chart" (inspired by the work of  
530 Bankole et al., 2021) allowing to locate and understand the repartition of contourite deposits and their  
531 related trends (Fig. 14).

532 The "Contourite Graphical Chart" highlights three contourite endmembers; the silty contourites,  
533 , the siliciclastic sandy contourite and the foraminiferal contourite. The silty contourites represent a

534 starting point from which the sedimentary facies will evolve during deposition to another type of  
535 contourite facies depending on the current speed and/or the source of sediments. As previously shown  
536 by Bankole et al. (2021), silty contourites become hemipelagites in the case where the current speed is  
537 almost nil.

538 Each endmember is associated to a sedimentary process; the silty contourites are associated to  
539 depositional processes under low bottom current speed, the sandy siliciclastic and foraminiferal  
540 contourites to winnowing or reworking processes (Fig. 14). During deposition or over the time, a  
541 siliciclastic sandy contourite can evolve into a foraminiferal contourite if terrigenous inputs decrease or  
542 if its distance from the contourite channel increases, as previously shown core MOZ3-CS02 (Fig. 9).

### 543 ***5.3. Bottom current processes and paleoceanographic record***

#### 544 *5.3.1. Contourite system in AAIW/NADW interface*

545 The contourite system studied is currently at the depth of the AAIW/NADW interface  
546 (Thiéblemont et al., 2019; Babonneau et al., 2022). The processes operating at water mass interfaces in  
547 the Mozambique Channel are described by Thiéblemont et al., (2019). Among them, internal waves are  
548 suggested by some authors as a relevant mechanism in the erosion and non-deposition of sediments in  
549 some contourite systems (e.g., MC/AAIW interface at 800 mbsl; Thiéblemont et al., 2019). The  
550 AAIW/NADW interface corresponds to a progressive transition zone where no high value in buoyancy  
551 (Brunt-Väisälä) frequency is observed (Thiéblemont et al., 2019), and thus there is probably no  
552 intensification of internal wave activity compared to the surrounding water masses.

553 The study area is on the main pathway of oceanic eddies (Fig. 1). In the Mozambique channel,  
554 eddies can affect the whole water column impacting the seafloor in the whole basin (de Ruijter et al.,  
555 2002). Schouten et al. (2003) showed that eddies current speed at 2000 mbsl can reach up to 10 cm.s<sup>-1</sup>.  
556 As previously demonstrated by Thiéblemont et al. (2019) and Miramontes et al. (2021), elongated-  
557 mounded drifts in the Mozambique Channel at the AAIW and NADW depths are formed by water mass  
558 channeling processes under the influence of Coriolis force creating erosive surfaces on the left sides of  
559 the channels. These processes would explain erosion surfaces on the eastern flanks of the contourite  
560 system (Fig. 2 and 15). Small erosional surfaces on some western flanks of the contourite system could

561 indicate southward flowing of the bottom current due to interactions with the bathymetry forming an  
562 anti-clockwise circular current also observed in the modelled bottom current by ROMS (CROCO version,  
563 Miramontes et al., 2021). Babonneau et al. (2022) proposed that this circular current around the  
564 contourite drift could facilitate the capture of other circular hydrodynamic processes, such as eddies  
565 (Fig. 15).

566 The variability of bottom current speed in the channels (cores MOZ3-CS03 and MOZ3-CS02) is  
567 high, allowing both silty-clayey and siliciclastic sediments to be deposited during certain glacial stages,  
568 in contrast to the variability of bottom current speed in core MOZ3-CS07, which is much lower and  
569 allows the formation of a continuous foraminiferal sandy contourite facies without erosional surfaces  
570 indicating relative stable hydrodynamic conditions over time. This difference in bottom current  
571 variability between the drift and the channels could be explained by the thickness of the AAIW/NADW  
572 interface (~700 m) offering stable conditions even with the Quaternary eustatic variations. The  
573 sedimentary variability observed in the western channel (Fig. 3 and 15) could be related to channeling  
574 processes that accentuate bottom current speed variations through climate cycles. These variations are  
575 also recorded in core MOZ3-CS07 facies and discuss in the following part.

### 576 *5.3.2. Paleoceanographic record during 100 kyr Quaternary climate cycles*

577 The end of the MPT is observed at 1.55 msbf on core MOZ3-CS07 corresponding to 632ka (Fig.  
578 11). After the MPT, sedimentation rates of 100 kyr climate cycles are calculated from the correlations  
579 with the reference curve LR04 (red lines in Fig. 11). The interglacial stages show a higher sedimentation  
580 than the glacial stages with an average rate of 0.5 cm.kyr<sup>-1</sup> compared to 0.15 cm.kyr<sup>-1</sup>. The ln (Zr/Rb)  
581 curve reveals a greater intensity of bottom currents during glacial stages than during interglacial stages.  
582 The work of Babonneau et al. (2022) has allowed us to propose a general circulation pattern at the scale  
583 of the contourite system during the Quaternary period. By combining these results with those of this  
584 study, it is possible to propose an interpretation of the dynamics of the AAIW/NADW interface during  
585 the 100 kyr climate cycles (Fig. 15):

586 -interglacial stages: bottom current speed is relatively low (compared to glacial stages). Sandy  
587 particles are transported through the western channel, bottom current induce winnowing of fine

588 particles which are deposited by hemipelagic sedimentation on site MOZ3-CS03 and CS02. On the drift,  
589 only foraminiferal sands are deposited, between which particles in suspension are trapped.

590 -glacial stages: bottom current speed is higher. Fine particles continue to be deposited on site  
591 MOZ3-CS03 and MOZ3-CS02, but in smaller proportions. For some glacial stages, cores MOZ3-CS03 and  
592 MOZ3-CS02 show siliciclastic sands that reflect higher intensity of bottom currents and greater  
593 transport (Figs. 3 and 15). On the western side of the drift, coarse foraminifer tests continue to be  
594 deposited and are sometimes winnowed and condensed into foraminiferal pockets.

595 Variations of bottom current speed generated at the AAIW/NADW interface during 100 kyr  
596 climate cycles result from the variations of intensity of the AAIW, NADW, the impact of internal waves,  
597 eddies and how all these factors are increased or reduced by interaction with the seafloor morphology.  
598 As the contourite system is close to the upper part of the NADW, it is assumed that the intensity of the  
599 AAIW/NADW interface at this depth depends more on the behavior of the NADW than that of the AAIW.

600 Molyneux et al. (2007) showed an increase in the influence of the NADW on the Agulhas Plateau  
601 (Fig. 1) during glacial periods over the last 200 kyr. Our results confirm that this behavior of the NADW  
602 during climatic cycles is the same over the last 633 kyr. The recent study of van der Lubbe et al. (2021)  
603 provides a 7 Myr record of wind-driven circulation of the tropical Indian Ocean, as recorded in  
604 Mozambique Channel Throughflow (MCT) flow speed variations at the IODP Site U1476 located on the  
605 Davie Ridge at 2166 mbsf (Fig. 1). Their results show an increase in MCT flow speed during glacial  
606 periods. Coupled with our study, it appears that from the Agulhas Plateau (southern entrance of the  
607 Mozambique Channel) to the Davie Ridge (northern entrance of Mozambique channel), the behavior of  
608 the surface and bottom ocean circulation is synchronous in this region over the 100 kyr climatic cycles.

609 The absence of the MIS 14 on the  $\delta^{18}\text{O}$  curves of MOZ3-CS07 and MOZ3-CS03 (Fig. 11), could  
610 be linked to the lower sedimentation rates in glacial stages. This isotopic stage corresponds to a  
611 short and moderately cold glacial stage, attenuated on the reference curve LR04. The sampling  
612 resolution and the condensation of the sedimentary records (especially for MOZ3-CS07) probably  
613 contribute to hide this glacial period in the  $\delta^{18}\text{O}$  curve of MOZ3-CS07.



614 4.08 Ma age is estimated at 11.45 m in core MOZ3-CS07 from the power regression on Sr-  
615 isotope measurements inside the grey area in figure 12. The points outside the grey area were not  
616 selected for the age estimation. These different choices are discussed below.

617 Measurements of series 1 and 2 were made on bulk sediment. Despite the presence of clay,  
618 the values appear consistent except for two samples (at 5 and 8.45 mbsf). These two points outside  
619 the grey zone with abnormally old ages (or low strontium ratios) can more likely be explained  
620 either by contamination via volcanic ash or by old carbonates from sedimentary structures outside  
621 the contourite system, than by a protocol or analytical errors during the analyses.

622 Measurements of series 3, 4 and 5 are performed on the fraction  $>250\ \mu\text{m}$  of the same  
623 samples but the samples of series 4 were placed in ultrasonic bath treated with ultrasounds. It  
624 would appear that the ultrasound waves destabilize the structure of clay (residual clays probably  
625 present within the foraminiferal tests), which are therefore more easily dissolved during the acidic  
626 passages and can influence the measured  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio (by increasing it because the measured  
627 Sr will be the result of both Sr from the detrital fraction which are very radiogenic and Sr from the  
628 carbonates).

