Space-time evolution of a large field of pockmarks in the Bay of Concarneau (NW Brittany)

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Évolution spatio-temporelle d'un champ de pockmarks dans la Baie de Concarneau (Nord-Ouest de la Bretagne)

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Abstract :

About a decade ago, a large field of pockmarks, covering an overall area of 36 km(2) was discovered in water depths of < 30m in the central part of the Bay of Concarneau (Southern Brittany, France). This field, composed of features from 5 m to 35 m in diameter and < 1 m in depth, is characterized by unusual high densities of pockmarks, up to 5840 per square kilometre. Geophysical data correlated with sedimentary samples acquired in 2005 and 2009 show that pockmarks and their immediate surroundings are associated with dense tubes benches cover, built by a filter-feeding amphipod: Haploops nirae, forming original benthic communities. Two complementary surveys were carried out in April 2011 (Pock and Ploops) and April 2014 (Pock and Tide), on the Oceanographic Vedette (O/V) Haliotis (Ifremer/Genavir), to map the limit of the pockmarks and Haploops fields with the maximum accuracy. The link between the presence of the Haploops nirae communities and the occurrence of pockmarks / gas was then established and the proposed hypothesis was that tidal cycles may provide a good candidate for a short-term (monthly) triggering mechanism of fluid expulsion (Baltzer A, Ehrhold A, Rigolet C, Souron A, Cordier C, Clouet H. 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). Due to the high-level precision (50 cm) of the positioning system (Magellan Aquarius Ixsea Hydrins) coupled with the RTK attitude system, these new bathymetric and imagery maps together with the sub-bottom Chirp profiles, allow us to compare the data sets from April 2011 and April 2014. The superimposition of the two data sets shows that the distribution of the

pockmarks remains similar between these 2 dates (i.e. for 3 years), for the group of large, widely scattered pockmarks, which are deeply rooted in the Holocene palaeo-valley infills and for the group of pockmarks identified as the trawl-scour pockmarks, initiated by trawling action. Most of the pockmarks present very recent shapes without any infilling but sonar imagery reveals that some of them have been covered by a thin muddy layer, thereby reflecting, at least, a temporary cessation of expulsion or a different activity. Chirp profiles indicate some acoustic flares above the pockmarks, revealing gas/fluid expulsion. Different gas clues within the sedimentary column, such as acoustic turbidity, enhanced gas reflectors (EGR), chimneys pipes, occur at exactly the same places on the chirp seismic profiles from 2011 and 2014. Therefore, contrary to most examples described in the literature, this pockmarks field is still active.

Résumé

Un large champs de pockmarks, couvrant une surface de 36 km^2, a été découvert il y a une dizaine d'années, dans la partie centrale de la Baie de Concarneau (Bretagne sud, France), par moins de 30 m de fond. Ce champs de pockmarks, composé de cratères mesurant de 10 à 30 m de diamètre pour des profondeurs de 1 m maximum est caractérisé par une densité exceptionnelle, atteignant jusqu'à 5840 structures par km^2. Des données géophysiques, corrélées et complétées par des prélèvements sédimentaires entre 2005 et 2009, ont montré que ce champs de pockmarks est associé à la présence de colonies de *Haploops nirae*, petit amphipode filtreur benthique, habitant dans des tubes fixés sur le fond et formant de larges banquettes. Deux campagnes complémentaires ont été réalisées en Avril 2011 (Pock and Ploops) et Avril 2014 (Pock and Tide), sur la vedette océnographique Haliotis (Ifremer/Génavir), afin de cartographier très précisément la limite des champs de *Haploops* et des pockmarks. Le lien constaté (mais non élucidé) de la présence des colonies de Haploops et de ces pockmarks implique une activité répétée des pockmarks, et la marée comme facteur déclenchant à court terme constitue l'hypothèse la plus robuste (Baltzer A, Ehrhold A, Rigolet C, Souron A, Cordier C, Clouet H. 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). Grâce au système de positionnement RTK, les données d'imagerie, de bathymétrie et de l'échosondeur à sédiments (chirp) ont pu être parfaitement superposées et donc comparées entre 2011 et 2014. Les premiers résultats montrent que la répartition des pockmarks reste similaire entre ces 2 dates pour le groupe de grands pockmarks dispersés, enracinés plus profondément dans le remplissage sédimentaire holocène des paléo-vallées et le groupe de pockmarks plus petits, plus denses, alignés le long des traces de chaluts de pêcheurs. La plupart des pockmarks présente des cratères sans remplissage sédimentaire, bien qu'il existe dans certains, un fin drappage de vase révélé par l'imagerie sonar, reflétant des arrêts temporaires de l'activité d'expulsion des fluides ou bien un fonctionnement différent. Les profils chirp montrent également des panaches dans la colonne d'eau, indiquant de probables expulsions de fluides/gaz. Plusieurs indices de la présence de gaz sont systématiquement visibles dans la colonne sédimentaire, tels que “la turbidité acoutisque”, les “réflecteurs acoustiques marqués”, les “chimneys pipes”. Ainsi, contrairement à beaucoup d'exemples cités dans la littérature, ce champs de pockmarks est encore actif.

