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Factors controlling frequency of turbidites in the Bengal fan during the last 248 kyr cal BP: Clues from a presently inactive channel

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1 **Factors controlling frequency of turbidites in the Bengal fan during the last 248 kyr cal BP:**
2 **clues from a presently inactive channel**

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12

13 **Author contributions:**

14 Kelly Fauquembergue directed the acquisition of data, helped by the EPOC lab technicians. She
15 realized and interpreted the MD12-3412 sedimentological analyses, and redacted the article. This
16 work was undertaken during her master thesis under the supervision of Sebastien Zaragosi that helped
17 for interpretations and redaction. Lea Fournier also participated to the redaction during her PhD. The
18 core was collected in the frame of the ANR (and cruise) MONOPOL directed by Franck Bassinot,
19 who established the age model. Catherine Kissel worked on the elaboration of the composite core used
20 in this study and helped for the redaction. Interpretations and redaction concerning Indo-Asian
21 monsoons were done by Thibault Caley and Bruno Malaizé. Eva Moreno acquired the physical
22 analyses onboard (e.g. p-waves data) and Franck Bachelery produced the geochemical analyses
23 recorded on the Toba tephra layer, they both advised for the redaction and improvement of this article.

24 **Highlights:**

25 - A supposed inactive channel-levee since 125 kyr is investigated on the Bay of Bengal

26 - The channel is reactivated mainly during low sea level stages

27 - Channel activity does not seem linked with monsoons intensity but sea level variation

28 **Keywords :**

29 Turbidites, Bay of Bengal, Bengal fan, Sea-level, Monsoons

30

31 **Abstract**

32 The seafloor of the Bay of Bengal is covered by thick sediment deposits that constitute the largest
33 turbiditic system in the world. This system is fed primarily by the Ganges and Brahmaputra rivers,
34 which drain the high Himalayan ranges. Sediment transfers from the delta to the deep-sea fan take
35 place as turbidity currents in channel-levee systems. Previous studies have shown that, during high
36 sea-level stand periods, the sediments were being mainly stored in the Ganges-Brahmaputra delta, and
37 turbiditic transfer was occurring through active channels. Most of these channels are now inactive and
38 sealed by hemipelagic deposits. However, the evolution of the inactive channels during the last sea-
39 level variations has never been described in detail. Sedimentation in the currently active channel, the
40 Active Valley, was particularly important during the last sea-level rise, which suggests a very good
41 connection between the fluvial systems and the deep turbidite system at this time. During the
42 MONOPOL cruise (2012), we retrieved a giant piston core (MD12-3412) near the currently inactive
43 E4 channel. Previous studies have hypothesized that this channel is connected to the Swatch of No
44 Ground canyon on the upper fan. The upper part of the core covers the last ~250 kyr. It reveals that,
45 contrary to what is known about the Active Valley, the turbidite activity in E4 took place mainly
46 during low sea-level phases (glacial stages), and stopped around 11.8 kyr cal BP. This different mode
47 of activity suggests that (i) E4 was not abandoned but served as a secondary channel, and (ii) that the
48 supply of turbidite material at the site of core MD12-3412 was not related to past changes in summer
49 monsoon strength. Periods of activation of the E4 channel observed on core MD12-3412 were
50 previously identified on the shelf area, by Hubscher and Spiess (2005), as thick Forced Regression
51 System Tracts (FRST) after a displacement of deltaic edifices. High turbidites record on the deep basin
52 are mainly synchronous with sea-level fall and rise conditions, but mostly during low sea-level
53 periods. This could be explained by a residual connection between the coastal system and the E4
54 channel during sea level low stands.

55

56 **1. Introduction**

57 Many high-discharge river outlets are connected to deep-sea channel-levee systems. Therefore, studies
58 focusing on the deep-sea channel-levee formation may help to retrace paleoclimate features, such as
59 discharge variabilities due to rainfall-increased intensities. Covault et al. (2010) demonstrated that El
60 Niño oscillations in southern California were clearly recorded by fluvial discharges of the Santa Ana
61 River that bypasses the New Port submarine canyon. Long-term records sometimes enable us to record
62 sea-level variations in the form of channel-activity cyclicities (Harris et al., 2018). The combined
63 study of turbidites sedimentology and frequency allows for the possibility of correlating channel
64 activity and the main factors that control it. Toucanne et al. (2012), who linked the turbidite activity in
65 the Armorican margin with the European ice-sheets melting phases, efficiently used this approach. The
66 same approach has been also used by Prins et al. (2000) and Bourget et al. (2013, 2010), who showed
67 that the Makran turbidites system activity and the Indus turbidite activity seem both conditioned by
68 continental climate as well as by the sea level. This methodology was applied to the Bengal turbidite
69 system by Fournier et al. (2017) for the Holocene turbidite activity of the Active Valley. Ganges and
70 Brahmaputra rivers have one of the most important sedimentary discharges in the world (1×10^9 t/an,
71 Milliman and Syvitski, 1992). This discharge reaches a seasonal maximum associated to heavy rains
72 of the Indo-Asian summer monsoon (June to September; Saraswat et al., 2014). Monsoon rainfall
73 activity results from the massive ocean-land water vapor transfer driven by the cross-equatorial
74 pressure gradient between the Asian continent and the south Indian Ocean in response to summer
75 insolation (Mohtadi et al., 2016). On a millennial time-scale, the link between the sediment supply and
76 the monsoon activity is evidenced in the delta by a maximum sedimentary supply during the early
77 Holocene (from 11ka to 7 ka; Goodbred and Kuehl, 2000), which was a climatic optimum period
78 characterized by a peak in orbitally-driven boreal summer insolation. Most of the sediment transfers
79 from the delta to the deep-sea Bengal fan takes place through a complex array of channel/levee
80 systems, which constitute the largest turbidite system in the world: the Bengal fan (Figure 1; Curray et
81 al., 2003). However, most of those channels are considered inactive today (Curray et al., 2003).

82 Recent system activity consists of frequent avulsions of the active canyon, the Active Valley (AV;
83 cycle of ± 750 yr; Schwenk et al., 2003). Morphological studies carried out by Hubscher et al. (1997),
84 who focused on the channel and levee structures of the middle and lower fans, showed that the AV
85 mostly developed during the last late glacial after the last main avulsion. Kolla et al. (2012) studied the
86 detailed morphology of channel curves located in the upper fan, and concluded that the channel
87 activity terminated about 6 ka BP. Weber et al. (1997) demonstrated that only the inner levee of the
88 AV records a potential control from the monsoonal activity. Fournier et al. (2017) provided new
89 insights about the main forcings that have affected the activity of the AV during the Holocene. They
90 proved that monsoonal variability is not the only factor controlling the AV activity.

91 The distance of the core relative to the main axis of the targeted channel has an impact on the sediment
92 section thickness and, therefore, on the time window covered by the core. The further away from the
93 channel, the thinner the sedimentary sequence is and, consequently, the older the period we can reach
94 with a given corer length. Thus, because cores are often located close to canyons axis, little is known
95 about the sedimentary activity in this area during the periods preceding the Holocene. In order to
96 address this question, inactive channels have been sampled during the 2012-MONOPOL cruise. Our
97 study is focused on a core collected in the middle fan, on the western levee of the inactive E4 channel
98 (the fourth channel located east of the AV; Curray et al., 2003). This core is far enough from the
99 canyon axis to obtain the record of the activity in the last ~ 250 kyr BP. We propose to retrace the
100 history of turbidites in of the E4 channel, considered as initiated and avulsed during the last 248 kyr
101 (Curray et al., 2003). Our study of core MD12-3412, focusing on the analysis of turbidite frequency
102 over the last ~ 250 kyr BP. This core was previously investigated by Joussain et al. (2016) that focused
103 on the origin of detrial material. Results will then be compared with those obtained for the Holocene
104 period on the MD12-3417 core: this core was collected on the Active Valley levee and previously
105 studied by Fournier et al. (2017) with a similar approach.