629 Despite these precautions, the uncertainties related to the SIS method do not allow  
630 confirming an age of 4.08 Ma at the base of core MOZ3-CS07. This age requires verification with  
631 other dating methods. Nevertheless, this estimation and the singularity of the foraminiferal sandy  
632 contourite facies of core MOZ3-CS07 highlight its potential as long-term palaeoceanographic  
633 record.

## 634 **6. CONCLUSIONS**

635 This study provides the characterization of a foraminiferal sandy contourite facies from the drift  
636 of a contourite system localized in the Limpopo Corridor. This foraminiferal sandy contourite facies  
637 diverges from the conceptual contourite facies model and, due to its condensed sedimentation, offers a  
638 long-term, low-resolution paleoceanographic record. The comparisons with others contourite facies  
639 from the near-by channels allow to understand bottom current processes and variations in sediment

640 distribution through 100 kyr climate cycles in a contourite system with low terrigenous inputs and  
641 influenced by the AAIW/NADW interface.

642 Core MOZ3-CS07 shows continuous and homogenous foraminiferal sandy facies over 11.45 m.  
643 This sedimentary facies results from the trapping of fine particles in suspension between the  
644 foraminifer tests interstices. This process of interstitial sedimentation induces the deposition of a  
645 significant content of clay and silt (about 20%) under stable and intense hydrodynamic conditions over  
646 a long period of time with an average sedimentation rate of 0.26 cm.kyr<sup>-1</sup>.

647 The cross-plot of "sorting versus D<sub>50</sub>" allows us to propose the concept of "Graphical Contourite  
648 Facies Chart" that helps to characterize the contourite facies and their related sedimentary processes.  
649 Three contourite endmembers are identified; silty contourite, siliciclastic sandy contourite and  
650 foraminiferal sandy contourite. The silty contourites are considered as a starting point from which the  
651 facies can evolve to another endmember depending on the bottom current speed and the nature of the  
652 sediment inputs.

653 At the scale of 100 kyr climate cycles, the contourite system is under the influence of the  
654 AAIW/NADW interface. The sedimentation rates are lower and bottom current speed is higher during  
655 glacial stages than interglacial stages. These hydrodynamic variations are not visible on the sedimentary  
656 facies of core MOZ3-CS07 unlike those of cores located in the near-by channels of the contourite system  
657 (MOZ3-CS03 and CS02). These results show that the sediments from the top of the drift (core MOZ3-  
658 CS07) are deposited under relatively stable hydrodynamic conditions compared to those from the  
659 channels.

660 Foraminiferal sandy contourite facies have great potential as sedimentary record. From this  
661 study, it appears that contourite systems disconnected from gravity flows provide more easily  
662 exploitable and interpretable sedimentary records. Following this reasoning, the depleted continental  
663 margins should host areas more favorable for the study of long paleoceanographic record from  
664 contourite systems.

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673 **8. CONFLICT OF INTEREST**

674 We declare that we have no commercial or associative aim that might represent a conflict of  
675 interest in connection with the work submitted.