Keywords : geophysics, pockmarks, tide, turbidity, gas, chimneys pipes, Concarneau

Mots clés : géophysique ; marée ; failles ; gaz

Introduction

Pockmarks are crater-like features found on the seabed, which occur in deep marine environments (King and MacLean 1970; Josenhans et al. 1978; Fader 1991) in lakes, shallow bays, estuaries and fjords (Hovland and Judd 1988; Kelley et al. 1994; Rogers et al. 2006). They may be classified according to three criteria: (1) their morphology: circular, elliptical, asymmetrical, composite (Hovland and Judd 1988; Judd and Hovland 2007); (2) their state of development: new, growing, decaying (Pickrill 1993); and (3) their mechanisms of formation: e.g. fault-strike pockmarks, iceberg-scour pockmarks, current modified pockmarks (Pilcher and Argent 2007). They can also be induced by anthropogenic activities such as trawling and ship anchoring (Harrington 1985; Fader 1991). They often form in muddy sediments, large deltas, around small basins and along irregular topographic highs (Hovland and Judd 2009). Deep sources exist for thermogenic hydrocarbons or gas hydrates

(Scanlon and Knebel 1989; Rogers et al. 2006; Miller et al. 2015), but they may be related to pore water expulsion by compaction (Harrington 1985) or may develop above buried paleo-channels that are rich sources of organic material (Gay et al. 2006; Pilcher et al. 2017; Leon et al. 2009; Leon et al. 2014). However, as active fluid flux is rarely observed in pockmarks, the trigger mechanisms can be difficult to identify and may result from natural disasters (earthquakes, tsunamis, storms) or occur more continuously over longer-term events (Kelley et al. 1994; Hovland et al. 2002). Judd and Hovland (2009) hypothesized that most pockmarks discovered are most of the time inactive, which was confirmed by Brothers et al. (2012). This paper presents the results of a study conducted on a field of shallow-water pockmarks (< 30 m of water depth) located in the eastern part of the Bay of Concarneau, Southern Brittany, France (Ehrhold et al. 2006; Baltzer et al. 2014; Reynaud and Baltzer. 2014). This area is characterised by a high density of pockmarks (an average of 3500 structures/km^2) associated with dense *Haploops* tube benches covering muddy environments. The limits of the pockmark field coincide with the expansion of the *Haploops* communities (Souron 2009), revealing specific link(s) between them. Reynaud et al. (2014) proposed 3 hypotheses for this link, a food link, a constructional link (fine sediments supplied by re-suspension is used for tubes building) or a reproduction/dispersion link (the pockmark activity may keep the larvaes inside a limited area with specific geochemical conditions. Each of these links supposed that pockmarks are active, at least sometimes.