107 **2. Previous studies**

108 During the Holocene, the discharge of the Ganges-Brahmaputra river reflects the regional climatic
109 forcing: the largest sedimentation rates are observed on the continental margin during high monsoon
110 intensity periods (Goodbred and Kuehl, 2000). Sediments eroded from the main river catchments form
111 the largest subaerial delta of the world (Goodbred et al., 2003). This delta plays a key role in the
112 connection between riverine sediment supplies and the deep-sea Bengal fan system. This fan system
113 evolves through time as a result of the interaction between sea level changes and monsoon-related
114 sediment supply, inducing variations in sedimentation rates, in accommodation space, and in the
115 location of the major site of deposition (Umitsu, 1993; Blum et al., 2018). The monsoon-related
116 sedimentation is evidenced, for instance, in the peak of the accumulation rates of lithogenic material
117 on the Mahanadi basin margin (south of Ganges-Brahmaputra system; Figure 1) during the Holocene
118 (Phillips et al., 2014). As far as the glacio-eustatism is concerned, its impact on sedimentation on the
119 nearby Bangladesh shelf is readily seen on seismic records, which display both thick Forced
120 Regression System Tracts (FRST) and thin transgressive system tracts (Hubscher and Spiess, 2005).
121 The northern Bengal shelf extends over 200 km seaward, and the shelf-break is located at around
122 120 m depth, and can reach 170 m along its main canyon edge, i.e. The Swatch of No Ground (SoNG).
123 As a result, most of the shelf can be exposed during the glacial maxima, resulting in a major impact of
124 the sea level on sediment transfer from the shelf to the deep sea (Miller et al., 2005). From 20 to 29%
125 of the total river load can reach the SoNG in the modern configuration (Michels et al., 2003), making
126 this canyon the main connection between the deltaic edifices and the deep sea fan. When sediments
127 leave the SoNG, they reach the upper continental slope and travel deeper through deep-sea channels as
128 turbidity currents (Kottke et al., 2003). Deliveries from the Ganges-Brahmaputra can travel more than
129 1400 km in the Bengal turbidites system (Blum et al., 2018). The AV (Figure 1) is supposed to be the
130 only channel connected to the SoNG during the Holocene. Nowadays, every clayey discharge from the
131 Ganges-Brahmaputra that bypasses the shelf is therefore supposed to flow into the AV (Weber et al.,
132 1997; Fournier et al., 2017). However, the entire system evolution through the Pleistocene and the

133 Holocene is difficult to reconstruct, mainly due to the frequent avulsions of the active channels
134 (Curry et al., 2003).

135 Indeed, channels other than the AV are supposed to have been abandoned over the last 125 kyr, even if
136 during the Pleistocene river mouths and coast lines could reach the shelf break and reactivate several
137 canyons and multiple channels (Curry et al., 2003; Clemens et al., 2016). A few studies managed to
138 identify Pleistocene turbidite activities on the distal fan (e.g. Kessarkar et al., 2005). However, in the
139 upper and the middle fan, past turbidite activity has not been studied yet. Moreover, many studies
140 focused on past channel activity using seismic data (Curry and Moore, 1971, 1974; Hubscher et al.,
141 1997; Thu et al., 2001; Curry et al., 2003; Kolla et al., 2012) or sediment physical properties (Weber
142 et al., 2003). Only the study by Fournier et al. (2017) utilized direct grain size measurements and
143 geochemistry methods to decipher past changes in the turbidite frequency in the AV. Here we try to
144 focus on the E4 channel (Figure 1) using precise measurements performed on core MD12-3412, which
145 was recovered from its western levee.

146146

147 **3. Material and methods**

148 **3.1 Imagery**

149 The echosounder Thomson Seafalcon 11 was used to acquire the bathymetry during the MONOPOL
150 cruise of the *R.V. Marion Dufresne* (2012; 12 kHz carrier; 80 to 11000 m depth). The echosounder
151 also included a sub-bottom profiler (3.75 kHz; ± 0.31 m; Figure 2).

152 Other authors (Curray and Moore, 1971, 1974; Thu et al., 2001; Curray et al., 2003; Weber et al.,
153 2003; Schwenk et al., 2003; Thomas et al., 2012; Kolla et al., 2012) precisely described each channel
154 of the Bengal fan, and the compilation of those data (Figure 1) leads to a precise channel location.

155 **3.2 Sediment core**

156 The giant piston core MD12-3412 (Calypso corer, 18°18.62'N, 89°34.26'E, 2367 m water depth, 32 m
157 long; Figure 2) has been collected in the northern Bay of Bengal, in the upper part of the middle fan
158 during the MONOPOL cruise. As already noticed by different studies, the Calypso corer can lead to
159 oversampling of the upper sedimentary section due to cable rebound (Skinner and McCave, 2003).
160 Despite being now operated with a stiffer coring cable and being set up with a longer piston cable loop
161 in order to dissipate much of the elastic rebound during coring, a slight oversampling took place in the
162 upper ~10 m of core MD12-3412. This was highlighted and corrected by comparing the volume low-
163 field magnetic susceptibility of this core with that of the twin gravity core (CASQ core MD12-3411Q,
164 9 m long). The depths of the upper sections were corrected and a composite depth was constructed for
165 core MD12-3412. Thus, core depths used in this work are “composite depths”.

166 **3.3 Sediment laboratory analyses**

167 The core was analyzed with the SCOPIX X-ray image-processing tool at EPOC lab (Bordeaux).

168 Semi-quantitative analyses of chemical elements were obtained through a XRF Core Scanner
169 (AVAATECH) at EPOC laboratory. A step of 1 cm has been used along the entire core length to study
170 the ratios Zr/Rb and Si/Al (Figures 3 and 4).

171 For the grain size, 1887 samples were collected along core MD12-3412. The measurements were
172 performed by a Malvern Mastersizer particle size analyzer. Grain size data were visualized with a
173 MatLAB® program to map the repartition percentage of the grain size fractions (Figure 4). Grain size
174 distribution is presented on Figures 3 and 4, together with a grain size map. The sampling resolution
175 varied from 0.5 cm for sequences that presented grain size variation to 5 cm for intervals that do not
176 present significant grain size variation.

177 Sediment sieving and washing (over 63 μm and 150 μm mesh-sieves), thin sections, and sediment
178 smears slides (Figure 5) were realized on core MD12-3412, in order to analyze the composition of the
179 grains. P-wave velocities and magnetic susceptibilities (Figure 4) were measured every 2 cm on board
180 the R.V. Marion Dufresne during the MONOPOL cruise with a Geotek multi-sensor track. The
181 volume low-field magnetic susceptibility was measured every 2 cm on u-channels using an MS2B
182 Bardington sensor with a 4.5 cm resolution (LSCE, Gif-sur-Yvette).

183 Radiocarbon dates were acquired by the ARTEMIS Accelerator Mass Spectrometry facility at the
184 CEA center of Saclay (Gif-Sur-Yvette), and converted into calendar ages using the MARINE 13 curve
185 (Reimer et al., 2013), that corrects the 400 yr standard reservoir age, usually used in the Bay of Bengal
186 (Dutta et al., 2001; Southon et al., 2002). The age model (Figure 6) has been established using the R
187 software package Clam (version 2.2; Blaauw, 2010) with a linear interpolation method at 0.1 cm
188 resolution.

189 Isotopic analyses of $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ (Figures 3 and 4) were performed on the shells of planktonic
190 foraminifera *Globigerinoides ruber sensu stricto*, *G. trilobus* and *G. sacculifer*. The sampling
191 resolution varied from 1 cm (last climatic cycle) to 20 cm in the deepest interval downcore (Figure 4).
192 The analyses were performed at LSCE laboratory using an ISOPRIME mass spectrometer, and
193 converted to PDB values using a laboratory standard calibrated relative to the international National
194 Bureau of Standards (NBS19). The internal reproducibility estimated from replicate analyses of the
195 laboratory standard was $\pm 0.06\text{‰}$ for $\delta^{18}\text{O}$ (1 sigma).

196 The composition of the oxides of a tephra layer found at 5.08 m depth in the core was analysed by
197 WDS electron microprobe CAMECA SX100 at Clermont Auvergne University (Laboratoire Magmas
198 et Volcans - Clermont-Ferrand, France).

199 **3.4 Stratigraphy and age model**

200 The stratigraphy of core MD12-3412 composite was established thanks to three different kinds of
201 proxies (Figure 6):

- 202 – Tephrochronology. Due to its oxides composition (Table 1) compared with Matthews et al. (2012)
203 and Schulz et al. (2002) data, a tephra layer found at 506 cm depth was clearly identified as
204 originating from the Toba eruption dated at $\sim 73.7 \pm 0.3$ kyr (Mark et al., 2017).
- 205 – Radiocarbon dates. The chronology of the upper part of our composite record was based on 7
206 radiocarbon dates obtained from foraminifera bulk tests picked from clayey hemipelagic horizons
207 (Table 2).
- 208 – $\delta^{18}\text{O}$ PDB. Two models were established: one using $\delta^{18}\text{O}$ PDB values of samples collected
209 exclusively on *G. ruber* from hemipelagic intervals, and another based on more numerous samples
210 without discriminating the origin of the sequences. Records show no significant difference,
211 especially at our study scale (periods of 5 kyr). Thus, the stratigraphy and age model were
212 established without correcting for the small turbidite layers.

