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

Authors:

Jean-Baptiste Champilou (1), Agnès Baltzer (2), Anne Murat (3,4), Marine Reynaud (5),  
Grégoire M. Maillet (1), Maria Pia Nardelli (1), Édouard Metzger (1)

<sup>1</sup>Laboratoire de Planétologie et Géodynamique Bio-Indicateur Actuels et Fossiles, LPG-BIAF,  
CNRS - UMR 6112, Université d'Angers UFR Sciences, CNRS, 2 Boulevard Lavoisier 49000  
Angers, France

<sup>2</sup>Laboratoire Littoral Environnement Télédétection Géomatique, LETG, CNRS – UMR  
6554, Université de Nantes, Campus Tertre, BP 81227 44312 Nantes Cedex 3, France

<sup>3</sup>LUSAC, EA 4253, Normandie Univ, Unicaen, 50100 Cherbourg, France

<sup>4</sup>Cnam/Intechmer, 50100 Cherbourg, France

<sup>5</sup>Laboratoire de recherche en Hydrodynamique, Énergétique et Environnement Atmosphérique,  
LHEEA, CNRS – UMR 6598, École Centrale de Nantes - SEM-REV, 1 Rue de la Noë BP 92101  
44321 Nantes Cedex 3, France

## **Abstract**

In the shallow waters of the Bay of Concarneau (South Brittany, France), previous studies reported a dense settlement of the species *Haploops* (tube-dwelling bioengineer amphipod) that perfectly overlaps a field of pockmarks. A possible mechanistic link may therefore exist between the *Haploops* colonies and the shallow pockmarks. To test this hypothesis, interferometry sonar and sub-bottom profiler chirp data were acquired in two new areas located in the marine estuary



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

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

## I - Introduction

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

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

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

In the same area, a large settlement of *Haploops* species, engineers tube-dwelling amphipods, was discovered by [Glemarec \(1969\)](#) and confirmed by other studies ([Dauvin and Bellan-Santini, 1990](#); [Desaunay and Guerault, 2003](#); [Ehrhold, 2003](#); [Ehrhold \*et al.\*, 2006](#)). More recent studies have highlighted the superimposition of *Haploops* settlements on the pockmark fields ([Souron, 2009](#); [Rigolet \*et al.\*, 2012](#); [Baltzer \*et al.\*, 2014](#); [Reynaud and Baltzer, 2014](#); [Dubois \*et al.\*, 2015](#); [Baltzer \*et al.\*, 2017](#)), which suggests a possible link. Although the amphipods have largely been reported in the literature regarding their biological characteristics such as their life cycle ([Dauvin and Bellan-Santini, 1990](#); [Rigolet \*et al.\*, 2012](#)) or their filtration activities ([Rigolet \*et al.\*, 2011](#); [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 ( $< -70\text{‰}$ ) found in the analysed tissues ([Rigolet, 2013](#)).

78 In the Bay of Concarneau, high densities of *Haploops* populations (up to 10,000 individuals/m<sup>2</sup>)  
79 were reported by [Rigolet, \(2013\)](#) which are exceptional in comparison to densities (about 4,000  
80 individuals/m<sup>2</sup>) 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

geochemical background would give clues to constrain the link between the methane stocked into the sediment, the pockmarks and *Haploops*.

All three sites exhibit an extensive field of shallow pockmarks that are populated by *Haploops* species colonies. The main objective of this study is to confirm the strict link between pockmarks fields and *Haploops*, as previously observed in the Bay of Concarneau. For this reason we investigated at high resolution the distribution of *Haploops* tubes on two other pockmarks fields, characterised by very different hydrodynamic and sedimentological conditions compared to the Bay of Concarneau. The second objective is to show that environmental conditions are less important for the development and prosperity of *Haploops* colonies compared to primary necessity of the presence of active pockmarks nearby.

## II - General settings

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

### II - 1 Concarneau site

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

([Tessier, 2006](#)). The tide is semi-diurnal with a range of 5.5 m, oriented north-northwest during the flow and south-southeast during the ebb. The shoals of Moutons, Pourceaux Glénans and 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) ([Glémarec \*et al.\*, 1987](#); [Tessier, 2006](#)). However, the turbidity has increased in the last few decades principally due to anthropic activities, such as fishing ([Hily \*et al.\*, 2008](#)).

## II - 2 Le Croisic site

Le Croisic is subject to higher hydrodynamic conditions as it is poorly protected from west-northwest swells by the Plateau du Four (Fig. 2B) and from the southwest swells by the shallow Guerande bank. Tidal current velocity averages 20 cm.s<sup>-1</sup> ([Chapelle, 1989](#)) with a maximum speed of 50 cm.s<sup>-1</sup> ([Tessier, 2006](#)). The tide is semi-diurnal with a tidal range of 6 m and has a general north-northwest direction during the flow and south-southeast during the ebb ([Gendronneau \*et al.\*, 2006](#)). Sediments from the Loire (Fig. 2B), are mostly carried offshore and 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 area of sediment accumulation ([Tessier, 2006](#); [Sanchez and Delanoë, 2006](#)) mainly supplied by river inputs (95 % from the Loire and 5 % from the Vilaine, with 2x10<sup>6</sup> T.yr<sup>-1</sup> and 0.1x10<sup>6</sup> T.yr<sup>-1</sup> of sediments supplied from each river respectively) ([Jouanneau \*et al.\*, 1999](#); [Lazure and Jegou, 1998](#)).

## II - 3 La Lambarde site

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

environment (Fig. 2B). The mean tidal current velocity is around 50 cm.s<sup>-1</sup> with a maximum speed of 90 cm.s<sup>-1</sup>. The tide is semi-diurnal with a range of 6 m, oriented northeast along the axis of the Loire estuary and rotates northwest offshore the Saint Gildas Cap during the flow (Tessier, 2006). Strongly exposed to western swells, sediment accumulations are low in this area (Sanchez and Delanoë, 2006). All year long, strong ebb currents wash away most of the particles in the water column maintaining a local turbidity of around 5 mg.l<sup>-1</sup>, except during the Loire flood events when turbidity increases up to 100 mg.l<sup>-1</sup> (Tessier, 2006). Our study site is located in the roadstead zone (light green frame on Fig. 2B), just behind the Lambarde dumping zone (light grey frame on Fig. 2B) where the “Grand Port Maritime de Nantes-Saint Nazaire” (Nantes Harbour) dumps the sediments dredged in the Loire River. In the last 10 years, an estimated average of 7 Mm<sup>3</sup> of dredging sediments have been dropped each year (GIP Loire Estuaire, 2018).

### III – Material, methods and data processes

#### III – 1 - Geophysical surveys

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

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

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

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

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

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

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

### III – 2 – Sediment analysis

#### III – 2 – 1 – Sampling

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

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

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



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

### III – 2 – 2 – Grain size

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

### III – 2 – 3 – Total organic carbon profiling

Ninety-five sediment samples were collected throughout the cores. Each sample was freeze-dried, crushed and homogenised. Samples were then acidified with  $\text{H}_3\text{PO}_4$  (1M) to remove carbonates dried on a hot plate at 40 °C and measured with a combustion infrared detection technique on a LECO CS 744 carbon sulphur analyser. Two or three sediment replicates (50 mg) per sample were analysed.

## IV – The acoustic signature of *Haploops* presence

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

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

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

On the sonar reflectivity map (Fig. 3B), medium to high reflectivity correspond to a heterogeneous and rough surface linked to the presence of irregular *Haploops* tubes (37 to 38 dB). Within the *Haploops* cover, pockmarks are identified by a specific morphology (hole) appearing as dark dots. In isolated cases, white round patches correspond to pockmarks with larger diameters, which are filled with mud ([Reynaud and Baltzer, 2014](#)). When pockmarks have smaller diameters, their centre appears covered by horizontal unoccupied *Haploops* tubes that show a similar grey scale on backscatter images as the one produced by healthy *Haploops* cover. The chirp profiles helped to identify precisely the *Haploops* cover as the acoustic reflector representing the seafloor shows a distinct discontinuous saw-tooth shape (Fig. 3C). This reflector corresponds to the high-density of tubes (see picture, Fig 3), whereas a smooth and continuous reflector corresponds to the seafloor without any *Haploops* (Fig. 3C). Combining the three data sets, bathymetry, sonar reflectivity and chirp data, the limits of the continuous *Haploops* cover was precisely mapped.

## V – Results

### V – 1 – Bathymetry and reflectivity

Bathymetry and sonar reflectivity maps acquired at the two new sites examined in this study are presented in Figures 4 and 5. Each site covers an area of about 3.5 km<sup>2</sup> and water depths vary from 17 to 21 m at Le Croisic, and from 28 to 35 m at La Lambarde.

