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New evidence of perfect overlapping of Haploops and pockmarks field: Is it a coincidence?

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1 **New evidence of perfect overlapping of *Haploops* and pockmarks field: is it a coincidence?**

2

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18 **Abstract**

19 In the shallow waters of the Bay of Concarneau (South Brittany, France), previous studies

20 reported a dense settlement of the species *Haploops* (tube-dwelling bioengineer amphipod) that

21 perfectly overlaps a field of pockmarks. A possible mechanistic link may therefore exist between

22 the *Haploops* colonies and the shallow pockmarks. To test this hypothesis, interferometry sonar

23 and sub-bottom profiler chirp data were acquired in two new areas located in the marine estuary

24 of the Loire River, “La Lambarde” and “Le Croisic”. The new sites share the same sedimentary
25 and geological characteristics as those found in the Bay of Concarneau. The three sites are
26 similarly located in shallow and muddy environments above a faulted Middle Eocene formation
27 that is incised by paleo-valleys. Despite different hydrodynamic conditions and estuarine
28 influence, in the two new investigated areas, the *Haploops* also settle within the pockmarks field
29 limits. To better constrain the association pockmarks/*Haploops*, we compared the sedimentary
30 features, seismic signatures and total organic carbon (TOC) content of the sediment. Active
31 pockmark chimneys displaying highly reworked profiles and slightly higher TOC contents
32 suggest a local deeper source of organic matter, which might be an important source of nutrient
33 for the *Haploops*. In Southern Brittany the pockmarks/*Haploops* spatial overlap is not a simple
34 coincidence and may therefore present a general pattern for identification of settlement
35 preferences of the specie.

36

37 Keywords: shallow waters, South Brittany (France), geophysics, pockmarks, *Haploops*

38 **I - Introduction**

39 Seafloor sub-circular depressions, known as “pockmarks” ([King and MacLean, 1970](#)), have been
40 widely investigated in various shallow and deep waters environments; such as deltas, estuaries,
41 lakes, continental shelves and deep-sea basins ([Brothers et al., 2012](#); [Gay and Migeon, 2017](#);
42 [Hovland et al., 1997](#); [Rollet et al., 2006](#)). Gas, essentially methane ([Gay et al., 2007](#); [Judd et al.,](#)
43 [2002](#)), and fluids such as pore water ([Harrington, 1985](#); [Whiticar, 2002](#)) or groundwater
44 ([Christodoulou et al., 2003](#)), are the main expelled products described in the literature. Various
45 triggering mechanisms for the release of gas/fluid from the subsurface have been identified, such
46 as seismic events ([Hasiotis et al., 1996](#)), iceberg scouring ([Pilcher and Argent, 2007](#)), trawling

47 ([Fader, 1991](#)), and tidal pressure ([Diez et al., 2007](#); [Judd and Hovland, 2009](#); [Baltzer et al.,](#)
48 [2014](#)). With increasing human activities in coastal environments (e.g. off-shore wind farms), the
49 occurrence of shallow water pockmarks (< 40 m of water depths) has been reported more often in
50 recent years ([García-García et al., 1999](#); [García-Gil, 2003](#); [Brothers et al., 2012](#); [Baltzer et al.,](#)
51 [2014](#); [Szpak et al., 2015](#)). Although smaller (from 5 to 40 m of diameter) compared to those
52 found in deeper environments (up to 600 m in diameter, [Ondréas et al., 2005](#); [Sultan et al., 2010](#);
53 [Riboulot et al., 2016](#)), shallow water fields of pockmarks are often characterised by a high
54 density distribution (a few thousands per square kilometres) occurring in relatively restricted
55 areas (several square kilometres) ([Gay and Migeon, 2017](#)).

56 In the Bay of Concarneau, located in South Brittany (West of France), a large field of pockmarks
57 was mapped in 2009, at water depths varying between 15 and 40 m ([Souron, 2009](#); [Baltzer et al.,](#)
58 [2014](#)). The estimated average width of pockmarks varies between 5 and 30 m while their depths
59 do not exceed 2 m. The field covers an overall area of 36 km² and is characterised by an unusual
60 high density of pockmarks in some locations, reaching up to 5,500 pockmarks/ km² ([Reynaud](#)
61 [and Baltzer, 2014](#); [Baltzer et al., 2017](#)).

62 In the same area, a large settlement of *Haploops* species, engineers tube-dwelling amphipods,
63 was discovered by [Glemarec \(1969\)](#) and confirmed by other studies ([Dauvin and Bellan-Santini,](#)
64 [1990](#); [Desaunay and Guerault, 2003](#); [Ehrhold, 2003](#); [Ehrhold et al., 2006](#)). More recent studies
65 have highlighted the superimposition of *Haploops* settlements on the pockmark fields ([Souron,](#)
66 [2009](#); [Rigolet et al., 2012](#); [Baltzer et al., 2014](#); [Reynaud and Baltzer, 2014](#), [Dubois et al., 2015](#);
67 [Baltzer et al., 2017](#)), which suggests a possible link. Although the amphipods have largely been
68 reported in the literature regarding their biological characteristics such as their life cycle ([Dauvin](#)
69 [and Bellan-Santini, 1990](#); [Rigolet et al., 2012](#)) or their filtration activities ([Rigolet et al., 2011](#);
70 [Dubois et al., 2015](#)), no ecological and physiological explanation were clearly stated regarding

71 their presence in coastal pockmark fields. [Reynaud and Baltzer \(2014\)](#) hypothesised that fluid
72 expulsion from the pockmarks provides fine and sorted sediment particles that favour tube
73 building of the *Haploops*. However, the authors gave no clear evidence for their suggestion. A
74 previous hypothesis suggested that pockmarks act as direct or indirect food supplier to the
75 *Haploops* ([Rigolet, 2013](#)). In the Bay of Concarneau, direct gas consumption by endosymbiosis
76 bacteria present in the *Haploops* was discarded due to the light signature of carbon stable isotopes
77 ($< -70 ‰$) found in the analysed tissues ([Rigolet, 2013](#)).

78 In the Bay of Concarneau, high densities of *Haploops* populations (up to 10,000 individuals/m²)
79 were reported by [Rigolet, \(2013\)](#) which are exceptional in comparison to densities (about 4,000
80 individuals/m²) reported in some northern hemisphere sites, such as the Øresund and Kattegat in
81 Sweden ([Petersen, 1924](#)), the Bay of Fundy in Canada ([Wildish and Dickinson, 1982](#)), the
82 Northumberland in the United Kingdom ([Allen, 1953](#)) and East Siberia in Russia ([Gukov, 2011](#)).

83 To our knowledge, no study other than the work conducted along the West coast of France, has
84 ever described the pockmarks/*Haploops* association. Moreover, only very few studies focused on
85 the influence of pockmark fields on the environment and their contribution to food webs
86 ([Straughan, 1982](#)) or nutrient cycles ([Wildish et al., 2008](#)) and possible links with benthic fauna
87 ([Dando et al., 1991](#); [Dubois et al., 2015](#)). The links between pockmarks and associated benthic
88 fauna is restricted to the comparison of species assemblages' occurring inside and outside some
89 selected pockmarks (never at the scale of the pockmark field). To test the recurrence of the spatial
90 overlap of *Haploops* cover and pockmark fields, two sites, “La Lambarde” and “Le Croisic”,
91 located in the Loire estuary (West France) were investigated using the same geophysical
92 approach carried out in Concarneau ([Baltzer et al., 2014](#)). More specifically, data collected from
93 Concarneau served as a reference to determine sedimentary facies, in terms of sedimentological
94 features, seismic properties, and to provide some geochemical arguments. Investigating the

95 geochemical background would give clues to constrain the link between the methane stocked into
96 the sediment, the pockmarks and *Haploops*.
97 All three sites exhibit an extensive field of shallow pockmarks that are populated by *Haploops*
98 species colonies. The main objective of this study is to confirm the strict link between pockmarks
99 fields and *Haploops*, as previously observed in the Bay of Concarneau. For this reason we
100 investigated at high resolution the distribution of *Haploops* tubes on two other pockmarks fields,
101 characterised by very different hydrodynamic and sedimentological conditions compared to the
102 Bay of Concarneau. The second objective is to show that environmental conditions are less
103 important for the development and prosperity of *Haploops* colonies compared to primary
104 necessity of the presence of active pockmarks nearby.

105

106 II - General settings

107 The three sites chosen for this study, “Concarneau”, “Le Croisic” and “La Lamberde”, are
108 located in shallow coastal environments, with depths ranging from 15 m to 45 m. The seafloor is
109 covered by a muddy layer deposited above a faulted and folded Middle Eocene formation (Fig. 1,
110 outcrops “e4-e5-e6” in yellow) that onlaps onto the crystalline bedrock ([Cogné et al., 1973](#);
111 [Béchenec et al., 1997](#)). These areas are also characterised by the presence of gas within the
112 sediments (Fig. 1, purple dots). Although the study sites all exhibit the same geological settings,
113 they differ in terms of hydrodynamic conditions and sediment sources and rates as described
114 hereafter.

115 II - 1 Concarneau site

116 In the Bay of Concarneau (Fig. 2A), a low energy environment predominates, influenced by weak
117 tidal currents, with a maximum velocity of 20 cm.s⁻¹ between Concarneau and Trévignon

118 ([Tessier, 2006](#)). The tide is semi-diurnal with a range of 5.5 m, oriented north-northwest during
119 the flow and south-southeast during the ebb. The shoals of Moutons, Pourceaux Glénans and
120 Basse Jaune protect the bay from the main west-southwest swells ([Pinot, 1974](#); [Ehrhold *et al.*,
2007](#)). Turbidity as well as riverine sediment influxes are both low (annual mean < 3.5 mg/l)
121 ([Glémarec *et al.*, 1987](#); [Tessier, 2006](#)). However, the turbidity has increased in the last few
122 decades principally due to anthropic activities, such as fishing ([Hily *et al.*, 2008](#)).