In order to explore the potential activity of this pockmark field, this paper presents the results of two surveys, Pock and Ploops (2011) and Ploops and Tide (2014), conducted at the same season (April), and using the interferometric sidescan sonar (I2S) and chirp tools of the O/V Haliotis, characterised by a very accurate positioning system, coupled to a RTK beacon. Thus it was possible to compare the state and the space-time evolution of this pockmark field between April 2011 and April 2014 using these high-level resolution tools. The analyses of the data sets from 2014 allow to determine the evolution of the acoustic clues of ascending gas, such as blank columns and gas chimneys, and thus will indicate the state of the vertical connections between the sources and the pockmarks (surface gas expression) over a 3 year time-frame. These observations better constrain the gas availability of the system and eventually provide some clues for the preferential pathways used for gas recharge and gas

expulsion. The only known fact is that gas is biogenic methane (Baltzer et al. 2014; Dubois et al. 2015). The questions addressed here are: 1) Is there a continuous activity for these pockmarks? 2) If not, what is the rhythm of expulsion? 3) Where does the gas come from?

1 General setting

Situated in Southern Brittany (Fig. 1), the Bay of Concarneau covers an area of approximately 200 km^2 above the 50 m isobath. It corresponds to a tectonic depression with a width of 5-6 km and a length of about 15 km. The bay is bounded by major structural features associated with the Kerforn fault system (N160) (Béchennec et al. 1997) which controls the incised valley of Concarneau (Proust et al. 2001). Middle Eocene sandstone and calcareous formation unconformably overlap the crystalline basement rocks. These Eocene series (e 5-6), faulted and folded, are incised by paleo-valleys that preserve sparse marine calcareous infillings of the upper Oligocene (Bouysse et al. 1974). Two paleo-valley systems, oriented N120, parallel to the south Armorican fault system and N160 (Kerforn system) respectively, were deepened from the end of the Eocene to the beginning of the Oligocene (Pinot 1974). These relatively narrow and sinuous palaeo-valleys (200-500 m in width for lengths of 20 and 18 km) converge to form a large and unique drainage system (4 km wide) in the South of the Pointe de Trévignon (Fig. 2). Fluviatile and estuarine pleistocene deposits infill this drainage system. An holocene sedimentary layer, characterised by a thickness of 3 to 5 m, covers the entire area (Menier 2003), except for some plateaus like the Maërl Terrasse between Concarneau and Trévignon (Ehrhold et al. 2006).

The hydrodynamic conditions of the study area are characterized by their close dependence on the geomorphological context. The strongest swells are generally associated with westerly gales. To the South of Belle-Ile, waves are of a height ranging from 4 to 6 m (Hs), a mean period of 6 to 8 s^{-1}, and mainly come from the W-NW (Tessier 2006). The Bay of Concarneau is relatively protected from swell dynamics, due to the presence of shallow waters and rocky platforms like the Pourceaux, and the Glénan Islands (Pinot 1974). The tide is semi-diurnal with a range of 5.5 m for a tidal coefficient of 120. Tidal currents are moderate with a mean value of 0.25 m/s^{-1}, integrated on the water column, for a tidal coefficient of 90 (unpublished data from P. Bailly du Bois, IRSN). Surface currents can reach a

velocity of 15 - 30 cm/s^{-1} whereas under-water velocities range from 0 - 5 cm/s^{-1} for a coefficient of 100 (Tessier 2006). Tidal currents describe a clock wise movement, from South to South-West during ebb to North to North-East during floods. Locally, the intensity of the current is lower than 30 cm/s^{-1} between Concarneau and Trévignon.

2 Data and methods

2-1 Acoustic measurements acquisition

The data used in this study is the result of two oceanographic sea surveys. The Pock and Ploops survey was conducted in April 2011 aboard the Oceanographiv Vedette O/V Haliotis (Ifremer/Génavir). This vessel is equipped with a hull-mounted interferometric sonar (GeoAcoustics GeoSwath, 250 kHz) which allowed simultaneous acquisition of bathymetric and sonar images. 1250 km of profiles were acquired, with 96 profiles obtained in four non-contiguous areas, area 1, area 2, area 3, area 4 (Fig. 1 & 2). The Pock and Tide survey in April 2014 aboard the O/V Haliotis complemented the 2011 data set with the acquisition of 205 additional profiles (shaded lines on figure. 1); additionally, some profiles acquired in 2011 were exactly replicated in 2014 (shaded lines within the areas 1, 2 , 3 and 4 on figure 1).