213 Beyond the ^{14}C dated interval, the chronology was derived by tuning the Lisiecki and Raymo (2005)
214 $\delta^{18}\text{O}$ PDB record to an empirical target function developed from the simple non-linear model of
215 Imbrie and Imbrie (1980), forced by summer boreal insolation. A similar approach was followed by
216 Bassinot et al. (1997), Lisiecki and Raymo (2005), and Shackleton et al. (1990) to develop Pleistocene
217 age models of reference isotopic records. The two parameters of the model (T_m , i.e. the mean time
218 constant, and b , i.e. the nonlinearity coefficient) were adjusted to ensure the best possible fit between
219 the estimated target curve and the $\delta^{18}\text{O}$ stratigraphy of the upper part of MD12-3412, which was dated
220 based on the seven ^{14}C tie-points and the Toba layer at 73.7 ± 0.3 kyr (Young Toba Tuff; Mark et al.,
221 2017). The model adjustment resulted in T_m being set to 9 ka, and b set to 0.2. This approach assumed

222 that, over several Glacial/Interglacial cycles, there existed a constant phase-lock of climatic response
223 embedded in the $\delta^{18}\text{O}$ record of core MD12-3412 (including the monsoon signal that affected past
224 changes in changes of $\delta^{18}\text{O}$ in regional seawater) relative to insolation forcing.

225 Based on the correlation with the target template modified from Imbrie and Imbrie (1980), the
226 chronology of core MD12-3412 was developed down to ~13.5 m. The sedimentary record extends
227 beyond that level, but the isotopic stratigraphy is difficult to interpret owing to possible large changes
228 in sedimentation rates and/or hiatuses, and to a potential diagenetic overprint on the $\delta^{13}\text{C}$ record (see
229 Results).

230230

231 **4. Results**

232 Acoustic data acquired attest that core MD12-3412 is located about 30 km west from the E4 channel.
233 Sense of sediment waves and high-amplitude reflectors, potentially beveled, observed on seismic
234 profiles (Figure 2) highlight that the MD12-3412 is located on the western levee of the E4.

235 The analyses performed on core MD12-3412 reveal that the $\delta^{13}\text{C}$ of *G. ruber* fluctuates between 0.5
236 and 1.5‰ over the top 16 m of the core (Figures 2 and 3), and then drops down to anomalously low
237 values (about -5‰). Very low $\delta^{13}\text{C}$ values in planktonic foraminifer shells had been observed by
238 Garidel-Thoron et al. (2004) in a core from the western Pacific margin, and interpreted as being
239 potentially linked to massive methane releases that could led to the depletion of foraminifer $\delta^{13}\text{C}$.
240 Anomalously low P-wave velocities, approaching values typical of the speed of sound in the air (~600
241 m/s), were recorded in the bottom part of the core (Figures 2 and 3).

242 This core is composed of fine-grained sediment, mostly clay to silty-clayed sized particles (4-15 μm),
243 observed on X-ray imagery as homogeneous light sequences (Figure 4). The grain size map (Figure 3)
244 shows 91 grain size excursions to coarser silts or very fine sandy grains (31.3-62.5 μm), corresponding
245 to dark, heterogeneous and finely laminated sequences in the X-ray imagery (Figure 4). Those
246 excursions form thin (1 cm scale), fining-upward layers, commonly associated with planar
247 laminations, and slightly erosional surfaces (Figure 5). Laminations are probably due to the variable
248 energy of the currents, and may correspond to Bouma's term sequences where cross laminations (Tc;
249 Bouma, 1962) are topped with planar laminations (Td). These coarse silt-to-clay excursions grade up
250 to decantation fall-out clay. These excursions reach a mean thickness of ~4.5 cm and are illustrated by
251 abrupt increasing Si/Al and Zr/Rb ratios at their base (Figure 4). Direct observations of the sediment
252 and thin sections (Figure 5) reveal that rapid changes in these ratios correspond to sudden occurrences
253 of detrital material (quartz, white & black mica for ~95% of total samples) and few foraminifera
254 broken tests (~5%) above bioturbated sediment layers rich in foraminifers. In this core, an increase in
255 Si/Al ratio illustrates the detrital supplies due to an increase of quartz grains, while Zr/Rb variations
256 are correlated with grain size variations and continental supply (Dypvik and Harris, 2001; Wang et al.,
257 2008).

258 On the deep-sea Bengal system, turbidites have a geochemical signature characterized by high Si and
259 Zr contents. Thus, those sequences are interpreted as turbidites that interrupted the hemipelagic
260 deposition.

261 The number of turbidites observed in 5 kyr time interval periods were counted in core MD12-3412
262 from 0 to 248 ka (from 0 to ~16 m on the composite core). Such a sub-orbital 5 kyr time-window
263 makes it possible to reconstruct changes in turbidite frequency at a resolution enabling us to look at
264 the glacio-eustatic oscillations and/or monsoon variations driven by low-latitude insolation changes,
265 chiefly paced by precession. Four distinct periods of major turbidite activity of E4 channel were
266 identified (Figure 7):

267 - an active phase during the glacial MIS 4-3-2, with peaks in activity reaching 4 turbidites/5 kyr, and
268 even a peak of 5 turbidites/5 kyr during the last deglaciation, between MIS 2 and 1.

269 - an active phase during MIS 6, which seems continuous but with peaks that can reach 7 turbidites/5
270 kyr.

271 - an active phase during MIS 7, where the turbidite frequency does not exceed 2 turbidites/5 kyr.

272 - a slightly active phase during the recorded period of MIS 8, where the turbidite frequency does not
273 exceed 1 turbidite/5 kyr.

274 Those 4 periods of stronger turbidite activity are separated by inactive periods during MIS 1, MIS 5, at
275 the onset, and at the end and the beginning of MIS 7 (Figure 7). The undated base of the core shows
276 numerous turbidites (Figure 4).

277 The thickness of the turbidites was measured using a combination of grain size data (difference of
278 depth between the coarse bases and the top of the hemipelagic layers; Figures 4 and 5), geochemical
279 data (difference of depth between the high and stable Si/Al & Zr/Rb ratios; Figure 4), and evidences of
280 internal structures in sequences (laminations and erosive surfaces; Figure 5). Turbidites thicknesses
281 vary from 1 to 13 cm during the activity periods. Even if the mean turbidite sizes seem greater during
282 MIS 4-3-2 than during MIS 6, the difference is not significant (mean value of 6.22 ± 2.14 cm for

283 MIS 4-3-2, and 4.1 ± 3.32 cm for MIS 6). The mean value of turbidites thickness during MIS 8 is not
284 relevant because MIS 8 is not entirely recorded.

285 **5. Discussion**

286 **5.1 Main forcings affecting the turbidites activity**

287 In MD12-3412, the anomalous $\delta^{13}\text{C}$ signal and p-waves velocities could be associated with a partial
288 re-crystallization of foraminifer shells in the presence of methane during diagenetic processes. Such
289 hypothesis is backed-up by the broad occurrence of gas hydrate areas in the Bay of Bengal (Figures 2
290 and 3; Dewangan et al., 2013). Anomalies are synchronous with a huge shift recorded during the MIS
291 8-7 on the lower fan, when the system became suddenly highly turbiditic according to the Mid-
292 Brunhes Transition (Weber and Reilly, 2018). To address a potential problem with $\delta^{18}\text{O}$ PDB values,
293 we will only focus on the upper part of the core, for which a precise age model could be achieved.

294 The presence of many sequences that exhibit finning upward associated with brutal increases of Si/Al
295 and Zr/Rb, followed by decreases, leads to the conclusion that core MD12-3412 records fine-grained
296 turbidites (coarse-silts or very fine-sand grain size excursions) interspersed by hemipelagic sequences
297 (lighter silty-clays). Based on our observations, grain size excursions showing these specific features
298 were considered as fine turbidite sequences (Figures 4 and 5). Geochemistry is well correlated with
299 turbidite sequences, X-ray images, and grain sizes. During the last 248 kyr cal BP, three active and
300 two inactive phases were observed on the channel.