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

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

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

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

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

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

## V – 2 – Seismic profiles

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

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

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

At Le Croisic, densities up to 13,000 pockmarks/km<sup>2</sup> were measured in some places. At the La Lambarde site, the exact density of pockmarks is more difficult to assess due to anchoring scars. However, on facies A', around 3,500 pockmarks/km<sup>2</sup> were counted.

### V – 3 – Organic matter content

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

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

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

## VI – Discussion

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

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

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

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



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

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

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

On the contrary, TOC values within pockmarks chimneys Alpha and Beta (Fig. 8) show higher variability and concentrations, without any trend with depth, in the first 20 cm, indicating sediment reworking. Bioturbation does not explain this observation as endofauna is sparse and rare within the pockmark chimneys (Dando et al. 1991; Webb et al. 2009a), the only logical explanation seems to be pockmarks activity through fluids movements. Furthermore, the Beta pockmark was probably recently active since the surface sediment was anoxic. Dissolved oxygen in the water column did not diffuse into the sediment (Arvidson et al. 2004; Maltby et al. 2016). Thus, the two of the thousands of pockmarks of the Bay of Concarneau appear to have been recently active. We therefore assume that, even if all the pockmarks are not active, a large proportion of them is active but not continuously as divers did not observe any expulsion. This observation is consistent with an activity linked to tide cyclicity (Ellis and McGuinness 1986 ; Boles et al. 2001; Baltzer et al. 2014).

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

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

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

## VII – Conclusions and perspectives

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

## References

- Allen, J., 1953. Observations on the epifauna of the deep-water muds of the Clyde Sea area, with special reference to *Chlamys septemradiata* (Müller). *The Journal of Animal Ecology*, 240-260.
- Arvidson, R.S., Morse, J.W., Joye, S.B., 2004. The sulfur biogeochemistry of chemosynthetic cold seep communities, Gulf of Mexico, USA. *Marine Chemistry* 87, 97-119.
- Augustin, J., Edy, C., Savoye, B., Le Drezen, E., 1994. Sonar mosaic computation from multibeam echo sounder, OCEANS'94. 'Oceans Engineering for Today's Technology and Tomorrow's Preservation.' *Proceedings. IEEE* 432, II/433-II/438.
- Baltzer, A., Ehrhold, A., Cordier, C., Clouet, H., Souron, A., Cagna, R., Gillier, A., 2011. Origine des pockmarks en surface des vasières à Haploops (Crustacé amphipode) de la Baie de Concarneau à partir des dernière données acquises lors de la campagne avec la vedette Haliotis en 2011, Ext Abstr, 17-18.
- Baltzer, A., Ehrhold, A., Rigolet, C., Souron, A., Cordier, C., Clouet, H., Dubois, S.F., 2014. Geophysical exploration of an active pockmark field in the Bay of Concarneau, southern Brittany, and implications for resident suspension feeders. *Geo-Marine Letters* 34, 215-230.
- Baltzer, A., Reynaud, M., Ehrhold, A., Fournier, J., Cordier, C., Clouet, H., 2017. Space-time evolution of a large field of pockmarks in the Bay of Concarneau (NW Brittany). *Bulletin de la Société géologique de France* 188, 23p.
- Béchenec, F., Guennoc, P., Guerrot, C., Lebre, P., Thieblemont, D., 1997. Notice explicative, Carte géologique, France (1/50 000), feuille de Concarneau (382). BRGM, Orléans.
- Bolam, S.G., Fernandes, T.F., 2003. Dense aggregations of *Pygospio elegans* (Claparede): effect on macrofaunal community structure and sediments. *Journal of Sea Research*, 49, 171-185

500 Boles, J., Clark, J., Leifer, I., Washburn, L., 2001. Temporal variation in natural methane seep  
501 rate due to tides, Coal Oil Point area, California. *Journal of Geophysical Research: Oceans*  
502 106, 27077-27086.

503 Brothers, L.L., Kelley, J.T., Belknap, D.F., Barnhardt, W.A., Andrews, B.D., Legere, C., Clarke,  
504 J.E.H., 2012. Shallow stratigraphic control on pockmark distribution in north temperate  
505 estuaries. *Marine geology* 329, 34-45.

506 Brown C.S., Newton A.M., Huuse M., Buckley F., 2017. Iceberg scours, pits, and pockmarks in  
507 the North Falkland Basin. *Marine Geology* 386, 140-152

508 Bussmann, I., Schlömer, S., Schlüter, M., Wessels, M., 2011. Active pockmarks in a large lake  
509 (Lake Constance, Germany): effects on methane distribution and turnover in the sediment.  
510 *Limnology and oceanography* 56, 379-393.

511 Cathles, L., Su, Z., Chen, D., 2010. The physics of gas chimney and pockmark formation, with  
512 implications for assessment of seafloor hazards and gas sequestration. *Marine and Petroleum*  
513 *Geology* 27, 82-91.

514 Chapelle, A., 1989. Modélisation écologique de la Baie de la Vilaine. Rapport annuel.

515 Christodoulou, D., Papatheodorou, G., Ferentinos, G., Masson, M., 2003. Active seepage in two  
516 contrasting pockmark fields in the Patras and Corinth gulfs, Greece. *Geo-Marine Letters* 23,  
517 194-199.

518 Cogné, J., Hassenforfer, B., Barbaroux, J., Guigues, J., Bambier, A., 1973. Notice explicative,  
519 Carte géologique, France (1/50 000), feuille de Saint-Nazaire (479). BRGM, Orléans.

520 Dando, P., Austen, M., Burke Jr, R., Kendall, M., Kennicutt, M., Judd, A., Moore, D., O'Hara, S.,  
521 Schmalijohann, R., Southward, A., 1991. Ecology of a North Sea pockmark with an active  
522 methane seep. *Marine Ecology Progress Series*, 49-63.

523 Dauvin, J.-C., Bellan-Santini, D., 1990. An overview of the amphipod genus *Haploops*  
 524 (*Ampeliscidae*). *Journal of the Marine Biological Association of the United Kingdom* 70, 887-  
 525 903.

526 Delisle, G., 2000. Temporal variability of subsea permafrost and gas hydrate occurrences as  
 527 function of climate change in the Laptev Sea, Siberia. *Polarforschung* 68, 221-225.

528 Desaunay, Y., Guerault, D., 2003. Evolution du peuplement halieutique de la baie de Vilaine au  
 529 cours des décennies 1980 et 1990.

530 Diez, R., García-Gil, S., Durán, R., Vilas, F., 2007. Gas-charged sediments in the Ría de Arousa:  
 531 Short-to long-term fluctuations? *Estuarine, Coastal and Shelf Science* 71, 467-479.

532 Dubois, S.F., Derian, F., Caisey, X., Rigolet, C., Caprais, J.-C., Thiébaud, E., 2015. Role of  
 533 pockmarks in diversity and species assemblages of coastal macrobenthic communities. *Marine*  
 534 *Ecology Progress Series* 529, 91-105.

535 Ehrhold, A., 2003. Cartographie des peuplements macro-benthiques par les méthodes acoustiques  
 536 en domaine subtidal. REBENT Cartographie et suivi par télédétection, Fiche technique.

537 Ehrhold, A., Hamon, D., Guillaumont, B., 2006. The REBENT monitoring network, a spatially  
 538 integrated, acoustic approach to surveying nearshore macrobenthic habitats: application to the  
 539 Bay of Concarneau (South Brittany, France). *ICES Journal of Marine Science: Journal du*  
 540 *Conseil* 63, 1604-1615.

541 Ehrhold, A., Blanchet, A., Hamon, D., Chevalier, C., Gaffet, J.-D., Sophie, A.A., 2007. Réseau  
 542 de surveillance benthique (REBENT) – Région Bretagne. Approche sectorielle subtidale :  
 543 Identification et caractérisation des habitats benthiques du secteur Concarneau. .  
 544 RST/IFREMER/DYNECO/Ecologie benthique/07-01/REBENT: 78 p. + 9 annexes.

545 Ellis, J.P., McGuinness, W.T., 1986. Pockmarks of the northwestern Arabian Gulf.  
 546 *Oceanology*, Springer, 353-367.

547 Fader, G.B., 1991. Gas-related sedimentary features from the eastern Canadian continental shelf.  
 548 Continental Shelf Research 11, 1123-1153.

549 García-García, A., Vilas, F., García-Gil, S., 1999. A seeping sea-floor in a Ria environment: Ria  
 550 de Vigo (NW Spain). Environmental Geology 38, 296-300.

551 García-Gil, S., 2003. A natural laboratory for shallow gas: the Rías Baixas (NW Spain). Geo-  
 552 Marine Letters 23, 215-229.

553 Gay, A., Lopez, M., Berndt, C., Seranne, M., 2007. Geological controls on focused fluid flow  
 554 associated with seafloor seeps in the Lower Congo Basin. Marine geology 244, 68-92.

