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

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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.

Highlights

► Three sites in South Britanny reveal a perfect overlapping of *Haploops* colonies and shallow depth pockmarks fields. ► Despite different environmental conditions, this superimposition *Haploops*/pockmarks is confirmed. ► A link may exist between the *Haploops* colonies and active shallow depth pockmarks fields. ► The possible hypothesis is that pockmarks provide food (directly or indirectly) to *Haploops*. ► This Haploops/pockmarks pattern should be tested elsewhere in the world.

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^2 and is characterised by an unusual high density of pockmarks in some locations, reaching up to 5,500 pockmarks/ km^2 (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 their presence in coastal pockmark fields. Reynaud and Baltzer (2014) hypothesised that fluid expulsion from the pockmarks provides fine and sorted sediment particles that favour tube building of the *Haploops*. However, the authors gave no clear evidence for their suggestion. A previous hypothesis suggested that pockmarks act as direct or indirect food supplier to the *Haploops* (Rigolet, 2013). In the Bay of Concarneau, direct gas consumption by endosymbiosis bacteria present in the *Haploops* was discarded due to the light signature of carbon stable isotopes (< -70 $^{0}/_{00}$) found in the analysed tissues (Rigolet, 2013).

In the Bay of Concarneau, high densities of *Haploops* populations (up to 10,000 individuals/m^2) were reported by Rigolet, (2013) which are exceptional in comparison to densities (about 4,000 individuals/m^2) reported in some northern hemisphere sites, such as the Øresund and Kattegat in Sweden (Petersen, 1924), the Bay of Fundy in Canada (Wildish and Dickinson, 1982), the Northumberland in the United Kingdom (Allen, 1953) and East Siberia in Russia (Gukov, 2011).

To our knowledge, no study other than the work conducted along the West coast of France, has ever described the pockmarks/*Haploops* association. Moreover, only very few studies focused on the influence of pockmark fields on the environment and their contribution to food webs (Straughan, 1982) or nutrient cycles (Wildish *et al.*, 2008) and possible links with benthic fauna (Dando *et al.*, 1991; Dubois *et al.*, 2015). The links between pockmarks and associated benthic fauna is restricted to the comparison of species assemblages' occurring inside and outside some selected pockmarks (never at the scale of the pockmark field). To test the recurrence of the spatial overlap of *Haploops* cover and pockmark fields, two sites, "La Lambarde" and "Le Croisic", located in the Loire estuary (West France) were investigated using the same geophysical approach carried out in Concarneau (Baltzer *et al.*, 2014). More specifically, data collected from Concarneau served as a reference to determine sedimentary facies, in terms of sedimentological 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 Lambarde”, 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; Béchennec *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 $cm.s^{-1}$ 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 $cm.s^{-1}$ (Chapelle, 1989) with a maximum speed of 50 $cm.s^{-1}$ (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 $2x10^6$ $T.yr^{-1}$ and $0.1x10^6$ $T.yr^{-1}$ 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 $cm.s^{-1}$ with a maximum speed of 90 $cm.s^{-1}$. 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 $mg.l^{-1}$, except during the Loire flood events when turbidity increases up to 100 $mg.l^{-1}$ (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^3 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 ($d \leq 3.9$ µm), silt (4 µm < $d \leq 63$ µm), sand ($d > 63$ µm) 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 H_3PO_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 Lambarde 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^2 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/km2 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^2 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 ± 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 ± 0.23 % for the *Haploops* areas, 2.45 ± 0.35 % for Alpha pockmark centre and 2.62 ± 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^2. 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 Cylyde (United Kingdom), *Haploops* patches (3.000 – 4.000 individuals/m^2) 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^2) 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^2, 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 deveopment, *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 development of present day ecosystems (largely studied in the deep-sea domain but that remain unknown and unexplored in coastal areas), and ii) means that *Haploops* can be used as bio-indicators for the presence of active pockmarks.

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

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(R/V) Haliotis Missions DOI

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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".

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

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

Figure 4: Bathymetry maps (left part) versus sonar imageries (right part) of Le Croisic site. The bathymetry and reflectivity maps show four facies, A, B, C, D delimited by a white continuous line and black dashed lines (taking into account the seafloor 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. Four Schipeck grab sample (BS3, BS4, BS9) and corresponding grain size analysis are also shown.

Figure 5: Bathymetry maps (left part) versus reflectivity map (right part) of La Lambarde site. The bathymetry and reflectivity maps show five facies A', B', C', D', E' delimited by a white continuous line, a brown continuous line and blacks dashed lines taking into account the seafloor 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^2). 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^2). 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.

- Three sites in South Britanny reveal a perfect overlapping of *Haploops* colonies and shallow depth pockmarks fields.
- Despite different environmental conditions, this superimposition *Haploops*/pockmarks is confirmed.
- A link may exist between the *Haploops* colonies and active shallow depth pockmarks fields.
- The possible hypothesis is that pockmarks provide food (directly or indirectly) to *Haploops*.
- This Haploops/pockmarks pattern should be tested elsewhere in the world.