2-2 Acoustic measurements processing

The 2011 and 2014 survey sidescan sonar data was processed with GeoTexture (GeoAcoustic) and bathymetry data with CARAIBES software, developed by Ifremer. The bathymetric and sidescan sonar resolutions are respectively 80 and 50 cm. This acoustic data was exported and interpreted in ESRI ArcGIS. Sidescan sonar data gives a picture of acoustic backscatter properties of the seabed which is illustrated by a grayscale image (Augustin et al. 1994). Acoustic backscatter varies depending on the angle of incidence of the acoustic wave front to the seabed, the impedance contrast across the sediment-water interface, surface roughness, and bathymetry and volume reverberation. Grey tones of the sonar image will depend on the nature and the compaction of the sediment, as well as on the

topography of the seabed. Light tones generally represent low backscatter, such as relatively finer-grained and underconsolidated sediments and dark tones represent high backscatter, such as relatively coarser-grained or compacted sediments, while a high slope gradient will appear darker. Seventeen Shipeck core boxes were sampled during the second survey to identify and confirm the *Haploops* acoustic facies on sonar images.

The picking of the pockmarks was realised manually, on ArcGIS (Reynaud and Baltzer, 2014) providing an accurate map (resolution of 50 cm) of the pockmark distribution. Tidal corrections and centimeter precision positioning of data were made possible thanks to an Aquarius Thalès GPS, an RTK beacon located on the coast and a tide-gauge-buoy.

3 Results

3-1 Bathymetry maps

For each of the areas (large black frame), of the bathymetry map, 1 focus zone (small white frame) was selected within areas that were surveyed both in 2011 and 2014 (Fig.1). The global bathymetry map, grouping data from 2011 and 2014 acquisitions, is shown on Figure 2. The exceptional density of the pockmarks (5 840 features/km ^{2}) is much higher than the usual descriptions found in the literature (Garcia-Garcia et al. 1999; Ferrin et al. 2003). Presenting a sub-circular to circular shape, in particular aalong the palaeo-valleys, and the diameter of the pockmarks varies from 5 m (exceptionnally less than 1 m-limit of the sonar resolution) to 35 m with only a few decimetres in depth. Pockmark depths are difficult to measure as chirp profiles do not often exactly pass through pockmarks. The comparison of bathymetry sets for the 4 focus zones (Fig. 3) clearly shows that almost all the pockmarks occurred at the same location in 2011 and 2014, without any substantial change between these two dates, except a trend towards more marked features in 2014. This may be explained by the data processing : the same resolution was used for both dates but not the same colour code, which explains the different aspect of the 2011 maps (Fig. 3). On all the focus zones, the global distribution remain similar with some very few changes in pockmarks locations: the black circle or oval covers the same area sample, and reveals a new pockmark distribution

On focus 1, trawl-scour pockmarks appear, perfectly visible and aligned, in 2011 and in 2014. On focus 2, a third pockmark seems to have occurred in the right circle, and two pockmarks appear more marked in the black oval, on the left. On focus 3, a new pockmark occurred in 2014, underlined by the circle on the right (Fig. 3). On focus 4, the black circle on the right designates the occurrence of new pockmarks. Eventually, Focus 5 shows an extract of the bathymetry acquired in 2011 (location on Figure 2), where it is possible to distinguish small pockmarks (around 8 meters), large pockmarks (around 25 meters) and within the large ones, some deeper pockmarks (alpha type), with a net crater shape or shallower pockmarks (beta type) with a smoothy crater shape.

3-2 Sidescan imagery

Sidescan imagery has revealed that the limits of the settlements of *Haploops* colonies (Fig. 2) coincide with the presence of a field (36 km^2) of pockmarks (Baltzer et al. 2014). This field extends to the South of Trévignon, up to the nort-east of the Glénan Islands (Fig. 2). The main result of the comparison of the sonar images from 2014, confirmed by direct-field observations with scuba-diving, is that the distribution of the *Haploops* colonies is related to the pockmark field limits all around the studied area. To the south, tubes benches have become discontinuous and have begun to be more and more fragmented, to finally disappear just after the pockmark field boundaries (Ehrhold et al. 2006; Baltzer et al. 2014)

The comparison of the two sonar mosaics reveals that for some pockmarks, located along the east edge of the area 2, there is some thin layer of mud deposit in 2014 which was not there in 2011.