555 Gay, A., Migeon, S., 2017. Geological fluid flow in sedimentary basins. EDP Sciences.

556 Gendronneau, M., Haure, J., Jeanneret, H., Le Merrer, Y., Lequette, C., Lomakine, C., Martin, J.-  
 557 L., Papin, M., Ponthoreau, C., Robin, M., 2006. Étude des secteurs du Croisic et de Pen-Bé:  
 558 estimation des apports continentaux et évaluation des stocks conchyliques.

559 GIP Loire Estuaire, 2018. Les dragages d'entretien dans l'estuaire. Cahiers Indicateurs L1E3, 6 p.

560 Glémarec, M., 1969. Les peuplements benthiques du plateau continental Nord-Gascogne. Atelier  
 561 offset de la Faculté des sciences.

562 Glémarec, M., Le Bris, H., Le Guellec, C., 1987. Modifications des écosystèmes des vasières  
 563 côtières du sud-Bretagne, Long-Term Changes in Coastal Benthic Communities. Springer, pp.  
 564 159-170.

565 Glémarec, M., Grall, J., 2003. Effets biogènes sur la sédimentation en baie de Concarneau. Les  
 566 Cahiers Nantais, 123-130

567 Gukov, A.Y., 2011. Monitoring of the bottom biocenoses of the Novosibirsk polynya.  
 568 Oceanology 51, 443-448.

569 Harrington, P., 1985. Formation of pockmarks by pore-water escape. Geo-Marine Letters 5, 193-  
 570 197.



571 Hasiotis, T., Papatheodorou, G., Kastanos, N., Ferentinos, G., 1996. A pockmark field in the  
572 Patras Gulf (Greece) and its activation during the 14/7/93 seismic event. *Marine geology* 130,  
573 333-344.

574 Hily, C., Le Loc'h, F., Grall, J., Glémarec, M., 2008. Soft bottom macrobenthic communities of  
575 North Biscay revisited: Long-term evolution under fisheries-climate forcing. *Estuarine,  
576 Coastal and Shelf Science* 78, 413-425.

577 Hovland, M., Judd, A., 1988. Seabed pockmarks and seepages: Impact on geology, biology  
578 and the marine environment. London, Graham and Trotman, 293p.

579 Hovland, M., Gallagher, J., Clennell, M., Lekvam, K., 1997. Gas hydrate and free gas volumes in  
580 marine sediments: Example from the Niger Delta front. *Marine and Petroleum Geology* 14,  
581 245-255.

582 Ingalls, A.E., Aller, R.C., Lee, C., Wakeham, S.G., 2004. Organic matter diagenesis in shallow  
583 water carbonate sediments. *Geochimica et Cosmochimica Acta* 68, 4363-4379.

584 Jørgensen, N.O., Laier, T., Buchardt, B., Cederberg, T., 1990. Shallow hydrocarbon gas in the  
585 northern Jutland-Kattegat region, *Bulletin of the Geological Society of Denmark* 38, 69-76.

586 Josenhans, H.W., King, L.H., Fader, G.B., 1978. A side-scan sonar mosaic of pockmarks on the  
587 Scotian Shelf. *Canadian Journal of Earth Sciences* 15, 831-840.

588 Jouanneau, J., Weber, O., Cremer, M., Castaing, P., 1999. Fine-grained sediment budget on the  
589 continental margin of the Bay of Biscay. *Deep Sea Research Part II: Topical Studies in  
590 Oceanography* 46, 2205-2220.

591 Judd, A., Hovland, M., Dimitrov, L., Garcia Gil, S., Jukes, V., 2002. The geological methane  
592 budget at continental margins and its influence on climate change. *Geofluids* 2, 109-126.

593 Arvidson, R.S., Morse, J.W., Joye, S.B., 2004. The sulfur biogeochemistry of chemosynthetic  
594 cold seep communities, Gulf of Mexico, USA. *Marine Chemistry* 87, 97-119

595 Baltzer, A., Ehrhold, A., Rigolet, C., Souron, A., Cordier, C., Clouet, H., Dubois, S.F., 2014.  
596 Geophysical exploration of an active pockmark field in the Bay of Concarneau,  
597 southern Brittany, and implications for resident suspension feeders. *Geo-Marine*  
598 *Letters* 34, 215-230

599 Baltzer, A., Reynaud, M., Ehrhold, A., Fournier, J., Cordier, C., Clouet, H., 2017. Space-time  
600 evolution of a large field of pockmarks in the Bay of Concarneau (NW Brittany).  
601 *Bulletin de la Société géologique de France* 188, 23

602 Boles, J., Clark, J., Leifer, I., Washburn, L., 2001. Temporal variation in natural methane seep  
603 rate due to tides, Coal Oil Point area, California. *Journal of Geophysical Research:*  
604 *Oceans* 106, 27077-27086

605 Brown, C.S., Newton, A.M., Huuse, M., Buckley, F., 2017. Iceberg scours, pits, and pockmarks  
606 in the North Falkland Basin. *Marine Geology* 386, 140-152

607 Bussmann, I., Schlömer, S., Schlüter, M., Wessels, M. 2011. Active pockmarks in a large lake  
608 (Lake Constance, Germany): effects on methane distribution and turnover in the  
609 sediment. *Limnology and Oceanography* 56, 379-393

610 Dando, P., Austen, M., Burke, Jr. R., Kendall, M., Kennicutt, M., Judd, A., Moore, D., O'Hara, S.,  
611 Schmalijohann, R., Southward, A., 1991. Ecology of a North Sea pockmark with an  
612 active methane seep. *Marine Ecology Progress Series*, 49-63

613 Ellis, J.P., McGuinness, W.T., 1986. Pockmarks of the northwestern Arabian Gulf. In:  
614 *Oceanology*. Springer, 353-367

615 Ingalls, A.E., Aller, R.C., Lee, C., Wakeham, S.G., 2004. Organic matter diagenesis in shallow  
 616 water carbonate sediments. *Geochimica et Cosmochimica Acta* 68, 4363-4379  
 617 Josenhans, H.W., King, L.H., Fader, G.B., 1978. A side-scan sonar mosaic of pockmarks on the  
 618 Scotian Shelf. *Canadian Journal of Earth Sciences* 15, 831-840  
 619 Maltby, J., Sommer, S., Dale, A.W., Treude, T., 2016. Microbial methanogenesis in the sulfate-  
 620 reducing zone of surface sediments traversing the Peruvian margin. *Biogeosciences*  
 621 (BG) 13, 283-299  
 622 Manley, P.L., Manley, T., Watzin, M.C., Gutierrez, J., 2004. Lakebed pockmarks in Burlington  
 623 Bay, Lake Champlain: I. Hydrodynamics and implications of origin. In: *Lake*  
 624 *Champlain: Partnerships and Research in the New Millennium*. Springer, 299-329  
 625 Menier, D., Augris, C., Briend, C., 2014. Les réseaux fluviaux anciens du plateau continental  
 626 de Bretagne Sud. Editions Quae  
 627 Michel, G., Dupré, S., Baltzer, A., Ehrhold, A., Imbert, P., Pitel, M., Loubrieu, B., Scalabrin, C.,  
 628 Lazure, P., Marié, L., 2017. Pockmarks on the South Aquitaine Margin continental  
 629 slope: The seabed expression of past fluid circulation and former bottom currents.  
 630 *Comptes Rendus Geoscience* 349, 391-401  
 631 Mosher, D.C., Piper, D.J., Campbell, D.C., Jenner, K.A. 2004. Near-surface geology and  
 632 sediment-failure geohazards of the central Scotian Slope. *AAPG bulletin* 88, 703-723  
 633 Reynaud, M., Baltzer A., 2014. L'étonnante association entre des crustacés amphipodes  
 634 (*Haplooids niraes*) et des pockmarks (cratères de dégazage) en baie de Concarneau.  
 635 *Les Cahiers Nantais*, 25-35

636 Rigolet, C., Le Souchu, P., Caisey, X., Dubois, S.F., 2011. Group sweeping: feeding activity and  
 637 filtration rate in the tubiculous amphipod *Haploops nira* (Kaim-Malka, 1976).  
 638 *Journal of Experimental Marine Biology and Ecology* 406, 29-37  
 639 Udden, J.A., 1914. Mechanical composition of clastic sediments. *Geological Society of*  
 640 *America Bulletin* 25, 655-744  
 641 Webb, K.E., Barnes, D.K., Gray, J.S. 2009a. Benthic ecology of pockmarks in the Inner  
 642 Oslofjord, Norway. *Marine Ecology Progress Series* 387, 15-25  
 643 Webb, K.E., Hammer, Ø., Lepland, A., Gray, J.S., 2009b. Pockmarks in the inner Oslofjord,  
 644 Norway. *Geo-Marine Letters* 29, 111-124  
 645 Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *The Journal of*  
 646 *Geology* 30:377-392  
 647 King, L.H., MacLEAN, B., 1970. Pockmarks on the Scotian shelf. *Geological Society of*  
 648 *America Bulletin* 81, 3141-3148.  
 649 Laier, T., Jensen, J.B., 2007. Shallow gas depth-contour map of the Skagerrak-western Baltic Sea  
 650 region. *Geo-Marine Letters* 27, 127-141.  
 651 LaRock, P., Hyun, J.-H., Bennison, B., 1994. Bacterioplankton growth and production at the  
 652 Louisiana hydrocarbon seeps. *Geo-Marine Letters* 14, 104-109  
 653 Lazure, P., Jegou, A.-M., 1998. 3D modelling of seasonal evolution of Loire and Gironde plumes  
 654 on Biscay Bay continental shelf. *Oceanologica acta* 21, 165-177.  
 655 Lurton, X., 1998. *Acoustique sous-marine: présentation et applications*. Editions Quae.  
 656 Maltby, J., Sommer, S., Dale, A.W., Treude, T., 2016. Microbial methanogenesis in the sulfate-  
 657 reducing zone of surface sediments traversing the Peruvian margin. *Biogeosciences (BG)* 13,  
 658 283-299.