301 According to Phillips et al. (2014), detrital material supplies and sedimentation rates were low during
302 the last glacial maximum at the outlet of the Mahanadi due to the weakened SW monsoon. However,
303 they increased during the early Holocene in association with increased monsoon activity driven by the
304 low-latitude summer insolation maximum. Erosion of the Godavari catchment erosion (Figure 1)
305 increased during the late Holocene due to a decrease in monsoon intensities, and could have led to an
306 increase in sedimentation rates during this period (Giosan et al.; 2017). Some studies suggest that the
307 summer Asian monsoon was enhanced during interglacial periods, and reduced during glacial periods
308 (Guo et al., 2000; Sun et al., 2006). According to Clemens and Prell (2003), and Caley et al. (2011),
309 internal climate forcing sets the timing of strong Indo-Asian summer monsoons within both the
310 precession and the obliquity cycles. Another hypothesis, based on Chinese cave speleothem records, is
311 that the monsoon response is nearly in phase with the summer boreal insolation (Cheng et al., 2009;

312 Dykoski et al., 2005; Wang et al., 2008). However, the increase in monsoon intensities during MIS 5
313 and 1 corresponds to inactive phase in the middle fan, while low monsoon intensities during MIS 6
314 and 2 correspond to high turbidite frequencies. Moreover, the sedimentation rates are slightly higher
315 during glacial periods than in interglacial periods (Figure 62). Hypotheses considered here in driving
316 the Indo-Asian monsoon at the orbital scale are not correlated with turbidites activity within the
317 MD12-3412 (Figure 7). The Indo-Asian monsoon intensity is therefore not the first-order forcing that
318 controls the turbidite activity in the middle Bengal fan and in the E4 channel at the glacial-interglacial
319 or orbital scales. During MIS 6, the evolution of the thickness of the turbidites seems negatively
320 correlated to the monsoons intensity (Figure 7), probably because low-intensity but frequent monsoons
321 lead to a progressive flushing of large amounts of sediment, while high-intensity but sporadic ones
322 lead to a strong punctual flushing. However, it is hard to establish a clear link between both records.
323 The study of the frequencies of other low-stand turbidites in other locations of the Bengal fan would
324 be necessary to propose monsoons as a secondary-order forcing that controls the turbidite activity in
325 the Bay of Bengal.

326 Based on geochemical and mineralogical evidences, Jousain et al. (2016) concluded that detrital
327 material at the site of core MD12-3412 was derived from the Ganges and Brahmaputra rivers during
328 interglacial periods (MIS 5 and 1), while it derived from a mixture of material originating from the
329 Ganges-Brahmaputra rivers and the Indo-Burman Ranges during MIS 6, 4, 3 and 2. Several major
330 changes in the sea level have been recorded during the last 248 kyr, namely three periods of low sea
331 level during MIS 8, MIS 6, and MIS 4-3-2, and three periods of high sea level during MIS 7, 5 and 1
332 (Grant et al., 2012). The main phases of turbidite activity are synchronous with both periods of low sea
333 level and sea level fall or rise (Figure 7). The low sea level configuration promotes the connection
334 between the rivers and the deep sea (Sijinkumar et al., 2016). During low stands, the Bangladesh shelf
335 is subaerial due to its shallowness (<120 m depth). Oolitic beach barriers accumulated during sea-
336 level low stands indicate that the current outer shelf was not influenced by massive terrigenous input
337 (Wiedicke et al., 1999). Thus, the Ganges-Brahmaputra outlet is probably connected to the SoNG that
338 incised the shelf (Figure 1). These periods (MIS 8, 6, 4-2) are recorded on the continental shelf by

339 thick FRST sequences, extending also beyond the break of the slope for MIS 8 and 6 (Hubscher and
340 Spiess, 2005). Low stand deposits are deltaic lobes on the continental slope, prograding during the
341 MIS 6, and retrograding during MIS 8 and 4-3-2 (Hubscher and Spiess, 2005). The low sea level
342 increases the area of deltaic sedimentation, and brings it closer to the Bengal fan. In fact, the greater
343 feeding induces an increase of the turbidite activity in the Bengal fan, which is consistent with Curray
344 et al.'s (2003) suggestion that channel/levee systems were built during periods of low sea level. The
345 deltaic sedimentation, taking place all along the continental shelf, may explain the mixed origin of the
346 sediments (Joussain et al., 2016) during MIS 6 and 4-3-2. Moreover, this lower sea level configuration
347 also explained the enhanced supply found by Panmei et al. (2018) on the upper fan. The magnetic
348 susceptibility curve relative to sediment source supply seems strongly correlated with sea level
349 variations during the last glacial period from MIS 4 to MIS 2. Conversely, high sea level stands are
350 characterized by the absence of turbidite activity in the upper fan (Figure 7). High stands make
351 possible the construction of thin transgressive system tracts sequences extending on the continental
352 shelf (Hubscher and Spiess, 2005). There is a landward shift of deltaic sedimentation during high
353 stands (Hubscher and Spiess, 2005), which can explain why only the major rivers supplies (Ganges-
354 Brahmaputra) can reach the upper Bengal fan (Joussain et al., 2016). Thus, the landward shift of
355 deltaic edifice induces a decrease of turbidite activity in the middle fan recorded by the western flank
356 of E4 (Figure 7). Those results highlighted that the turbiditic transfer to the upper fan is mainly related
357 to the glacial – interglacial changes of sea level. During a low stand, the canyon is the main conduit,
358 whereas during a high stand the sediment is stored in the delta.

359 **5.2 Evolution of turbidite activity in the Bengal fan**

360 According to Curray et al. (2003), the Quaternary upper Bengal fan is subdivided into four subfans,
361 showing some lateral shifts in the Bay of Bengal. Two of them concern the period since 250 kyr,
362 which was also considered in this work. The first subfan, fed between 465 and 125 kyr cal BP (before
363 the MIS 5), is located on the eastern side of the AV, and was mainly fed by the SoNG, but with
364 multiple sources on the platform margins (Curray et al., 2003). The modern fan configuration, with the
365 SoNG as the only fan feeder, is considered to be in place since 125 kyr cal BP (since the MIS 5). Thus,

366 turbidites recorded since 125 kyr cal BP are characterized by a shift in sedimentation from a channel
367 on the east side of the fan (the E4 channel) to the AV (Curray et al., 2003). This shift is not due to a
368 canyon shift but to a lateral channel shift around 19 °N on the upper fan (Figure 1; Curray et al.,
369 2003). Thus, the E4 channel is supposed connected to the SoNG outlet as the AV. Glacial MIS 4-3-2
370 presents a lower activity than the previous glacial MIS 6, and interglacial MIS 5 does not present any
371 activity, contrary to the previous interglacial MIS 7 that presents a low activity. Our results are
372 consistent with a change in turbidite activity that took place around 125 kyr cal BP, but they also
373 reveal that turbidite activity is still recorded after 125 kyr cal BP near the E4 channel during periods of
374 regression and low sea level stand (Figure 7). The E4 was probably a rare reactivated channel during
375 low stand, and was not completely avulsed after 125 ka, contrary to the suggestion of Curray et al.
376 (2003). Turbidite activity recorded near the E4 channel terminated around 11.8 kyr cal BP, and
377 hemipelagic sedimentation settled above, with a sedimentation rate around 2 cm/kyr (Figure 7).

378 The E4 terminated its activity around 11.8 ka cal BP, while the AV initiated around 14.5 kyr cal BP
379 (Weber et al., 1997), and turbidite activity was highest during periods of sea level rise and during the
380 first stages of the Holocene high stand (Weber et al., 1997; Fournier et al., 2017). This is contrary to
381 what we observe close to the E4 channel. These two channels therefore functioned differently
382 depending on the sea level (Figure 8). Because our data suggest that E4 channel was activated during
383 low stands, the connection between the E4 channel and the SoNG outlet on the upper fan could still be
384 active, meaning that the AV was not the only channel connected to the SoNG shelf during the period
385 between 14.5 and 11.8 ka cal BP.

386 **5.3 Comparisons with the modern Bengal configuration**

387 Even if some discharges are recorded in the AV (Fournier et al., 2017; Figure 8), the turbidites supply
388 shows a clear shift from a direct supply before 9.2 kyr to a more complex model with different factors
389 involved since 9.2 kyr (Figure 8; river migrations, delta construction, and potentially anthropogenic
390 impact). Turbidite activity in the E4 channel suggests that it has been reactivated as a secondary
391 channel during regression, transgression, and low sea level stand periods since at least the Mid-
392 Brunhes Transition (Figure 8; Weber and Reilly, 2018). This functioning does not seem common to

393 every canyon and channels in the Bay of Bengal, but it has already been observed on other turbidite
394 systems. A close but quite different functioning system was observed for the Indus system (Bourget et
395 al., 2013). A delta formed during forced regression conditions reactivated multiple canyons and gullies
396 that fed several channels. In our case, only the SoNG was recognized as a feeding canyon along the
397 shelf during the last 125 kyr.