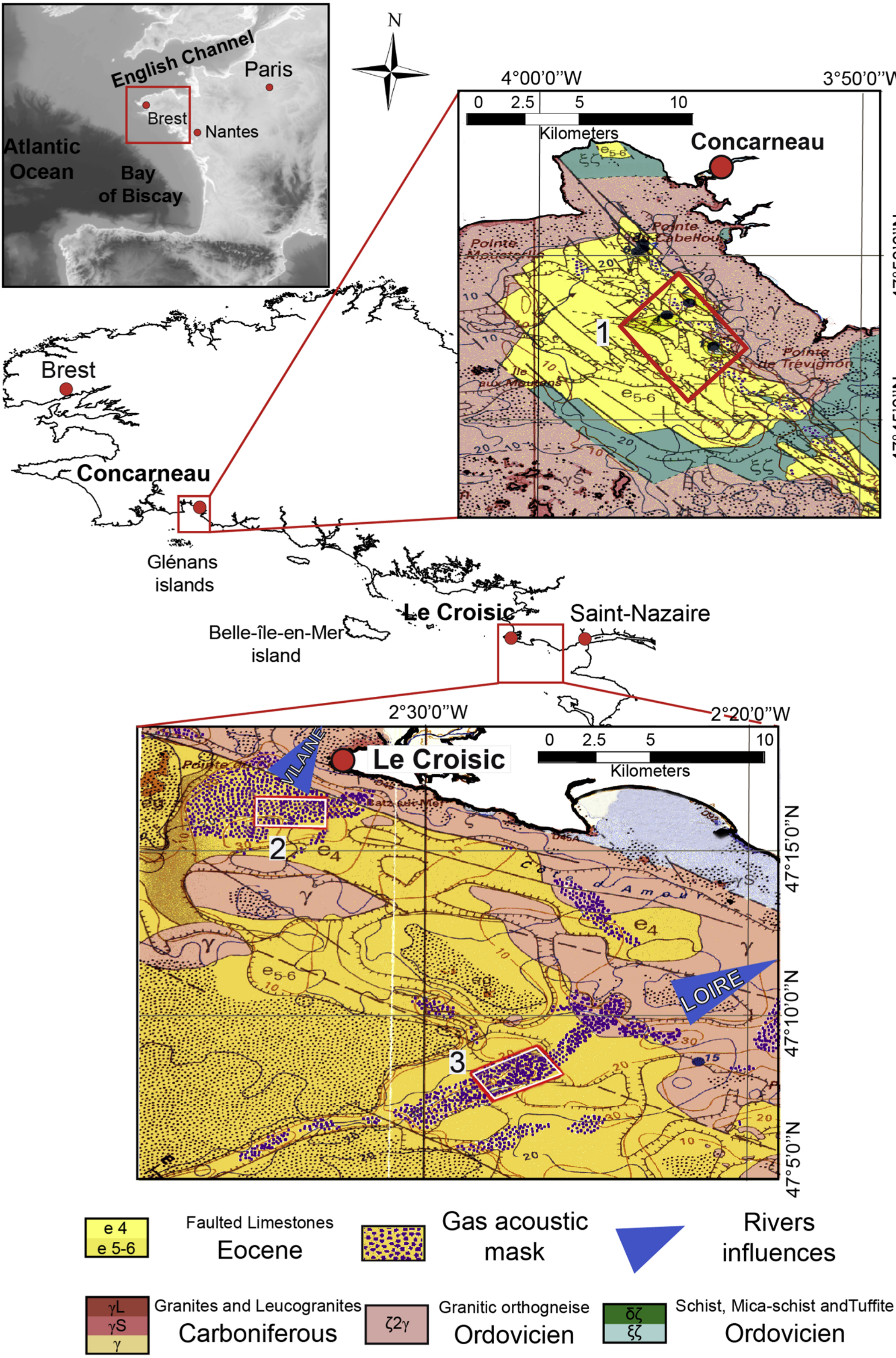

English Channel
Paris
Brest
Nantes
Atlantic Ocean
Bay of Biscay
N
4°00'0"W
3°50'0"W
0 2.5 5 10
Kilometers
Concarneau
Pointe du Cabellou
Pointe Mousterlin
Pointe de Trévignon
Ile aux Moutons
1
e5-6
47°50'0"N
47°45'0"N
Brest
Concarneau
Glénans islands
Le Croisic
Saint-Nazaire
Belle-île-en-Mer island
2°30'0"W
2°20'0"W
0 2.5 5 10
Kilometers
Le Croisic
VILAINE
LOIRE
2
3
e4
e5-6
47°15'0"N
47°10'0"N
47°5'0"N
e 4
e 5-6
Faulted Limestones
Eocene
Gas acoustic mask
Rivers influences
γL
γS
γ
Granites and Leucogranites
Carboniferous
ζ2γ
Granitic orthogneise
Ordovicien
δζ
ξζ
Schist, Mica-schist andTuffite
Ordovicien