676 **9. DATA AVAILABILITY**

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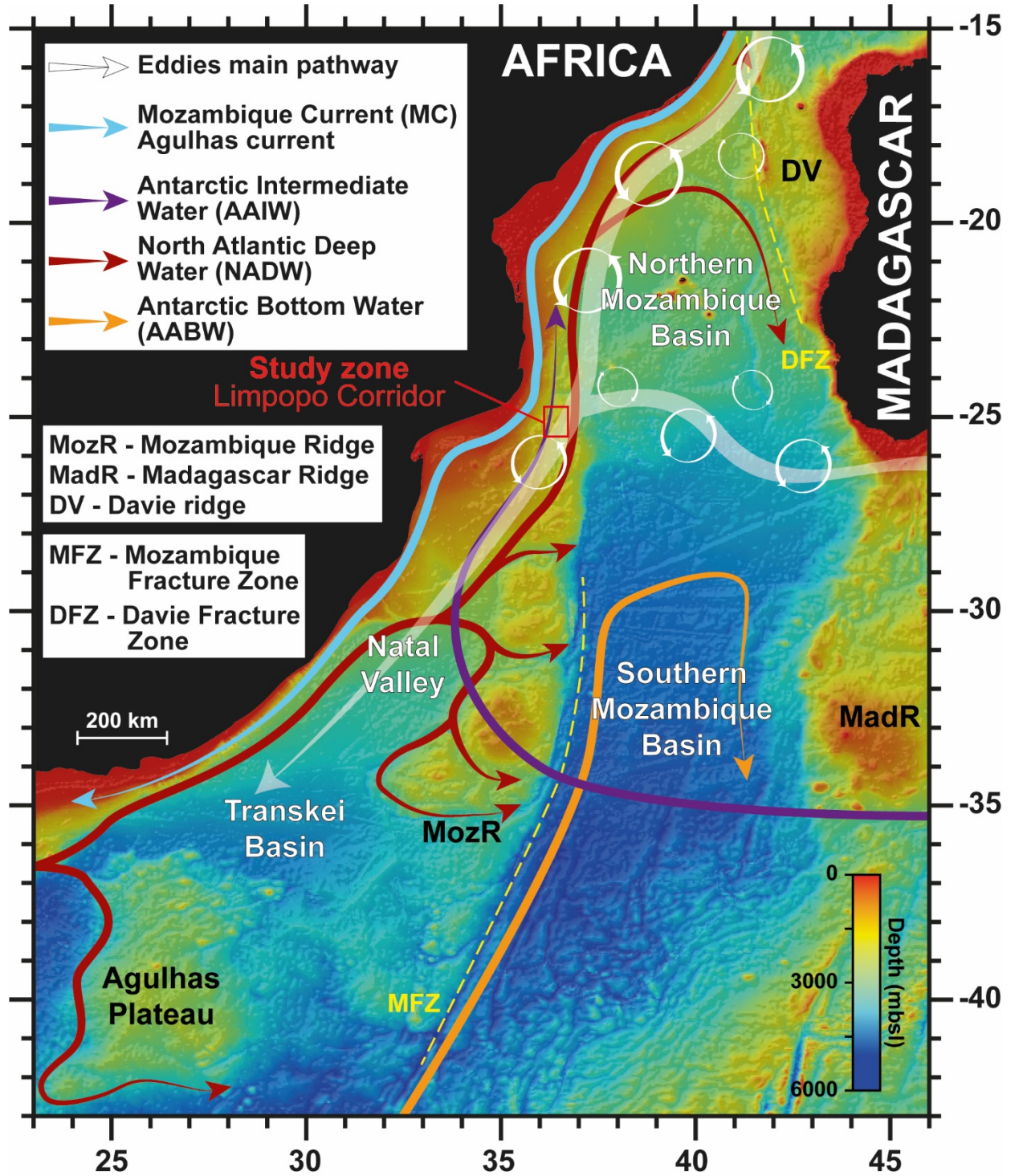
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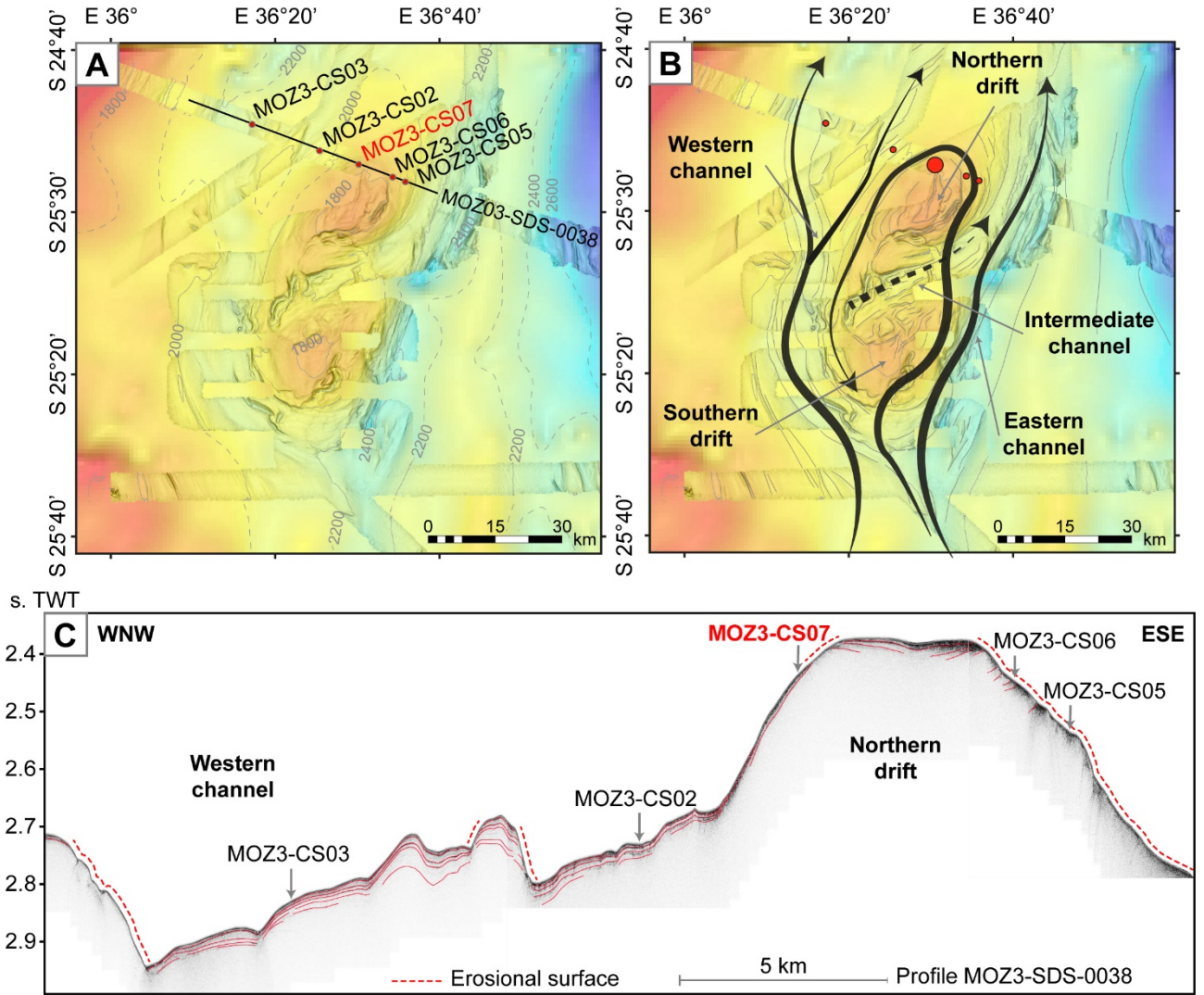
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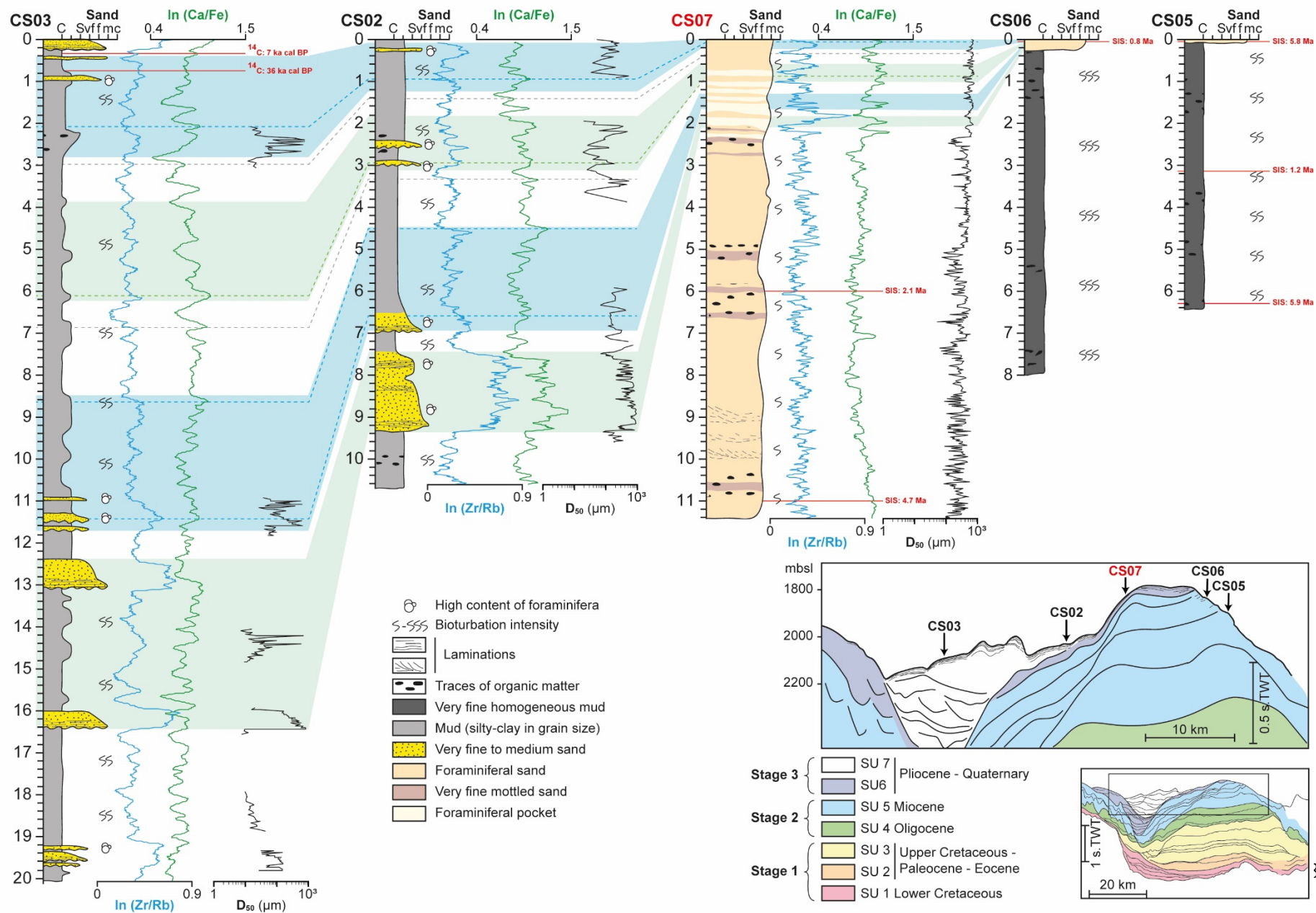
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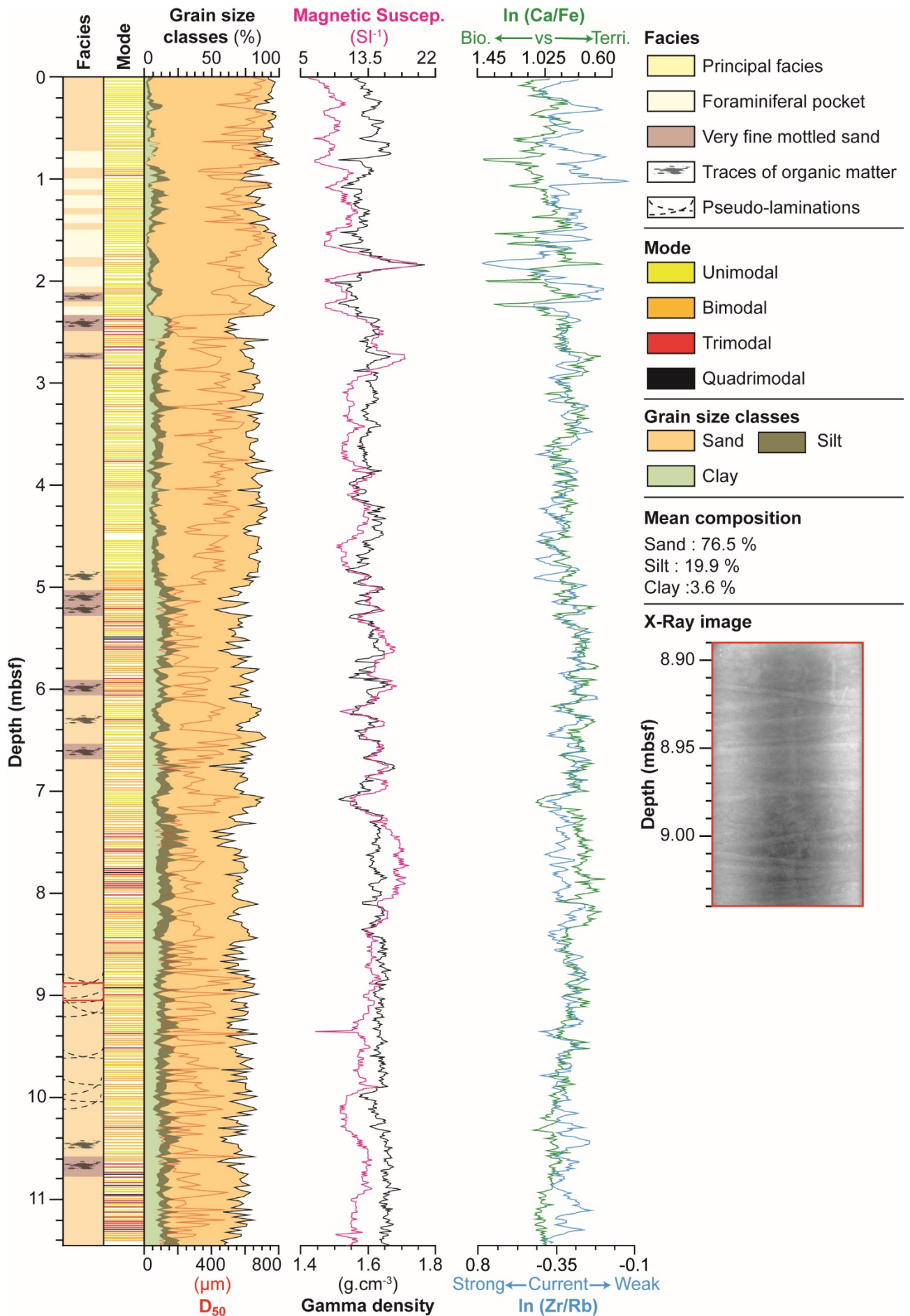
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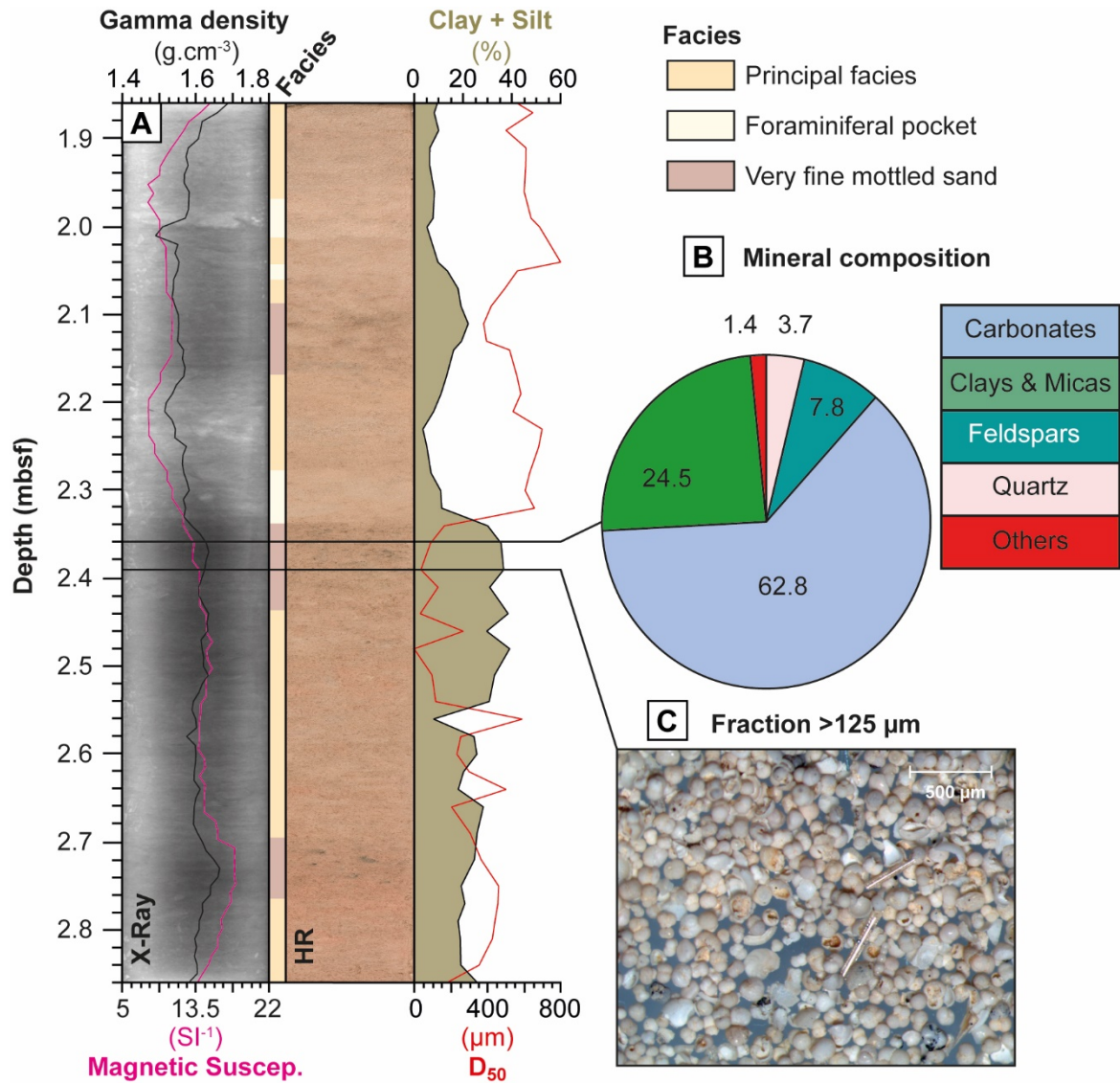


