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Multi-disciplinary investigation of fluid seepage on an unstable margin: The case of the Central Nile deep sea fan

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Abstract:

We report on a multidisciplinary study of cold seeps explored in the Central Nile deep-sea fan of the Egyptian margin. Our approach combines *in situ* seafloor observation, geophysics, sedimentological data, measurement of bottom-water methane anomalies, pore-water and sediment geochemistry, and ²³⁰Th/U dating of authigenic carbonates. Two areas were investigated, which correspond to different sedimentary provinces. The lower slope, at ~ 2100 m water depth, indicates deformation of sediments by gravitational processes, exhibiting slope-parallel elongated ridges and seafloor depressions. In contrast, the middle slope, at not, vert, ~ 1650 m water depth, exhibits a series of debris-flow deposits not remobilized by post-depositional gravity processes.

Significant differences exist between fluid-escape structures from the two studied areas. At the lower slope, methane anomalies were detected in bottom-waters above the depressions, whereas the adjacent ridges show a frequent coverage of fractured carbonate pavements associated with chemosynthetic vent communities. Carbonate U/Th age dates (~ 8 kyr BP), pore-water sulphate and solid phase sediment data suggest that seepage activity at those carbonate ridges has decreased over the recent past. In contrast, large (~ 1 km²) carbonate-paved areas were discovered in the middle slope, with U/Th isotope evidence for ongoing carbonate precipitation during the Late Holocene (since ~ 5 kyr BP at least).

Our results suggest that fluid venting is closely related to sediment deformation in the Central Nile margin. It is proposed that slope instability leads to focused fluid flow in the lower slope and exposure of 'fossil' carbonate ridges, whereas pervasive diffuse flow prevails at the unfailed middle slope.

Keywords: Nile; continental margin; cold seep; U-Th; authigenic carbonate

59 **1 – Introduction**

60 Submarine pockmarks are widespread features on continental margins, which are
61 often related to seepage of gas-rich fluids at the seafloor and/or to the presence of gas
62 hydrates in marine sediments (e.g. Hovland and Judd, 1988; Judd and Hovland, 2007).
63 Over recent years, there has been much interest in the study of seafloor pockmarks
64 because they represent potential pathways for important quantities of gas from sediments
65 to the ocean and, perhaps, to the atmosphere (e.g. Vogt et al., 1999; Paull et al., 2002;
66 Ussler et al., 2003; Dimitrov and Woodside, 2003; Hovland et al., 2002, 2005; Gay et al.,
67 2006). In active seepage sites, expulsion of gas-rich fluids commonly supports the
68 development of chemosynthetic communities and the formation of authigenic carbonates,
69 both of which are of interest for the understanding of biogeochemical and
70 microbiological processes related to fluid seeping.

71 Increasing evidence of vast submarine pockmark fields in areas of destabilised
72 seafloor sediments has questioned the relationship between slope instability and fluid
73 circulation on continental margins (e.g. Hovland et al., 2002; Gay et al., 2004; Lastras et
74 al., 2004; Loncke et al., 2004; Trincardi et al., 2004). Are sediment slides responsible for
75 fluid release on the seafloor or, instead, does fluid circulation within margin sediments
76 favour mass movements? A recent compilation of published dates for major submarine
77 failures occurring in the North Atlantic area has shown that most sediment failures took
78 place during two distinct periods over the last 45,000 years: the Bølling-Ållerød (15 – 13
79 ka) and the Preboreal (11 – 8 ka), which correlate with peaks of enhanced atmospheric
80 methane concentrations recorded in ice cores (Maslin et al., 2004). It has been speculated
81 that dissociation of gas hydrates in marine sediments, in response to environmental

82 changes, has been instrumental in triggering such sediment failures, possibly releasing
83 significant quantities of methane into the atmosphere (e.g. Paull et al., 2000; Nisbet,
84 2002; Kennett et al., 2002; Mienert et al., 2005). Isotopic records of atmospheric CH₄ in
85 ice cores suggest, however, that marine gas hydrate reservoirs have remained stable
86 during the Late Quaternary (Sowers, 2006). In-depth investigations of selected key
87 regions are now needed, however, to bring further insights on the mechanisms linking
88 slope instabilities, fluid circulation and methane emission on continental margins (e.g.
89 Mienert, 2004).

90

91 Here, we report on a multidisciplinary study of cold seeps and mass movements
92 explored off Egypt (Eastern Mediterranean basin), which brings interesting information
93 on the relationship between fluid seepage and slope instabilities on continental margins.
94 Fluid-related structures are particularly abundant in the central province of the Nile deep-
95 sea fan, between 1500 and 2500 m water depth - an area where sediments are completely
96 destabilised by gravitational processes (Loncke et al., 2002; Loncke et al., 2004).
97 Selected targets of the Nile deep-sea fan were explored during two expeditions (Nautinil
98 2003 - R/V Atalante; Mimes 2004 - R/V Pelagia), funded through the MEDIFLUX
99 project (ESF Euromargins Programme). This work represents a synthesis of *in situ*
100 seafloor observation with the *Nautile* submersible, geophysical (3.5 kHz profiles, deep-
101 tow sidescan sonar seafloor imagery), sedimentological and geochemical data (dissolved
102 sulphate, elemental analyses, ²³⁰Th/U carbonate ages), some of which include preliminary
103 results.

104

105 **2 – Geological setting**

106 The Nile deep sea fan is a large sedimentary wedge, which has developed mainly since
107 the Late Miocene in the eastern Mediterranean Sea (e.g. Salem, 1976). The morphology
108 of the Nile deep sea fan results from the complex interplay between pre-Messinian
109 inherited topography, salt-related deformation, and sediment gravity processes. Salt
110 tectonism (e.g. diapirism, gravity spreading and gliding) on the Nile margin is related to
111 the presence of a ductile Messinian salt layer within the sedimentary edifice (Masclé et
112 al., 2000; Gaullier et al., 2000; Loncke et al., 2006). Sediment mass-wasting (e.g.
113 slumping, debris flows) has occurred on the entire Nile fan, in response to various
114 processes, such as salt-tectonism, sediment overloading and fluid circulation. In
115 particular, the Central Nile Province is characterized by a highly destabilised seafloor
116 surface, which shows repeated sediment failures and debris flows (Loncke et al., 2002;
117 Loncke et al., 2004). Loncke et al. (2004) suggested that sediment instability in the
118 Central Nile Province may be related to circulation of gas-rich fluids within sub-surface
119 sediments.

120

121 A large number of seafloor structures related to fluid venting were recognised on the
122 Nile margin during recent geophysical surveys (Fig. 1; Bellaïche et al., 2001; Loncke et
123 al., 2002; Loncke et al., 2004). Numerous gas chimneys and associated mud volcanoes
124 and cones were identified in Eastern (e.g. Isis, Amon, Osiris; see Fig. 1) and Western
125 provinces. Many of these structures have been emplaced in areas where Messinian salt
126 layers are absent in the sedimentary cover or have thinned down significantly, thereby
127 allowing deep pre-Messinian fluids to migrate upward along major faults. Other smaller

128 seafloor structures related to fluid venting were identified on the Nile margin from ship-
129 borne multibeam acoustic images. They correspond to numerous highly-reflective
130 patches, attributed to small pockmarks and/or mounds (Fig. 1; Loncke et al., 2004).
131 Those patches are clustered in two areas (Fig. 1): in the Eastern province, in close
132 proximity to gas chimneys; and in the Central Nile Province, associated with destabilized
133 sediments. In the Central Province, those highly reflective acoustic patches occur mainly
134 at water depths ranging from ~ 500 m down to 2500 m. One important objective of the
135 MEDIFLUX project was to characterise those acoustic patches identified on ship-borne
136 multibeam seafloor maps and to establish their relationship with fluid seepage and slope
137 instability.

138

139

140 **3 – Materials and Methods**

141 3.1. Geophysics

142 An extensive set of geophysical data (3.5 kHz profiles, Simrad EM12-Dual and EM300-
143 Dual multibeam echosounder and seismic data) was acquired during the Nautinil 2003
144 expedition, as well as during previous Géosciences-Azur cruises (PrismedII 1998, Fanil
145 2000 and Vanil 2004), which provided bathymetric and acoustic maps for the entire Nile
146 deep sea fan (Loncke et al., 2004). Multibeam EM12- and EM-300 data were combined
147 and processed at a grid size of 50m/pixel, using the Caraïbes software. High-resolution
148 EdgeTech DTS-1 side-scan sonar data were acquired during the Mimes 2004 expedition.
149 The deep tow side scan sonar was deployed and towed at around 100 m above the
150 seafloor and operated at a 75-kHz frequency, with a 1500m wide swath of the seafloor.

151

152 3.2. *Nautila* dives

153 *Nautila* dives took place in two different areas on the Central Nile Province: 1) the lower
154 slope, at ~ 2100 m water depth (dives NL6 and NL14; Fig. 1), and 2) the middle slope, at
155 ~ 1650 m water depth (dive NL7; Fig. 2B,C). Microbathymetric profiles along each dive
156 transect were acquired using *Nautila* sensors (pressure sensor and sounder). A methane
157 sensor (Capsum METS) was installed on the *Nautila* frame to detect methane in bottom-
158 waters. Note that concentrations measured with the methane sensor are qualitative only.