398 Jipa and Panin (2018) highlighted two main models explaining the functioning of modern canyons in
399 the Black Sea: the active eastern narrow shelf canyons, and the inactive western wide shelf canyons.
400 The wide shelf canyons are mainly active during low stand periods, while narrow shelf canyons are
401 active during both low stand and high stand conditions. Narrow shelf canyons in the Black Sea seem
402 to record the same kind of configuration of the Newport submarine canyon (Covault et al., 2010),
403 while the Bengal shelf mainly belongs to the wide shelf class and presents the same features. Fluvial
404 outlets are disconnected to the main canyon head (SoNG) during high stands, and this configuration
405 limits the direct flushing of fluvial supply to the canyon and then to the deep-sea channel system, even
406 during periods of high monsoon intensity.

407407

408 **6. Summary and conclusion**

409 Grain size and geochemical analyses of MD12-3412 allowed for the reconstruction of the E4 channel
410 turbidite activity in the upper part of the middle Bengal fan. The following main conclusions have
411 been drawn from the results of the analyses:

412 (1) For the last 248 kyr cal BP, periods of higher turbidite activity mainly occurred during the
413 glacial periods MIS 6 and MIS 2-3-4. These results coincide with Forced Regression System
414 Tracts deposition periods observed on the shelf (Hubscher and Spiess, 2005), suggesting an
415 exceptional narrow link between the sedimentary supply by-passing the shelf during glacial
416 periods and the E4 channel activity.

417 (2) Sea level variations seem to be the main forcing affecting the turbiditic sedimentation in the
418 middle part of the Bengal fan at glacial/interglacial time scale. Even if avulsion is observed in
419 the Bengal fan (Curry et al., 2003), the E4 channel and the middle fan are reactivated during
420 low stand periods. Thus, the E4 channel has not been abandoned and avulsed after 125 ka.

421 (3) A link between sea level variations and channel activity might have conditioned both the delta
422 extent and the break slope position, similarly to what was observed for the Indus system and
423 for the Black Sea systems. A decrease in sea level leads the delta to become subaerial, with
424 sediments having no buffer tank and not enough accommodation space. Such configuration
425 enables the reactivation of secondary channels, such as the E4, so as to offset this lack of
426 space.

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634

635 Table 1: Comparison between Toba eruption features (Matthews et al., 2012; Schulz et al.,
636 2002) and the MD12-3412 tephra sequence.

	MD12-3412 samples analyses (%)	Analyses from continental samples (%; Matthews et al., 2012)	Analyses from the middle fan (%; Schulz et al., 2002)
	n=14	n=274	n=4
SiO₂	77.13 ± 0.08	76.80-77.44	78.60
TiO₂	0.068 ± 0.007	0.05-0.08	0.06
Al₂O₃	12.62 ± 0.06	12.40-12.70	12.59
FeO	0.91 ± 0.04	0.77-0.97	1.03
MnO	0.06 ± 0.02	0.06-0.08	0.06
MgO	0.062 ± 0.006	0.04-0.07	0.06
CaO	0.80 ± 0.02	0.69-0.89	0.76
Na₂O	3.14 ± 0.05	2.98-3.38	1.80
K₂O	5.20 ± 0.04	4.98-5.17	5.03
P₂O₅	0.017 ± 0.007	(unknown)	(unknown)
Tephra thickness (cm)	8	2-15	x

637

638 Table 2: Results of MD12-3412 foraminifers bulk radiocarbon datings after calibrations

Depth (cm)	Age (yr cal BP)	Error (yr cal BP)
25.8	1776	85
41.5	10738	150
78.4	13823.5	137.5
101.4	16651	241
124.3	19467	219
169.7	28327.5	334.5
205.4	31420.5	366.5

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640

641 Figure 1: Location map and physiography of the Ganges-Brahmaputra sedimentary system, from the
642 catchment to the deep-sea fan. Fluvial systems are in light blue, and channelizations of the Bengal fan
643 according to different sources and interpretations are visible in a shade of blue. Names of each channel
644 are from Curray et al. (2003). The inset shows an enlarged view of the upper and middle fan with the
645 location of the core MD12-3412 and -120 m isobaths. The summary of channels morphology was
646 reported thanks to Curray et al. (2003), Kolla et al. (2012), Kottke et al. (2003), Thomas et al. (2012),
647 Thu et al. (2001), Weber et al. (2003).

648

649 Figure 2: Very High seismic profile and interpretation from MD12-3412 environments.

650 Figure 3: Interpretative log, grain size distribution (D50= Decile50 and colours illustrate the % of
651 sieve non-passing fraction, see scale at the bottom), $\delta^{18}\text{O}$ results for *G. ruber*, and position of Marine
652 Isotopic Stages (MIS). P-waves velocities and $\delta^{13}\text{C}$ *G. ruber* highlight abnormal high values below
653 13.80 m depth. The correlation established between MD12-3411Q and MD12-3412 to correct MD12-
654 3412 oversampling is illustrated on the right side. Stratigraphic data are represented (MIS boundaries
655 according to age model, positions of radiocarbon dates in red dots, Toba eruption in purple dots, and
656 $\delta^{18}\text{O}$ *G. ruber* pointers in black dots). Location of Figure 4 is shown. The grey rectangle corresponds
657 to the core bottom unexploited here according to potential methane releases.

658 Figure 4: Example of turbidite sequences successions: Zr/Rb and Si/Al ratios, D50, grain size
659 distribution, and Scopix radiography. Location of Figure 5 is shown.

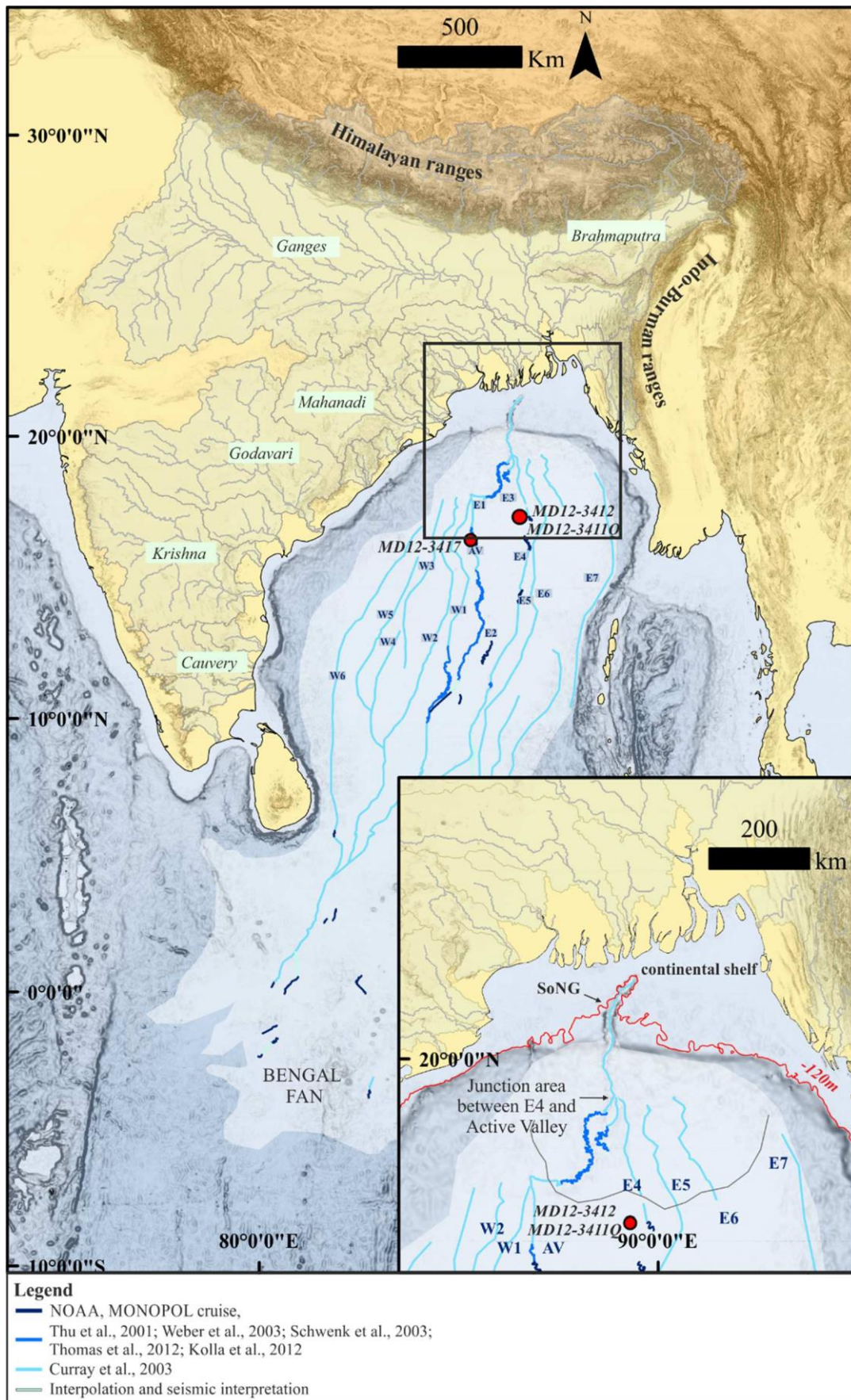
660 Figure 5: Example of grain size excursion and detailed composition of bases in plane-polarised light
661 (PPL) and cross-polarised light (XPL). d.: hemipelagic decantation, p.l.: planar lamination, b.:
662 bioturbation, c.b.: coarser bed, c.l.: cross lamination, e.s.: erosional surface, m.f.: mud rich in forams.
663 Planar laminations (Td), cross laminations (Tc), and erosional surfaces with decrease in grain size
664 from erosional surface to decantation are typical of Bouma's sequences (Bouma, 1962).