659 Malver Instruments, 2015. New Mastersizer reduces sample volume for particle size analysis,  
660 Metal Powder Report 70, 47p,

661 Manley, P.L., Manley, T., Watzin, M.C., Gutierrez, J., 2004. Lakebed pockmarks in Burlington  
662 Bay, Lake Champlain: I. Hydrodynamics and implications of origin, Lake Champlain:  
663 Partnerships and Research in the New Millennium. Springer, 299-329.

664 Menier, D., 2003. Morphologie et remplissage des vallées fossiles sud-armoricaines: apports de  
665 la stratigraphie sismique. Lorient.

666 Menier D., Augris C., Briend C., 2014. Les réseaux fluviaux anciens du plateau continental de  
667 Bretagne Sud. Editions Quae

668 Michel, G., Dupré, S., Baltzer, A., Ehrhold, A., Imbert, P., Pitel, M., Loubrieu, B., Scalabrin, C.,  
669 Lazure, P., Marié, L., 2017. Pockmarks on the South Aquitaine Margin continental slope: The  
670 seabed expression of past fluid circulation and former bottom currents. Comptes Rendus  
671 Geoscience 349, 391-401.

672 Mosher D.C., Piper D.J., Campbell D.C., Jenner K.A., 2004. Near-surface geology and sediment-  
673 failure geohazards of the central Scotian Slope. AAPG bulletin 88, 703-723

674 Ondréas, H., Olu, K., Fouquet, Y., Charlou, J.-L., Gay, A., Dennielou, B., Donval, J.-P., Fifis, A.,  
675 Nadalig, T., Cochonat, P., 2005. ROV study of a giant pockmark on the Gabon continental  
676 margin. Geo-Marine Letters 25, 281-292.

677 Petersen, C., 1924. Brief survey of the animal communities in Danish waters. American Journal  
678 of Science, 343-354.

679 Pilcher, R., Argent, J., 2007. Mega-pockmarks and linear pockmark trains on the West African  
680 continental margin. Marine geology 244, 15-32.

681 Pinot, J.-P., 1974. Le précontinent Breton: entre Penmarc'h, Belle-Ile et l'escarpement  
682 continental, étude geomorphologique. Imprim Lannion, France.

683 Reynaud, M., Baltzer, A., 2014. L'étonnante association entre des crustacés amphipodes  
 684 (Haploops niraе) et des pockmarks (cratères de dégazage) en baie de Concarneau. Les Cahiers  
 685 Nantais, 25-35.

686 Riboulot, V., Sultan, N., Imbert, P., Ker, S., 2016. Initiation of gas-hydrate pockmark in deep-  
 687 water Nigeria: Geo-mechanical analysis and modelling. Earth and Planetary Science Letters  
 688 434, 252-263.

689 Rigolet, C., Le Souchu, P., Caisey, X., Dubois, S.F., 2011. Group sweeping: feeding activity and  
 690 filtration rate in the tubiculous amphipod Haploops niraе (Kaim-Malka, 1976). Journal of  
 691 Experimental Marine Biology and Ecology 406, 29-37.

692 Rigolet, C., Dubois, S.F., Droual, G., Caisey, X., Thiébaud, E., 2012. Life history and secondary  
 693 production of the amphipod Haploops niraе (Kaim-Malka, 1976) in the Bay of Concarneau  
 694 (South Brittany). Estuarine, Coastal and Shelf Science 113, 259-271.

695 Rigolet, C., 2013. Diversité structurelle et fonctionnelle des peuplements sablo-vaseux de  
 696 Bretagne sud: impact de l'expansion d'Haploops niraе. Paris 6.

697 Rigolet, C., Dubois, S.F., Thiébaud, E., 2014. Benthic control freaks: Effects of the tubiculous  
 698 amphipod Haploops niraе on the specific diversity and functional structure of benthic  
 699 communities. Journal of Sea Research, 85, 413-427

700 Rollet, N., Logan, G., Kennard, J., O'Brien, P., Jones, A., Sexton, M., 2006. Characterisation and  
 701 correlation of active hydrocarbon seepage using geophysical data sets: an example from the  
 702 tropical, carbonate Yampi Shelf, Northwest Australia. Marine and Petroleum Geology 23,  
 703 145-164.

704 Sanchez, M., Delanoë, Y., 2006. L'envasement dans différents ports de Loire-Atlantique.  
 705 Proceedings of the IXèmes Journées Nationales Génie Civil–Génie Côtier (Brest, France),  
 706 419-430.

707 Shaw, J., Todd, B.J., Li, M.Z., 2014. Geologic insights from multibeam bathymetry and seascape  
708 maps of the Bay of Fundy, Canada. *Continental Shelf Research* 83, 53-63.

709 Souron, A., 2009. Sédimentologie des vasières subtidales à Haploops spp. sur les fonds à  
710 pockmarks de Bretagne sud. Mémoire de Master2, Institut Universitaire Européen de la Mer,  
711 Plouzané.

712 Straughan, D., 1982. Observations on the effects of natural oil seeps in the Coal Oil Point area.  
713 *Philosophical Transactions of the Royal Society B* 297, 269-283.

714 Sultan, N., Marsset, B., Ker, S., Marsset, T., Voisset, M., Vernant, A.-M., Bayon, G., Cauquil, E.,  
715 Adamy, J., Colliat, J., 2010. Hydrate dissolution as a potential mechanism for pockmark  
716 formation in the Niger delta. *Journal of Geophysical Research: Solid Earth* 115.

717 Szpak, M., Monteys, X., O'Reilly, S., Lilley, M., Scott, G., Hart, K., McCarron, S., Kelleher, B.,  
718 2015. Occurrence, characteristics and formation mechanisms of methane generated micro-  
719 pockmarks in Dunmanus Bay, Ireland. *Continental Shelf Research* 103, 45-59.

720 Taylor, D., 1992. Nearshore shallow gas around the UK coast. *Continental Shelf Research* 12,  
721 1135-1144.

722 Tessier, C., 2006. Caractérisation et dynamique des turbidités en zone côtière: l'exemple de la  
723 région marine Bretagne Sud. Université de Bordeaux 1.

724 Thorson, G., 1957. Bottom communities (sublittoral or shallow shelf). *Treatise on marine*  
725 *ecology and paleoecology* 1, 461-534.

726 Udden, J.A., 1914. Mechanical composition of clastic sediments. *Geological Society of America*  
727 *Bulletin* 25, 655-744

728 Webb KE, Barnes DK, Gray J.S., 2009a. Benthic ecology of pockmarks in the Inner Oslofjord,  
729 Norway. *Marine Ecology Progress* 387, 15-25

730 Webb, K.E., Hammer, Ø., Lepland, A., Gray, J.S., 2009b. Pockmarks in the inner Oslofjord,  
 731 Norway. *Geo-Marine Letters* 29, 111-124.  
 732 Wentworth, C.K., 1922. A scale of grade and class terms for clastic sediments. *The Journal of*  
 733 *Geology* 30, 377-392  
 734 Whiticar, M.J., 2002. Diagenetic relationships of methanogenesis, nutrients, acoustic turbidity,  
 735 pockmarks and freshwater seepages in Eckernförde Bay. *Marine geology* 182, 29-53.  
 736 Wildish, D., Dickinson, J., 1982. A new species of Haploops (Amphipoda, Ampeliscidae) from  
 737 the Bay of Fundy. *Canadian journal of zoology* 60, 962-967.  
 738 Wildish, D., Akagi, H., McKeown, D., Pohle, G., 2008. Pockmarks influence benthic  
 739 communities in Passamaquoddy Bay, Bay of Fundy, Canada. *Marine Ecology Progress Series*  
 740 357, 51-66.  
 741  
 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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## FIGURE CAPTIONS

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

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

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

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

Both data sets are plotted on an ortho-photo (May 2017) extracted from the website “Copernicus 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.