124

125 II - 2 Le Croisic site

126 Le Croisic is subject to higher hydrodynamic conditions as it is poorly protected from west-
127 northwest swells by the Plateau du Four (Fig. 2B) and from the southwest swells by the shallow
128 Guerande bank. Tidal current velocity averages 20 cm.s⁻¹ ([Chapelle, 1989](#)) with a maximum
129 speed of 50 cm.s⁻¹ ([Tessier, 2006](#)). The tide is semi-diurnal with a tidal range of 6 m and has a
130 general north-northwest direction during the flow and south-southeast during the ebb
131 ([Gendronneau *et al.*, 2006](#)). Sediments from the Loire (Fig. 2B), are mostly carried offshore and
132 reworked by marine currents and ultimately deposited in the coastal area ([Sanchez and Delanoë,
2006](#)). This region, between Le Croisic coast and the Plateau du Four, constitutes an important
133 area of sediment accumulation ([Tessier, 2006](#); [Sanchez and Delanoë, 2006](#)) mainly supplied by
134 river inputs (95 % from the Loire and 5 % from the Vilaine, with 2x10⁶ T.yr⁻¹ and 0.1x10⁶ T.yr⁻¹
135 of sediments supplied from each river respectively) ([Jouanneau *et al.*, 1999](#); [Lazure and Jegou,
1998](#)).

138

139 II - 3 La Lambarde site

140 Located in the lowest part of the Loire estuary, La Lambarde is characterised by a very dynamic

141 environment (Fig. 2B). The mean tidal current velocity is around 50 cm.s⁻¹ with a maximum
142 speed of 90 cm.s⁻¹. The tide is semi-diurnal with a range of 6 m, oriented northeast along the axis
143 of the Loire estuary and rotates northwest offshore the Saint Gildas Cap during the flow ([Tessier,
144 2006](#)). Strongly exposed to western swells, sediment accumulations are low in this area ([Sanchez
145 and Delanoë, 2006](#)). All year long, strong ebb currents wash away most of the particles in the
146 water column maintaining a local turbidity of around 5 mg.l⁻¹, except during the Loire flood
147 events when turbidity increases up to 100 mg.l⁻¹ ([Tessier, 2006](#)). Our study site is located in the
148 roadstead zone (light green frame on Fig. 2B), just behind the Lambarde dumping zone (light
149 grey frame on Fig. 2B) where the “Grand Port Maritime de Nantes-Saint Nazaire” (Nantes
150 Harbour) dumps the sediments dredged in the Loire River. In the last 10 years, an estimated
151 average of 7 Mm³ of dredging sediments have been dropped each year ([GIP Loire Estuaire,
152 2018](#)).

153 III – Material, methods and data processes

154 III – 1 - Geophysical surveys

155 This study presents a comparison of previously obtained data in Concarneau with data acquired
156 since 2016 in Le Croisic and La Lambarde. Data from Concarneau (site 1 on Figure 2A) were
157 used as a reference to determine an acoustic signature of the *Haploops* presence, which was then
158 applied to assign a *Haploops* acoustic facies in Le Croisic and La Lambarde (Fig. 2B).

159 Previous geophysical surveys were conducted in the reference Concarneau zone between year
160 2000 and 2014. Two of them, POCK&PLOOPS in 2011 (99 transects representing 248 km) and
161 POCK&TIDE in 2014 (205 transects representing 820 km), were conducted on board of the *R/V*
162 *Haliotis* (Ifremer, operated by Genavir), using an interferometry sonar (Geoacoustic Geoswath -
163 250 kHz) coupled with a chirp echosounder profiler (1.7 to 5.5 kHz) fixed into the hull. Transects

164 were acquired at a boat speed of 3,5 knots, providing a vertical resolution of 25 cm and a
165 horizontal resolution of 50 cm.

166 Using the same boat (*R/V Haliotis*) and the same geophysical system, a second dataset was
167 acquired in Le Croisic (site 2 named Le Croisic on Fig. 2B) thanks to 18 transects representing 49
168 km and La Lambarde (site 3 named La Lambarde on Fig. 2B) thanks to 23 transects representing
169 69 km during the POPCORE survey in 2016. This survey was conducted off the Croisic shore
170 (site 2 named Le Croisic on Figure 2B).

171 In order to have a centimetre-scale spatial resolution for data positioning, an Aquarius Thalès
172 GPS coupled to a RTK beacon located on the coast were used. For Concarneau, tidal corrections
173 were obtained from a tide-gauge buoy located in the Bay of Concarneau, whereas for La
174 Lambarde and Le Croisic, corrections were obtained using an harmonic model based on the tide
175 database from the French Navy Hydrographic Service (SHOM).

176 Bathymetric maps were processed using Caraibes® software (Ifremer) with a 50 cm grid
177 resolution. Reflectivity maps obtained by sonar mosaics were processed using the Sonarscope®
178 software (Ifremer) with a grid resolution of 30 cm (see examples in Figure 3). The backscatter
179 properties of the seabed were then analysed as grayscale images ([Augustin et al., 1994](#)). The
180 shades of grey vary with the type of sediments, their compaction and heterogeneity, as well as
181 seafloor roughness and topography ([Lurton, 1998](#)). In our study, in agreement with Lurton
182 (1998), white colour tones correspond to low backscatter values that are correlated to flat, fine-
183 grained, homogeneous and/or unconsolidated sediments. High reflectivity or high backscatter
184 values, identified by darker grey tones, represent coarser-grained, heterogeneous and/or
185 compacted sediments, but also high slope gradients ([Lurton, 1998](#)). The Subop® software
186 (Ifremer) was used to process all the chirp profiles. Superimposed on the bathymetry, pockmark
187 features were manually plotted (black dots on Fig. 4 and 5) with an Arcgis® project, at a scale of

188 1:2500, in order to limit interpretation errors and overestimation of the number of pockmarks.
189 With such enlargement, some over-interpretations of circular sedimentary features, such as gaps
190 created by bio-construction, were avoided.

191 III – 2 – Sediment analysis

192 III – 2 – 1 – Sampling

193 In Le Croisic and La Lambarde sites, surface sediment samples were collected with a “Schipeck”
194 grab in order to calibrate the sonar reflectivity data. Sampling locations were chosen according to
195 the acoustic facies identified on the reflectivity and bathymetry maps. Each sample was collected,
196 photographed and stored at a low temperature (4°C) for subsequent analyses. In addition to the
197 grab samples, submarine videos (Go-pro and mini-ROV films) were recorded whenever possible
198 at different locations, nearby and around the *Haploops* settlement.

199 In the Concarneau site, twelve sediment cores were collected at 30 m of water depth from inside
200 two selected pockmarks (named Alpha and Beta) and outside the pockmarks, within the
201 *Haploops* field (Fig. 3). Both pockmarks were chosen for their accessibility to scuba-divers
202 (water depth < 32m) and for their different shapes: the first (Alpha) has a sharp round edge
203 possibly indicating a newly formed feature and the second (Beta) showed smoother edges and
204 was identified as an infilled pockmark. The Alpha pockmark is 10 m in diameter and 1 m deep.
205 Beta is 17 m in diameter and 0.5 m deep. From both pockmarks, sediments were collected in their
206 centres where no living *Haploops* were found, as well as in the surrounding areas (in around a 5
207 m radius), which were covered by dense *Haploops* settlements.

208 Scuba divers acquired 20 to 40 cm long sediment cores. Seven cores were acquired in the
209 pockmark Alpha (two in the centre and five outside the pockmark). Five cores were obtained in

210 the pockmark Beta (two in the centre, and three outside the pockmark).

211 [III – 2 – 2 – Grain size](#)

212 Sediments collected with the Schipeck grab were subsampled, 2000 μm sieved and analysed for
213 particle size distribution using a Malvern 3000 Mastersizer laser diffraction particle size analyser
214 ([Malvern Instruments, 2015](#)). Grain size analysis was based on the following classes: clays ($d \leq$
215 $3.9 \mu\text{m}$), silt ($4 \mu\text{m} < d \leq 63 \mu\text{m}$), sand ($d > 63 \mu\text{m}$) following the methods of Udden (1914) and
216 Wentworth (1922).

217 [III – 2 – 3 – Total organic carbon profiling](#)

218 Ninety-five sediment samples were collected throughout the cores. Each sample was freeze-dried,
219 crushed and homogenised. Samples were then acidified with H_3PO_4 (1M) to remove carbonates
220 dried on a hot plate at 40°C and measured with a combustion infrared detection technique on a
221 LECO CS 744 carbon sulphur analyser. Two or three sediment replicates (50 mg) per sample
222 were analysed.

223

224 [IV – The acoustic signature of *Haploops* presence](#)

225 The acoustic signature of *Haploops* has been identified and precisely defined in the Bay of
226 Concarneau during the last two decades ([Souron, 2009; Rigolet et al., 2012; Baltzer et al., 2014;](#)
227 [Reynaud and Baltzer, 2014, Dubois et al., 2015; Baltzer et al., 2017](#)). Similar acoustic
228 characteristics were applied in Le Croisic and La Lambarde sites to detect the presence of
229 *Haploops*.

230 On the bathymetry maps (Fig. 3A), *Haploops* cover occurs as a slightly elevated surface (0.5 to 1
231 m) compared to surrounding areas. For example, on the northeast corner of the detailed map in

232 Figure 3A, the *Haploops* settlement (located at a water depth of 23 to 24.5 m) occurs 0.5 to 1 m
233 above the southwest corner (24 to 25.5 m of water depth). The seafloor appears heterogeneous
234 and rough because of the presence of a large number of *Haploops* tubes (Fig. 3) interrupted by
235 “scoured-like” and “hole-like” features. The latter correspond to pockmarks, widely described in
236 the literature ([King and MacLean, 1970](#); [Hovland and Judd, 1988](#); [Judd and Hovland, 2009](#)) They
237 appear as circular to sub-circular holes slightly deeper (1 m) than their immediate surroundings.
238 Successions of aligned holes (“scoured-like”), with the same size, are interpreted as pockmarks
239 activated by trawling activities ([Baltzer et al., 2014](#); [Reynaud and Baltzer, 2014](#)). The heavy
240 trawls of fishing boats dig and exert a pressure on the sediment layers down to the gas reservoir.
241 The pressure initiates a preferential pathway for gas escape along the trawl scars, yielding
242 pockmarks that resemble iceberg-scours (Mosher *et al.* 2004; Brown *et al.* 2017).

243 On the sonar reflectivity map (Fig. 3B), medium to high reflectivity correspond to a
244 heterogeneous and rough surface linked to the presence of irregular *Haploops* tubes (37 to 38
245 dB). Within the *Haploops* cover, pockmarks are identified by a specific morphology (hole)
246 appearing as dark dots. In isolated cases, white round patches correspond to pockmarks with
247 larger diameters, which are filled with mud ([Reynaud and Baltzer, 2014](#)). When pockmarks have
248 smaller diameters, their centre appears covered by horizontal unoccupied *Haploops* tubes that
249 show a similar grey scale on backscatter images as the one produced by healthy *Haploops* cover.