665 Figure 6: Age model (black line) of the MD12-3412 core and associated sedimentation rate (dashed
666 line). Radiocarbon dates are represented by red dots, Toba eruption is represented by a green dot, and
667 $\delta^{18}\text{O}$ *G. ruber* pointers tuned on the revised template by Imbrie and Imbrie (1980) are represented by
668 black dots.

669 Figure 7: Relation between turbidite occurrence and thickness, Indian monsoon, and global sea-level
670 variability over the last 250 ka. Note that turbidites occurred during glacial sea-level low stands (grey
671 bars), and do not follow the monsoonal trends.

672 Figure 8: Comparison between MD12-3412 (E4 channel; this study) and MD12-3417 (Active Valley;
673 Fournier et al., 2017) controlling factors. The location of both cores is reported in Figure 1.

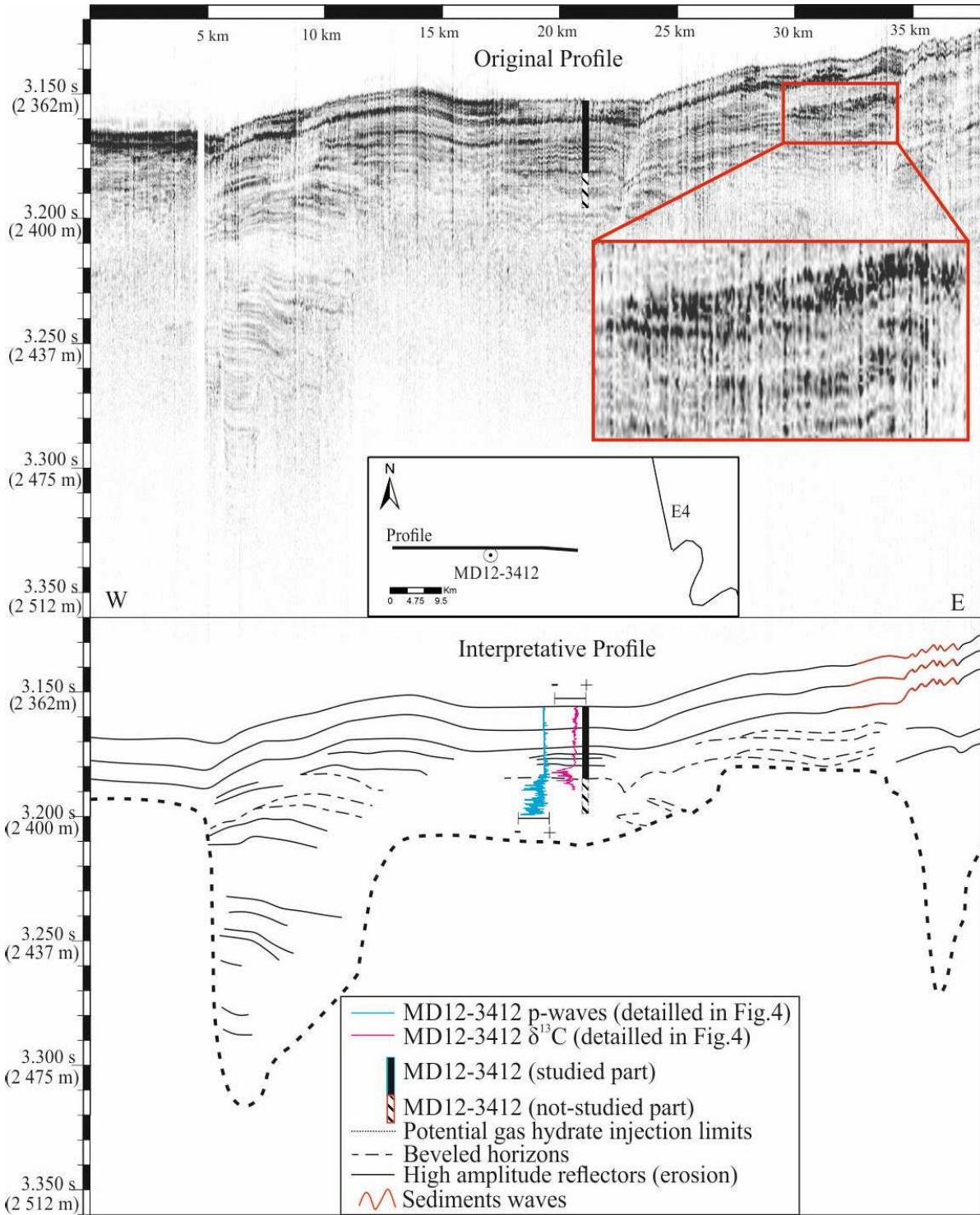
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Figure 1