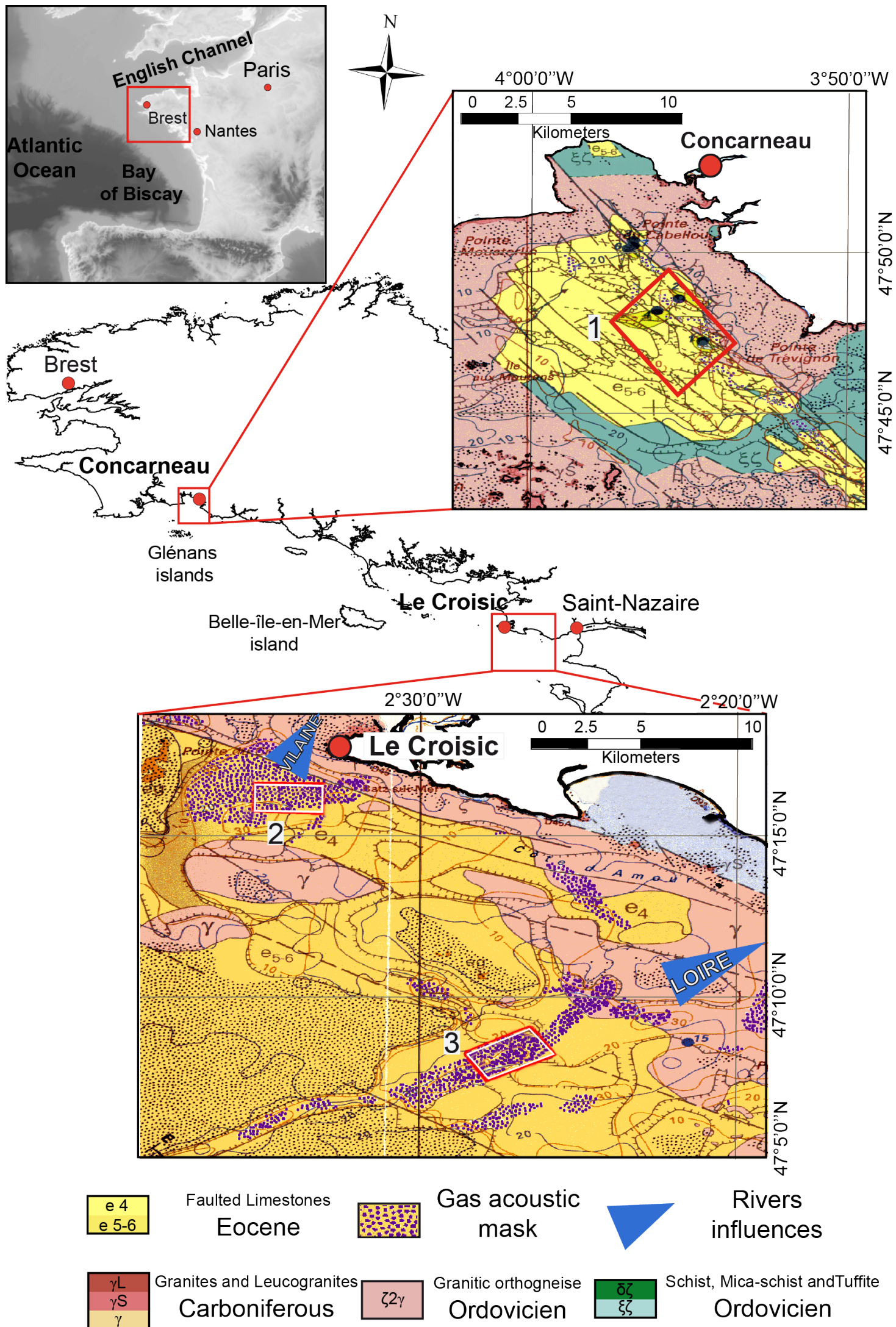
797  
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799 Figure 5: Bathymetry maps (left part) versus reflectivity map (right part) of La Lambarde site.  
800 The bathymetry and reflectivity maps show five facies A', B', C', D', E' delimited by a white  
801 continuous line, a brown continuous 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

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

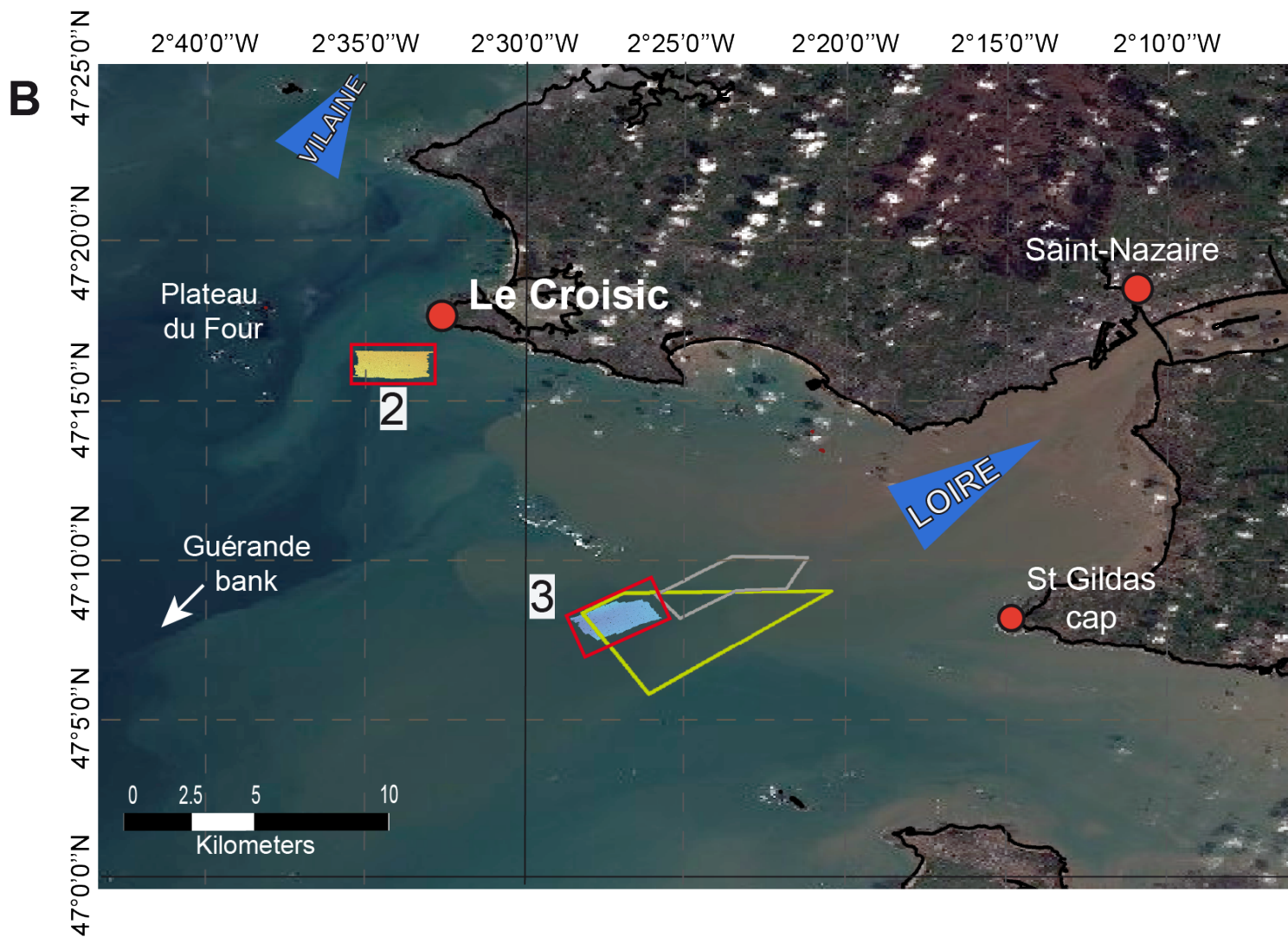
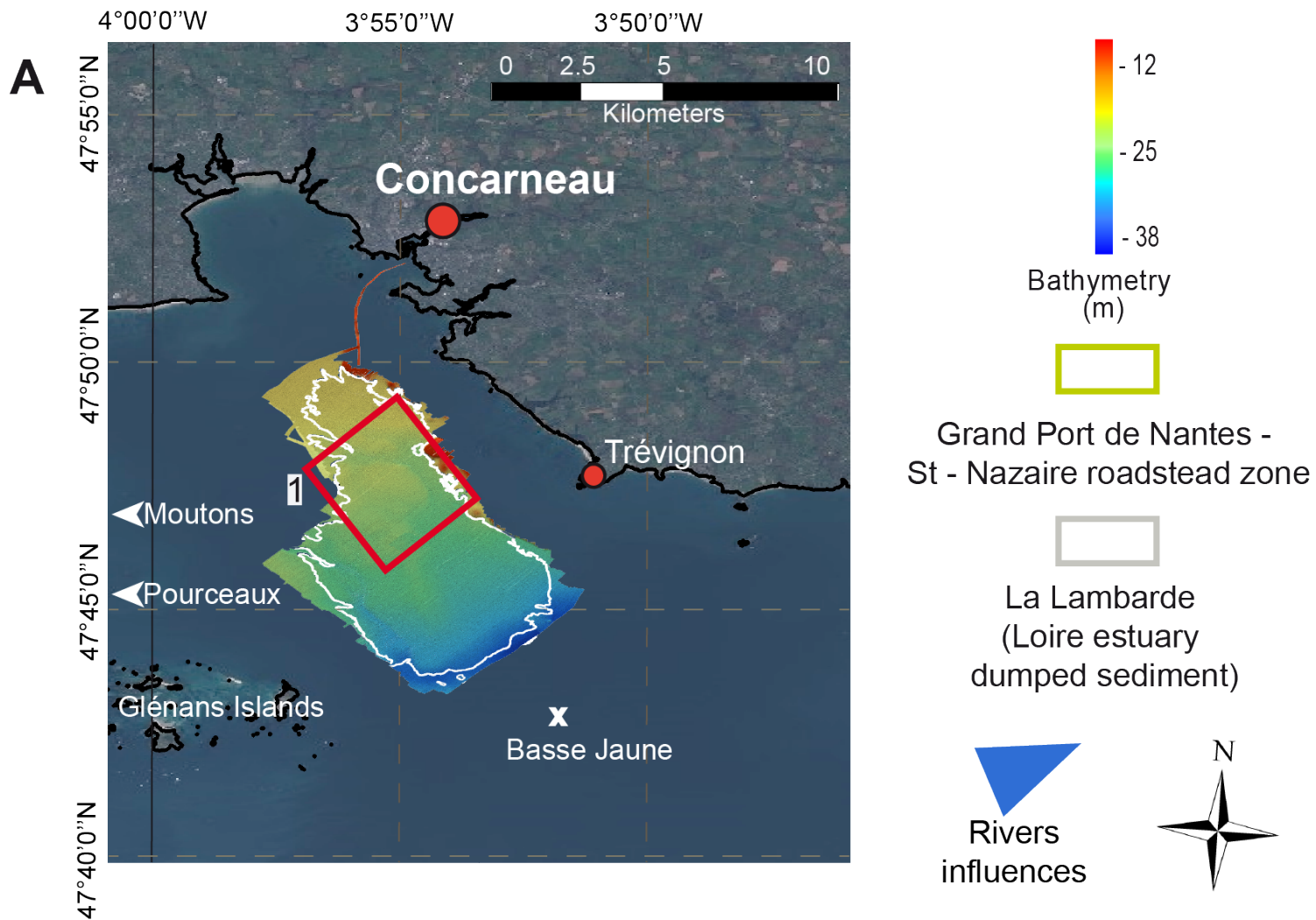
Figure 6: Site of Le Croisic. The interpretative map of the area is superimposed to the density map of pockmarks (pockmarks Nb/km<sup>2</sup>). Two chirp profiles, profile P08 and profile P19 (blue continuous lines), are shown. The left column shows the raw profiles and the second column presents interpreted profiles.