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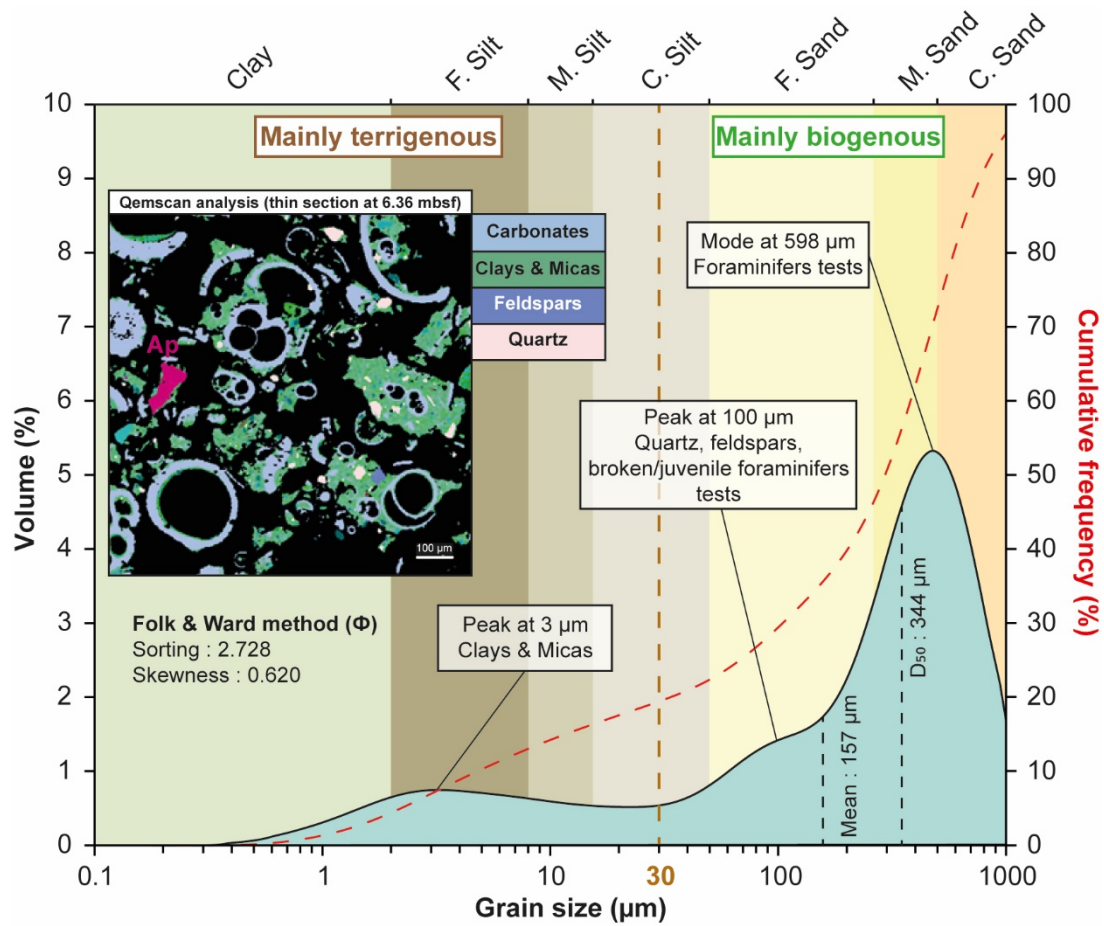