Figure 1

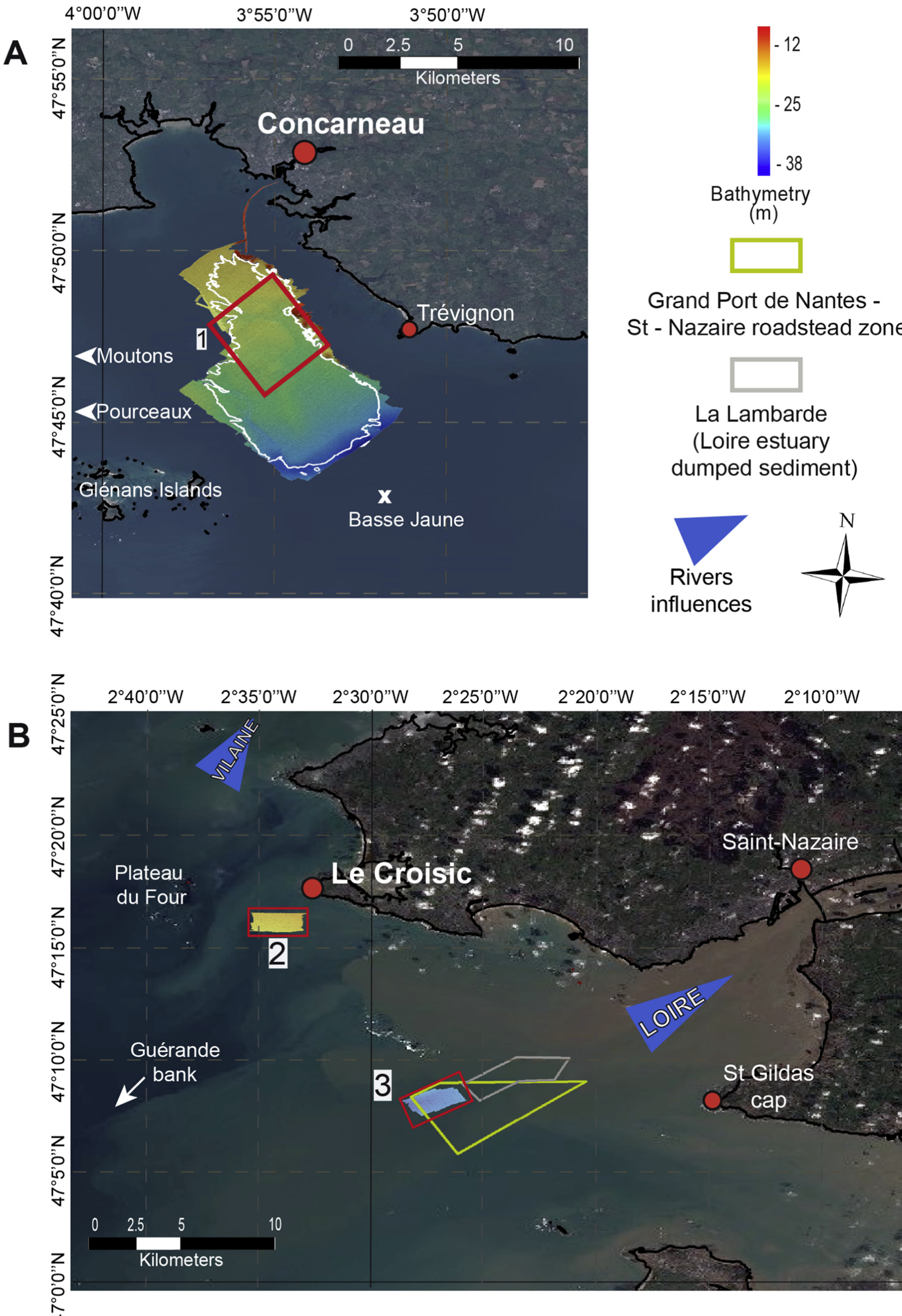