250 The chirp profiles helped to identify precisely the *Haploops* cover as the acoustic reflector
251 representing the seafloor shows a distinct discontinuous saw-tooth shape (Fig. 3C). This reflector
252 corresponds to the high-density of tubes (see picture, Fig 3), whereas a smooth and continuous
253 reflector corresponds to the seafloor without any *Haploops* (Fig. 3C). Combining the three data
254 sets, bathymetry, sonar reflectivity and chirp data, the limits of the continuous *Haploops* cover
255 was precisely mapped.

256

257 V – Results

258 V – 1 – Bathymetry and reflectivity

259 Bathymetry and sonar reflectivity maps acquired at the two new sites examined in this study are
260 presented in Figures 4 and 5. Each site covers an area of about 3.5 km² and water depths vary
261 from 17 to 21 m at Le Croisic, and from 28 to 35 m at La Lambarde.

262 At Le Croisic, facies A and B (separated by a black dashed line, Fig. 4) correspond to areas
263 covered by *Haploops* (white continuous line). Facies A appears as a light grey zone (35-37 db)
264 with high density of *Haploops* tubes (see picture BS3) within a matrix of sandy-mud (19.3% clay,
265 62.2% silt and 18.5% sand, according to grain size analysis). In this area, pockmarks are well
266 developed (circular) and thus clearly visible. Facies B reveals a higher proportion of shorter tubes
267 (see picture BS4) within a matrix of slightly coarser sediments (18.4% clay, 57.9% silt and 23.7%
268 sand, according to grain size analysis). In the southern part, pockmarks appear smoother and
269 sometimes “anastomosed” as previously described by Josenhans et al. (1978) and Michel et al.
270 (2017)

271 Facies C, nearly white in colour (29 db), corresponds to sandy mud sediments (14.4 % clay, 58.8
272 % silt and 26.8 % sand, according to grain size analysis) without any *Haploops*. Brownish at the
273 surface (because of oxidation), the sediments become black when buried (see picture BS10). This
274 area is devoid of pockmarks. Finally, the dark grey facies D (49 to 51 db), corresponds to coarser
275 sediments, rich in sand and shell fragments (14.1 % clay, 39.1 % silt and 46.8 % sand, according
276 to grain size analysis), without any *Haploops* tubes (see picture BS9). Along its fringe with facies
277 B, very short *Haploops* tubes are observed in the video records (*cf.* supplementary data).

278 In the La Lambarde site (Fig. 5), facies A' and B' correspond to areas covered by *Haploops*

279 tubes, characterised by a middle grey facies (35-37 db). Located North and South and delineated
280 by a black dashed line, facies A' appears as marbled dark grey zones (35-45 db) with a high
281 density of long *Haploops* tubes (see picture BS30) within a matrix of sandy-mud sediments
282 (16.1% clay, 57.2% silt and 26.7% sand, according to grain size analysis). Pockmarks are
283 distinctly present on the seafloor. Facies B' (delineated by a black dashed line) appears with a
284 lighter grey (35-37 db), covered by high density of *Haploops* tubes (see picture SB25) within a
285 matrix of sandy-mud sediments (16.4% clay, 54.6% silt and 29% sand, according to grain size
286 analysis). Facies B' shows strong impacts of human activities such as trawling, anchor scouring
287 and skidding. The pockmark features are partially destroyed by these human activities making
288 them almost undistinguishable.

289 Facies C', located at the southwest of facies B', corresponds to small white patches (25 db) of
290 sandy-mud sediments without any *Haploops* cover or pockmarks. No sedimentary samples were
291 collected in facies C' because of its limited surface and location in a roadstead zone.
292 Nevertheless, the results were checked on video records (*cf.* supplementary data). A transitional
293 zone, named facies D', was highlighted between the continuous brown and white line and related
294 to a reduced and/or scattered *Haploops* cover identifiable on the chirp profiles.

295 Finally, facies E', a large patch of marbled light grey (26-27 db, delineated by the white
296 continuous line in Fig. 5), corresponds to a seafloor without *Haploops* cover. Facies E' was not
297 sampled but video records were acquired and used in this area (*cf.* supplementary data). In facies
298 E', some pockmarks were observed on bathymetry and sonar imagery maps. This last facies E'
299 also corresponds to a perturbed sedimentary zone due to the impact of anchoring and other
300 human activities.

301 **V – 2 – Seismic profiles**

302 Chirp profiles are shown in Figure 6 for Le Croisic and in Figure 7 for La Lambarde. Seismic
303 sequences described in the Bay of Concarneau ([Menier, 2003](#)) and in the Loire estuary (Menier *et*
304 *al.* 2014) were used as a guide for a better characterisation of the sedimentary sequences in the
305 studied areas. Although similar seismic infilling patterns of sedimentary sequences were
306 observed in both La Lambarde and Le Croisic areas, no chronological framework is established
307 yet due to a lack of existing age model.

308 For the Le Croisic site (Fig. 6), an Enhanced Gas Reflector (EGR) can be observed into the
309 sediment, at depths varying from 6 ms TWT (Two-Way Traveltime, around 5 m) to 10 ms TWT
310 (around 7.5 m). An EGR corresponds to the top of an impermeable sediment layer (rich in clays),
311 which hinders gas ascension. The strong impedance contrast between gas (stucked under the
312 EGR) and sediment explains the occurrence of such a marked reflector. In the hydro-sedimentary
313 conditions of this study site, pockmarks are observed on the sea floor when the EGR depth does
314 not exceed 9 ms TWT (around 7 m). When the EGR depth increases, no more pockmarks are
315 observed on the surface (*cf.* pockmarks density map on Fig. 6).

316 For the La Lambarde site (Fig.7), a continuous EGR was located at a sediment depth between 3
317 and 5 ms TWT (around 2.5 m) within the sedimentary section and a discontinuous EGR occurred
318 at a sediment depth between 2 and 2.5 ms TWT (around 1.5 m). Gas is present everywhere as a
319 gas blanket in the subjacent sedimentary layers, but it is only visible on the upper layers as gas
320 escape features (blank chimneys, enhanced reflector patches, acoustic turbidity). These features
321 are observed in the southeastern area (Fig. 7).

322 At Le Croisic, densities up to 13,000 pockmarks/km² were measured in some places. At the La
323 Lambarde site, the exact density of pockmarks is more difficult to assess due to anchoring scars.
324 However, on facies A', around 3,500 pockmarks/km² were counted.

325

326 V – 3 – Organic matter content

327 Figure 8 shows the location of the twelve cores collected at the Concarneau site. No tube
328 fragments were found in the centre of pockmark Beta, while some of them occurred in one core
329 located in the Alpha pockmark chimney. The sediments collected within the chimneys were dark,
330 fine-grained and unconsolidated. In the case of the Beta pockmark, the sediments strongly
331 smelled hydrogen sulphide.

332 Figure 8 shows the Total Organic Carbon (TOC) percentage (% of dry weight of sediments).
333 Profiles are shown from the left with the cores taken outside the *Haploops* cover, to those located
334 inside the chimneys (on the right) for both pockmarks (Alpha and Beta). The eight cores
335 collected within the *Haploops* cover exhibit a similar TOC versus depth pattern. The maximum
336 TOC content (2.47 ± 0.14 %) is recorded at the seafloor surface, and decreases downwards with a
337 progressive trend. The TOC reaches a value of about 1.5 % at a depth of 30 cm. This trend may
338 be related to the occurrence at the surface of numerous *Haploops* tubes and fecal pellets
339 (binocular observation). With depth, the organic-mineral structures were gradually degraded and
340 disappeared.

341 The four cores collected in the pockmark centres do not show any particular variation of TOC
342 with depth. Organic carbon is highly variable along these profiles (1.82 % to 3.75 %) without any
343 trend. Not only the shape of TOC profiles differs between the chimney of pockmarks and the
344 *Haploops* area, but also the absolute TOC contents. In fact, the mean TOC values in the upper 20
345 cm of sediment are 2.20 ± 0.23 % for the *Haploops* areas, 2.45 ± 0.35 % for Alpha pockmark
346 centre and 2.62 ± 0.32 % for Beta pockmark centre. It is noticeable that half of the samples from
347 pockmark centres had TOC values higher than 2.5%, while such a high value was only found
348 once in the *Haploops* area.

349

350 VI – Discussion

351 *Haploops* settlements (delineated by a black continuous line in Fig. 6 and 7) are not observed on
352 all the surface of the studied areas even when the gas is present in the sedimentary layers
353 (delineated by a purple dashed line). Their occurrence does not seem to be related to the simple
354 presence of buried gas/fluids but particularly to the existence of pockmarks, and therefore to
355 possible strong and episodic gas/fluids release. At Le Croisic (Fig. 6), the pockmark field edges
356 do not coincide with the buried gas limits and the *Haploops* distribution perfectly matches with
357 the area covered by pockmarks. In the facies C (Fig. 4), despite a shallow EGR (2 to 6 m),
358 indicating possible diffusion/percolation of fluids, no pockmarks or *Haploops* were documented.
359 This is also evident at La Lambarde, in the facies C' (Fig. 5). Thus, settlements are limited to
360 areas where gas/fluids could be released by pockmarks. As described by Cathles *et al.*, (2010),
361 formation of pockmarks depends on the possibility for gas, stored below the EGR, to escape with
362 a sufficient pressure to form a chimney which moves upward. Pockmarks form when this
363 chimney extends about half way (from EGR) to the seafloor. In our study area, pockmarks can
364 only form if the depth of EGR is located less than 8-9 ms TWT (around 6,5 m) below the seafloor
365 (Fig. 6 and Fig. 7). When the EGR appears below 9 ms TWT (around 7 m), no pockmarks occur
366 on the seafloor.