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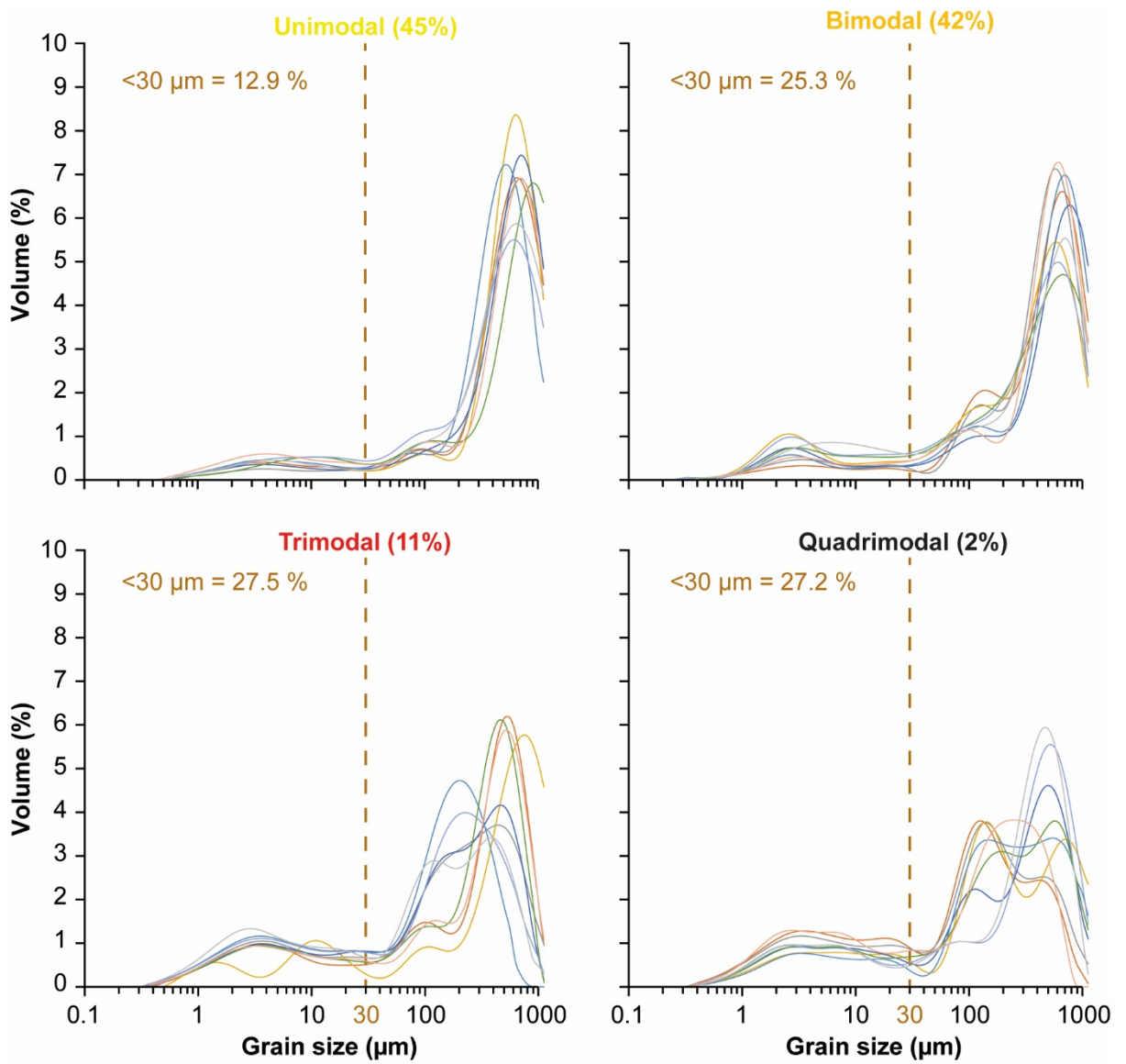
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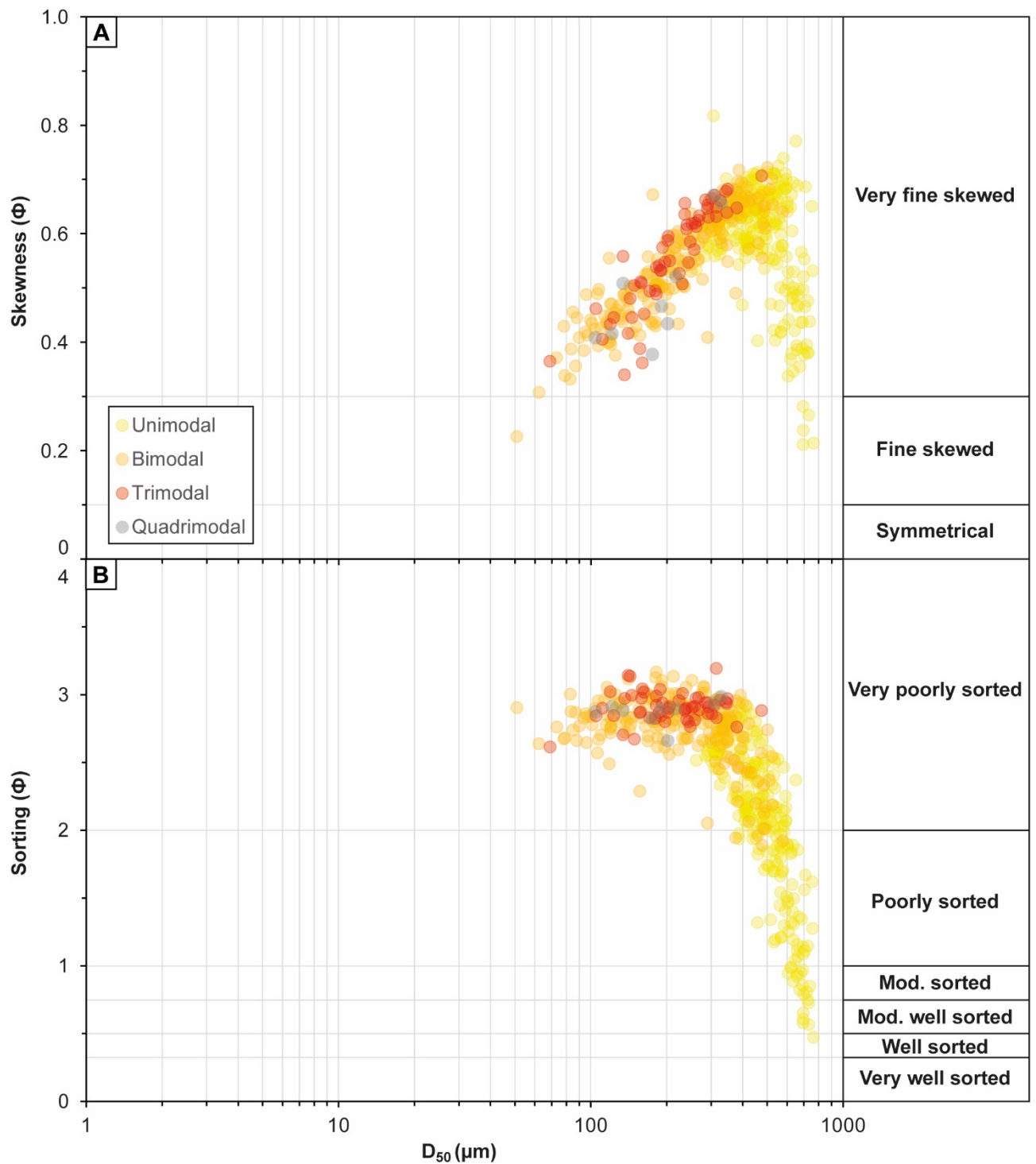
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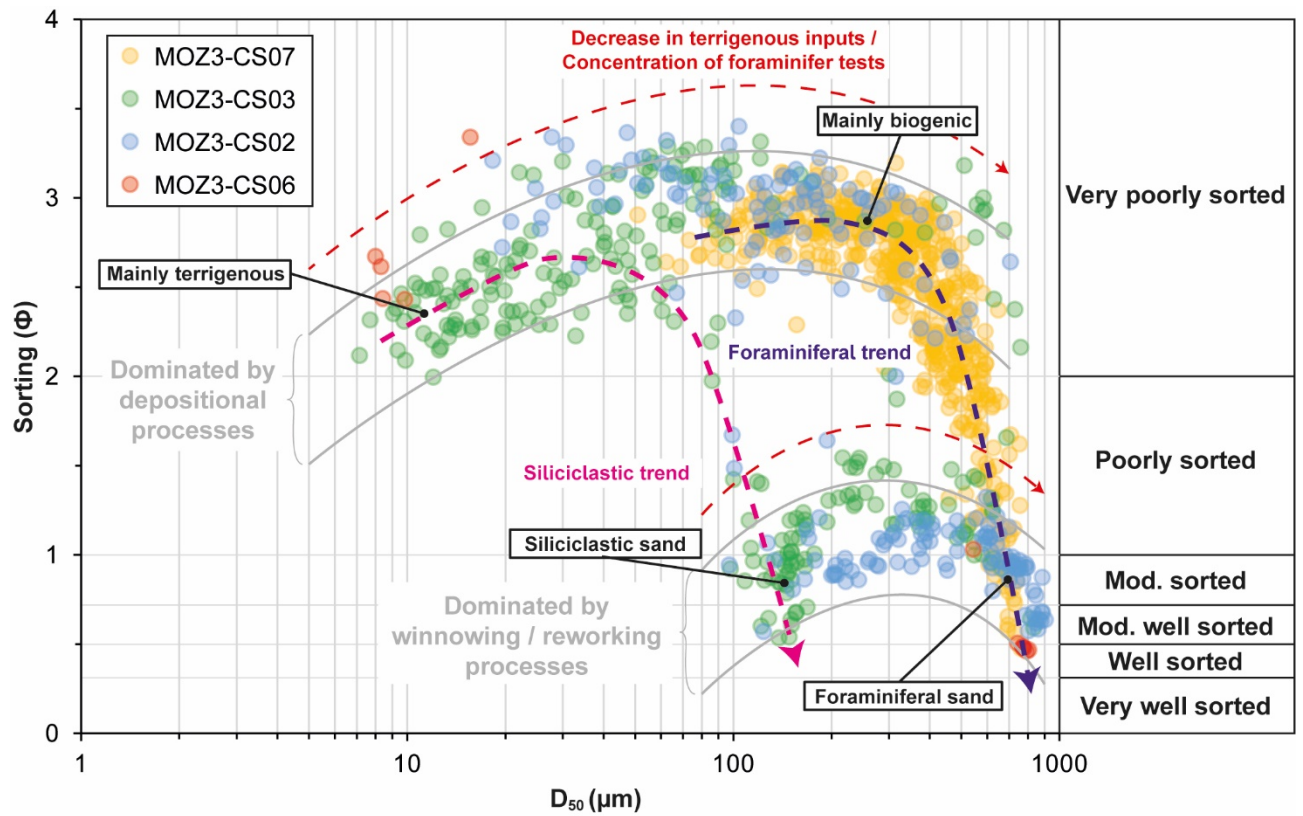
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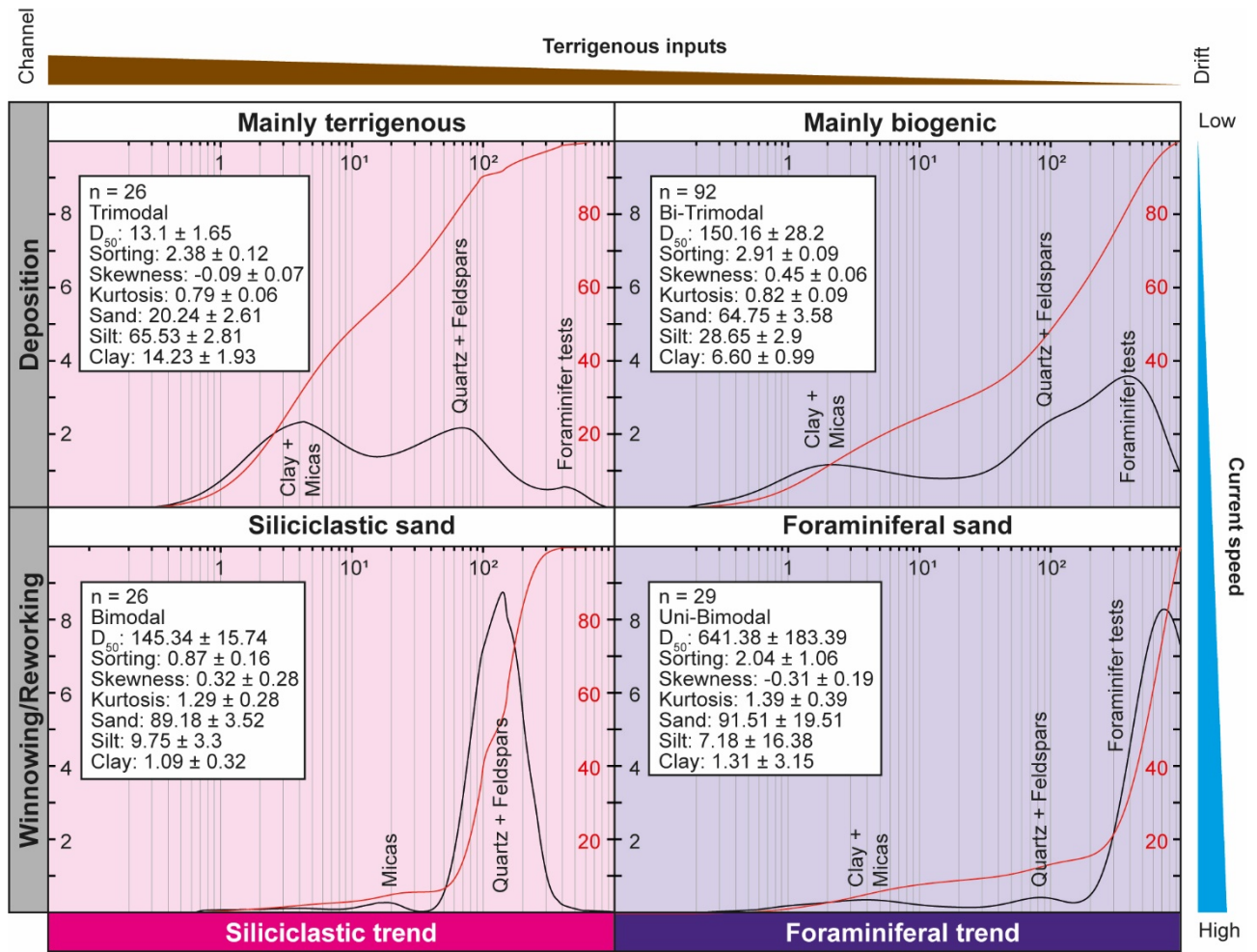
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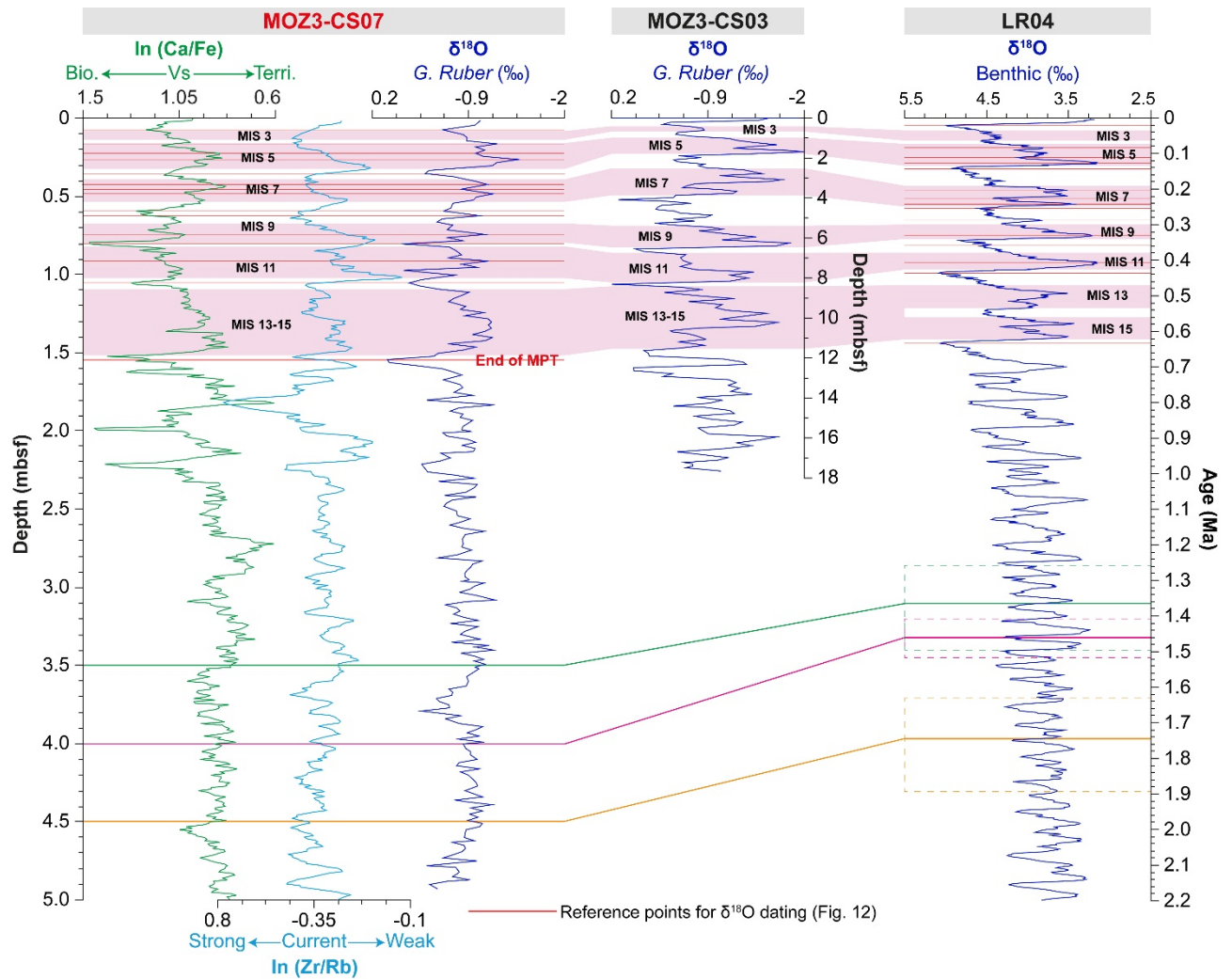
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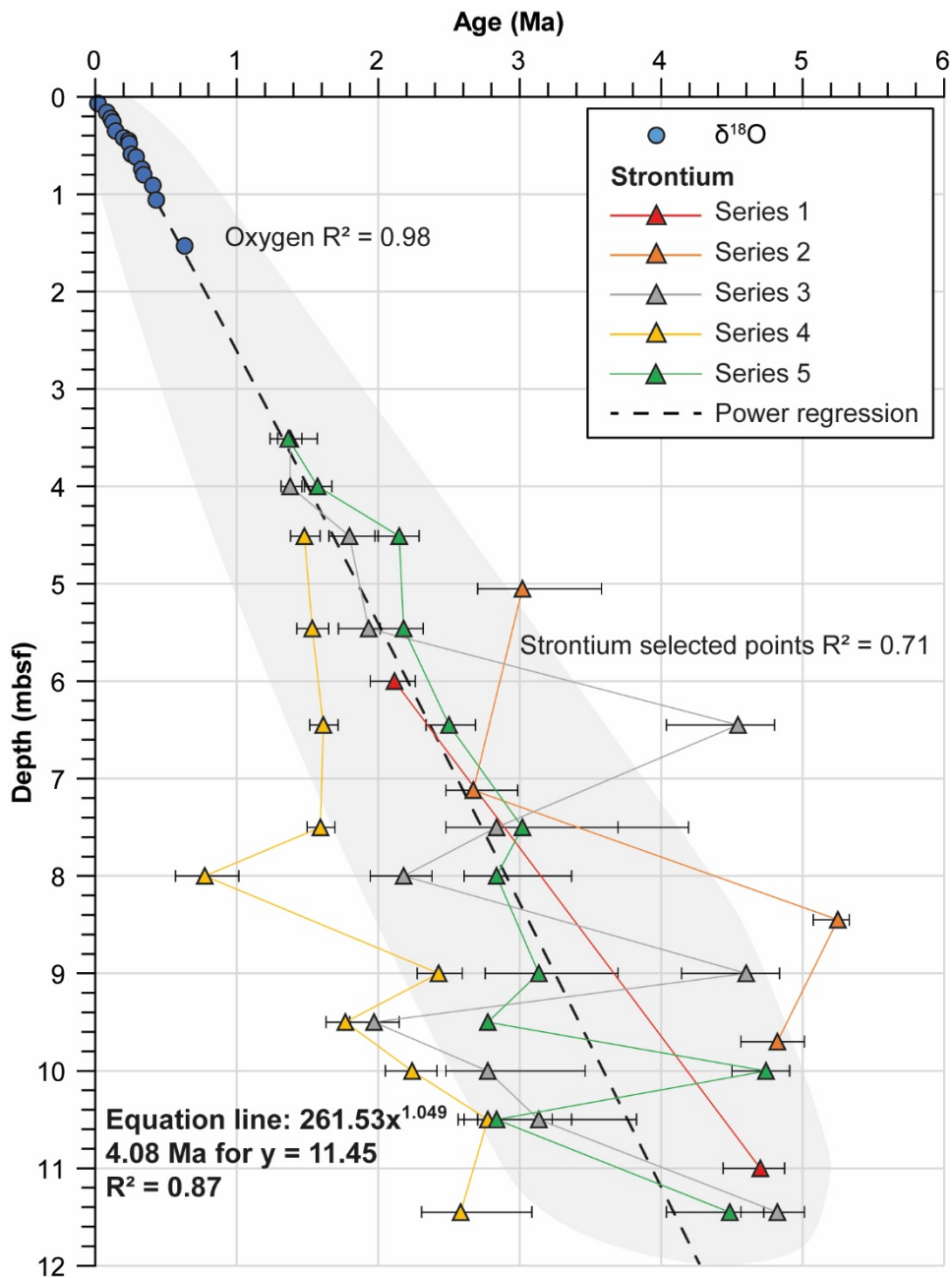
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**Figure 11.** Stratigraphic correlations between the first 5 mbsf of MOZ3-CS07, MOZ3-CS03 and the reference curve LR04 (Lisiecki and Raymo, 2005) using XRF log-ratios (Ca/Fe and Zr/Rb) and  $\delta^{18}\text{O}$  measurements. The end of the MPT is estimated at 1.53 mbsf on core MOZ3-CS07 (632 ka). The green, purple and orange lines correspond to strontium isotope measurements and their uncertainties in dashed lines.