3-3 Seismic profiles

A total of 98 seismic chirp profiles were acquired during the sea surveys realised in 2011 in 4 areas (Fig. 1 & Fig. 2), and 205 profiles were acquired in 2014 to complete the survey. In each area, some profiles acquired in 2011 were exactly replicated in 2014. Figures 4, 5, 6 and 7 present one

225 characteristic profile realised for each area. The sedimentary infilling of the Bay of Concarneau has
226 been studied for decades and the interpretation is based on the four seismic units described by Menier
227 (2003) and used by Baltzer et al. (2014). Above the bedrock composed of paleozoic granite and
228 oligocene sandy limestone (Unit 0), three seismic units infill the incised palaeo-valley (Figs. 4, 5, 6, &
229 7). Unit 1, not observed in the area because of gas occurrence, is a relict unit, only preserved as
230 patches in the deepest parts of the valley, correlated to braided fluvial sediments aged from middle
231 Pleistocene by Laurent (1993),.. Unit 2 is composed of low amplitude flat parallel reflectors, which
232 onlap the valley sides and locally downlap the base unit, interpreted as inner mud flat facies. Unit 3
233 occurs above Unit 2 and presents a surface characterised by a smooth sided U-shaped channel. The top
234 of this Unit corresponds to an erosional surface and represents tidal flat deposits with coarser lag
235 deposits within tidal channels. Unit 4 extends over the whole of the valley system, except on the
236 terrace situated between Concarneau and Trévignon, which is covered by rocky shoals and maerl beds
237 (Fig. 2) (Ehrhold et al. 2007). Most of this unit is composed of flat-bedded agrading deposits,
238 characterised by low seismic amplitude reflectors and corresponds to unconsolidated Holocene muds,
239 rich in turritelids (Bouysse et al. 1974; Ehrhold et al. 2006).
240
241 The limits of the pockmark field correspond to the lateral extension of seismic Unit 3 (Baltzer et al.
242 2014). This unit is cut by different acoustic anomalies, called “acoustic turbidity”, “acoustic blanket”,
243 “acoustic curtain”, “acoustic column” or “pillar shaped” and chimney pipesdepending on their lateral
244 extension, (Hovland and Judd 1988; Garcia-Gil 2002; Baltzer et al. 2005; Akulichev et al. 2015).
245 While the pockmark distribution is related to the existence of Unit 3, the size of the pockmarks tends
246 to correspond to the thickness of this unit. The small pockmarks are correlated with a maximum
247 thickness of 3 ms (4,5m) for Unit 3, with a gassy reflector situated around 2 ms (1,5m) below the
248 seabed. The larger pockmarks correspond to a thickness of up to 12 ms (9 m) for Unit 3, with a gassy
249 reflector observed from 4 ms (3,5 m) to 8 ms (6 m). Within this large pockmark group, some of them
250 appear to be aligned along the palaeo-valley edges, related to the sedimentary infilling of these paleo-
251 valleys (Baltzer et al. 2014).
252

Figure 4 presents profile 82 (2011) and profile 72 (2014), revealing 3 branches of the palaeo-river along the Kerforne fault (Fig. 3). Gas facies occur in the two eastern branches and cross through units 2 and 3 up to the surface. The seabed surface corresponds to a serrated (saw-shaped) reflector, due to the presence of *Haploops* tubes and pockmarks, clearly visible between shots 400 and 1600. It is framed by a continuous sea bottom reflector, with no *Haploops* benches, visible from shot 0 to 100 and from 1650 to 2100. Profile 72, (the poor quality is due to the weather), shows that gas was still present in 2014, confined exactly to the same places, reaching the surface via the same acoustic columns.

Figure 5 shows profiles 68 (2011) and 32 (2014) which cross the Kerforne paleo-valley and the western branch (Fig. 3). Bench tubes colonize the whole seabed surface (serrated seabed reflector) and some large pockmarks occur above the main palaeo-valley, especially along the valley edges, connected to the gas ascension seen in the acoustic columns or chimney pipes. The blanket acoustic facies correspond to the infilling of the western branch, characterized by smaller pockmarks issued from the interfluve. The same pathways crossing units 2 and 3 were used, with three chimney pipes (red circles) reaching the seabed.