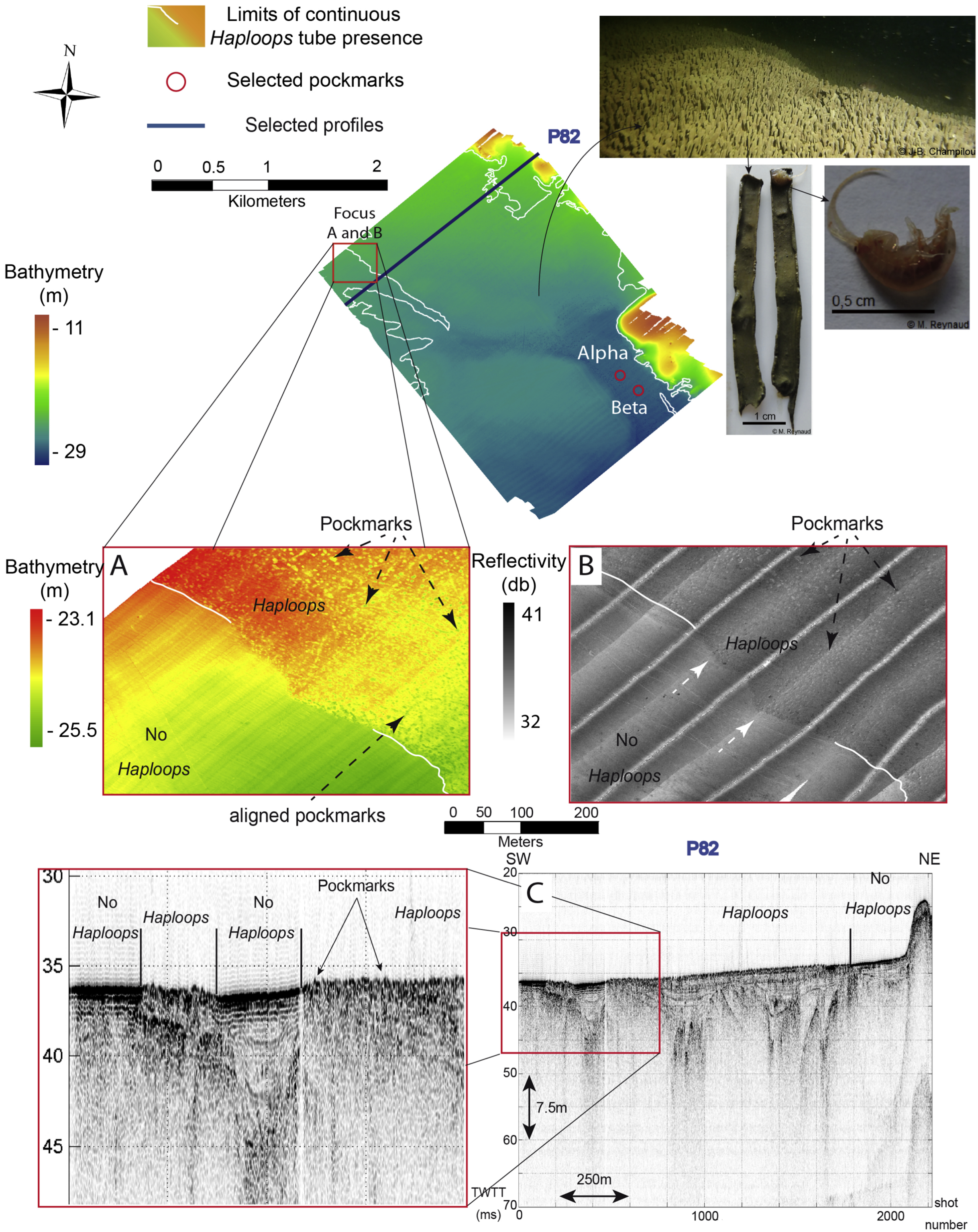
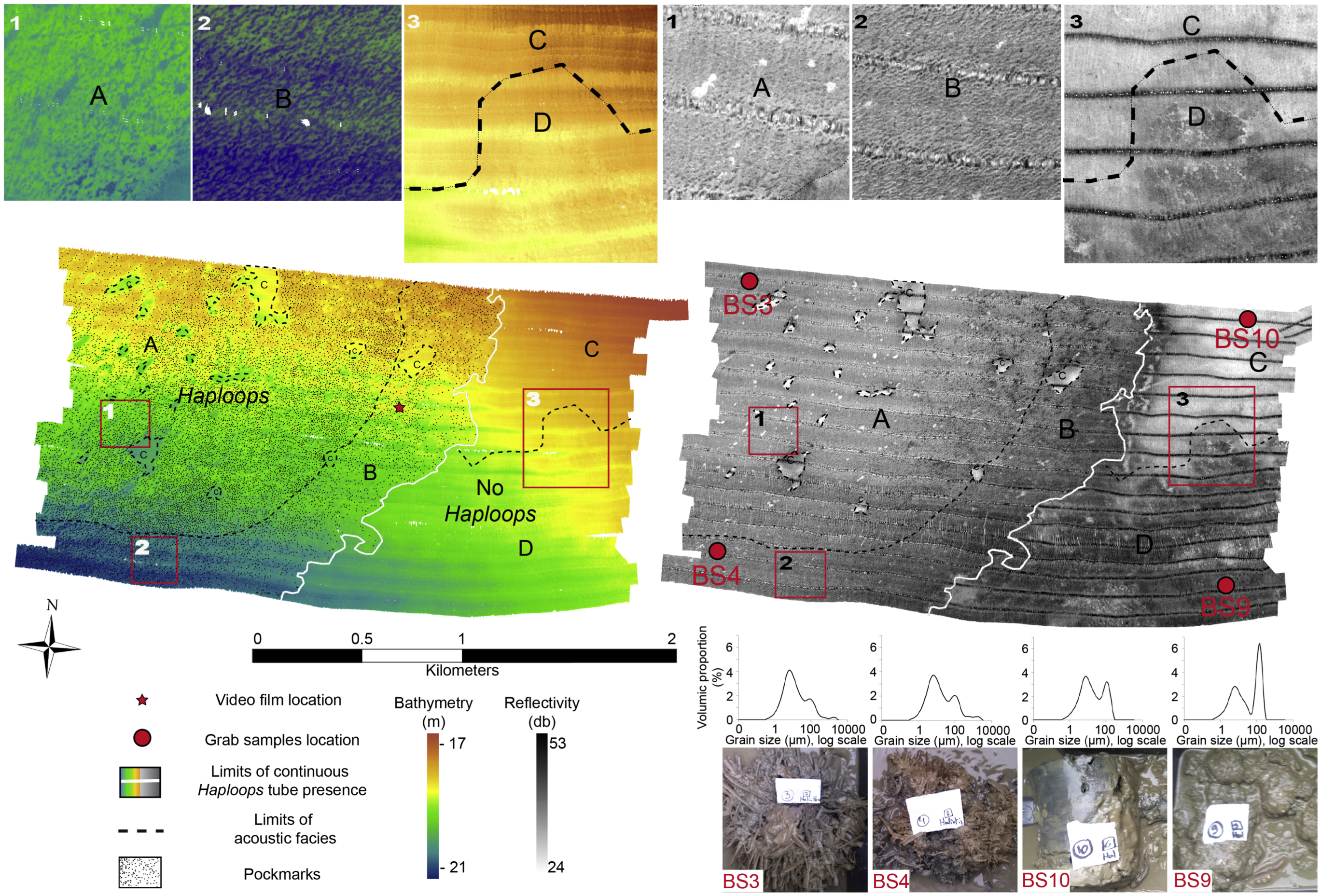