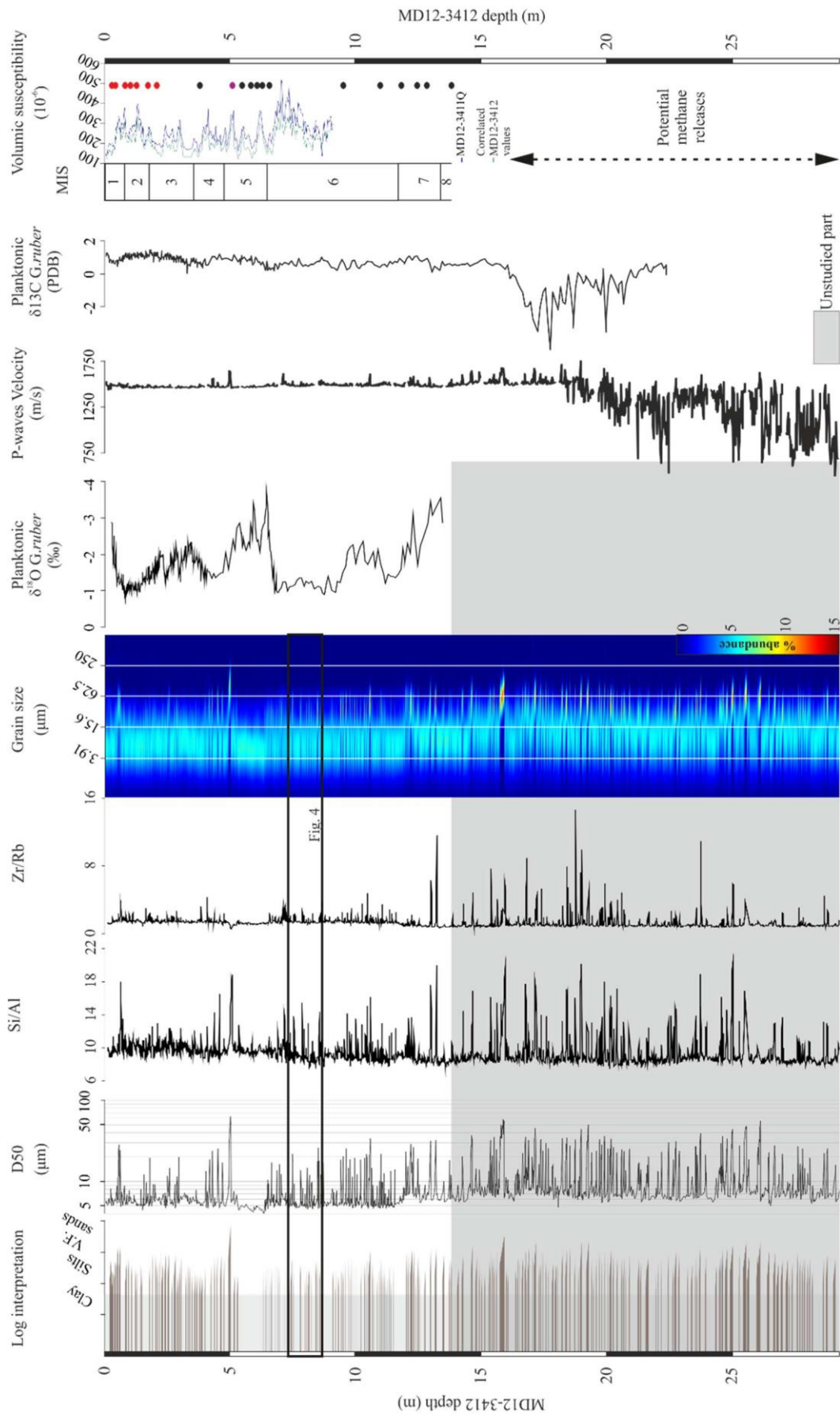


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Figure 2

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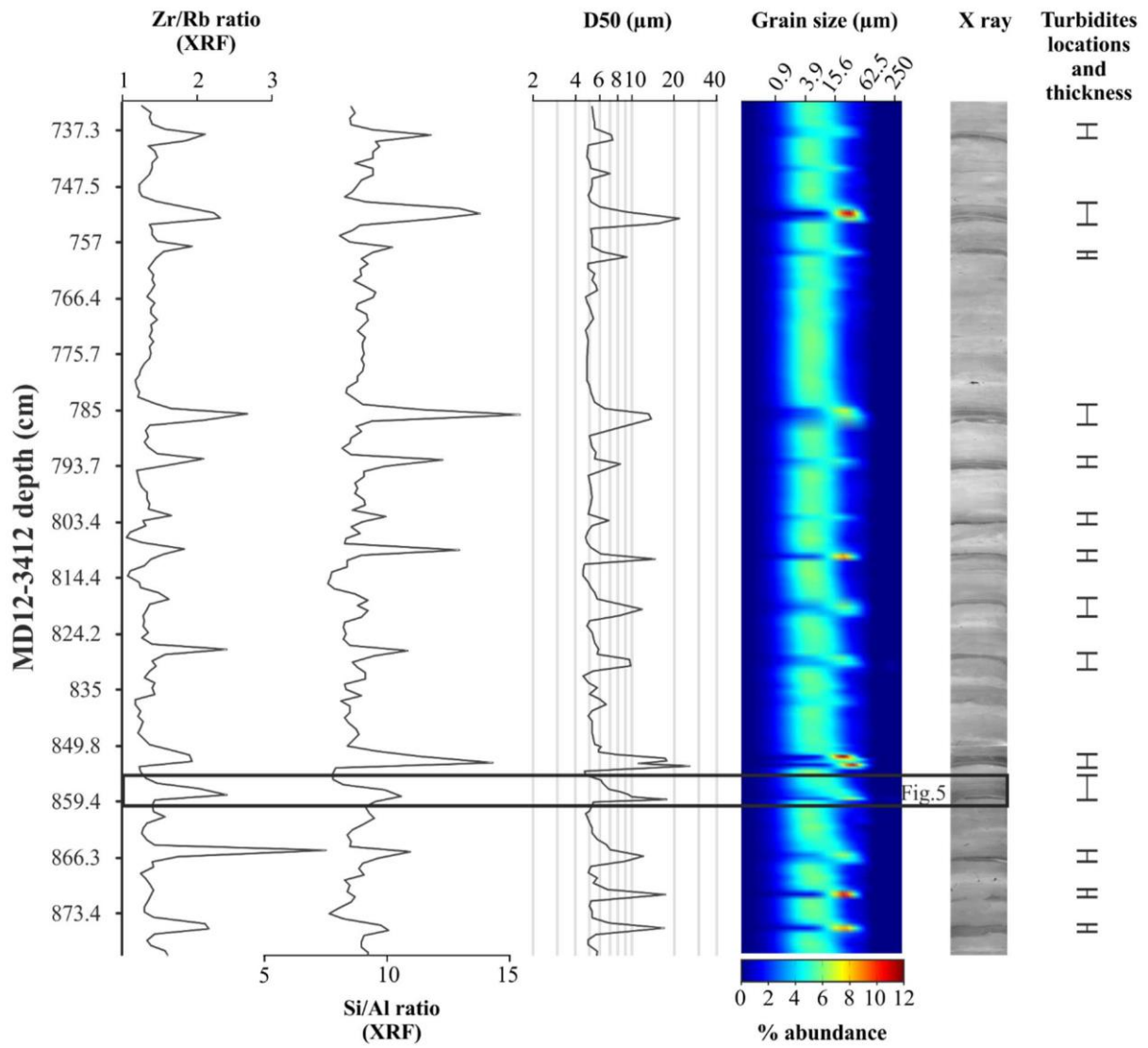