Figure 7: Site of La Lambarde. The interpretative map of the area is superimposed to the density map of pockmarks (pockmarks Nb/km<sup>2</sup>). Two chirp profiles, profile P03 and profile P14 (blue continuous lines), are shown. The left column shows the raw profiles and the second column presents interpreted profiles.

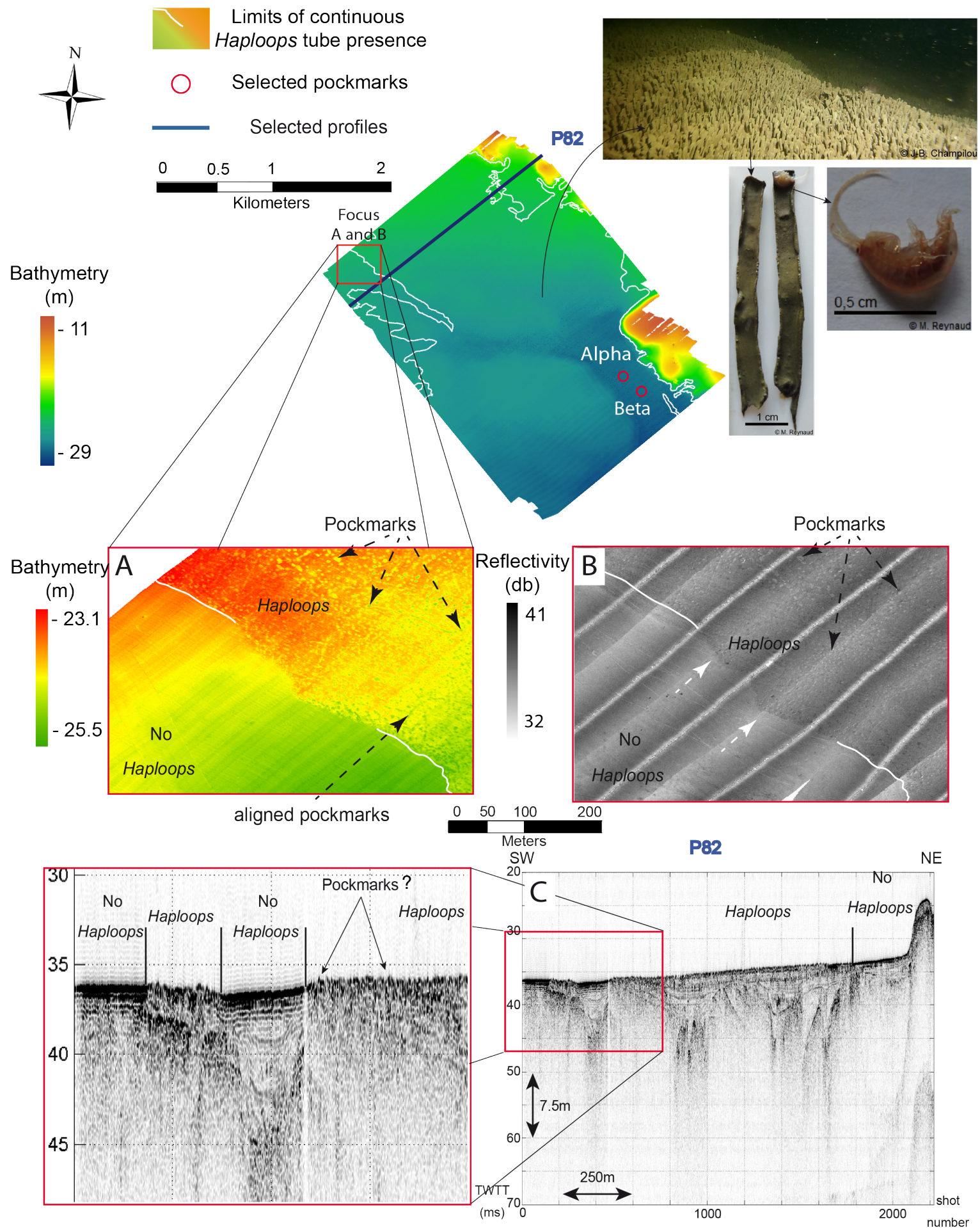
Figure 8: Relative location and bathymetric images of two pockmarks, Alpha and Beta, in the Bay of Concarneau. Eight cores were taken by divers in the area of *Haploops* cover (white dots) and four cores were taken into the pockmarks centers, with no *Haploops* (called pockmarks chimneys) by divers.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