159

160 3.3. Sediment cores

161 A set of push-cores and blade-cores (i.e. a submersible-mounted corer equipped with a
162 guillotine-like cutter, which allows efficient sampling of unconsolidated sediments) was
163 collected in the Central Nile province during the *Nautila* dives. One piston core (NLK11)
164 was also collected from the lower slope during the Nautinil cruise. The position of all
165 sediment cores used for this study is given in Table 1 and shown in Figs. 1, 3B,C and 4.
166 Push-cores NL14-PC1 and NL14-PC3 were retrieved in carbonate ridge areas (see
167 description of fluid-venting structures in section 4.2). Push-core NL6-PC1 was collected
168 from a small pockmark on the lower slope. The blade core NL7-BC1 is a reference core
169 recovered in the middle slope, away from fluid venting structures. The lithological
170 description for those cores is presented in Fig. 5. Hemipelagic sediments in the Nile deep
171 sea fan correspond typically to reddish-brown foraminiferal and pteropod oozes (core
172 NL7-BC1; uppermost part of cores NL14-PC1/3). In contrast, dark-grey sediments are
173 encountered frequently at cold seep sites (core NL6-PC1; lower part of cores NL14-PC

174 1/3), which may contain small (mm- to cm- size) concretions of authigenic carbonates
175 (Fig. 5).

176

177 3.4. Sediment geochemistry and pore water analyses

178 The inorganic geochemical composition of authigenic carbonates and sediments was
179 determined by wavelength dispersive X-ray fluorescence (WD-XRF) analysis of fusion
180 beads or compressed powder pellets for major and trace elements, respectively. Both
181 total and oxidised (SO₄) sulphur contents of sediment samples were measured by XRF,
182 allowing the determination of reduced sulphur concentrations (e.g. pyrite) by subtraction.
183 Pore waters were extracted from core NL14-PC1 sediments by centrifuge. Dissolved
184 sulphate concentrations were measured in 1:10 diluted solutions by ion chromatography
185 with an accuracy better than 4%.

186

187 3.5. U/Th dating of authigenic carbonates

188 Bayon et al. (2007) reported ²³⁰Th/U ages for a set of samples drilled across a
189 carbonate crust recovered from the middle slope (NL7-CC2 crust; see location in Fig. 4),
190 which provided evidence for continuous carbonate precipitation at that studied location
191 over the last ~ 5000 years at least. In this study, we performed additional U-Th isotope
192 measurements for two other carbonate crusts (NL6-CC1 and NL14-CC5; see location in
193 Figs. 3B,C), collected from carbonate ridges in the lower slope. NL6-CC1 and NL14-
194 CC5 crusts correspond to carbonate pavements characterized by a homogeneous matrix
195 of terrigenous sediment (silt, clay), foraminifers and nannofossils, cemented by fine-
196 grained aragonite (Gontharet et al., 2007).

197 Details on chemical and analytical procedures are presented elsewhere (Bayon et al.,
198 2007), and a brief description is given here. Selected areas of carbonate crusts were
199 hand-drilled carefully to obtain ~100 mg of carbonate powder. Carbonate samples were
200 spiked with a mixed $^{236}\text{U}/^{229}\text{Th}$ spike prior to sample digestion. U and Th were then
201 separated chemically using conventional anion exchange techniques. U and Th
202 concentrations and isotope ratios were measured by multiple collector inductively
203 coupled plasma mass spectrometry (MC-ICPMS) at the University of Oxford. Detrital
204 contamination was typically too high for allowing calculation of ages using the
205 conventional ^{230}Th age equation and required instead the use of isochron methods (e.g.
206 Bourdon et al., 2003). For this approach, a sediment end-member was defined as the
207 average of two sediments from the studied area (Bayon et al., 2007), assumed to be
208 representative of the sediment fraction incorporated within the carbonate crusts.

209

210 **4 – Results**

211 4.1. Morphology of the Central Nile Province

212 New geophysical data acquired during the Nautinil cruise and other recent Geosciences-
213 Azur expeditions allow to distinguish three distinct areas in the Central Nile Province,
214 which are described briefly below (Fig. 1; Fig. 2):

215

216 a) The upper slope (between ~ 500 and 700 m water depth), characterised by the presence
217 of a few large gas chimneys (up to 4 km in diameter) corresponding to the leakage of gas-
218 rich fluids from poorly sealed hydrocarbon reservoirs (e.g. North Alex; Fig. 1).
219 Numerous slides observed in deeper parts of the Central Nile Province initiate at the

220 location of the gas chimneys (Loncke et al., 2004). Note that one *Nautila* dive took place
221 in this area (i.e. North Alex chimney) during the Nautinil cruise, but those results are
222 discussed elsewhere (Dupré et al., 2007).

223

224 b) The middle slope (between ~ 700 and 1650 m water depth), characterised by a series
225 of transparent acoustic bodies (debris-flow deposits) overlapping surface sediments in the
226 lower slope (Fig. 2A). The most recent debris-flow deposits in this area are overlain by a
227 thin hemipelagic cover (~ 0.5 m), which suggests recent deposition. Ship-borne
228 multibeam backscatter imagery reveals the presence of a few highly reflective patches in
229 this area (Loncke et al., 2004).

230

231 c) The lower slope (between ~ 1650 and 2200 m water depth), characterised by rough
232 and chaotic seafloor morphology. The sedimentary cover is deformed by repeated
233 undulations (i.e. a succession of elongated ridges and troughs), between 300 to 1500 m
234 wide, sub-parallel to the slope (Figs. 1, 2A,C). Loncke et al. (2002) interpreted those
235 undulations as a result of creep and gliding processes, rather than sediment waves created
236 by bottom currents. Examination of 3.5 kHz profiles (Fig. 2A; Loncke et al., 2002) also
237 suggests that some ridges observed in this area correspond to small rotated blocks. This
238 deformed sedimentary cover is about 10 to 50 m thick and is underlain by debris-flow
239 deposits (Fig. 2A). In core NLK11 (see location in Fig. 1), debris-flow deposits occur at
240 sediment depths below 12 m (Fig. 5). A large number of highly reflective patches were
241 identified in this area (Loncke et al., 2004), some of which were investigated during the
242 Nautinil cruise (Figs. 1 and 2).

243

244 4.2. Fluid venting structures

245 Microbathymetric profiles and maps for sediment facies and carbonate crust occurrences
246 along each *Nautila* dive transect are shown in Figures 3 and 4, together with EM-300
247 Multibeam acoustic map (Fig. 3A) and side-scan sonar seafloor imagery (Fig. 4). Note
248 that only the dive NL7 area (middle slope area) was surveyed by the EdgeTech deep tow
249 sonar during the Mimes expedition. Combining geophysical data, *in situ* observation and
250 microbathymetric profiles, four types of fluid venting structures can be identified in the
251 lower slope and middle slope parts of the Central Nile province, which are described
252 below.

253

254 4.2.1. Carbonate ridges (lower slope)

255 Three carbonate-paved areas were discovered on the lower slope during the *Nautila*
256 dives, which correspond clearly to highly reflective patches (dark spots) on EM-300
257 multibeam mosaic (Fig. 3A). Microbathymetric profiles generated from the submersible
258 sensors reveal that they correspond to aligned carbonate mounds, up to ~ 500 m long and
259 5 m high (Fig. 3B,C). Clearly, these carbonate-paved areas occur on top of the elongated
260 ridges related to downslope mass movements (Fig. 2). Carbonate pavements were mainly
261 covered by hemipelagic sediments (Fig. 6A). Fractured carbonate pavements were
262 observed typically in topographically steep areas (Fig. 3B; Fig. 6B,C), often associated to
263 faults with orientations ~ N70 and N160.

264

265 4.2.2. Elongated sediment depressions or troughs (lower slope)

266 In situ observations show the occurrence of large elongated depressions (~100 m long; 3
267 m deep) with signs of intense bioactivity, which occur in the immediate vicinity of
268 carbonate ridges. The bioactivity is documented by the presence of light grey shell-rich
269 sediments associated with numerous bioturbation mounds (Fig. 6G). Those depressions
270 correspond to those slope-parallel troughs associated with undulations (Fig. 2), identified
271 previously on multibeam bathymetric maps (Loncke et al., 2004). During the *Nautila*
272 dives, many faults were observed in sediments (Fig. 3; Fig. 6H), with directions parallel
273 (~N70) or perpendicular (~N160) to the slope (Fig. 3).

274

275 4.2.3. Other carbonate-paved areas (middle slope)

276 Two large (~ 1 km²) carbonate-paved areas with irregular shapes and partly covered by
277 sediments were identified from the side-scan sonar data in the middle slope (i.e. the large
278 high backscatter areas shown as white patches in Fig. 4). The southernmost edge of one
279 of these structures was visited during *Nautila* dive NL7 (Fig. 4), which corresponds to
280 unfractured massive carbonate pavements. Bathymetric data acquired during the *Nautila*
281 dive did not provide any evidence of topographic irregularities associated with carbonate
282 pavements at that location.

283

284 4.2.4. Pockmarks

285 Numerous pockmarks were observed during the *Nautila* dives, both in the lower and
286 middle slope areas. Pockmarks correspond to sub-circular depressions on the seafloor of
287 variable size (typically 3-20 m across and up to 3 m deep), which can be isolated or occur
288 as clusters (Figs. 4 and 6E). In the lower slope, pockmarks were observed in close

289 vicinity to troughs (Fig. 3). Authigenic carbonate crusts occur typically in the central part
290 of pockmarks, forming in some cases chimney-like build-ups (Fig. 6F). Shell debris,
291 authigenic carbonate crusts and infilled burrows often accumulate within the depressions
292 (Fig. 6F). In contrast to the reddish-brown foraminiferal and pteropod oozes
293 characterising hemipelagic sediments on the Nile deep-sea fan (see reference core; Fig.
294 5), dark grey sediments were observed frequently in pockmarks (pushcore NL6-PC1; Fig.
295 5).