A
4°00'0"W
3°55'0"W
3°50'0"W
47°55'0"N
47°50'0"N
47°45'0"N
47°40'0"N
0 2.5 5 10
Kilometers
Concarneau
Trévignon
1
Moutons
Pourceaux
Glénans Islands
x
Basse Jaune
- 12
- 25
- 38
Bathymetry (m)
Grand Port de Nantes - St - Nazaire roadstead zone
La Lambarde (Loire estuary dumped sediment)
Rivers influences
N
B
2°40'0"W
2°35'0"W
2°30'0"W
2°25'0"W
2°20'0"W
2°15'0"W
2°10'0"W
47°25'0"N
47°20'0"N
47°15'0"N
47°10'0"N
47°5'0"N
47°0'0"N
VILAINE
Plateau du Four
Le Croisic
2
Saint-Nazaire
LOIRE
Guérande bank
3
St Gildas cap
0 2.5 5 10
Kilometers

Figure 2



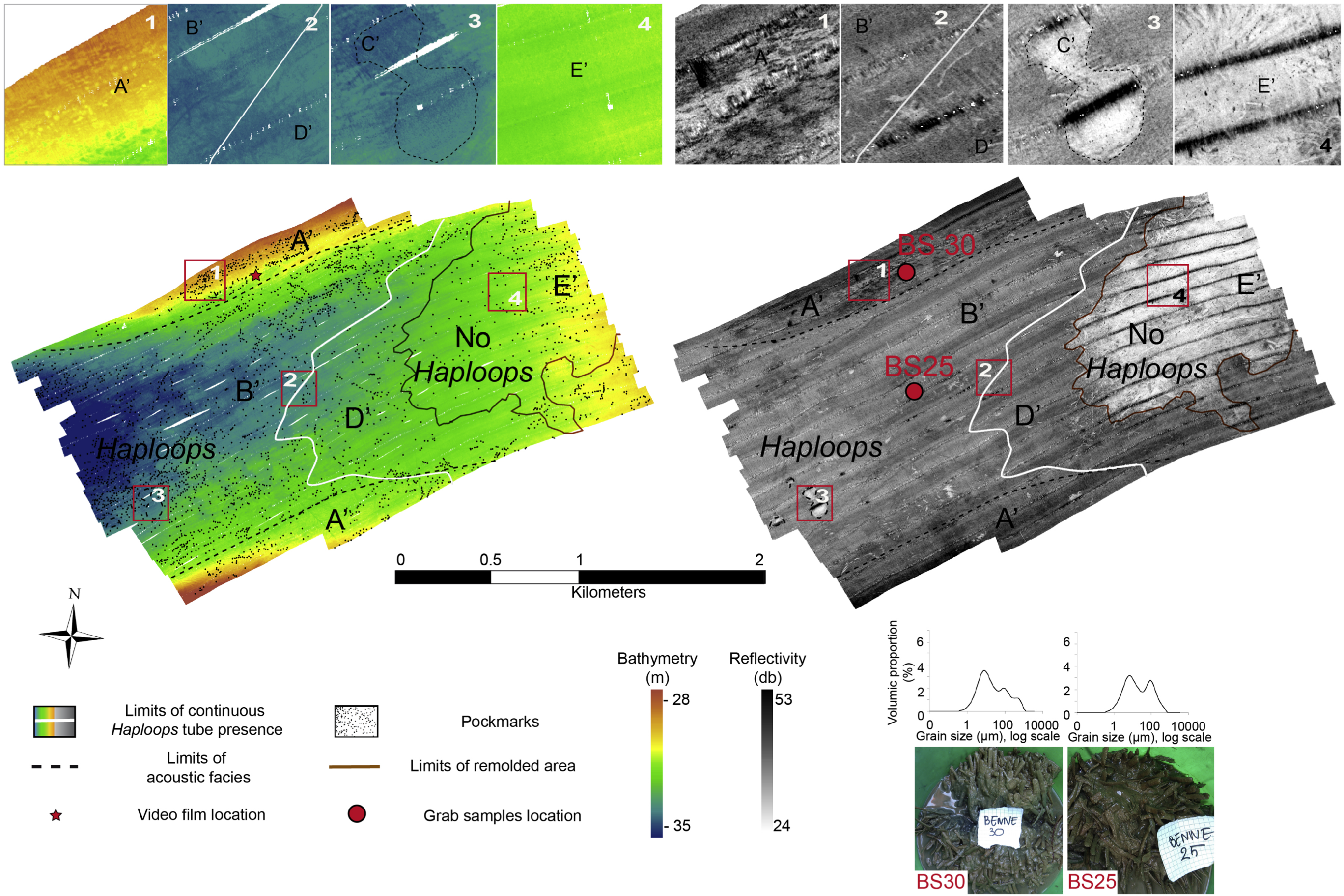
Limits of continuous
Haploops tube presence
Selected pockmarks
Selected profiles
N
0
0.5
1
2
Kilometers
Focus
A and B
P82
Bathymetry
(m)
- 11
- 29
Alpha
Beta
© J-B. Champilou
1 cm
© M. Reynaud
0,5 cm
© M. Reynaud
Pockmarks
Bathymetry
(m)
- 23.1
- 25.5
A
Haploops
No
Haploops
aligned pockmarks
Reflectivity
(db)
41
32
B
Pockmarks
Haploops
No
Haploops
0
50
100
200
Meters
P82
SW
NE
C
No
Haploops
Haploops
No
Haploops
Pockmarks
Haploops
Haploops
No
Haploops
30
35
40
45
20
30
40
50
60
70
TWTT
(ms)
7.5m
250m
0
1000
2000
shot
number