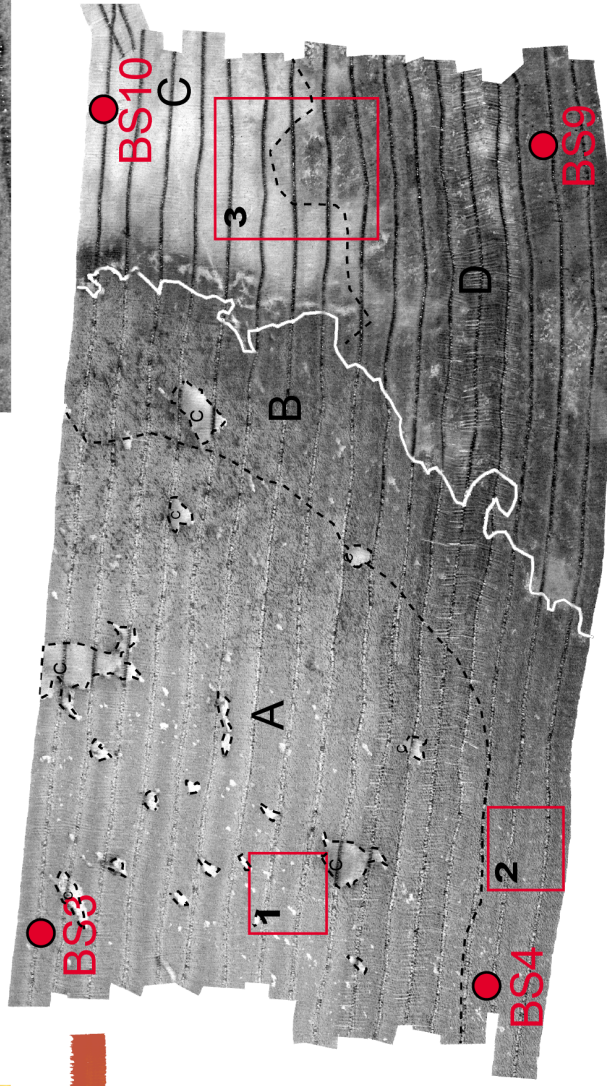
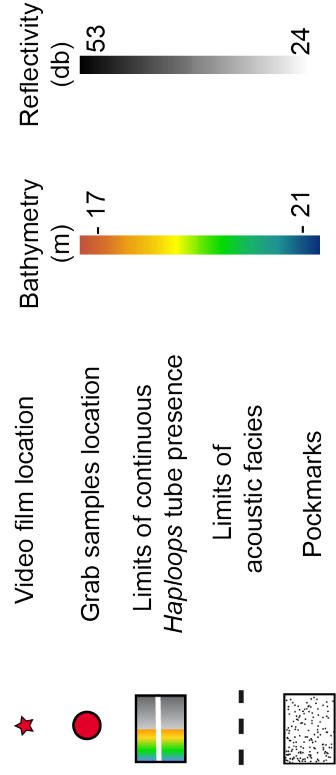
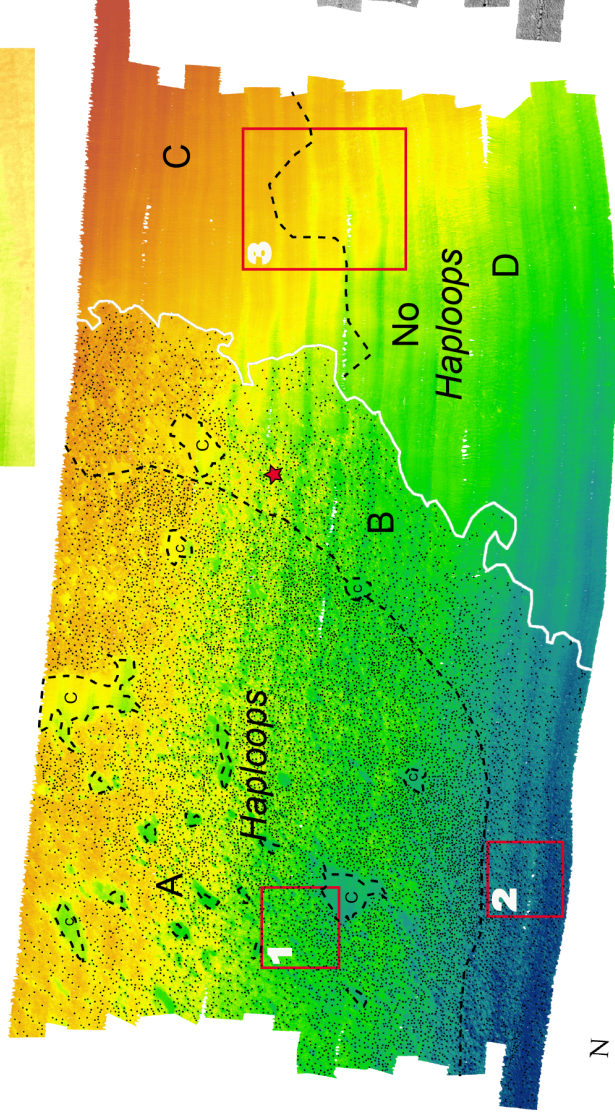
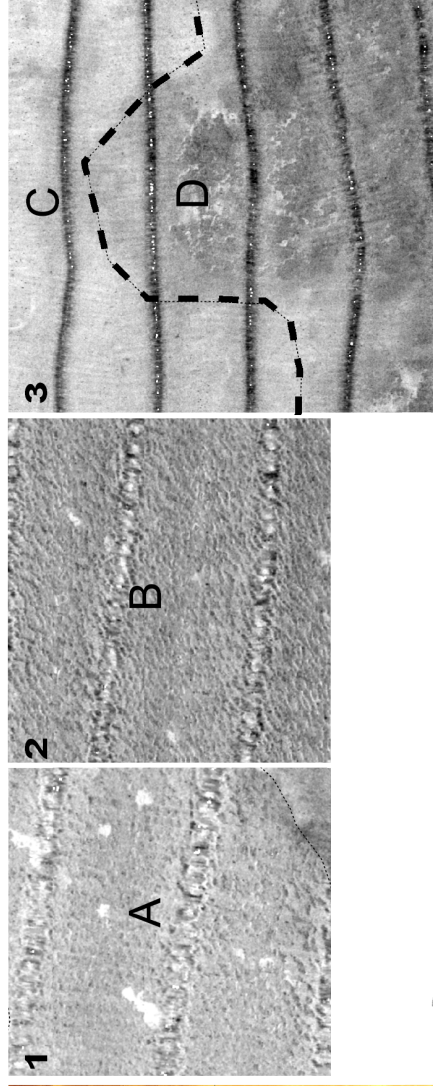
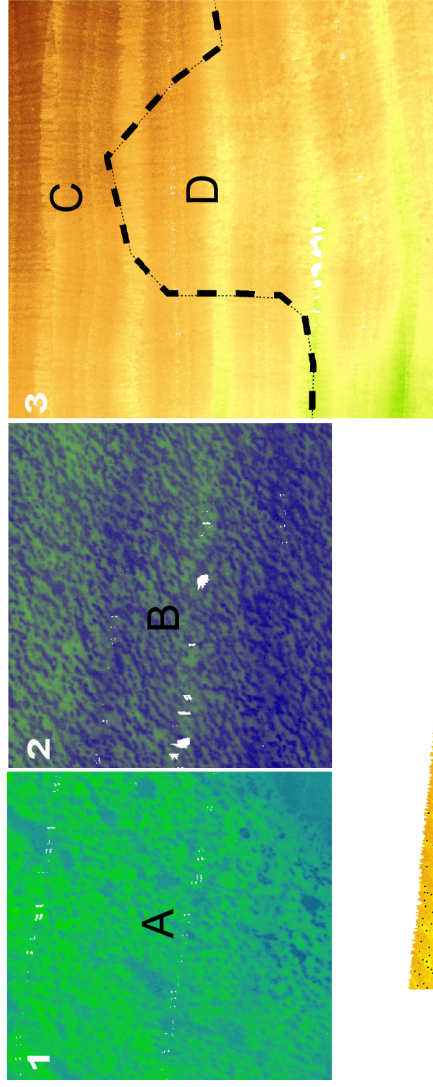