367 These new observations confirm that the *Haploops* settlement, as hypothesized after the first
368 records in the Bay of Concarneau (Baltzer *et al.* 2014 ; Reynaud and Baltzer 2014; Baltzer *et al.*
369 2017), is defined by the presence of a pockmarks field. The fact that Le Croisic and la Lambarde
370 sites are very different from the Bay of Concarneau in terms of hydrology, oceanography,
371 sediment dynamics, organic matter supply and anthropic impact allows to exclude these
372 parameters as the main driving factors for *Haploops* settlement. These observations give rise to
373 new questions 1) is this co-occurrence systematic (at global scale) and 2) why do *Haploops* and

374 pockmarks co-occur? It is not easy to answer the first question because very few studies exist on
375 *Haploops* fields and their co-existence with pockmarks is never directly investigated. Only partial
376 indications can be found in the literature. For example, in the area of Skålderviken (Kattegat-
377 Øresund, Sweden), at around 30 m of depth, [Petersen \(1924\)](#) described for the first time
378 *Haploops tubicola* and *H. tenuis*. In the same area, [Thorson \(1957\)](#) estimated *Haploops* densities
379 at around 3.000 to 4.000 individuals/m². In the southern edge of this area, [Laier and Jensen](#)
380 [\(2007\)](#) noticed the presence of gas between 2 and 4 m below the surface, but did not further
381 prospect the area. Similarly, [Jørgensen et al. \(1990\)](#) revealed gas seeps and methane-derived
382 carbonates in the eastern part of the same area, but again the overlap was not investigated. In the
383 Firth of Clyde (United Kingdom), *Haploops* patches (3.000 – 4.000 individuals/m²) have been
384 described by [Allen \(1953\)](#), between 55 and 65 m of depth, while shallow gas accumulations have
385 been reported later by [Taylor \(1992\)](#). In the southwest area of the Bay of Fundy (Canada), the
386 presence of a community of *Haploops fundiensis* (average density of 400 individuals/m²) has
387 been observed at 80 m of depth ([Wildish and Dickinson, 1982](#)). Moreover, some pockmarks and
388 gas mask zones have been described in the same area (north-east of Grand Manan Island, in the
389 south-western mouth of the Bay of Fundy, [Shaw et al., 2014](#)). Both studies described amphipods,
390 which may be an indication of a possible presence of *Haploops* and pockmarks within the same
391 area. Finally, in the Laptev Sea (East Siberian Sea), a *Haploops laevis* community, with a mean
392 density of 400 individuals/m², has been described at a depth range of 23 to 58 m ([Gukov, 2011](#)).
393 This corresponds to an area where subsea methane permafrost of 300 to 800 m of thickness has
394 been described by [Delisle \(2000\)](#) who also questioned the formation of pockmarks in those
395 conditions.

396 In all these examples, when high densities of *Haploops* have been observed by biologists, the
397 surrounding areas coincide with the presence of gas, gas leaking chimneys or pockmarks that

398 have been reported by geologists. These observations suggest that overlapping of *Haploops*
399 settlements and pockmarks fields may be a general occurrence. This point needs to be confirmed
400 by specific studies directly investigating this question: why do *Haploops* need pockmarks to
401 develop?

402 After the first observation in the Bay of Concarneau, [Reynaud and Baltzer \(2014\)](#) hypothesized
403 that pockmark activity may facilitate tubes building by providing fine and sorted sediments.
404 Results from the two locations near the Loire Estuary indicate that this explanation may
405 contribute to the settlement of *Haploops* but is not the key factor. Indeed, the Loire river inputs
406 are high and coastal currents provide a large amount of sediments (Fig. 2). Therefore, sediment
407 supply is not a limiting factor as in the Bay of Concarneau. If the need of fine sediment was the
408 only requirement for their development, *Haploops* would not be confined to the pockmark fields
409 (Fig. 4 and 5). We therefore now hypothesize that pockmark activity (fluid/gas expulsion) may be
410 the mechanism allowing some specific particles (maybe organic), issued from chimney or deep
411 sediment layers, to be suspended into the water column. Simultaneously, fluid expulsion may
412 diffuse dissolved nutrients. These particles and nutrients will be dispersed in a restricted volume
413 (few metres away?) all around the pockmark. Thus, a pockmark may provide a certain quality of
414 organic matter that would be directly eaten by the *Haploops* and/or provide dissolved nutrients
415 that would be indirectly absorbed by autotroph organisms (probably phytoplankton), which in
416 turn would be filtered and digested by the *Haploops* (Rigolet et al. 2011). As it is a field of active
417 pockmarks, the addition of all these inputs may provide a sufficient concentration of particles to
418 feed large and dense *Haploops* settlements in a restricted zone closed to the pockmarks. Such
419 regular supplies would allow the *Haploops* population to buffer the seasonality of food supplies
420 driven by floods and photosynthetic primary production. Therefore, the *Haploops* may thrive in
421 large colonies only within the pockmarks field.

422 Total organic carbon (Fig. 8) provide elements to discuss about the pockmarks' activity,
423 exploring a possible trophic link between *Haploops* and pockmarks. In the *Haploops* cover,
424 outside pockmarks features, high TOC values may be explained by the occurrence at the surface
425 of numerous bioengineered tubes partially made of mucus and faeces/pseudo-faeces of animals.
426 During burial, organic/mineral particles are gradually degraded. This progressive trend is found
427 to be identical in all the studied cores, showing a consistency of both the quality and quantity of
428 organic matter supplies, generally observed in stable environments (Ingalls et al. 2004).

429 On the contrary, TOC values within pockmarks chimneys Alpha and Beta (Fig. 8) show higher
430 variability and concentrations, without any trend with depth, in the first 20 cm, indicating
431 sediment reworking. Bioturbation does not explain this observation as endofauna is sparse and
432 rare within the pockmark chimneys (Dando et al. 1991; Webb et al. 2009a), the only logical
433 explanation seems to be pockmarks activity through fluids movements. Furthermore, the Beta
434 pockmark was probably recently active since the surface sediment was anoxic. Dissolved oxygen
435 in the water column did not diffuse into the sediment (Arvidson et al. 2004; Maltby et al. 2016).

436 Thus, the two of the thousands of pockmarks of the Bay of Concarneau appear to have been
437 recently active. We therefore assume that, even if all the pockmarks are not active, a large
438 proportion of them is active but not continuously as divers did not observe any expulsion. This
439 observation is consistent with an activity linked to tide cyclicity (Ellis and McGuinness 1986 ;
440 Boles et al. 2001; Baltzer et al. 2014).

441 The frequency of fluid/gas emission in these sites remains unknown but the shape of TOC
442 profiles should be explained by a transfer of organic matter from deep sediment layers, which
443 would have mixed the vertical TOC content at the surface and erased the classical decreasing
444 trend observed in the *Haploops* cover.

445 TOC measurements obtained in the pockmark chimneys have higher values compared to the

446 sediment sampled within the *Haploops* cover (Fig. 8). Several studies proposed that a higher
447 content of TOC within a pockmark could be related to preferential deposition in its centre
448 (Manley et al. 2004; Webb et al. 2009b; Bussmann et al. 2011). As previously suggested, the
449 activity of pockmarks is not continuous and pockmarks act as traps for sediments, as soon as
450 expulsion events stop. Therefore, TOC variability in the crater centre may result from a
451 combination of different sources: deep internal and external sources. This hypothesis needs to be
452 confirmed by detailed studies on the trophic status of these pockmarks.

453

454 VII – Conclusions and perspectives

455 Our investigations in Le Croisic and La Lambarde sites, confirm the perfect overlapping of
456 *Haploops* settlements with pockmark fields as it was observed at the reference site of
457 Concarneau. In South Brittany, regardless of the environment, in the presence or absence of river
458 inputs, in high or low hydrodynamic conditions, the *Haploops* need the vicinity of active
459 pockmarks to develop in large colonies. Our hypothesis is that pockmarks expel some nutrients or
460 organic particles, from deeper sediment layers that are essential for *Haploops* development.
461 These nutrients may directly be used by the *Haploops* or by other organisms such as
462 phytoplankton, which in turn feed the *Haploops*. A complete characterisation of organic matter
463 inside and outside the pockmark as well as the analysis of methanotrophic bacterial communities
464 are needed to complete the present study. Only a multidisciplinary approach will allow to
465 consider the population dynamics associated to gas/fluid emissions and fully understand the
466 physiologic and trophic mechanisms of this specific ecosystem. Data from other geographical
467 areas of the world are needed to confirm if this association is systematic on a global scale. If
468 confirmed, this observation i) underlines the key role of sedimentary fluids/gas for the

469 development of present day ecosystems (largely studied in the deep-sea domain but that remain
470 unknown and unexplored in coastal areas), and ii) means that *Haploops* can be used as bio-
471 indicators for the presence of active pockmarks.

472 Finally, the monitoring of *Haploops* cover and its associated pockmarks field activity could bring
473 new lights on another concern. The estimation of seafloor surface covered by
474 pockmarks/*Haploops* settlements and the gas expulsion rate would help to evaluate the coastal
475 contribution (ignored until now) to the present global methane emission into the oceans.

476

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742 [\(R/V\) Haliotis Missions DOI](#)

743 - POCK&PLOOPS (<https://doi.org/10.17600/11120020>)

744 - POCK&TIDE (<https://doi.org/10.17600/14011100>)

745 - POPCORE (<https://doi.org/10.17600/16005300>)

746

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756

757 **FIGURE CAPTIONS**

758

759 Figure 1: Location of the study sites off South Brittany coasts delimited by solid red squares: 1)
760 Reference site of Concarneau offshore the town of Concarneau ; 2) the site of Le Croisic offshore
761 the town of Le Croisic, near the Loire estuary, and 3) the site La Lambarde located on the
762 external part of the Loire river. Studied sites are superimposed on the geological maps (modified
763 from the geological map of France and continental shelf: Lorient - South Brittany, 1:250 000,
764 BRGM - CNRS), which show the presence, in all cases, of Eocene outcrops (e4, e5-6) and gas
765 masks. Projection scales are similar for all sites.

766

767

768 Figure 2: 2A) Site 1 of Concarneau. Bathymetric map with the limit of the *Haploops* settlement,
769 delimited by solid white line. Data are plotted on an ortho-photo of the bay (May 2017) extracted
770 from the website “Copernicus Open Access Hub”. It shows clear waters, without any turbidity or
771 massive river discharges. Data presented in this paper are issued from the area delimited by the
772 solid red square.

773 2B) Site 2 of Le Croisic and site 3 of La Lambarde. Bathymetric map of Le Croisic site (solid red
774 square labeled 2). This site covers water depths from 17 to 21 m.

775 Bathymetric map of La Lambarde site (solid red square labeled 3), southwest the Loire estuary
776 dumped sediment zone (solid light grey polygon) within the waiting area for merchant vessels
777 (solid green polygon). This site covers water depths from 28 to 35 m.

778 Both data sets are plotted on an ortho-photo (May 2017) extracted from the website “Copernicus
779 Open Access Hub”.

780
781
782 Figure 3A, 3B and 3C (P82 line) located in the general map, as well as location of pockmarks
783 Alpha and Beta selected for total organic carbon profiling (Alpha : -3°54. 4954 N, 47°47. 7616
784 W; Beta : -3°54.331 N , 47°47.654 W).