296

297 4.3. Biological observations

298 Several animal communities were observed during the *Nautilite* dives in the two studied
299 areas. Vestimentiferan tubeworms (Polychaeta: Siboglinidae) were often present in close
300 association with carbonate crusts (Fig. 7), both in pockmarks and carbonate-paved areas.
301 Two morphotypes of siboglinids were distinguished after examination of photographs
302 and videos collected during the dives, but only one of them (assigned to the genus
303 *Lamellibrachia*; Webb, 1969) was sampled successfully (Fig. 7A).

304 Numerous small mussels (length < ~1 cm) were found on carbonate crusts and
305 associated sediments, occurring frequently inside small cavities within carbonate
306 deposits. Those mussels have been shown recently to harbour 6 distinct types of bacterial
307 symbionts, including sulphur- and methane-oxidizing bacteria, a diversity larger than
308 reported from any other bivalve to date (Duperron et al, 2008). They display
309 morphological similarities to *Idas modiolaeformis* (Sturany, 1896), a species reported at
310 other eastern Mediterranean cold seep sites (Olu-Le Roy et al., 2004). Additional fauna
311 associated with crusts includes anemones, serpulid polychetes and small galatheid crabs.

312 Empty bivalve shells were observed in carbonate-paved areas and pockmarks, but also in
313 those large depressions close to carbonate ridges (P. Briand & K. Olu-Le Roy, pers.
314 com.). These shells are similar to shells of *Isorropodon perplexum* (Vesycomyidae) and
315 *Thyasira striata* (Thyasiridae), reported previously in the Nile deep-sea fan (Sturany,
316 1896) and on Anaximander mud volcanoes (Olu-Le Roy et al. 2004). A few living
317 specimens of lucinids were sampled, which exhibit close morphological similarities to
318 *Lucinoma kazani* (Anaximander mud volcanoes; Salas and Woodside 2002) and *Myrtea*
319 *amorpha* (Mediterranean Ridge cold seeps; Olu-Le Roy et al. 2004). The former were
320 shown recently to harbour sulphur-oxidizing bacteria (Duperron et al, 2007).

321

322 4.4. Detection of gas seeps

323 Methane profiles acquired in the lower slope with the Capsum METS sensor along
324 selected dive transects are shown in Figs. 3B and C. Significant methane anomalies were
325 measured in bottom waters above the large depressions associated with bioturbation
326 mounds. Clearly, this shows that those troughs correspond to active sites of methane
327 seepage. In contrast, no (dives NL6) or weak (dive NL14) methane anomalies were
328 detected above carbonate-paved areas (Figs. 3B and C). In the middle slope, the Capsum
329 sensor did not detect any methane anomaly (not shown here), but evidence for active
330 fluid seepage is suggested by acoustic anomalies of side-scan sonar records of the water
331 column attributed to gas bubbles (S. Dupré, personal communication; not shown here).
332 One such acoustic gas anomaly was identified in close proximity to those large carbonate
333 structures with irregular shapes.

334 At pockmarks, seepage of methane-rich fluids was inferred frequently by the presence
335 of dark grey sediments (e.g. indicating the presence of an abundant organic fraction not
336 decomposed). Evidence for on-going anaerobic oxidation of methane and bacterial
337 sulphate reduction in one of those pockmarks was also given by a strong H₂S smell upon
338 opening of core NL6-PC1 (Fig. 5).

339

340 4.5. Pore water and sediment geochemistry

341 Down-core high resolution profiles of CaO (wt. %), reduced and oxidized sulfur (wt.
342 %) and barium (ppm) contents in sediment from push-cores NL14-PC1 and NL14-PC3
343 are presented in Fig. 8. Dissolved sulphate concentrations in pore waters (for core NL14-
344 PC1 only) are also reported in Fig. 8. Pore water SO₄²⁻ concentrations are quasi-constant
345 down to ~17 cm depth, with values (~ 30 mM) close to seawater concentrations.

346 In contrast to dissolved SO₄²⁻ concentrations, S concentrations in solid sediment
347 phases increase from just a few centimeters (~ 7 cm) below the sediment/water interface
348 (Fig. 8). In core NL14-PC1, enrichments of Ba and reduced S are related to the presence
349 of barite (barium sulphate) and pyrite (iron sulfide), respectively. Mineralogical analyses
350 and microscope observations reveal that authigenic gypsum (calcium sulphate) is also
351 present within sediments.

352

353 4.6. Carbonate ²³⁰Th/U ages

354 U-Th data for the two carbonate crusts analysed are listed in Table 2. Only one
355 meaningful age was obtained for those lithified carbonate samples collected on the
356 carbonate ridges (Table 2). This is due to an important ²³⁰Th detrital contamination in

357 those clay-rich samples. The calculated age for sample NL14-CC5 is $\sim 7.9 \pm 1.4$ ka
358 (Table 2).

359

360 **5 – Discussion**

361 5.1. Deformation style in the Central Nile margin

362 Significant differences were observed between the lower slope and the middle slope,
363 which are summarised in Table 3. In the lower slope, downslope mass movements lead
364 to formation of elongated ridges and troughs parallel to the slope (Loncke et al., 2002).
365 Observation of numerous fractures in sediments during the *Nautila* dives provides direct
366 evidence that active mass gravity processes occur in the lower slope. The presence of
367 similar ridges and troughs at the base of continental margins has been extensively
368 described in the literature (e.g. Mulder and Cochonat, 1996; van Weering et al., 1998;
369 Lee and Chough, 2001; Gay et al., 2004). In the case of creep and downslope gliding,
370 gravitational processes create typically two distinct structural domains: an extensional
371 domain in the upper slope and a compressive domain located downslope (e.g. Allen,
372 1985; Pickering et al., 1989; Stow, 1994). In most cases, ridges and troughs form in the
373 distal compressive parts of creeping or gliding sediment masses. By analogy, the lower
374 slope on the Central Nile deep-sea fan could also correspond to a regional compressive
375 domain. However, the occurrence of small rotated blocks in the lower slope indicates
376 that extensional deformation takes place instead in this area, leading to faulting and
377 associated rotated blocks. Most probably, it is likely that creeping of surface sediments
378 in this lower slope domain also induces local compression, which could contribute, at
379 least to some extent, to the formation of ridges and troughs.

380 In contrast to the lower slope, there is no direct evidence for active deformation
381 processes taking place in the middle slope area. Most probably, the evidence that debris-
382 flow deposits accumulated in the middle slope overlap surface sediments in the lower
383 slope indicates that those two domains are decoupled.

384

385 5.2. Temporal evolution of fluid circulation

386 In cold seep environments, reduction of sulphate in pore waters is closely related to
387 methane oxidation (Niewöhner et al., 1998; Borowski et al., 1999). The depth at which
388 sulphate reduction occurs in sediments is controlled primarily by the upward flux of
389 methane, being closer to the seafloor for high methane fluxes (Niewöhner et al., 1998;
390 Borowski et al., 1999). Information on the temporal evolution of fluid venting at any site
391 can be obtained by comparing pore water data (which give information on present-day
392 fluid circulation) and solid sediment geochemical data (which may provide an integrated
393 record of fluid seepage over the last few thousand years). In core NL14-PC1, the
394 constant dissolved sulphate profile indicates that sulphate reduction does not proceed in
395 the top sediment layer (~ 0-20 cm) at present. This suggests that methane-rich fluids
396 probably do not circulate in sub-surface sediments at this location.

397 In contrast, the presence of authigenic sulphate (oxidized S) and sulfide (reduced S)
398 minerals within sediment cores collected at carbonate ridges implies that reduction of
399 pore-water sulphate was active at these sediment depths in the recent past. The dark grey
400 sulfur- and barium-rich sediment layer in cores NL14-PC1/3 probably does not
401 correspond to the Holocene Sapropel layer S1 (e.g., Olausson, 1961), which is buried at
402 deeper sediment depths in the studied area (> 15 cm in our reference push-core NL7-

403 BC1; Fig. 5). The occurrence of S-rich minerals in NL14-PC1/3 sediments is probably
404 related to oxidation of methane-rich fluids at that location in the recent past. At present,
405 cold seep settings where sulphate reduction proceeds at only a few centimeters below the
406 seafloor correspond to sites characterized by active fluid advection (e.g. see Haese et al.,
407 2003 and references therein).

408 Absolute dating of authigenic carbonates with U-series also provides a means for
409 reconstructing the evolution of cold seeps and associated fluid circulation through time
410 (Teichert et al., 2003; Bayon et al., 2007). Certainly, additional U-Th isotope
411 measurements would be needed to better constrain any spatial and temporal variations of
412 fluid circulation activity in the lower slope. However, the U-Th age (~ 8 kyr BP)
413 calculated for crust NL14-CC5 suggests that carbonate precipitation and hence fluid
414 seepage was active at the studied carbonate ridge in the early Holocene. Taken together,
415 our U-Th data and sediment geochemical profiles suggest therefore that the activity of
416 fluid venting at carbonate ridge locations may have decreased over a recent period.