Figure 3



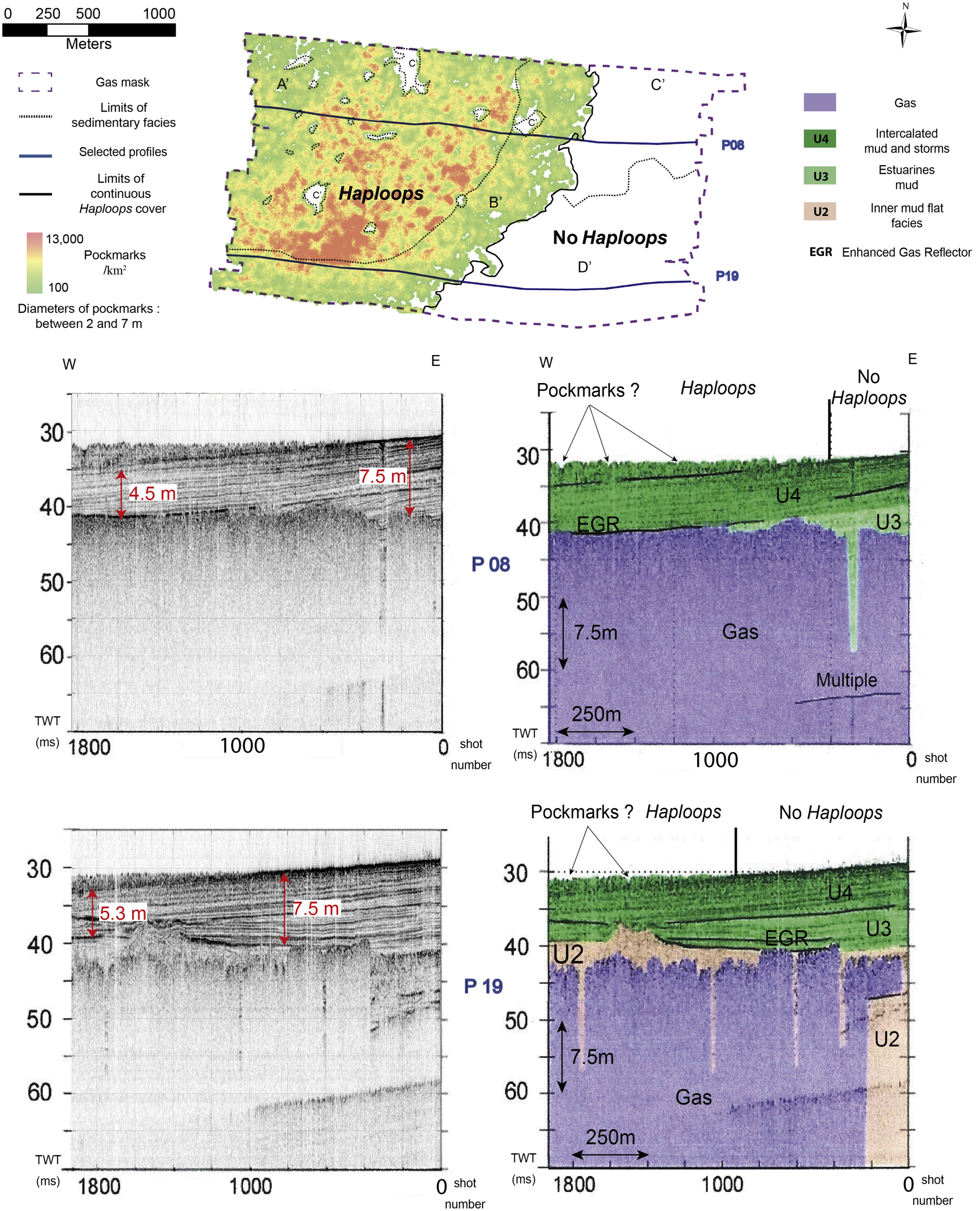
1
A
2
B
3
C
D
1
A
2
B
3
C
D
C
A
Haploops
1
2
B
No
Haploops
3
C
D
BS3
BS10
C
1
A
B
3
D
BS4
2
BS9
N
0
0.5
1
2
Kilometers
Video film location
Grab samples location
Limits of continuous
Haploops tube presence
Limits of
acoustic facies
Pockmarks
Bathymetry
(m)
- 17
- 21
Reflectivity
(db)
53
24
Volumic proportion
(%)
Grain size (µm), log scale
Grain size (µm), log scale
Grain size (µm), log scale
Grain size (µm), log scale
BS3
BS4
BS10
BS9