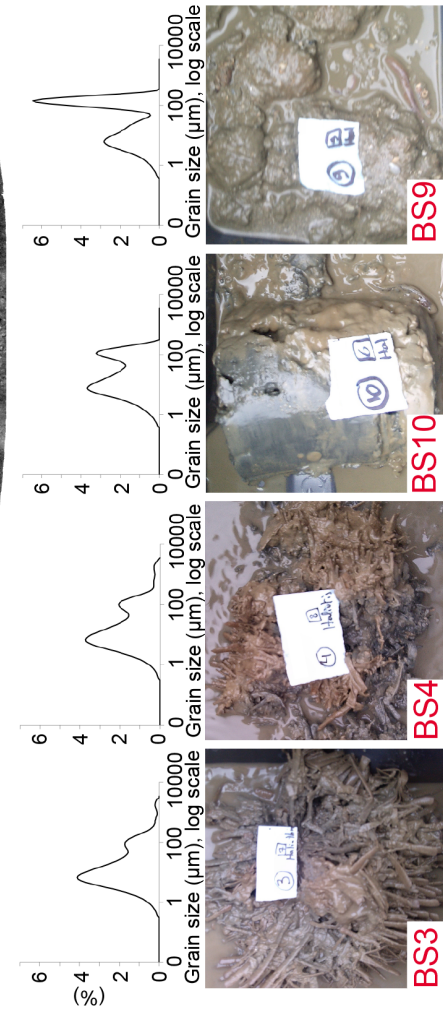




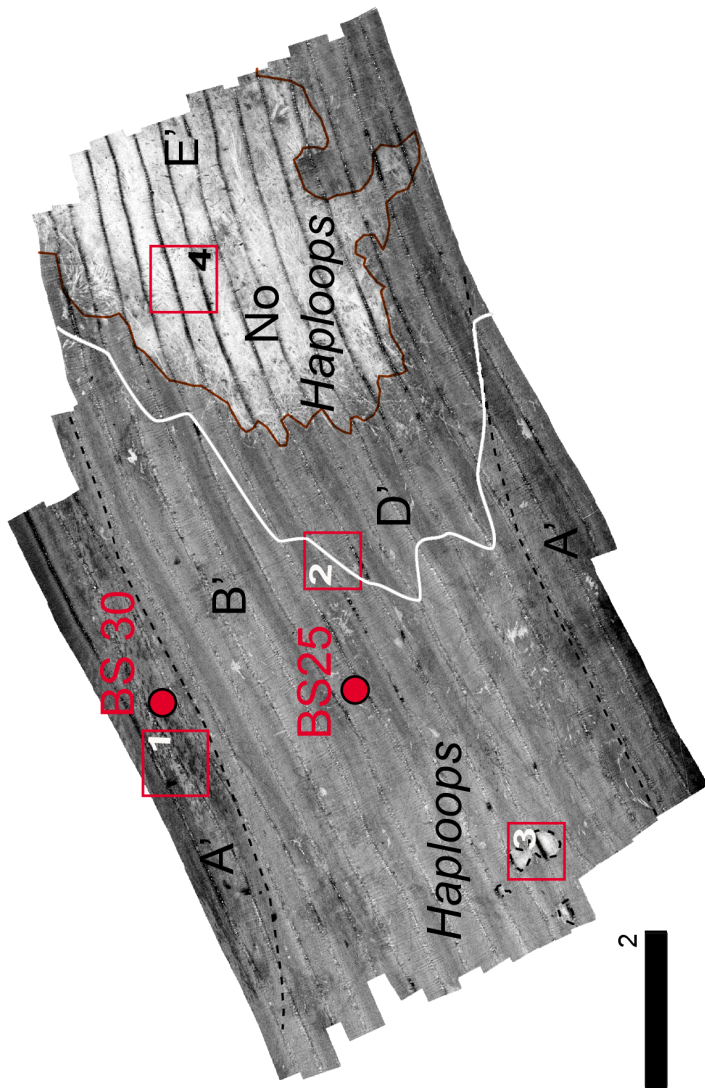
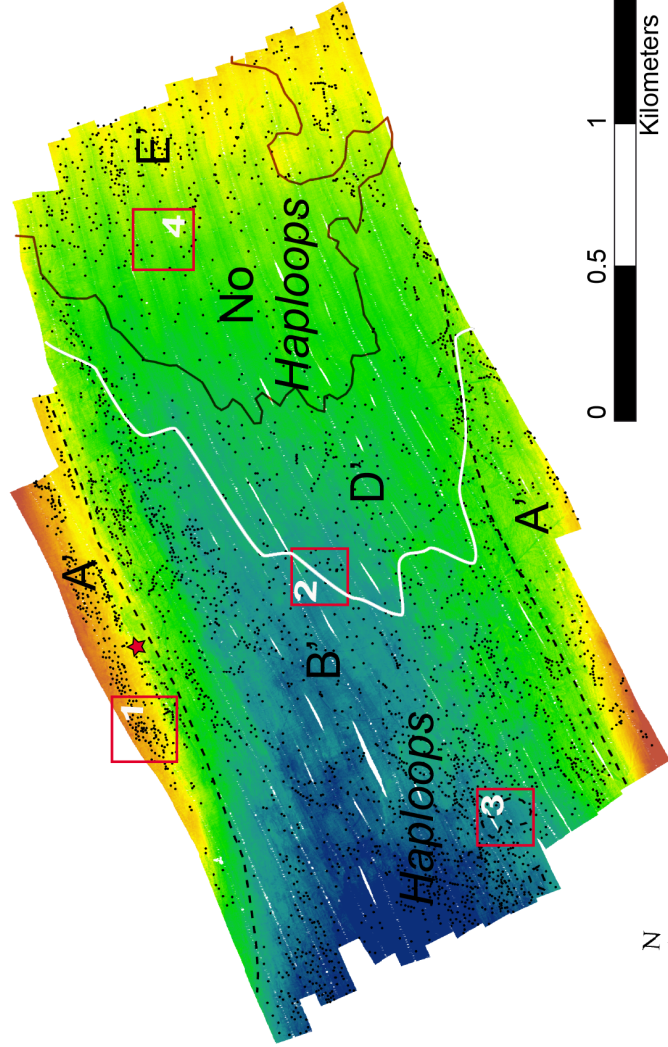
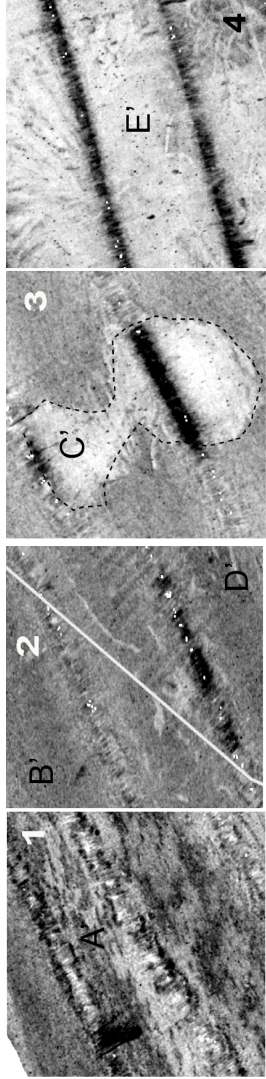
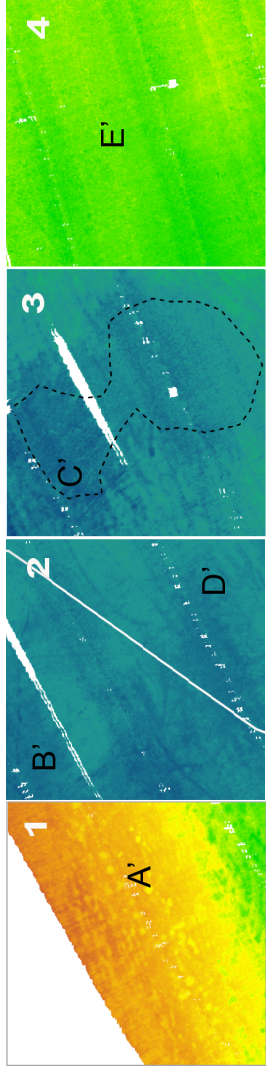




Volumic proportion (%)







Limits of continuous  
Haploids tube presence



Limits of  
acoustic facies



Video film location



Pockmarks

Limits of remolded area



Grab samples location

Reflectivity  
(db)

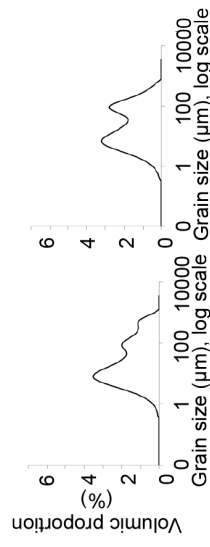
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24

Bathymetry  
(m)

- 28

- 35

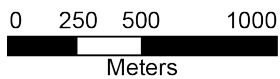


BS30

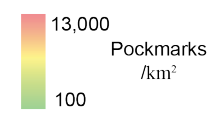


BS25

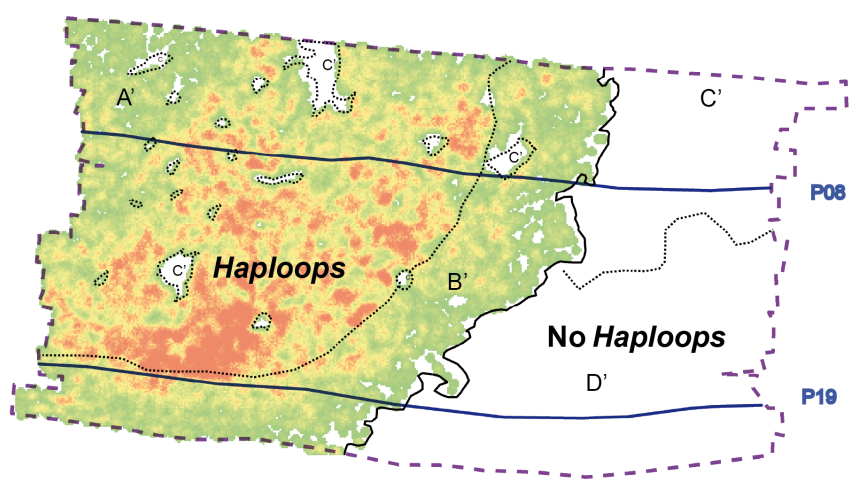




- Gas mask
- Limits of sedimentary facies
- Selected profiles
- Limits of continuous Haploops cover



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