417

418 5.3. The origin of fluids

419 Fluids expelled at cold seeps on the Nile deep-sea fan may derive from shallow and/or
420 deep sediment sources. Potential deep fluid sources include messinian and pre-messinian
421 thermogenic hydrocarbon reservoirs (Abdel Aal et al., 2000; Samuel et al., 2003; Loncke
422 et al., 2004). During the Nautinil expedition, the discovery of brine lakes on the seafloor
423 (Menes Caldera, Western Nile province; Huguen et al., in revision) has provided clear
424 evidence that fluids passing through or originating from deep evaporite deposits could be
425 emitted on the seafloor in the Nile Delta area. Shallow fluid sources at cold seeps are

426 most often related to formation of biogenic methane in superficial sediment layers; a
427 consequence of the microbial degradation of organic matter during early diagenetic
428 processes. Several organic-rich sediment layers (sapropels) have accumulated in Eastern
429 Mediterranean basins during the Late Quaternary period (e.g., Olausson, 1961; De Lange
430 and Ten Haven, 1983; Rossignol-Strick et al., 1982), which represent potential sources of
431 methane-rich fluids to cold seeps in the Nile deep sea fan area. Fine-grained turbidites
432 deposited on the deep-sea fan during the Late Quaternary may represent an additional
433 source of biogenic methane. None of the data presented in this study can be used to
434 discriminate the origin of fluids in the Central Nile area. However, stable isotope
435 measurements ($\delta^{13}\text{C}$ and $\delta^{18}\text{O}$) on authigenic crusts collected during the Nautinil
436 expedition (Gontharet et al., 2007) suggest that the fossil carbon source involved in
437 carbonate precipitation in this area derives from biogenic methane primarily (i.e. a
438 shallow source).

439

440 5.4. Formation mode of fluid-escape structures and links with sediment deformation

441 5.4.1. Lower slope

442 One major result of this study is the close relationship between slope parallel elongated
443 ridges/troughs and the occurrence of fluid-escape structures (see Fig. 9; Table 3). In the
444 lower slope, carbonate-paved areas are located clearly on top of ridges, whereas methane
445 venting occurs above troughs (Fig. 9). It is very likely that gravity processes and
446 deformation in the lower slope have created preferential pathways for fluid migration and
447 gas escape. The large depressions or troughs, characterized by intense bioactivity and
448 active methane venting, corresponds most probably to the present-day seafloor

449 expression of those preferential pathways (e.g. faults) related to sediment deformation
450 (Fig. 9). Pockmarks observed in close vicinity to the troughs could form from excess
451 volumes of fluids periodically migrating upslope from the troughs, possibly aided by the
452 creation of migration pathways along fractures (Fig. 9).

453 At present, it is likely that carbonate precipitation occurs within sediments in those
454 depressions associated to active methane venting. Instead, we propose that carbonate
455 pavements emplaced on top of ridges were outcropped on the seafloor in response to
456 sediment instability, *after* initial formation of carbonate crusts. The exposure of those
457 carbonate pavements could be due either to compressional deformation as pressure ridges
458 or, alternatively, be related to faulting associated with the rotated blocks. This
459 exhumation process would be in agreement with the presence of intensively fractured
460 carbonate crusts on top of those ridges. Carbonate ridges would hence correspond to
461 'paleo-troughs' (i.e. ancient sites of active fluid venting). Our geochemical results
462 suggest that fluid seepage at those ridges has decreased most probably since the early
463 Holocene (see section 5.2). Most likely, this indicates that slope instability may induce a
464 change in fluid flow conditions at any given location; from focused flow to diffuse flow
465 for the case of those carbonate ridges. The persistence of seep habitats on top of ridges at
466 present would hence be related to pervasive microseepage only.

467

468 Other carbonate ridges were discovered recently on the continental slope off Norway
469 (Hovland et al., 2005), though in a different geological setting (e.g. proximity to gas
470 hydrate reservoirs). Hovland et al. (2005) proposed that such ridges were formed during
471 catastrophic fluid-flow events, in response to abrupt breaking of carbonate seals above

472 preferential fluid pathways. In the Central Nile province, however, observation that
473 carbonate ridges occur only on one side of those large sediment depressions (see
474 bathymetric profile in Figs. 3B and C) argues against such a formation by catastrophic
475 fluid flow event. Therefore, our preferred explanations remain that: 1) fluid migration is
476 controlled by slope instability in the lower slope, and 2) sediment gliding is responsible
477 for formation of carbonate ridges.

478

479 During the last few hundred thousand years, sediment mass-wasting has been active in
480 the Nile deep sea fan, leading to deposition of a series of debris-flows and turbidites
481 (Ducassou et al., 2007). It is likely that sediment accumulation on the middle and lower
482 slopes has led, to some extent, to compaction/dewatering in sub-surface sediments,
483 generating ultimately excess pore water pressure and fluid migration. Investigation of
484 core NLK11 shows that sediments deposited above those debris-flow deposits (i.e. the
485 top ~ 12 m of core NLK11) exhibit vertical pipes filled with fluidised sediments, which
486 correspond to fluid migration structures (Fig. 5). In contrast, sediments associated with
487 debris-flow deposits are highly compacted. One hypothesis would be that the upper
488 surface of debris-flow deposits act as a décollement layer, along which fluids would
489 migrate preferentially. The presence of such a décollement layer at a few meters below
490 the seafloor would favour both sediment instabilities (i.e. creeping) and fluid seepage in
491 the lower slope (Fig. 9).

492

493 5.4.2. Middle slope

494 Significant differences in e.g. surface, morphology, fracturation have been observed
495 between carbonate-paved areas from the lower and middle slopes (see section 4.2),
496 indicating that they were formed most probably through distinct processes. U/Th isotope
497 ages calculated on authigenic carbonates recovered from the middle slope (Bayon et al.,
498 2007) showed that fluid emission in this area (at least in that carbonate-paved area
499 explored during dive NL7) has remained active for the last 5,000 years at least. This
500 suggests that the middle slope has remained stable (i.e. no major slope instability) during
501 that period. In contrast with the lower slope, the absence of any significant preferential
502 conduits and/or faulting within surface sediments in this area may provide possibilities
503 for broad diffusive, perhaps not focused, but permanent fluid venting through time.

504

505

506 **5. Conclusions**

507 Fluid venting is active on the Central Nile margin, as demonstrated by the observation
508 of fluid-related structures (pockmarks, carbonate pavements), abundant associated
509 chemosynthetic communities and the detection of bottom-water methane anomalies.
510 Detailed investigations of cold seeps from two distinct areas in the Central Nile province
511 indicate a link between fluid seepage and sediment instability.

512 The lower slope from 1650 m to 2200 m water depth is a zone of regional sediment
513 creeping, where active gravitational processes create a series of elongated slope-parallel
514 ridges and depressions. Fossil carbonate ridges up to 5m high occur on top of those
515 slope-parallel ridges, whereas the deep depressions correspond to areas of active fluid
516 flow. The middle slope from 700 m to 1650 m water depth corresponds to an area

517 recently covered by debris flow deposits, which overlap surface sediments in the lower
518 slope. In contrast with the lower slope, it shows no signs of sediment creeping, but
519 exhibits large patchy areas (~1 km²) of carbonate pavements associated to broad and
520 more diffuse fluid flow.

521 We propose that sediment instability in the lower slope area creates preferential
522 pathways for focused fluid flow and leads to the exposure of carbonate ridges. Evidence
523 that debris-flow deposits buried under the destabilized sedimentary cover in this area are
524 highly compacted may suggest that the top of this debris-flow unit acts as a décollement
525 layer, along which fluids would migrate preferentially and, in turn, favor sediment
526 gliding. Overall, our results have general implications for understanding the processes
527 controlling methane fluxes at continental margins, and how slope instability may
528 contribute to methane release into the water column.

529

530

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703 **Figure Captions**

704

705 **Figure 1:** Bathymetric map of the Nile deep-sea fan (Sardou and Mascle, 2003) and
706 distribution of fluid-escape structures (Loncke et al., 2004) showing the two sites
707 investigated with the *Nautila* submersible, at 2100 m depth (lower slope) and 1650 m
708 depth (middle slope). Note the presence of elongated ridges sub-parallel to the slope
709 (direction ~ N70) in the lower slope of the Central Province.

710

711 **Figure 2:** (A) 3.5-kHz sub-bottom profile perpendicular to the slope in the Central Nile
712 Province (see Fig. 1 for NL2-6 trackline position). (B,C) Shaded bathymetric maps of
713 the two sites investigated in the Central Nile Province with position of the *Nautila*
714 transects (see location of sites in Fig. 1). (B) Middle slope, dive NL7, 1650 m water
715 depth; (C) Lower slope, dives NL6 and NL14, 2100 m water depth. Note the marked
716 morphological contrast between the middle slope and the lower slope. The lower slope is
717 characterised by a rough and morphological seafloor morphology, which exhibits
718 repeated elongated ridges and depressions parallel to the slope.

719

720 **Figure 3:** Seafloor observations of fluid-escape structures in the lower slope domain.
721 (A) Multibeam seafloor acoustic imagery showing the distribution of highly reflective
722 patches (dark spots) with indication of the *Nautila* transects (see location of sites in Fig.
723 1). (B,C) Maps for sediment and carbonate facies, microbathymetric profiles and
724 bottom-water methane anomalies recorded along the dive transects. Fault positions and
725 sampling sites for sediment cores and carbonate crusts are also shown.

726

727 **Figure 4:** Side-scan sonar image of the seafloor in the middle slope showing the
728 presence of large carbonate paved-areas with indication of the *Nautilite* transect (see
729 location in Fig. 1). Sampling sites for sediment cores and carbonate crusts collected
730 during the dive are also reported.

731

732 **Figure 5:** Lithological description of sediment cores recovered during the submersible
733 dives. Push cores NL6-PC1, NL14-PC1 and NL14-PC3 were collected in the lower
734 slope, in fluid-venting areas (pockmark, carbonate ridges). Box core NL7-BC1 was
735 recovered in the middle slope, away from any fluid-escape structure. The location of
736 these cores is shown in Figs. 1, 3B,C, and 4.