Figure 4



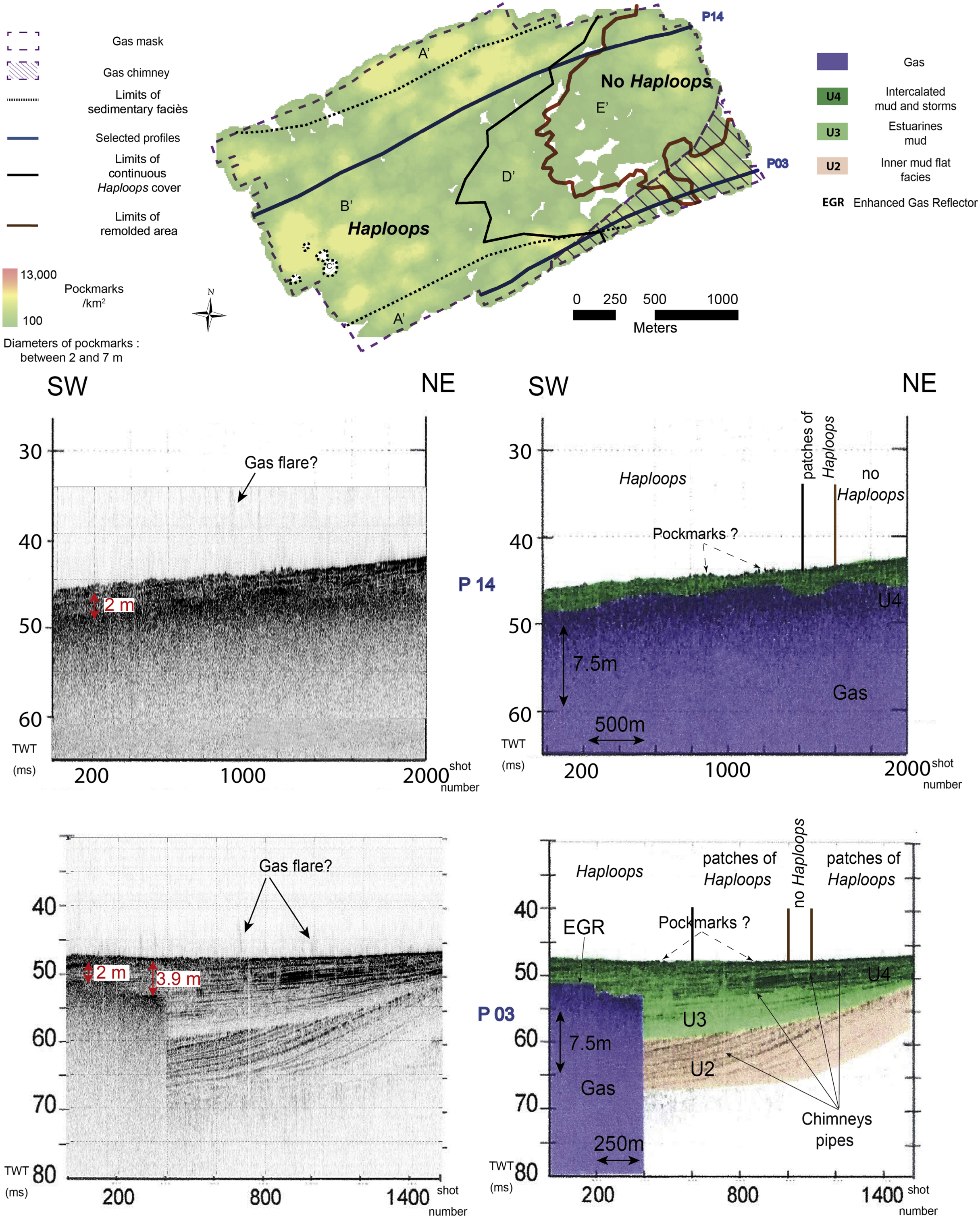
A'
B'
D'
C'
E'
1
2
3
4
No Haploops
Haploops
BS 30
BS25
0
0.5
1
2
Kilometers
N
Limits of continuous Haploops tube presence
Limits of acoustic facies
Video film location
Pockmarks
Limits of remolded area
Grab samples location
Bathymetry (m)
28
35
Reflectivity (db)
53
24
Volumic proportion (%)
Grain size (µm), log scale
BENNE 30
BENNE 25
BS30
BS25

Figure 5



0 250 500 1000
Meters
Gas mask
Limits of sedimentary facies
Selected profiles
Limits of continuous *Haploops* cover
13,000
Pockmarks /km²
100
Diameters of pockmarks : between 2 and 7 m
A'
C'
B'
D'
Haploops
No *Haploops*
P08
P19
N
Gas
U4 Intercalated mud and storms
U3 Estuarines mud
U2 Inner mud flat facies
EGR Enhanced Gas Reflector
W
E
30
40
50
60
4.5 m
7.5 m
TWT (ms)
1800
1000
0
shot number
Pockmarks ?
Haploops
No *Haploops*
U4
U3
EGR
P 08
7.5m
Gas
Multiple
250m
5.3 m
U2
P 19