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Figure 3

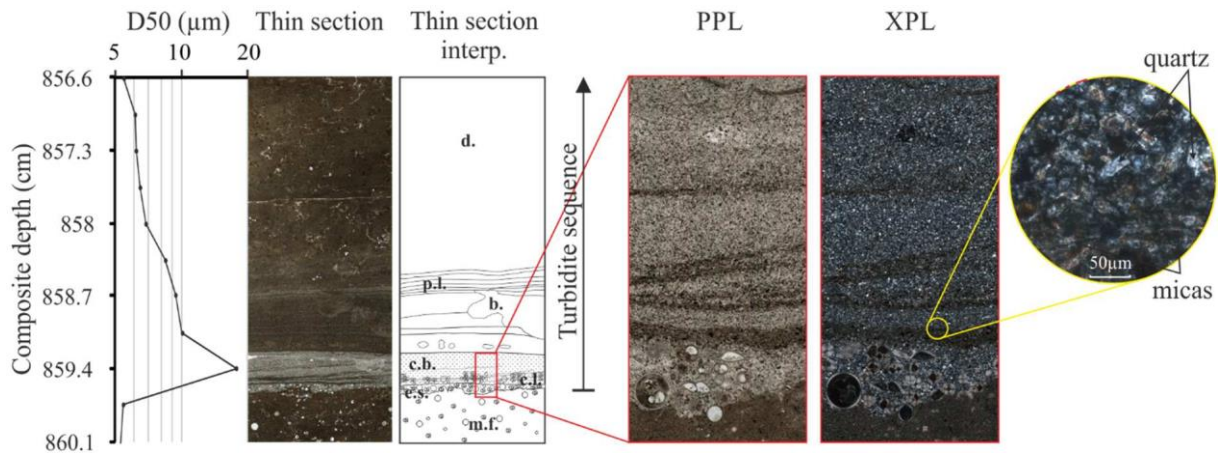


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Figure 4

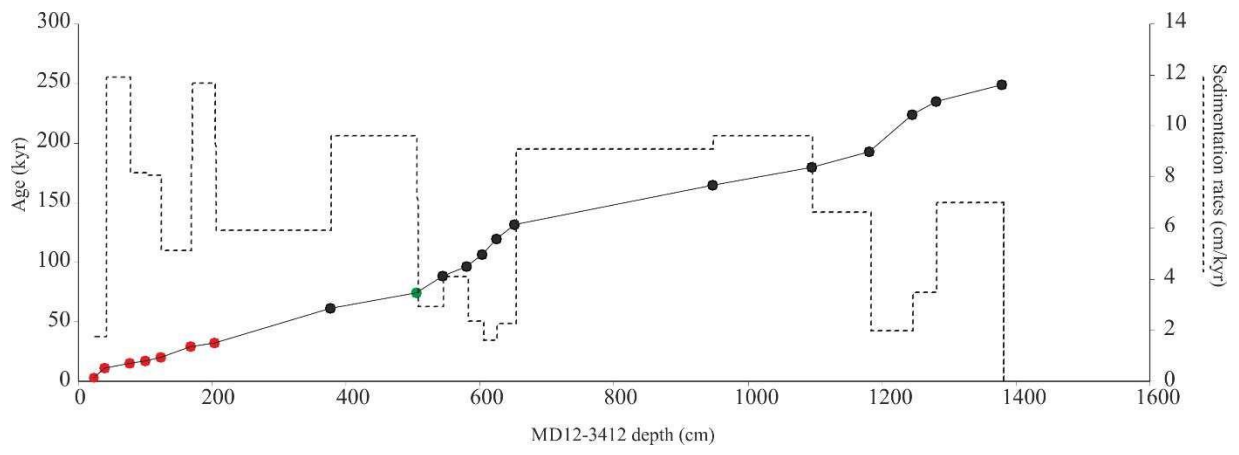


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Figure 5



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Figure 6

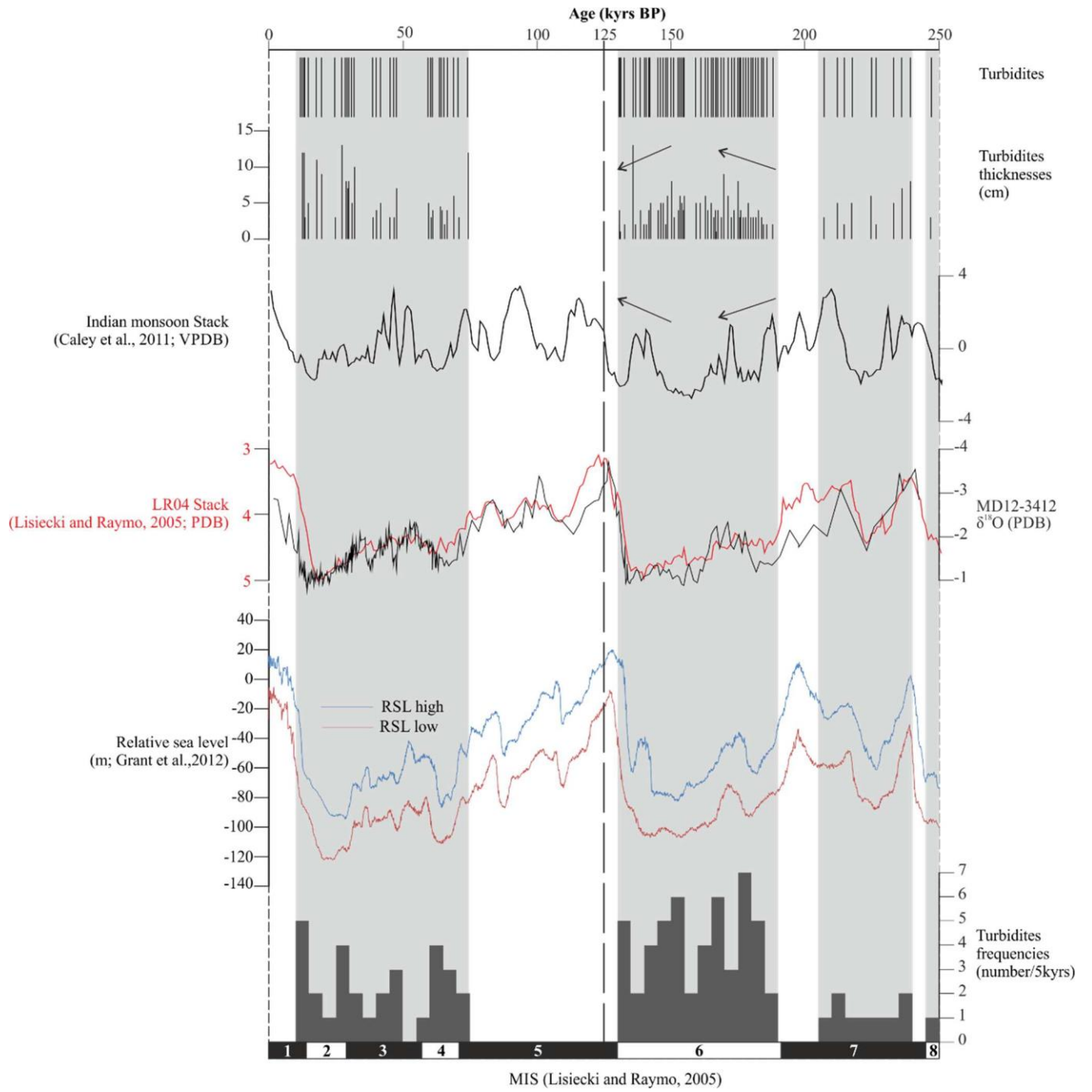


Figure 7

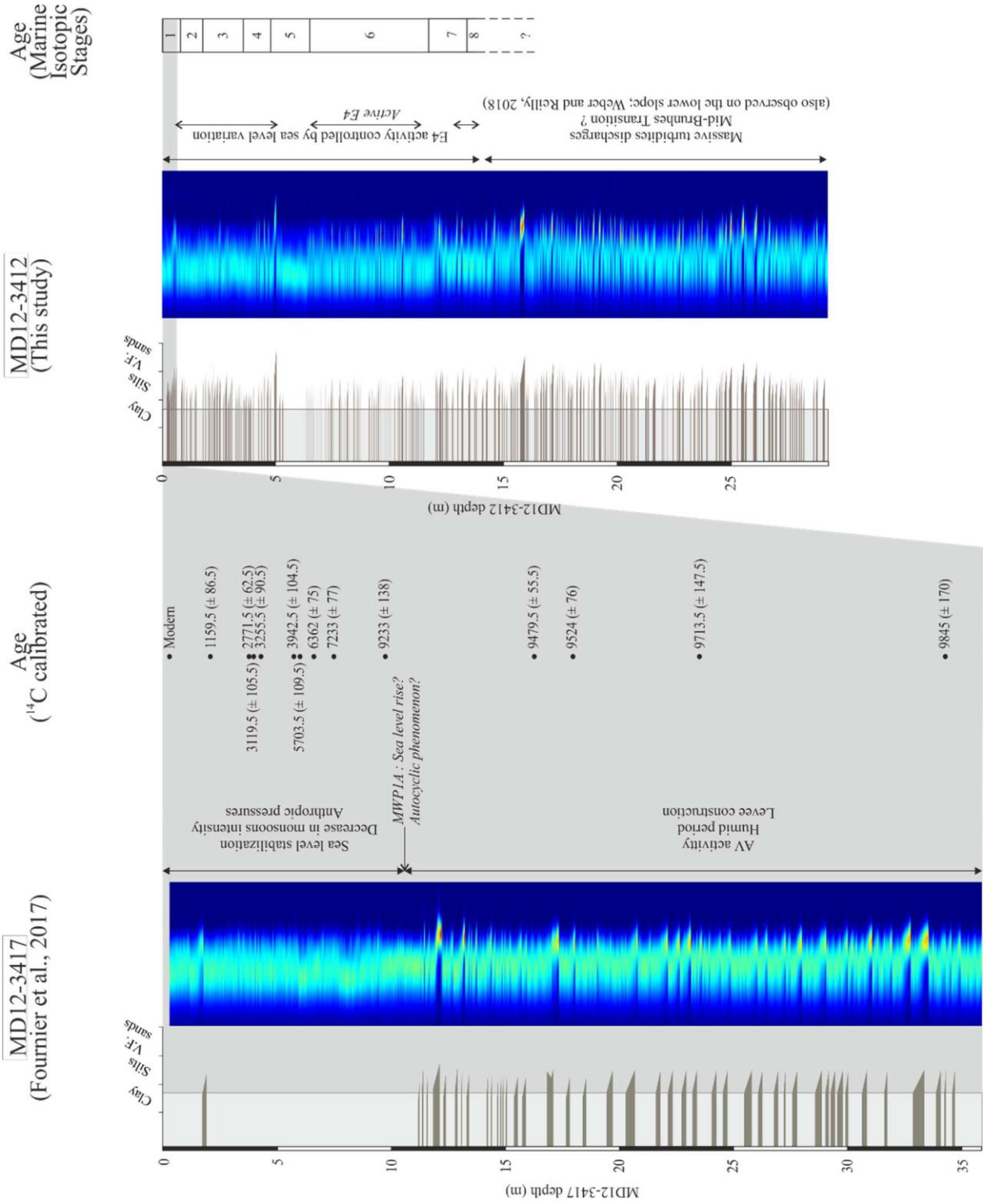


Figure 8

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