785 3A) Bathymetric data 3B) Reflectivity map with the same area than 3A, 3C) Chirp profile P82
786 with detailed area shown on the left side. Note .the *Haploops* saw-tooth shaped reflector in
787 opposite to areas without any *Haploops*, which show a continuous sea-floor reflector.

788
789
790 Figure 4: Bathymetry maps (left part) versus sonar imageries (right part) of Le Croisic site. The
791 bathymetry and reflectivity maps show four facies, A, B, C, D delimited by a white continuous
792 line and black dashed lines (taking into account the seafloor roughness linked to the pockmarks
793 number, the *Haploops*_tubes density and the sizes of these tubes). The limits of the facies were
794 also checked on the chirp profiles. An example of each facies is presented in the frames (1, 2, 3,
795 4) above each map. Four Schipeck grab sample (BS3, BS4, BS9) and corresponding grain size
796 analysis are also shown.

797
798
799 Figure 5: Bathymetry maps (left part) versus reflectivity map (right part) of La Lambarde site.
800 The bathymetry and reflectivity maps show five facies A', B', C', D', E' delimited by a white
801 continuous line, a brown continuous line and blacks dashed lines taking into account the seafloor
802 roughness linked to the pockmarks number, the *Haploops* tubes density and the sizes of these

803 tubes). The limits of the facies were also checked on the chirp profiles. An example of each facies
804 is presented in the frames (1, 2, 3, 4) above each map. Two Schipeck grab sample (BS25, BS30)
805 and corresponding grain size analysis are also shown.

806

807

808 Figure 6: Site of Le Croisic. The interpretative map of the area is superimposed to the density
809 map of pockmarks (pockmarks Nb/km²). Two chirp profiles, profile P08 and profile P19 (blue
810 continuous lines), are shown. The left column shows the raw profiles and the second column
811 presents interpreted profiles.

812

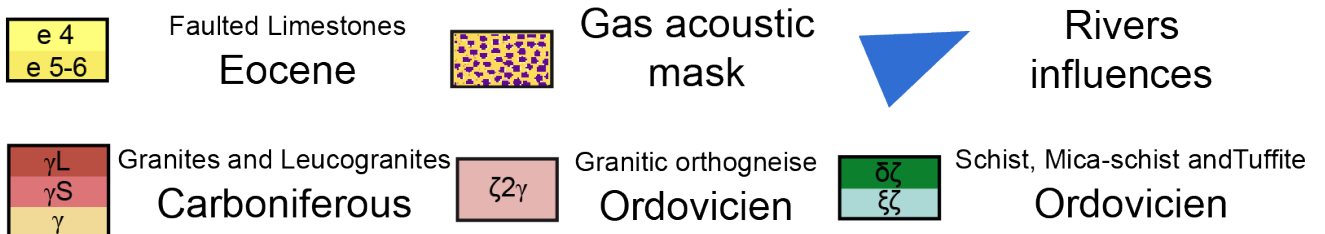
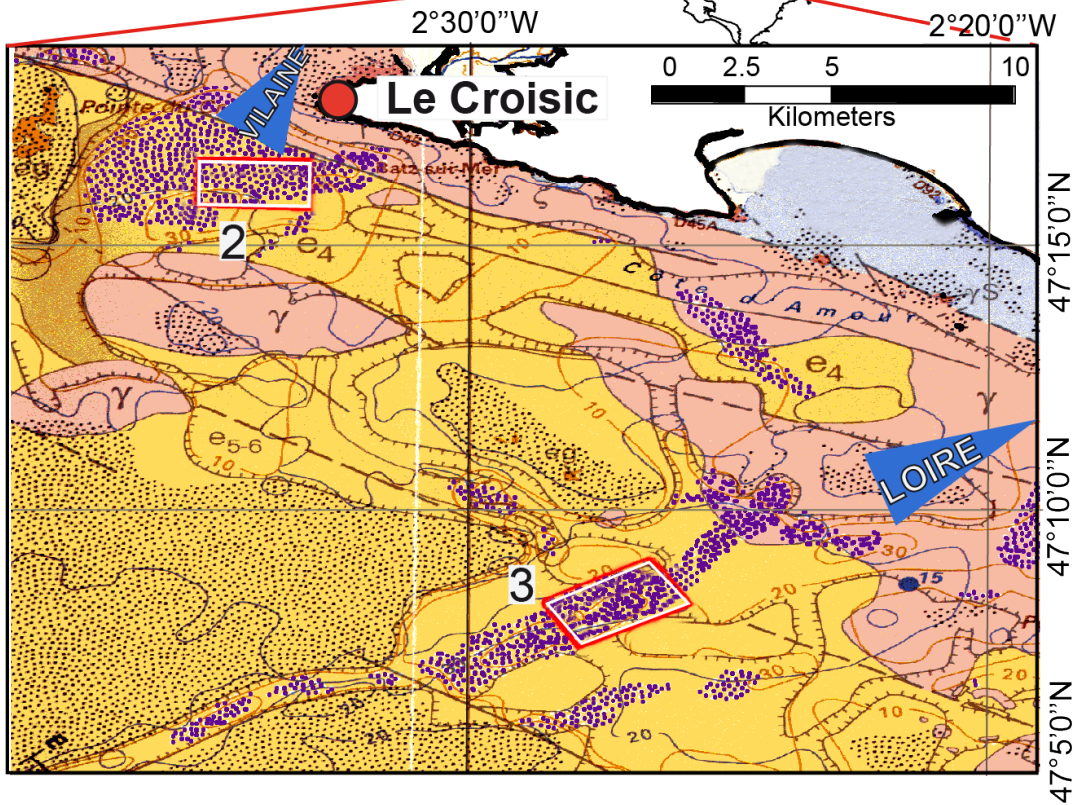
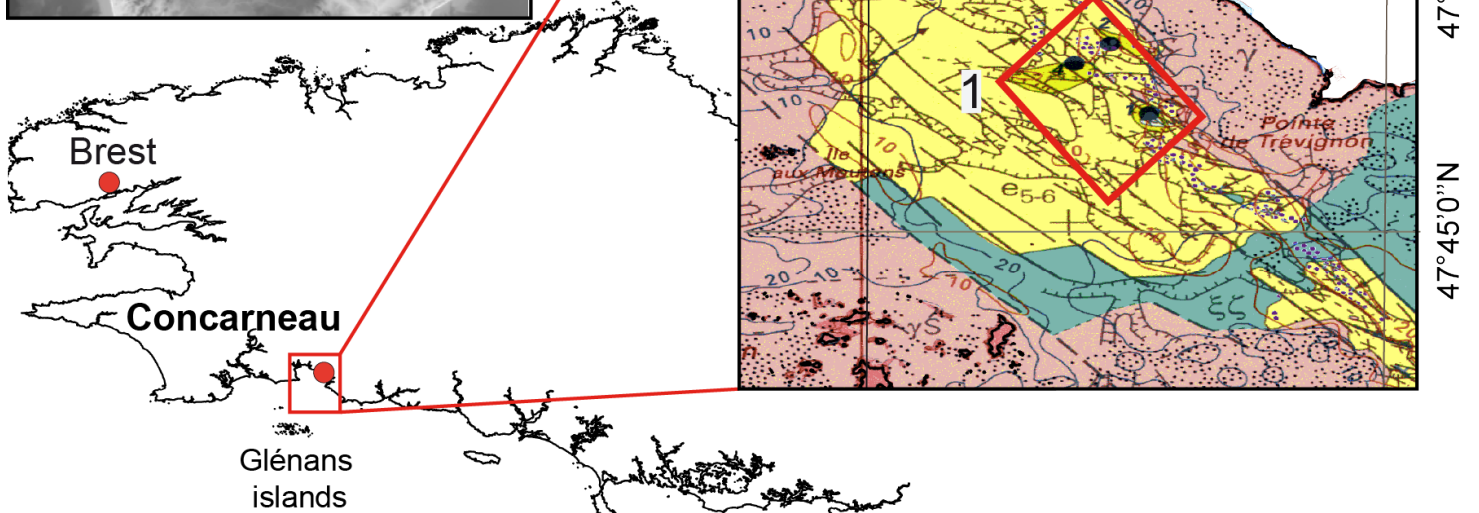
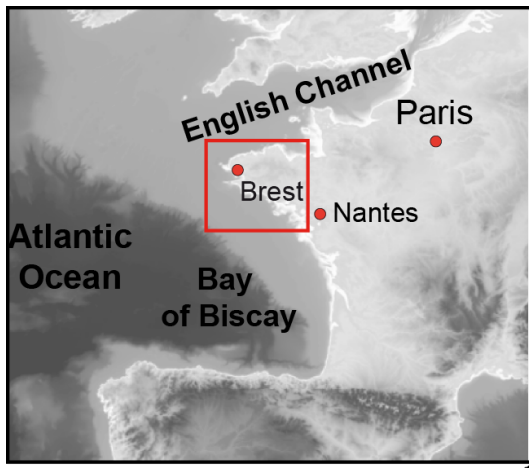
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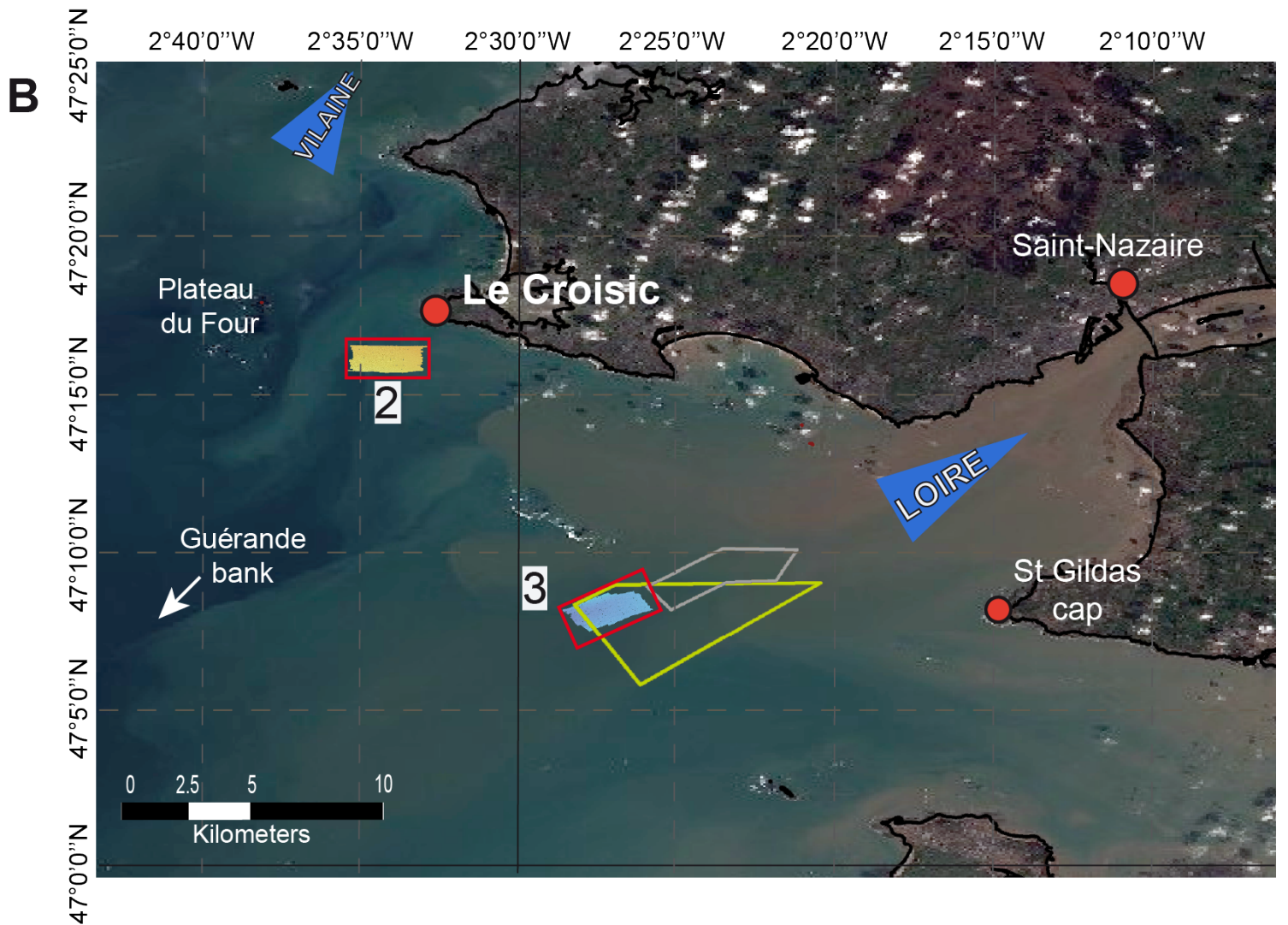
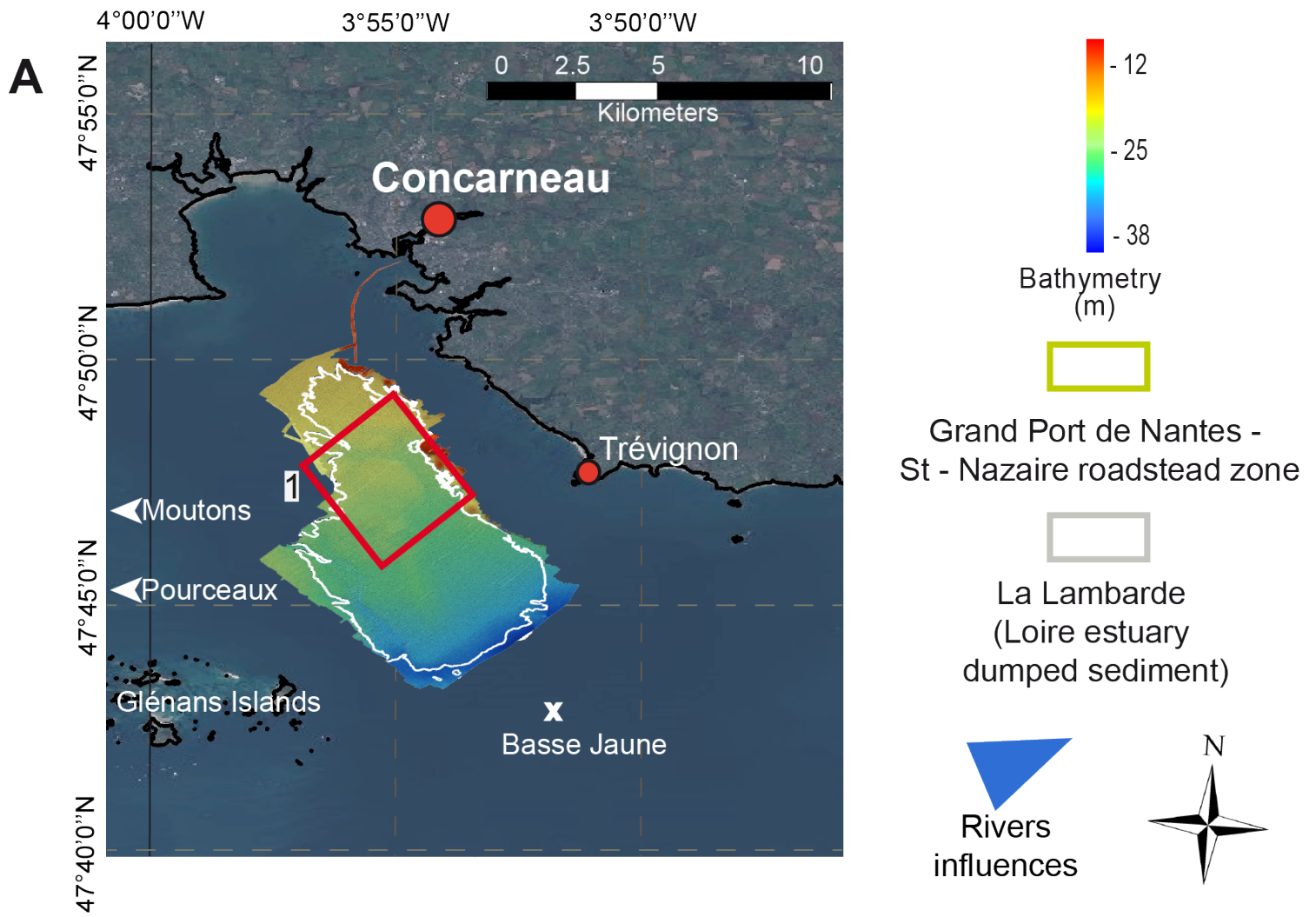
814 Figure 7: Site of La Lambarde. The interpretative map of the area is superimposed to the density
815 map of pockmarks (pockmarks Nb/km²). Two chirp profiles, profile P03 and profile P14 (blue
816 continuous lines), are shown. The left column shows the raw profiles and the second column
817 presents interpreted profiles.