Figure 6 reveals large pockmarks on the surface connected with subjacent acoustic blanket facies. The seabed topography underlines the interfluve between the palaeo-valleys. The top of Unit 2 presents a discontinuous surface, slightly hummocky, with large and irregular depressions. These depressions are connected with the acoustic blanket underneath and resemble to the actual surface pockmarks, but larger in size. Note that the he density of surface pockmarks reflects the proximity of the sub-bottom gas blanket.

Figure 7 shows a clear bulge corresponding to the actual interfluve superimposed on a paleo bulge, together with depressions (similar to large pockmarks?). The occurrence of large pockmarks on the left part of the bulge seems to be related to the presence of a gas “diapir”, which is connected to reflectors underneath. Does this reflector represent a preferential conduit for gas circulation, down-lapping the bulge? Each time gas is close to the surface, large pockmarks occur.

All the seismic profiles, within each of the different areas, present very similar profiles in 2011 and 2014, with the same visible gas column ascension pathways (chimney pipes), occurring at the same places with the same connections to the surface towards the pockmark features.

Discussion

The first question is whether these pockmarks are still active, just dormant or fossil features? Judd and Hovland (2007) hypothesized that most pockmarks discovered are indeed inactive and Brothers et al. (2011), (2013) have shown that pockmarks may be self-scouring features after initial formation.
In the Concarneau's pockmarks field, bathymetry maps show that most of the pockmarks seem to be empty craters like the pockmark Alpha (Fig. 3 – Focus 5), except some pockmarks with unclear crater limits like the pockmark Beta (Fig. 3 – focus 5). Reflectivity images present white backscattering inside some of these pockmarks, attesting that they are infilled with muddy deposits, whereas most of them appear to be free of infilling (Ehrhold et al. 2006; Souron 2009). Video images confirm the presence of fluid mud inside some pockmarks, whereas most of them are empty and surrounded by *Haploops* colonies (Reynaud and Baltzer 2014). The occurrence of several "flares" on the chirp profiles (Figs. 4, 5 and 6) together with flares observed in the water column during mid-current flowing tides for spring tides (Baltzer et al. 2014) indicate the activity of, at least, some pockmarks. Moreover, turbidity was observed by divers during 2011 explorations for biologists works (Dubois et al., 2015) and significant turbidity was observed in the global area in summer 2015 during a SHOM (Service Hydrographique et Océanographique de la Marine) oceanographic cruise (com. pers. from E. Marshes). Two more direct observations tend to confirm the activity of this pockmark field: 1) the persistance of "nude" pockmarks, without any haploops tubes inside, in contrast to the density of the surrounding colonies and 2) the existence of fragmented tubes in some pockmarks, revealing recent gas/fluid expulsion. All these arguments attest the presence of active pockmarks in this field but with a discontinuous activity. Eventually, the presence itself of *Haploops* settlements confirm this observation.

Thus, the second question addressed here where does the gas come from ?

Chirp profiles analyses have highlighted the availability and depth of gas sources (Baltzer et al. 2014), which will, in turn, control the pockmark distribution. Then, the pockmark distribution on the seabed represents the spatial arrangement of individual upward-seepage drainage-conduits connected to the deeper sediment layers and sources. Gas migration and seepage to the surface are usually related to the existence of two geological features, a gas migration source and a preferential route for gas motion (fewer resistance pathways). The comparison of the data sets of 2011 and 2014 reveals that the global distribution of the pockmarks remains similar, and that only a few new pockmarks occurred in 2014. The permanence of this pockmark pattern observed in the 2014 bathymetry (Fig. 3) tend to attest the presence of permanent preferential pathways.

Chirp profiles show these preferential pathways, revealed by enhanced reflectors and chimneys pipes (Figs. 4, 5, 6 and 7). Moreover, the comparison of the chirp profiles, from April 2011 to April 2014, revealed that the gas pathways occurred at the same depth, in the same location, without any or very few vertical or horizontal fluctuations. This observation confirms the stability of the system which supplies, at least for 3 years, gas from palaeo-valley floor sources to the surface.