737

738 **Figure 6:** Seafloor bottom photographs of fluid-escape structures. (A) Carbonate
739 pavements partly covered by thin sediments (carbonate ridge; lower slope). (B) Fractured
740 carbonates on a carbonate ridge (lower slope). (C) Fracture on a carbonate ridge (lower
741 slope). (D) Non fractured massive carbonate pavement (middle slope). (E) Small
742 pockmark (~ 3 m across) in the lower slope. Note the presence of authigenic carbonates,
743 grey anoxic sediments and vestimentiferan tubeworms. (F) Large pockmark (~ 25 m
744 across) exhibiting two carbonate chimneys and a dense network of infilled burrows
745 (middle slope). The central part of the pockmark corresponds to accumulated debris of
746 dead shells, authigenic carbonates and burrows. (G) Shell-rich sediments and bioturbation
747 mounds in one of those troughs (large seafloor depression) related to gravity tectonics

748 (lower slope). (H) Fault in hemipelagic sediments away from fluid-escape structures
749 (lower slope). White scale bars correspond to ~ 1 m.

750

751 **Figure 7:** Vestimentiferan tubeworms associated with carbonate crusts. (A) First
752 morphotype observed, assigned preliminarily to the genus *Lamellibrachia* (dive NL7;
753 middle slope). (B) Second morphotype observed, but not collected (dive NL6; lower
754 slope). Note that the morphology of the chitinous tube differs from that of the first morphotype.
755 White scale bars correspond to ~ 20 cm.

756

757 **Figure 8:** Down-core profiles of CaO (wt%), S_{oxidized} (wt%), S_{reduced} (wt%), Ba (ppm)
758 for push-cores NL14-PC1 and NL14-PC3 taken at a carbonate ridge (lower slope, see
759 location in Figs. 3B and C). Dissolved pore water SO₄²⁻ (mM) contents are also plotted
760 for core NL14-PC1. Enrichments of oxidized/reduced sulphur and barium in solid
761 sediment phases indicate that reduction of dissolved sulphates has been active at these
762 locations in the recent past. In contrast, the flat dissolved SO₄²⁻ profile, with seawater-
763 like values, shows that sulphate reduction does not take place in sub-surface sediments at
764 present.

765

766 **Figure 9:** Conceptual model linking fluid seepage and sediment deformation in the lower
767 slope. Active gravitational processes (creep and/or gliding) create a series of elongated
768 slope-parallel sediment ridges and depressions in the lower slope. Sediment instability
769 leads to exhumation of fractured carbonate pavements on top of ridges, which correspond
770 to 'fossil' vent sites. The exhumation of those carbonate ridges can be due either to

771 compressional deformation (i.e. creep) or be related to faulting associated with rotated
772 blocks (i.e. gliding). The depressions correspond instead to preferential pathways for
773 focused fluid flow. The top of debris-flow deposits (highly compacted) buried under the
774 destabilized sediment cover could act as a décollement layer along which fluids would
775 migrate preferentially, favouring in turn sediment gliding.

776

Table 1. Positions and water depths of the cores and carbonate crusts investigated

| Core / Carbonate | Description | Length (m) | Water depth (m) | Latitude N | Longitude E |
|-------------------------|-----------------|---------------|--------------------|---------------|----------------|
| Sediment cores | | | | | |
| NL6-PC1 | Push core | 0.36 | 2115 | 32°38.14' | 29°56.12' |
| NL14-PC1 | Push core | 0.35 | 2116 | 32°38.33' | 29°55.80' |
| NL14-PC3 | Push core | 0.25 | 2130 | 32°38.44' | 29°54.98' |
| NLK11 | Kullenberg | 14 | 2207 | 32°40.99' | 29°54.00' |
| NL7-BC1 | Blade core | 0.15 | 1623 | 32°30.50' | 30°23.09' |
| Carbonate crusts | | | | | |
| NL6-CC1 | lithified crust | | 2132 | 32°38.38' | 29°54.87' |
| NL14-CC5 | lithified crust | | 2130 | 32°38.44' | 29°54.98' |
| NL7-CC2 | porous crust | | 1686 | 32°31.61' | 30°21.16' |

Table 2. U-Th data for authigenic carbonates

| Sample | Depth (cm) | ^{238}U (ppm) | ^{230}Th (ppt) | $(^{230}\text{Th}/^{232}\text{Th})$ | $\delta^{234}\text{U}_{(0)}$ | Isochron age (ka) |
|----------|---------------|---------------------------|----------------------------|-------------------------------------|------------------------------|----------------------|
| NL14-CC5 | 0.5 | 2.997 ± 0.004 | 28.67 ± 0.14 | 2.44 ± 0.01 | 128.7 ± 1.7 | - |
| ' | 2 | 5.158 ± 0.006 | 17.15 ± 0.04 | 3.62 ± 0.01 | 144.2 ± 1.7 | 7.9 ± 1.4 |
| NL6-CC1 | 2 | 3.702 ± 0.004 | 35.29 ± 0.15 | 2.52 ± 0.01 | 129.3 ± 1.7 | - |

Table 3. Geological setting and fluid-vent structures in the lower and middle slope

| | Lower slope | Middle slope |
|----------------------------|--|--|
| Geological setting | <ul style="list-style-type: none"> ▪ Debris-flow deposits overlain by a 'thick' creeping hemipelagic cover (~15 m) | <ul style="list-style-type: none"> ▪ Debris-flow deposits overlain by 'thin' hemipelagic cover (~ 0.5 m) |
| Seafloor surface | <ul style="list-style-type: none"> ▪ Rough (ridges and troughs) | <ul style="list-style-type: none"> ▪ Flat |
| Gravitational processes | <ul style="list-style-type: none"> ▪ Active creeping processes leading to formation of ridges and troughs ▪ Extensional regime mainly (rotated blocks) ▪ Probably local compressive ridges distally and above irregularities of decollement plane | <ul style="list-style-type: none"> ▪ Not active at present ▪ Uniformly disorganised debris-flow deposits |
| Fluid-vent structures | <ul style="list-style-type: none"> ▪ Carbonate ridges (~500 m long) associated with compressional ridges ▪ Troughs (methane emission) ▪ Small pockmarks | <ul style="list-style-type: none"> ▪ Large carbonate-paved areas (> 1 km²) with irregular shapes ▪ Pockmarks |
| Degree of seepage activity | <ul style="list-style-type: none"> ▪ Reduced activity at carbonate ridges ▪ Active methane venting above furrows | <ul style="list-style-type: none"> ▪ Continuous activity for at least the last ~5 kyr |