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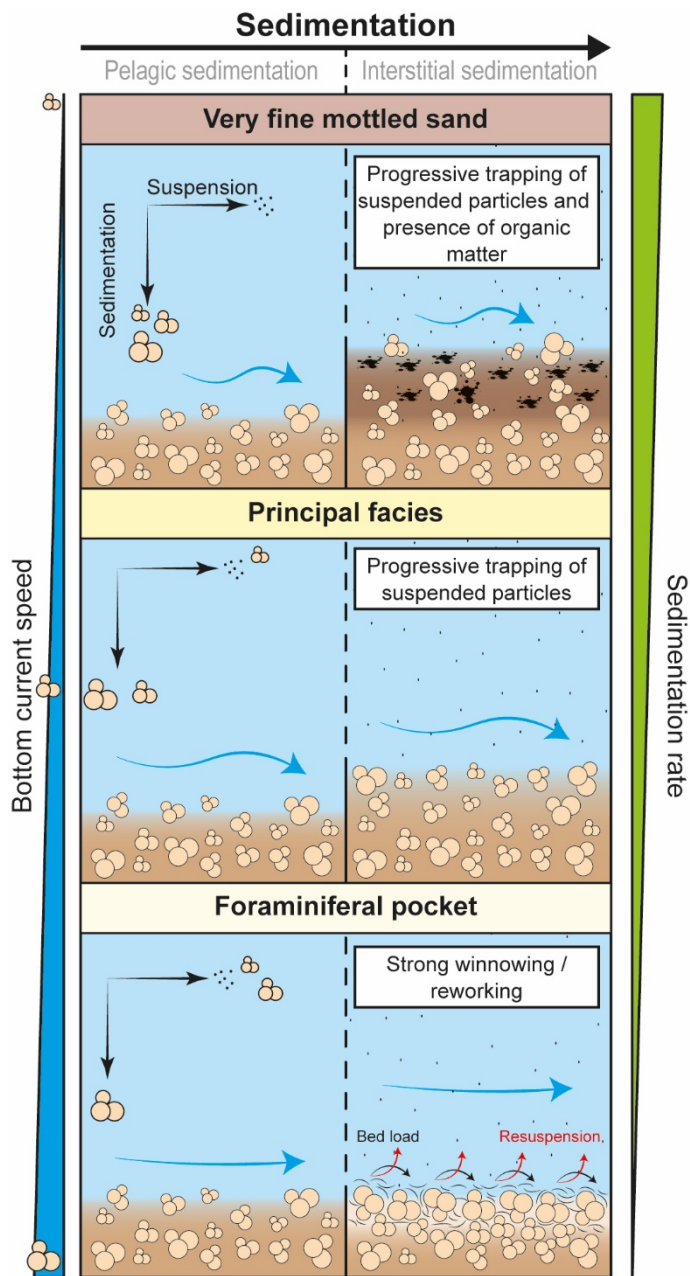
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**Figure 12.** Graph gathering estimated ages from correlations of the  $\delta^{18}\text{O}$  curve (red lines in Fig. 11) and ages obtained by Sr-Isotope Stratigraphy method for core MOZ3-CS07. The grey area indicates points selected for the power regression. The dashed black line corresponds to the power regression giving an age of 4.08 Ma at the base of the core.