The distribution of the pockmarks related to the palaeo-valleys is in agreement with several scientific papers (Garcia-Gil et al. 2002; Ussler et al. 2003; Rogers et al. 2006; Brothers et al. 2012; Weschenfelder et al. 2016). Enhanced Gas Reflector identified on chirp profiles (Fig. 4, 5, 6 and 7) correspond to gassy sediment levels issued from biogenic gas, methane (Baltzer et al. 2014; Dubois et al. 2015), generated by bacterial activity buried under a few metres in sediment rich in organic matter along the paleo rivers (at least 7% from Floodgate and Judd (1992); Garcia-Gil et al. (2002). Different authors describe such gassy sediment levels at the Pleistocene/Holocene interface (Chronis et al. 1991; Gontz et al, 2002; Weshenfelder et al. 2016) as being related to the significant organic matter degradation in the infilling transgressive deposits, sealed by thin Holocene muds. The combination of the permeability of this sealing layer and its resistance to stress build-up controls the rate of gas/fluid leakage from the reservoir to the surface. Once the upward pressure decreases, a pockmark will form a circular shape. Cathles et al. (2011) have shown that when a gas chimney reaches halfway from the reservoir to the seabed, liquefaction of overlaying sediments initiate pockmark formation. Kluesner et

al. (2013) shows that gas migrates upwards through conduits (e.g. faults) and intra sedimentary discontinuities, along the valley edges, (e.g. until gas is blocked by a sealing layer). The figure 8 shows on the left-hand side, the pockmark distribution obtained by hand made plotting (Reynaud and Baltzer, 2014). On the right-hand side, the superimposition of the pockmark density map with the geological BRGM map, shows that the limits of the pockmark field is restricted almost exactly to the eocene calcareous outcrop in (e 5-6), a nummulitic limestone (Lutetian to Bartonian age). This formation is strongly faulted, faults belonging to the Kerforne faults system, and underlined by black lines on the Figure 8. The pockmark density appears to be exceptional, with densities up to 5840 features/ km^2, when faults are combined with the presence of palaeo-valleys junctions. Patches without any (or very few) pockmarks (<290) do not show specific distribution, probably related to the sedimentary cover itself and the different permeability and resistance to stress of the intrasedimentary sealing layer. Thus, the preferential pathways supplying large pockmarks, situated along the palaeo-valley edges and within the palaeo-valley infilling itself, were initiated during seismic events which have shaken the faulted Eocene, creating migration pathways into the sedimentary column (U2, U3,U4) for escaping methane. Cathles et al. (2010) pointed out that once a pockmark forms, depletion of the gas reserve can occur as quickly as within one year. After this period, the pockmark will become dormant and during dormancy, shallow gas reservoirs can recharge. Judd and Hovland (2007) noted that vertical stacking of pockmarks in seismic data points to episodic reoccurrence of discharge.

Then, the last question is related to the dormancy period of the pockmarks of Concarneau and the rhythm of the gas/fluid/ expulsion. Baltzer et al., (2014) proposed as triggering mechanisms that short term pressure controlled by the tide could be superimposed on longer term temperature controlled processes and episodically on earthquake occurrence.

The results presented in this paper reveal that pockmarks activity is discontinuous but sufficiently frequent to keep chimneys pipes and intra sedimentary pathways permanent (visible) for 3 years into the sedimentary columns. Combining these observations, two models are proposed in Figure 9, illustrating two cases: the “bottom-up” and the “top-down” preferential pathways for gas migration.

The first one illustrates the natural migration of the gas stored in the valley sedimentary infilling, through the units U2, U3, and U4 and the second one shows the anthropogenic induced migration, through the trawl-scours pathways. For both models, the gas (biogenic methane) is issued from the bottom of a paleo-valley, deep enough to allow the maturation of buried organic matter. If the thickness of the sedimentary infilling is not sufficient (palaeo-valley on the left of the block diagram), there is no clue of any gas discharge (no pockmarks).