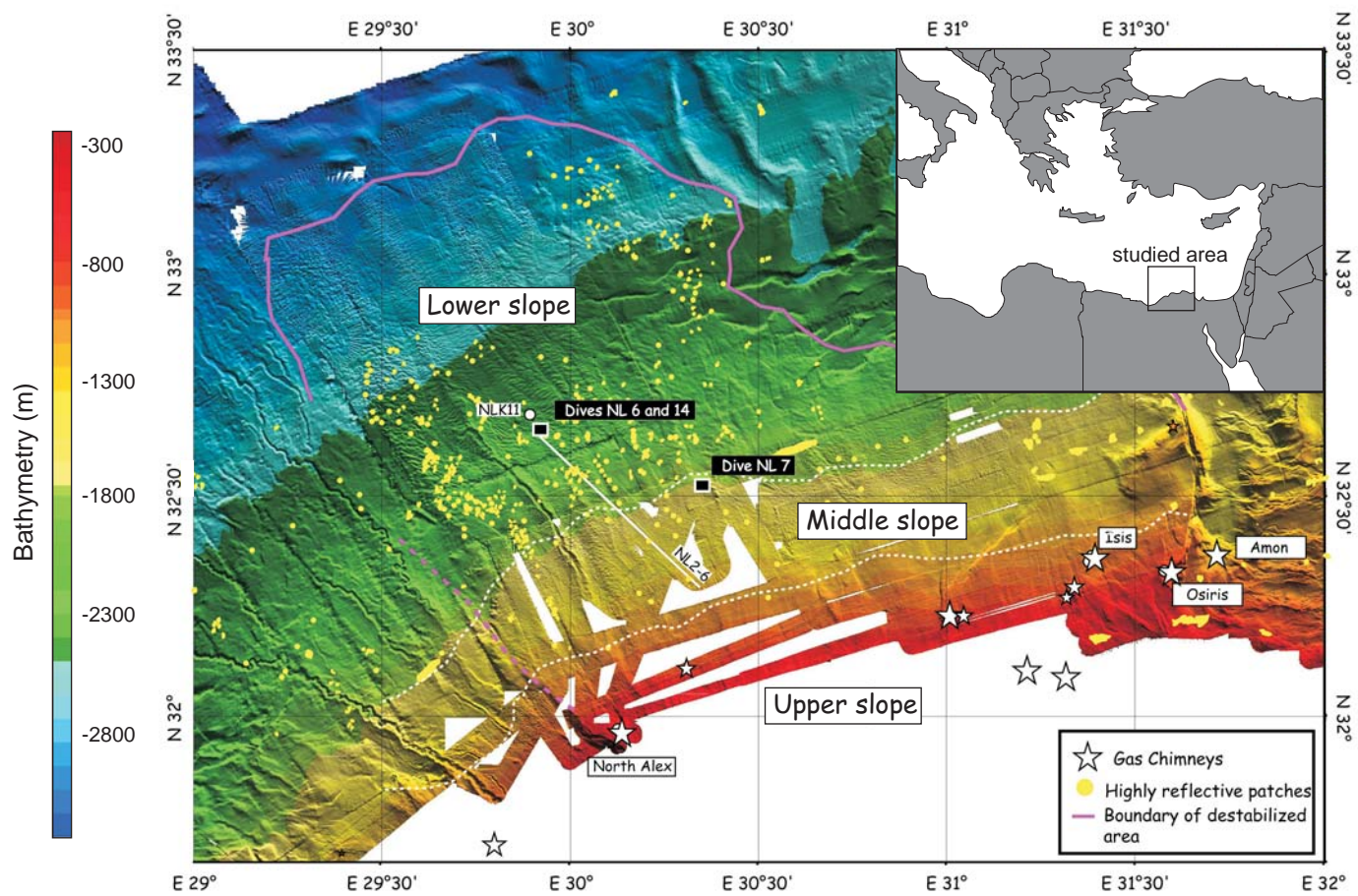


Fig1

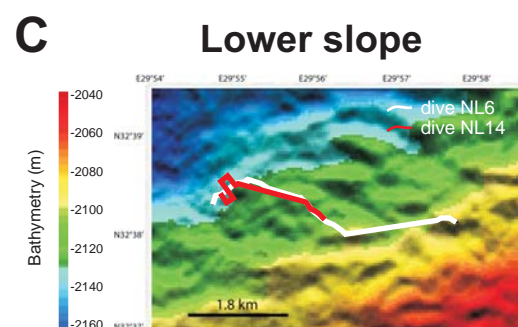
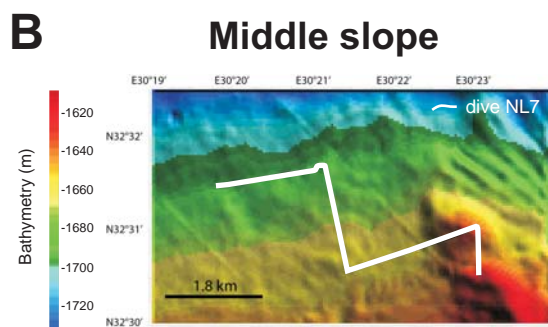
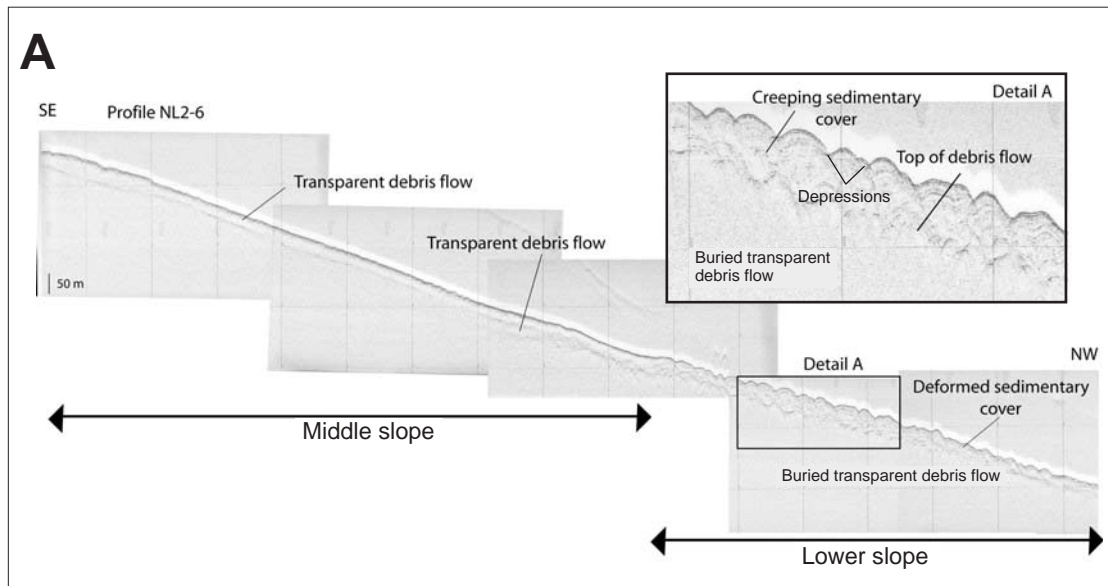


Fig2

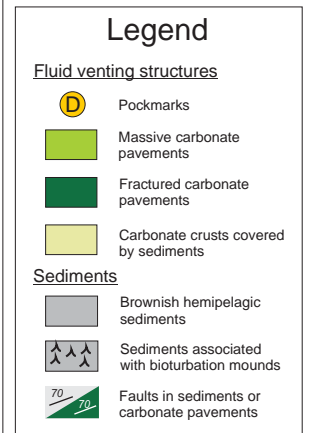
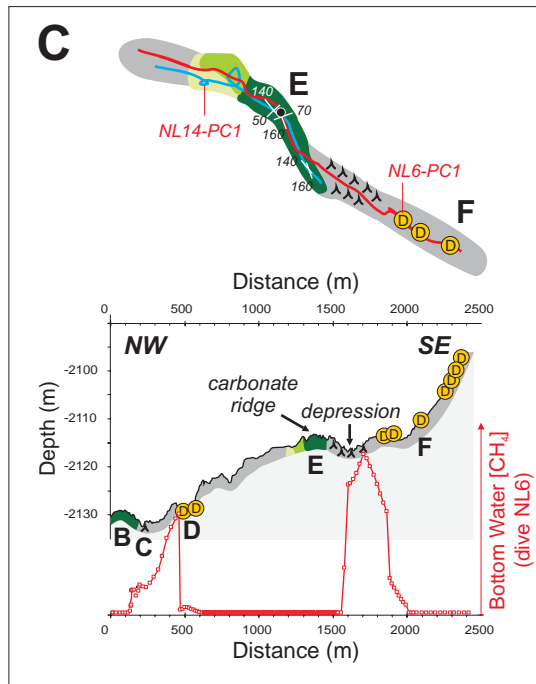
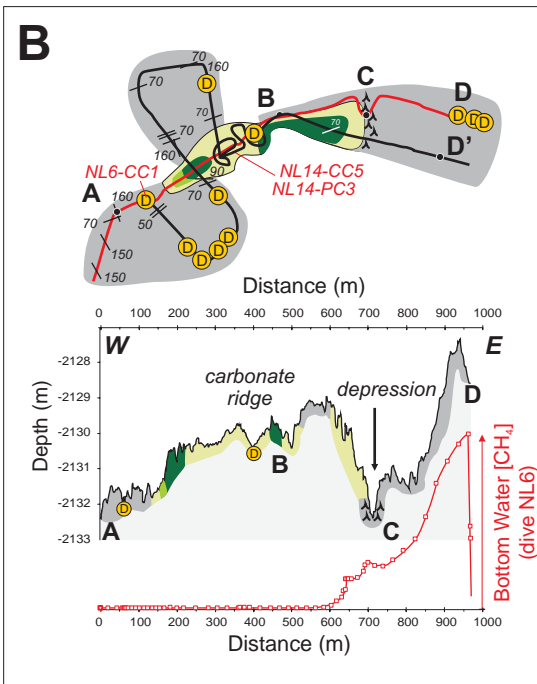
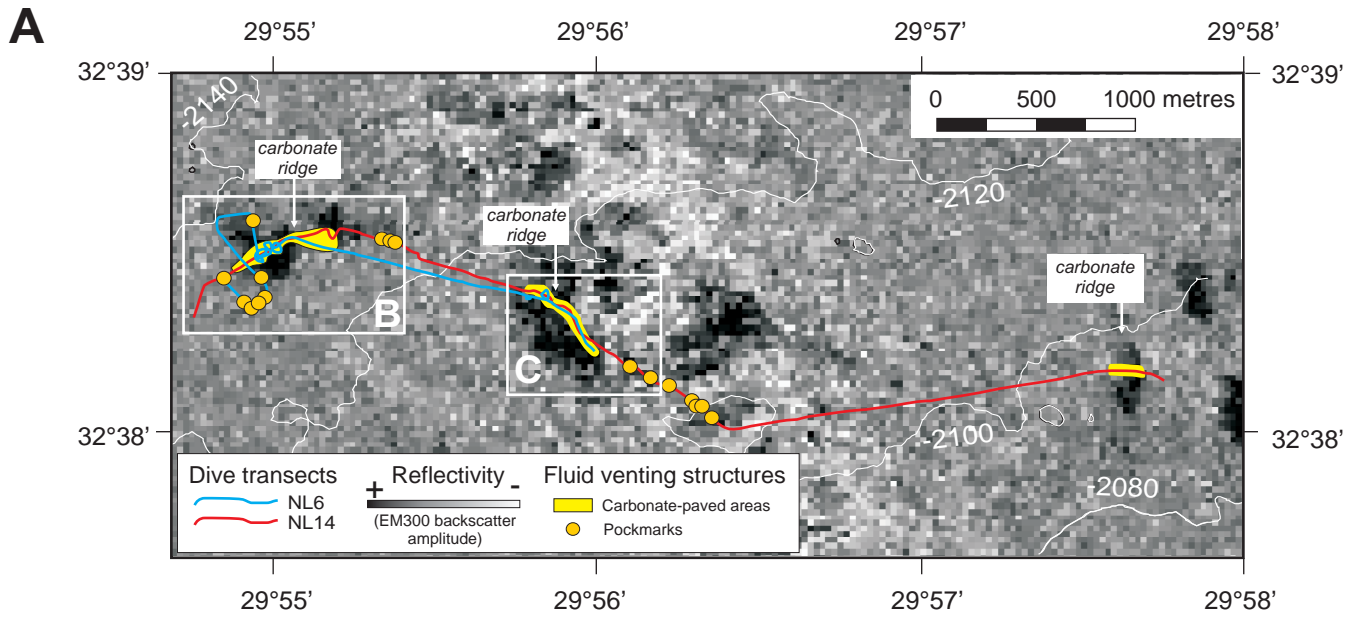