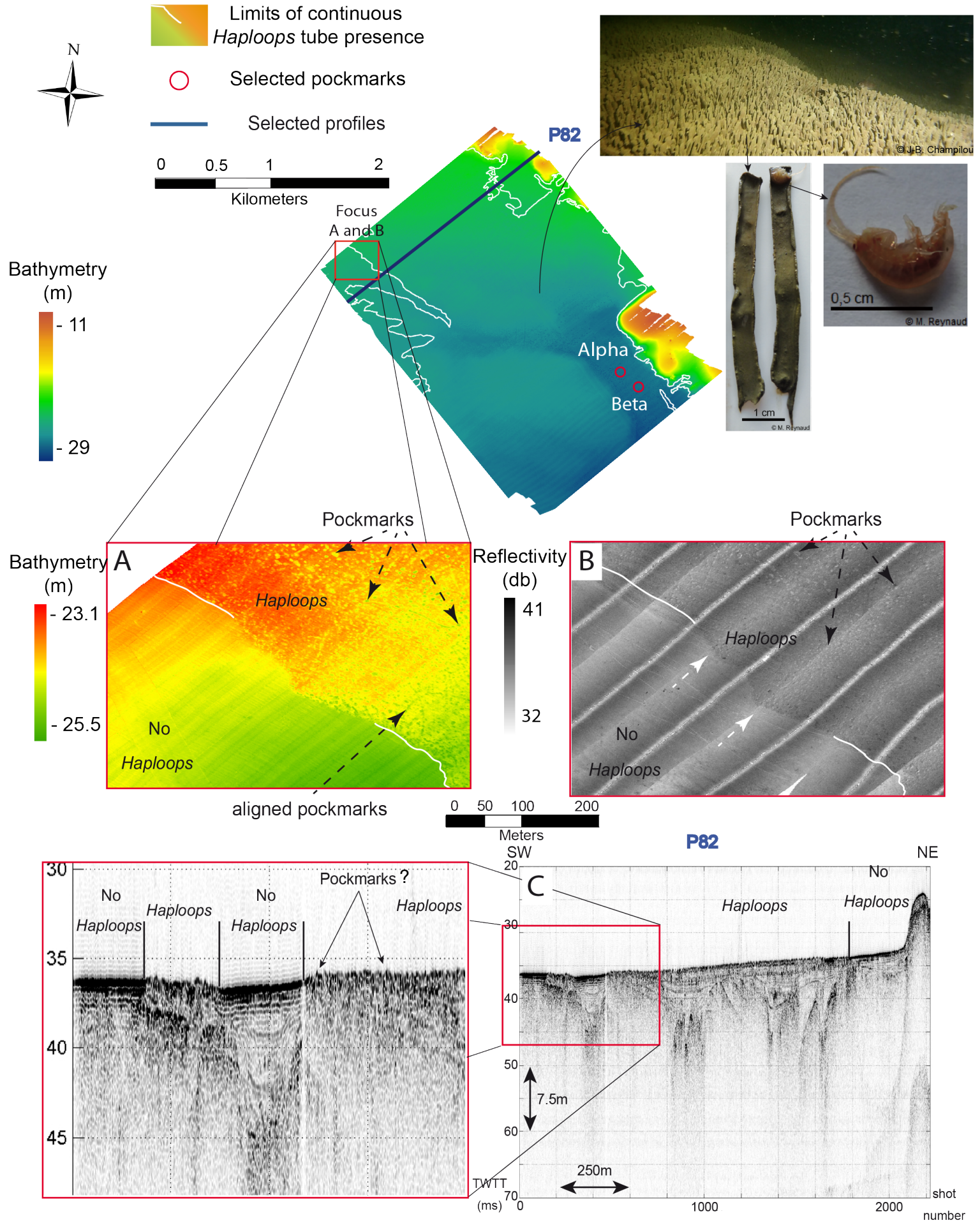
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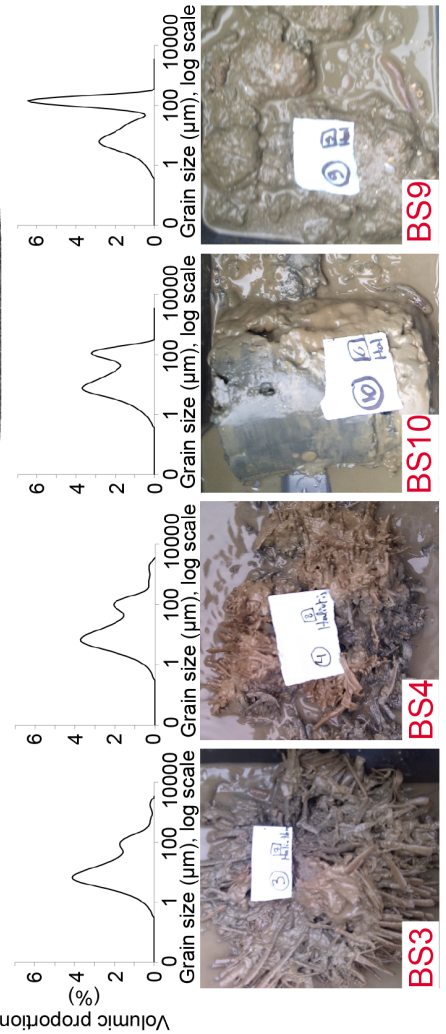
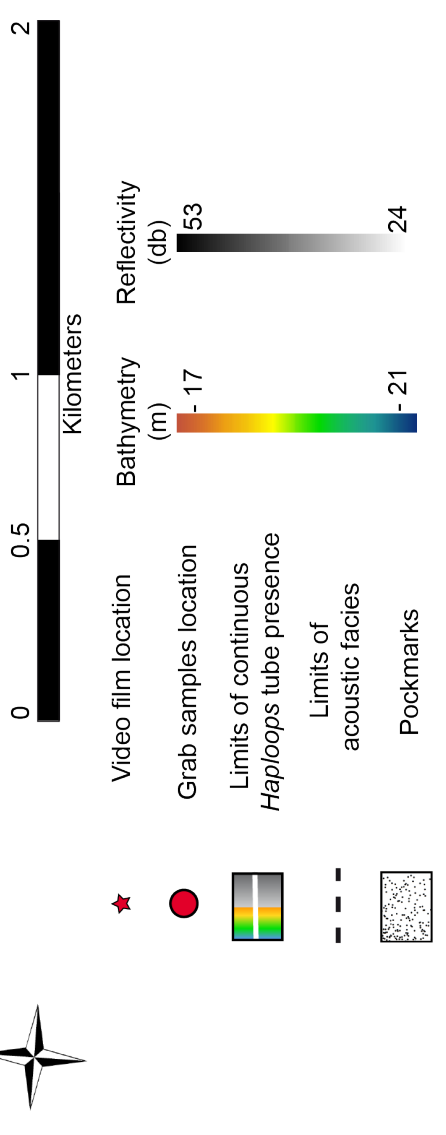
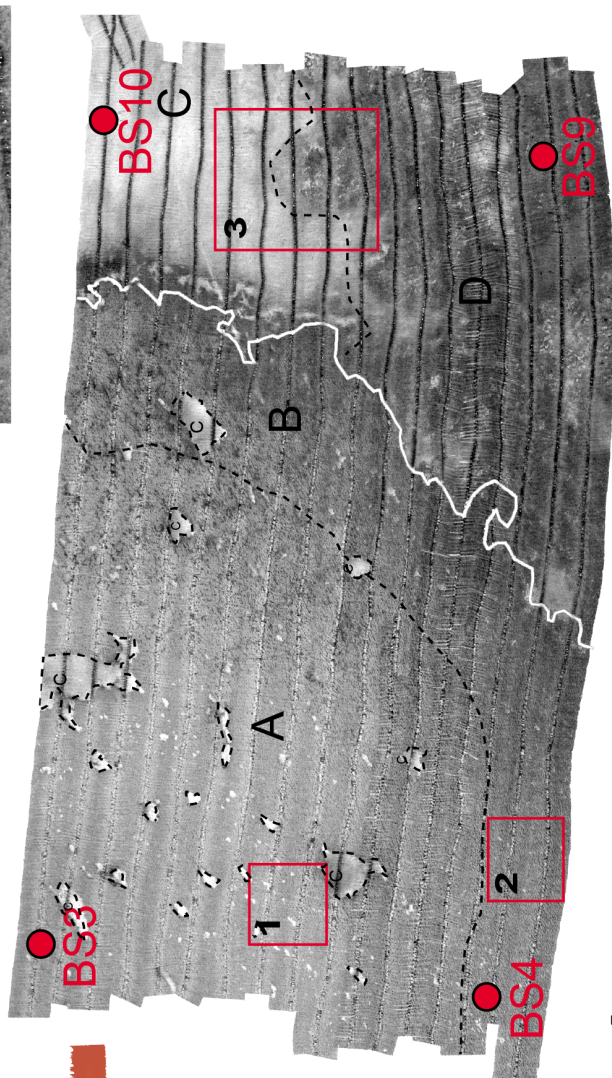
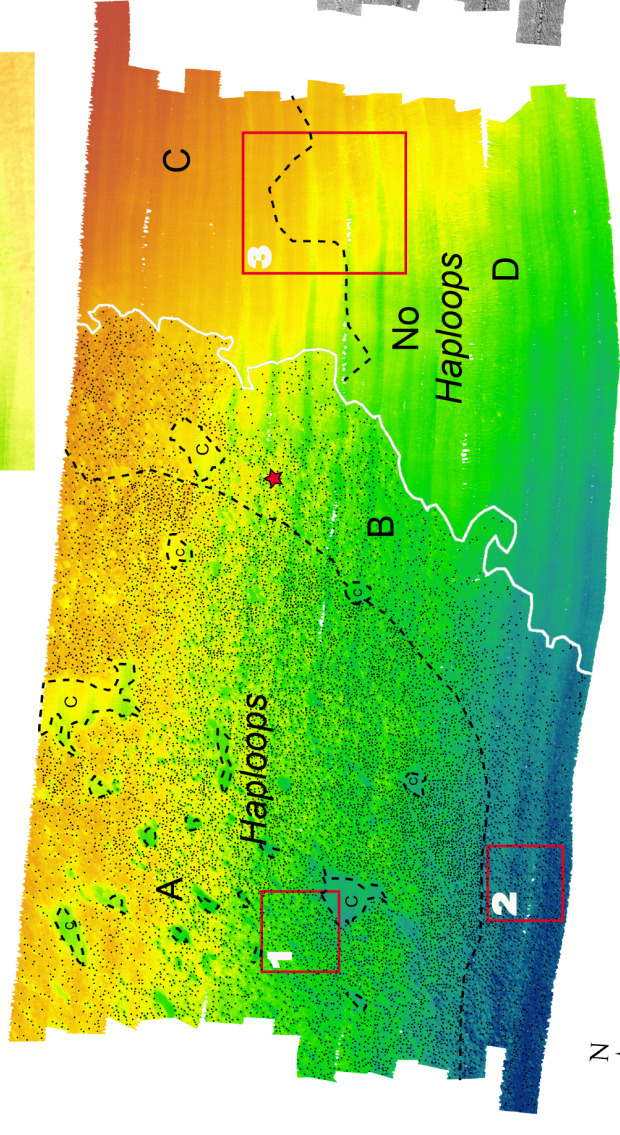
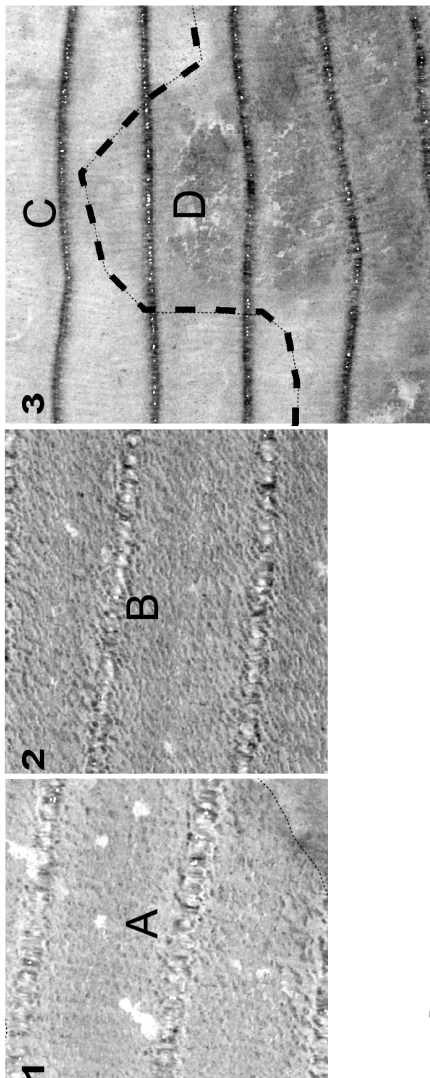
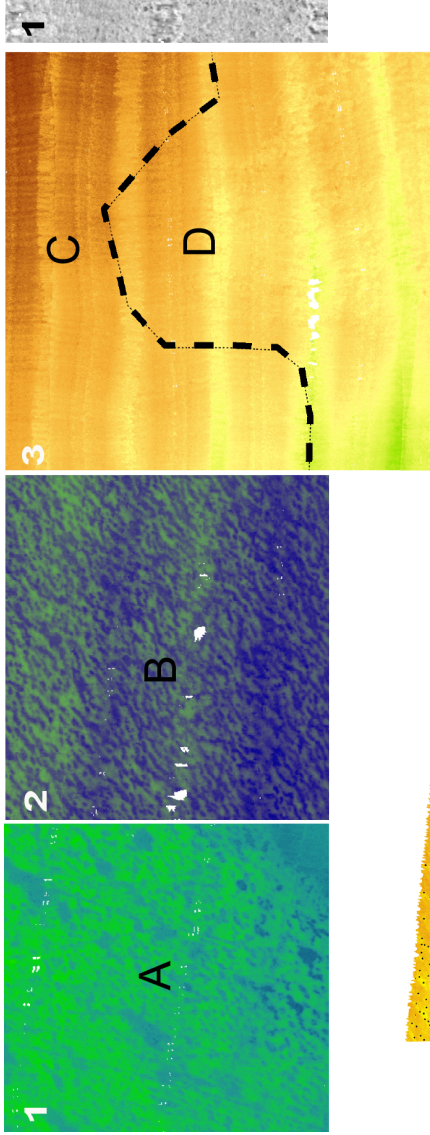
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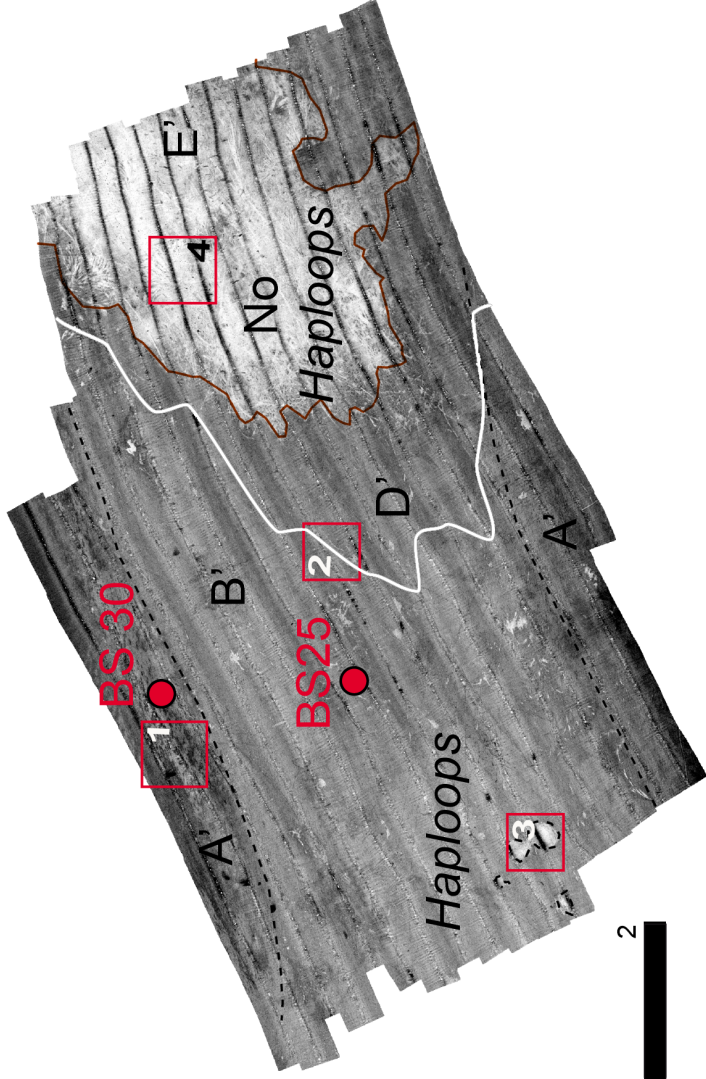
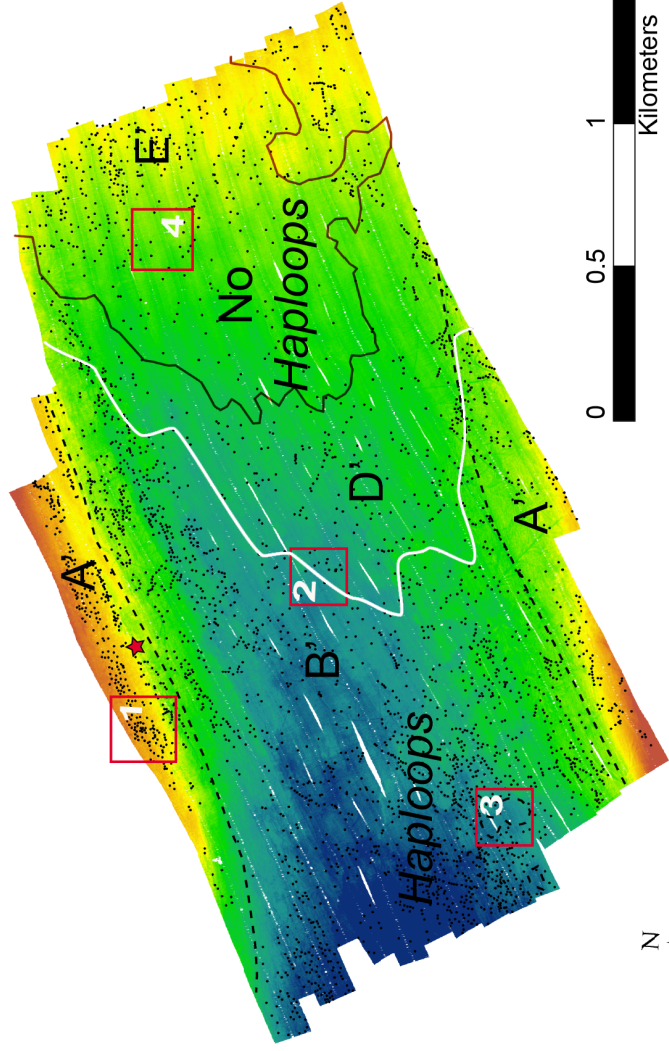
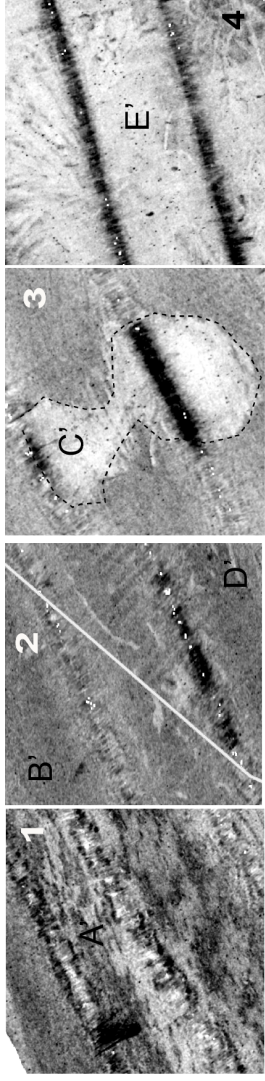