Figure 6



Gas mask
Gas chimney
Limits of sedimentary faciès
Selected profiles
Limits of continuous Haploops cover
Limits of remolded area
13,000
Pockmarks /km²
100
Diameters of pockmarks : between 2 and 7 m
P14
P03
A'
B'
C'
D'
E'
Haploops
No Haploops
0 250 500 1000
Meters
Gas
U4 Intercalated mud and storms
U3 Estuarines mud
U2 Inner mud flat facies
EGR Enhanced Gas Reflector
SW
NE
Gas flare?
2 m
TWT (ms)
shot number
P 14
Haploops
patches of Haploops
no Haploops
Pockmarks ?
U4
7.5m
Gas
500m
3.9 m
P 03
EGR
U3
U2
250m
Chimneys pipes

Figure 7

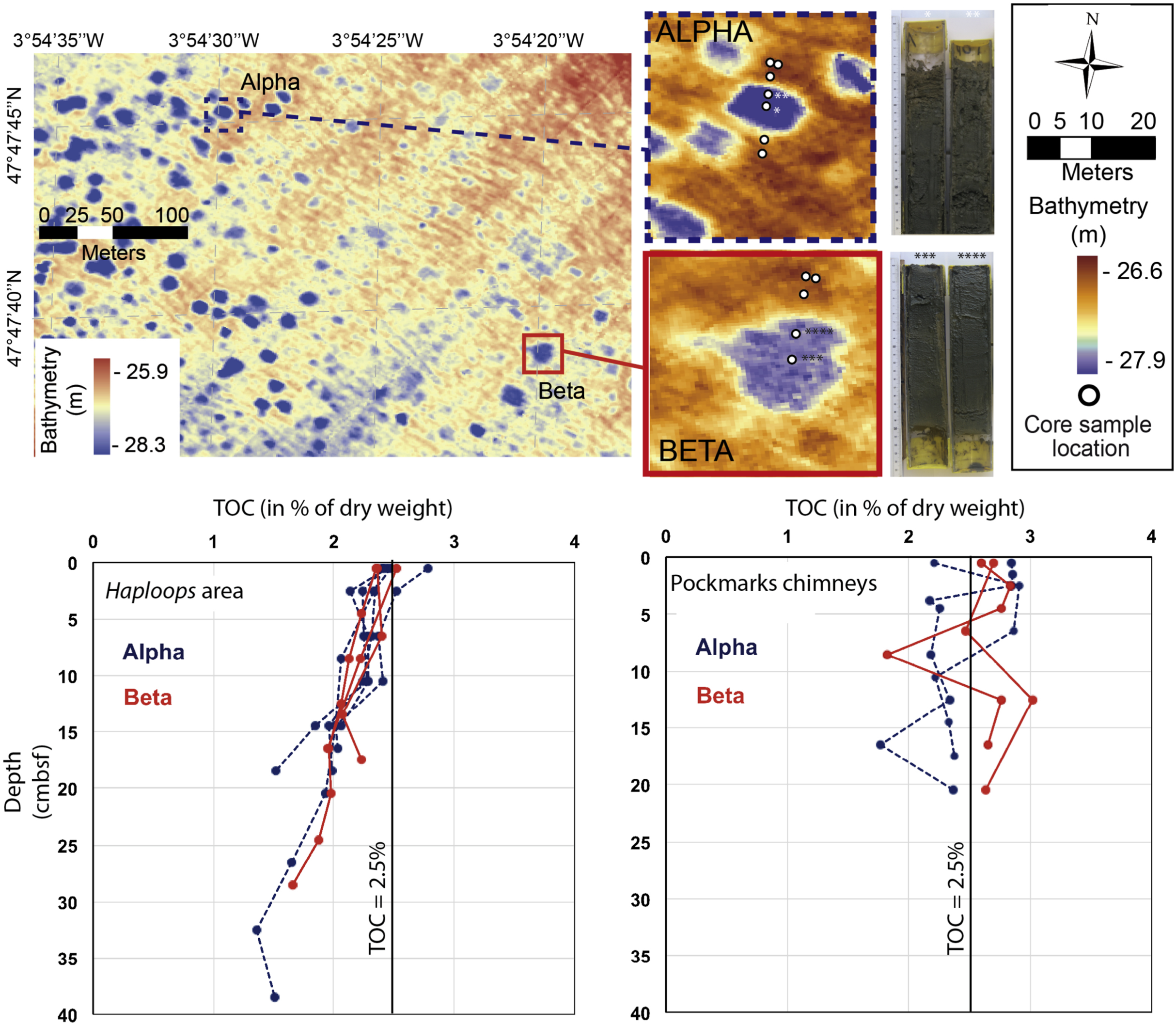

3°54'35''W
3°54'30''W
3°54'25''W
3°54'20''W
47°47'45''N
47°47'40''N
Alpha
Beta
0 25 50 100
Meters
Bathymetry (m)
- 25.9
- 28.3
ALPHA
BETA
N
0 5 10 20
Meters
Bathymetry (m)
- 26.6
- 27.9
Core sample location
TOC (in % of dry weight)
Haploops area
Alpha
Beta
Depth (cmbsf)
TOC = 2.5%
TOC (in % of dry weight)
Pockmarks chimneys
Alpha
Beta
TOC = 2.5%

Figure 8