Fig3

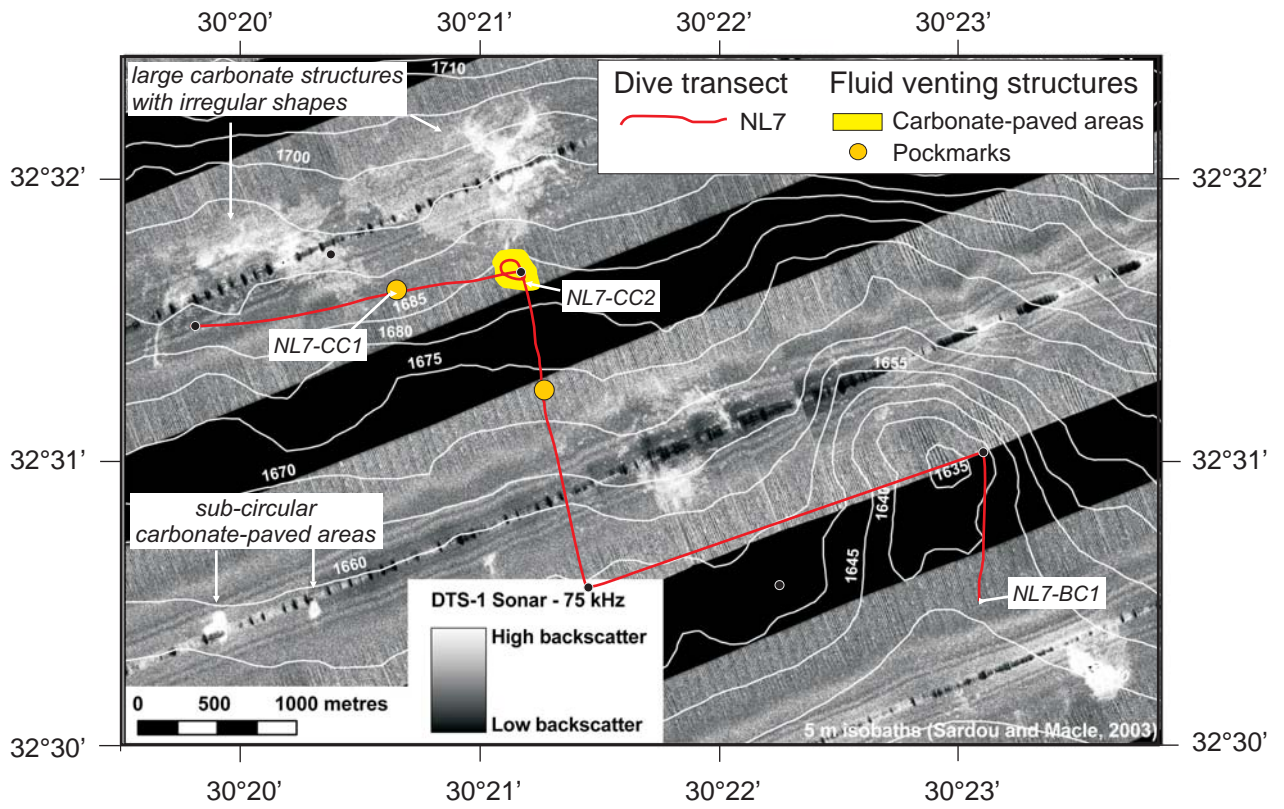


Fig4

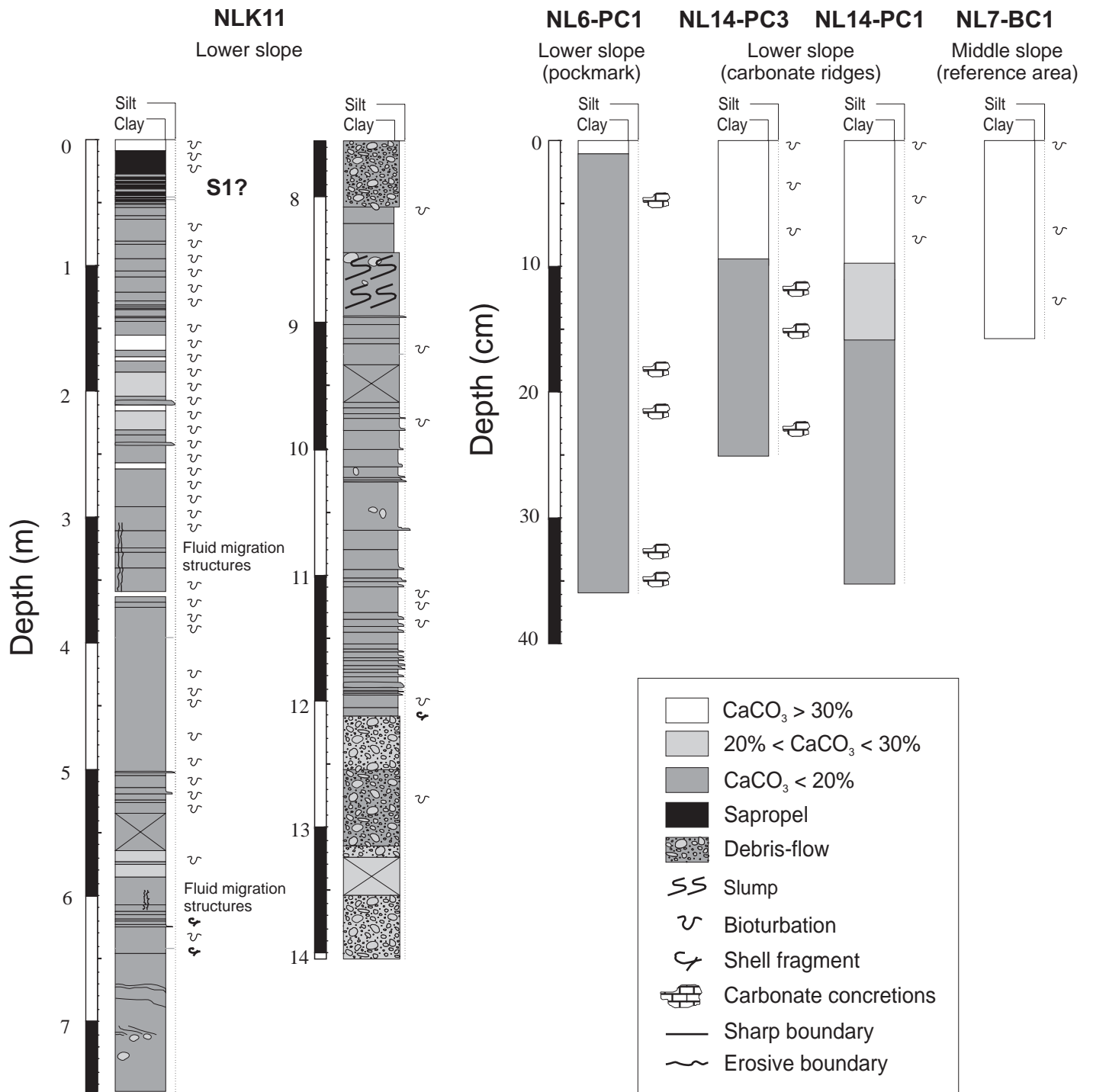


Fig5

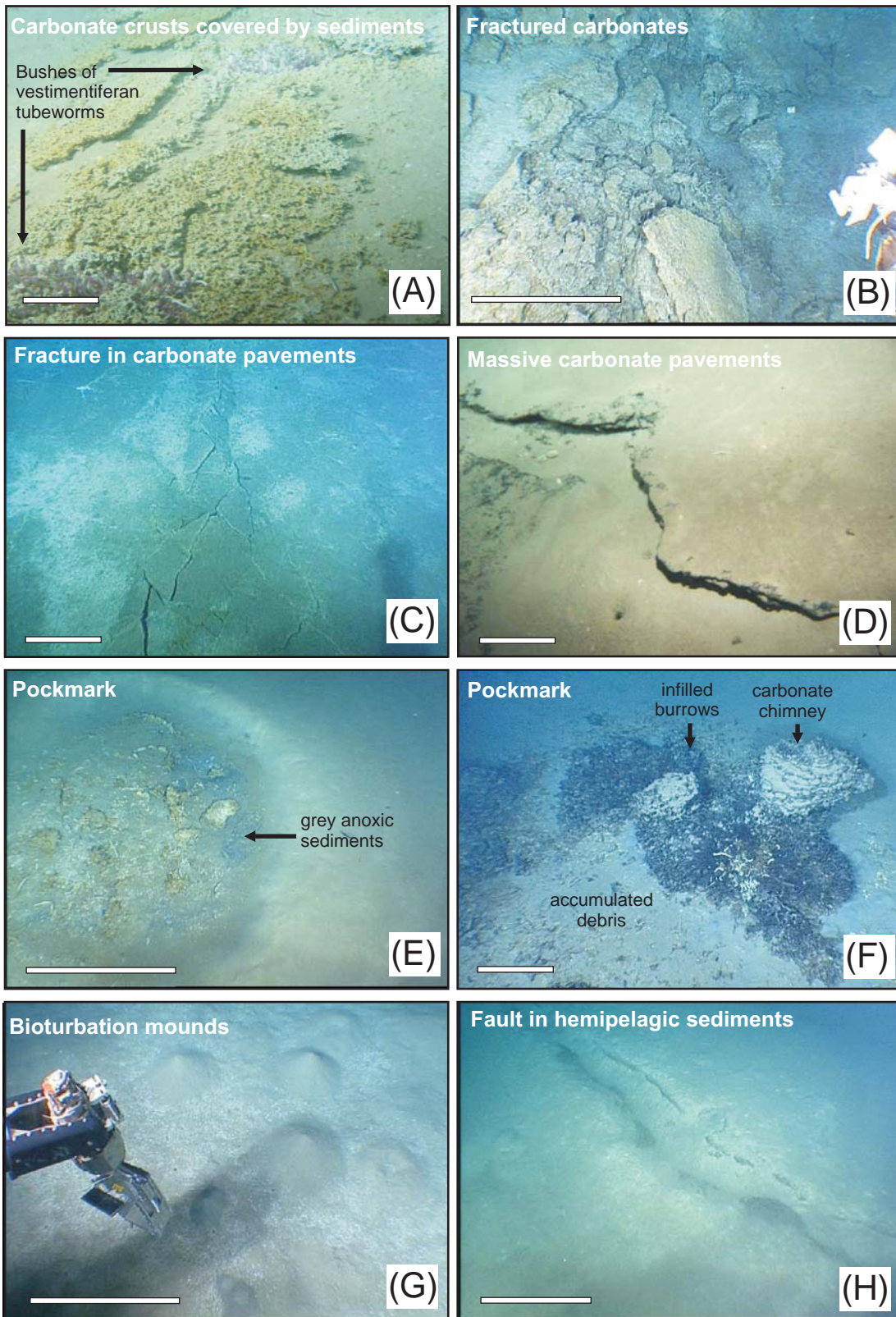