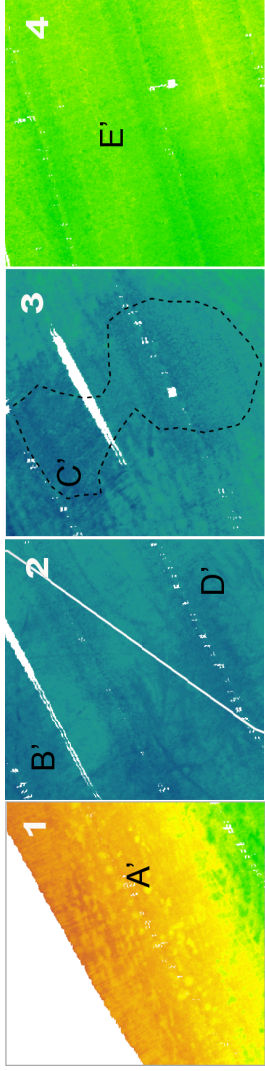
820 Figure 8: Relative location and bathymetric images of two pockmarks, Alpha and Beta, in the
821 Bay of Concarneau. Eight cores were taken by divers in the area of *Haploops* cover (white dots)
822 and four cores were taken into the pockmarks centers, with no *Haploops* (called pockmarks
823 chimneys) by divers. The graphics show the dry weight TOC (percentage) evolution with depth
824 (centimetres below seafloor), Alpha data in dashed blue lines and Beta data in solid red lines.