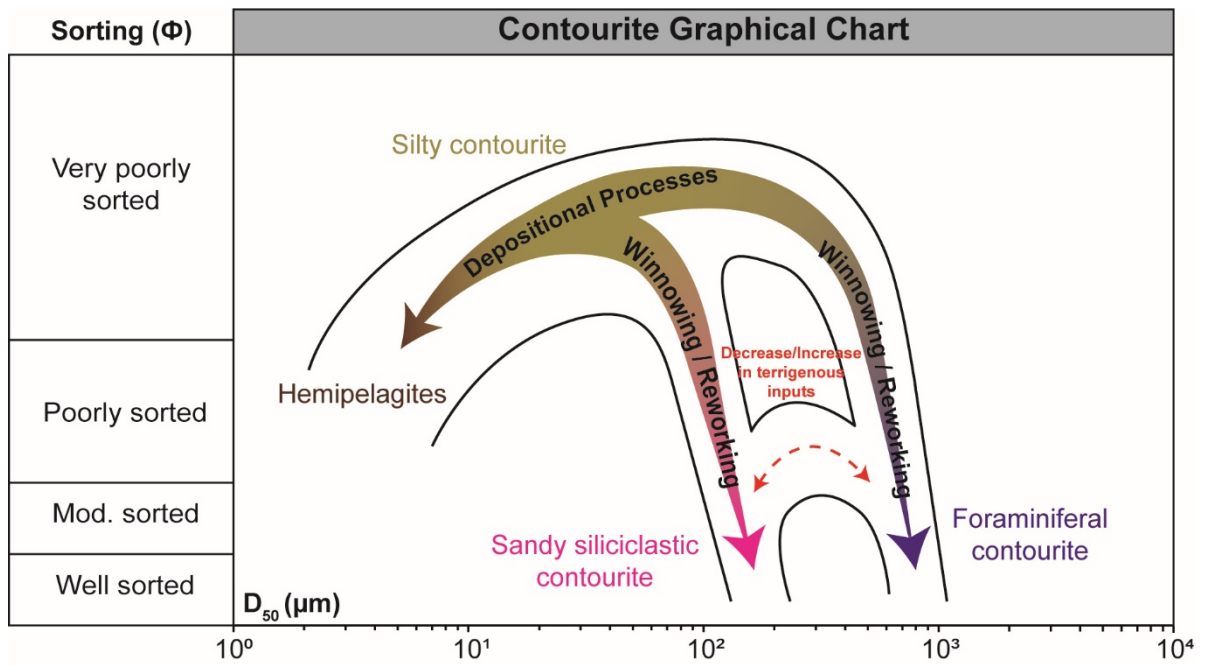


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**Figure 13.** Interpreted sedimentological process at the origin of the foraminiferal sand of core MOZ3-CS07 and its facies variations by interstitial sedimentation.