Fig6

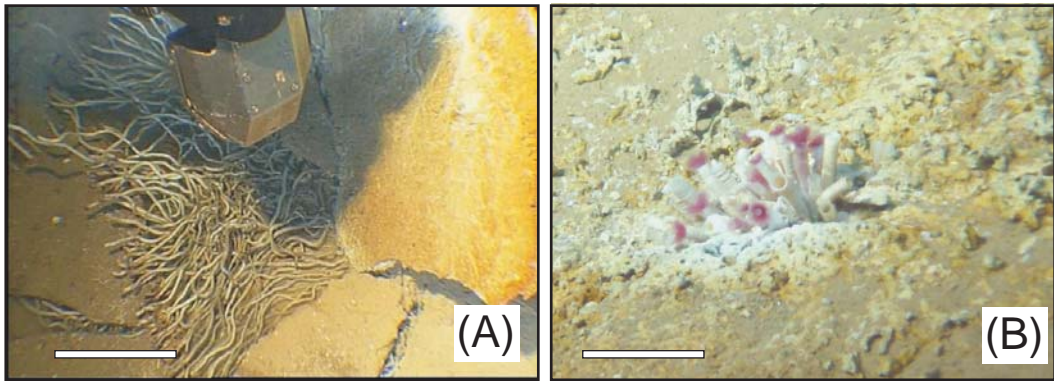


Fig7

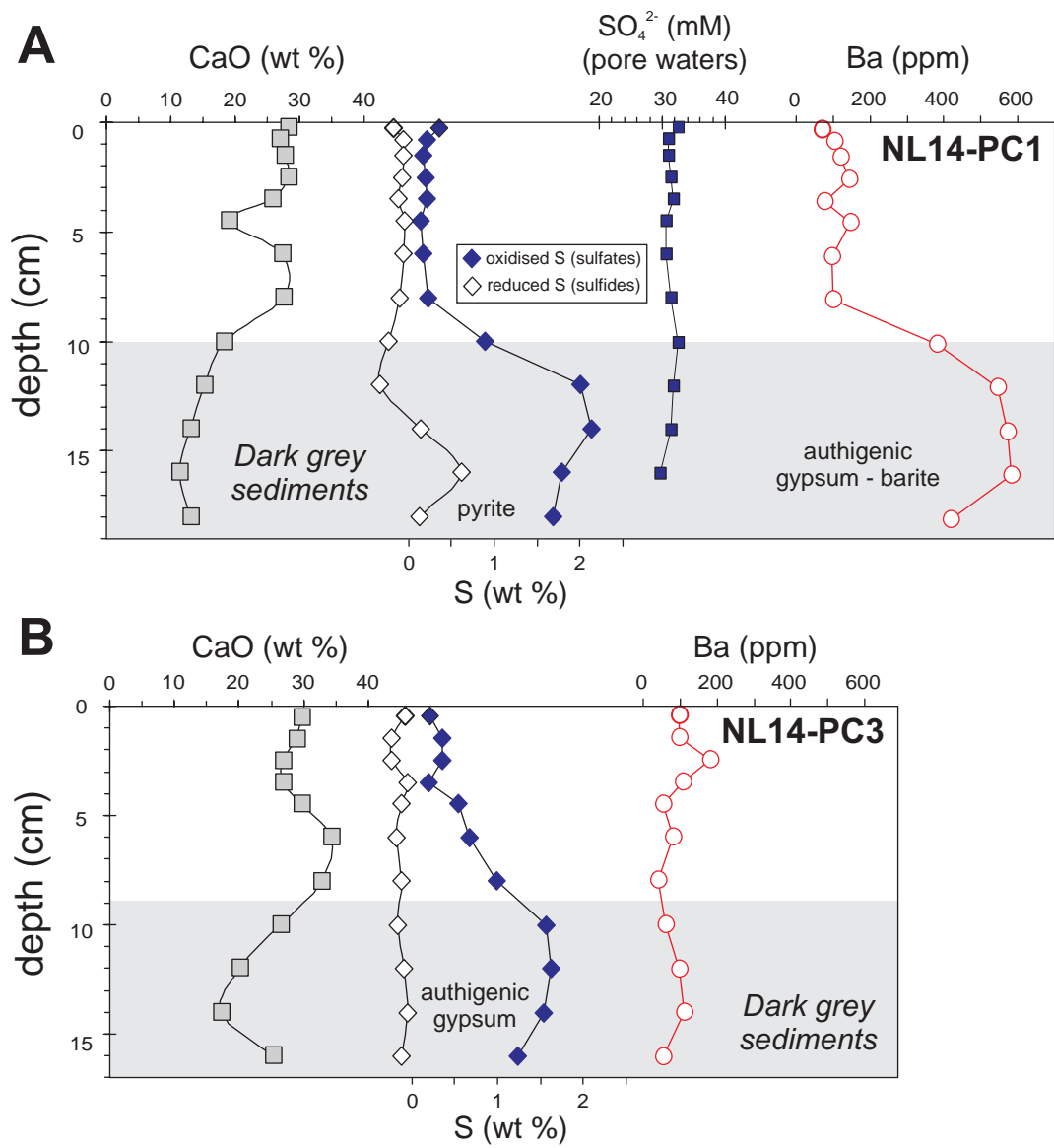


Fig8

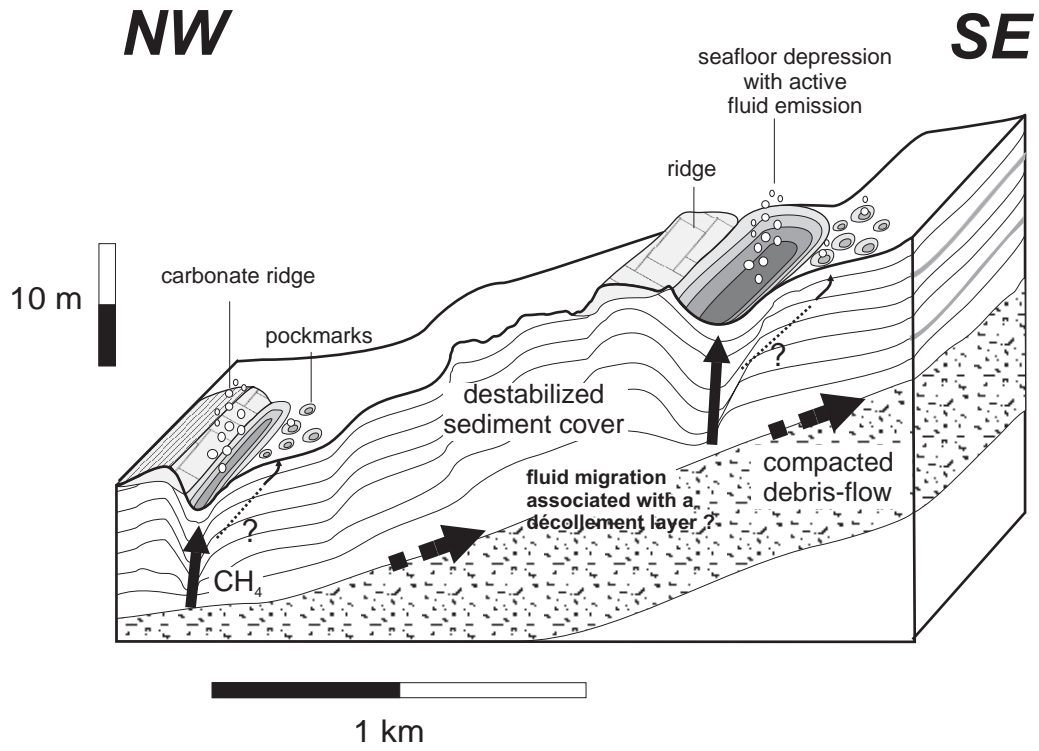


Fig9