Limits of continuous
Haploops tube presence



Limits of
acoustic facies



Video film location

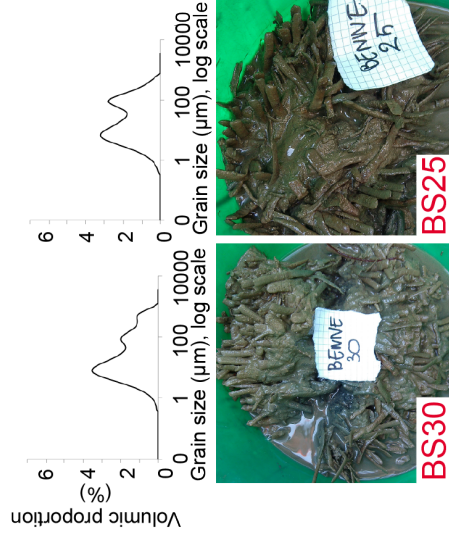
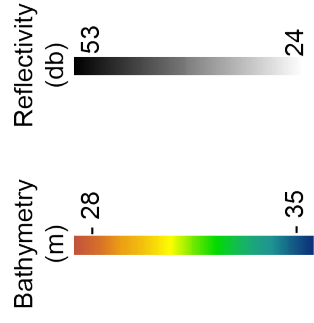


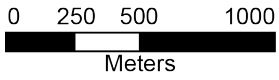
Pockmarks

Limits of remolded area

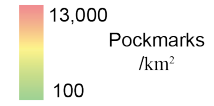


Grab samples location

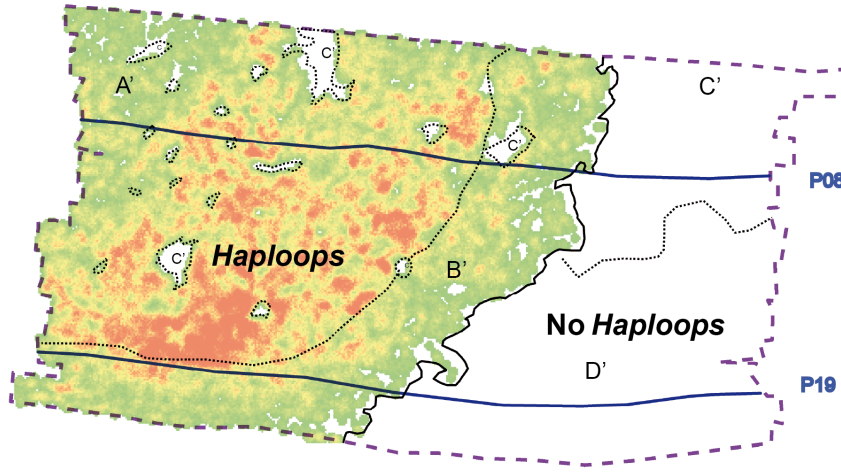




- Gas mask
- Limits of sedimentary facies
- Selected profiles
- Limits of continuous Haploops cover



Diameters of pockmarks :
between 2 and 7 m



- Gas
- U4 Intercalated mud and storms
- U3 Estuarines mud
- U2 Inner mud flat facies
- EGR Enhanced Gas Reflector