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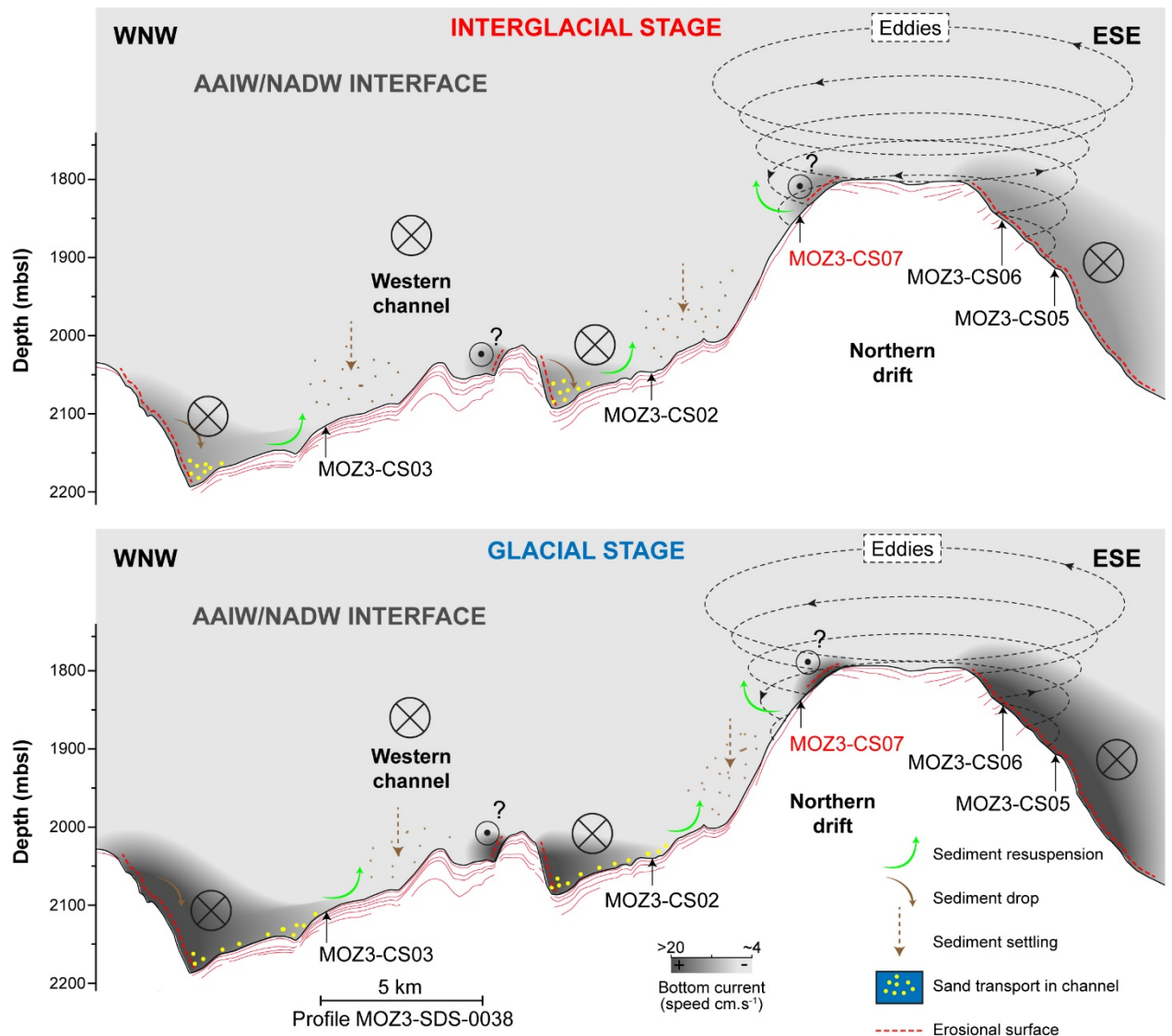
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**Figure 14.** Concept of “Contourite Graphical Chart” corresponding to the preferential location of contourite deposits in cross-plot sorting ( $\Phi$ ) versus  $D_{50}$  and the existing continuity between them (inspired from Bankole et al., 2021). Three contourite endmembers are identified.





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**Figure 15.** Schematic representation of sedimentary processes, bottom current speed variations over 100 kyr climatic cycles in the AAIW/NADW interface and possible impact of deep anti-clockwise eddies in the contourite system (modified from Babonneau al., 2022). During interglacial stages, bottom current speed is lower than during glacial stages.

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#### 14. TABLES

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**Table 2.** List and characteristics of the CALYPSO piston cores collected during the PAMELA-MOZ3 cruise.

Core	Latitude	Longitude	Water depth (mbsl)	Core length (m)	Section number
<b>MOZ3-CS03</b>	S 24° 49.195	E 36° 17.210	2125	20.06	21
<b>MOZ3-CS02</b>	S 24° 52.441	E 36° 25.424	2041	10.66	11

<b>MOZ3-CS07</b>	S 24° 54.129	E 36° 30.192	1853	11.47	12
<b>MOZ3-CS06</b>	S 24° 35.685	E 36° 34.311	1868	7.89	8
<b>MOZ3-CS05</b>	S 24° 56.685	E 36° 35.854	1926	6.35	7

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1123 **Table 2.** Summarize of data acquired on the CALYPSO piston cores. In red are the data previously  
 1124 acquired by Babonneau et al. (2022). Res. = Resolution; MSCL = Multi-Sensor Core Logger; XRF = X-Ray  
 1125 Fluorescence; <sup>14</sup>C = radiocarbon dating; δ<sup>18</sup>O = O-isotope measurements (*G. ruber*); <sup>87</sup>Sr/<sup>86</sup>Sr = Sr-  
 1126 isotope measurements.

Core	Spectrocolorimetry (Res.)	MSCL (Res.)	XRF (Res.)	Mineral composition (No.)	<sup>14</sup> C (No.)	δ <sup>18</sup> O (Res.)	<sup>87</sup> Sr/ <sup>86</sup> Sr (No.)	Laser grain size
<b>MOZ3-CS03</b>	1 cm	1 cm	1 cm	8	3	10-20 cm	ND	1-7 cm on coarsest parts
<b>MOZ3-CS02</b>	1 cm	1 cm	1 cm	6	ND	ND	ND	1-20 cm
<b>MOZ3-CS07</b>	1 cm	1 cm	1 cm	12	ND	1-4 cm	2 + 38	1-4 cm (27 + 484 analyses)
<b>MOZ3-CS06</b>	1 cm	1 cm	1 cm	ND	ND	ND	ND	12 analyses
<b>MOZ3-CS05</b>	1 cm	1 cm	1 cm	ND	ND	ND	ND	ND

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1128 **Table 3.** Mineral composition obtained on thin sections by QEMSCAN analysis on core MOZ3-  
 1129 CS07.

Depth (mbsf)	Carbonates	Quartz	Feldspars	Clays & Micas	Others
<b>0.33</b>	76,4%	12,5%	4,8%	1,8%	4,6%
<b>1.33</b>	70,7%	20,9%	5,5%	2,4%	0,7%
<b>2.36</b>	62,8%	24,5%	7,8%	3,7%	1,4%
<b>3.33</b>	65,0%	23,7%	7,7%	3,2%	0,6%
<b>4.33</b>	73,3%	16,7%	6,2%	3,5%	0,5%
<b>5.33</b>	64,0%	22,9%	8,7%	3,7%	0,8%
<b>6.33</b>	60,6%	25,8%	10,0%	3,2%	0,5%
<b>7.33</b>	62,2%	24,6%	9,1%	3,7%	0,7%
<b>8.33</b>	66,3%	22,2%	8,1%	2,9%	0,7%

<b>9.33</b>	67,6%	21,4%	7,7%	3,0%	0,5%
<b>10.33</b>	66,5%	18,1%	6,8%	3,4%	5,2%
<b>11.33</b>	69,4%	20,4%	6,9%	2,9%	0,6%
<b>Average</b>	67,1%	21,1%	7,5%	3,1%	1,4%

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**Table 4.** Summarize of strontium series measurements made on core MOZ3-CS07 presented in figure 12. Sigma ( $\sigma$ ) correspond to the standard deviation of the 6<sup>th</sup> decimal. In red are the data previously acquired by Babonneau et al., (2022).

<b>Series</b>	<b>No. of samples</b>	<b>Fraction</b>	<b>Ultrasound</b>	<b>NBS 987 Measured</b>	<b>NBS 987 Standard</b>
<b>1</b>	<b>2</b>	<b>Total</b>	<b>No</b>	<b>0.710248 (2<math>\sigma</math>)</b>	
<b>2</b>	4	Total	No	0.710272 (3 $\sigma$ )	
<b>3</b>	12	>250 $\mu\text{m}$	No	0.710279 (2 $\sigma$ )	0.710250
<b>4</b>	10	>250 $\mu\text{m}$	Yes	0.710269 (2 $\sigma$ )	
<b>5</b>	12	>250 $\mu\text{m}$	No	0.710267 (3 $\sigma$ )	

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