The "bottom-up" model supposes that the initial pockmark craters were formed during seismic events which have shaken the faulted Eocene, creating preferential pathways in the sedimentary column (U2, U3,U4). The shifting of the gas horizon (EGR), materialised by red arrows on Figure 9, illustrates the shifting of methane solubility due to the spring tidal pressure (Diez et al. 2007). This shifting would enable the gas horizon (EGR) to reach the chimneys pipes, possibly at different levels, like at the base of estuarine muds of U3 or at the base of intercalated storm deposits of U4. Thus, each time the tidal pressure is high enough, during spring tides or storms, the tidal pumping effect connects the "bottom-up" pathways to the chimney pipes and pockmarks are re-activated: flares may be observed in the water column.

The "top-down" model illustrates the case of a preferential pathway originated from the seafloor and descending to reach the gaz horizon (ENG). In this case, these preferential patways have been created by the trawling action and result in trawl-scour pockmarks, a process similar to the iceberg-scour pockmarks one . As for the first model, the connection is realised and the pockmark is active when spring tide overpressure is sufficient.

These observations give an intermittent pattern of pockmarks activity, which will be a function of the EGR depth, the water depth and the tidal (or storms) overpressure conditions. The proposed hypothesis is that during each spring tide, some permanent pockmarks are re-activated, depending on their water depth and the spring tide coefficent. New pockmarks may be created only during storms or earthquake events, which would explain their small numer.

These observations imply that the quantity of gas supplied in the water column may be substantial and that the gas recharge is continuous. Such observations were made by Hasiotis et al. (1996) who described such acoustic turbidity in the Gulf of Patras and suggested that there is a continuous supply of gas towards the pockmarks from below, and that the sediments within the migration path are loaded with gas.

To undertake further study in this area, the objective will be to record gas/fluid expulsion in the water column, and to understand the rhythm of these expulsions. To do so, one long piezometer and a special monitoring tool for gas/fluids and turbidity measurements (from SHOM/IFREMER), will be implanted for longer term observations in this pockmark field.

Conclusion

The pockmarks of the Bay of Concarneau appear to be active, probably due to combined trigger processes occuring at different time scales. Earthquake movement (common in this area) may be relayed or added to short-term controlled tidal pressure (spring tide) processes, thereby triggering gas escape along preferential pathways. These pockmarks are connected to the paleo-valley infillings, along intra-sedimentary and structural discontinuities, continuously supplying gas to the upper sedimentary layer. The expulsion process is activated when connection between the gas horizon (ENG) and preferential pathways is realised. This system appears to be stable, at least for a short time scale (decades) revealed by the constant distribution of pockmarks. An intermittant regular pattern of expulsions is proposed here, which is function of the tidal overpressure, the water depth, and the depth of the ENG. It is suggested that exceptionnal overpressure induced by storms or earthquakes may create new pockmarks. Neverthless, the rhythm of expulsion together with the nature itself of the expulsed gas/fluid need to be explored. Future work will focus on the above water column study with the implantation during at least 6 months of a camera and a piezometer. This next research project will allow the measurement of the volume of gas produced and injected into the water column of this bay.

Acknowledgements

Special thanks are due to the captains of the Oceanographic Vedette Haliotis Arnaud Gillet and the informatic engineer Renaud Cagna. The first sea survey (2011) was partly funded by the Total Foundation for Biodiversity and the Sea in the framework of an IFREMER/TOTAL project. This article benefitted from rich and constructive feedback from the two reviewers.

Figure captions:

Figure 1: Location of the profiles acquired during the two oceanographic sea surveys realised with the O/V Haliotis in 2011 (Pock and Ploops) and 2014 (Pock and Tide) between Concarneau estuary, Trevignon spur and Glénan Islands. For each profile, bathymetric, sonar images and chirp data have been acquired. Four areas were delimited (black frames) during the 2011 sea survey and were completed during the 2014 sea survey (dashed grey lines). White frames delimit 5 focus zones. For focus zones 1, 2, 3 and 4, profiles were renewed in 2014 (figure 2). The black line limits the extension of the *Haploops nirae* mats.

Figure 2: Bathymetric map of the area compiled from data acquired in 2011 and 2014. Palaeo-valleys, determined from chirp profiles, have been superimposed on the map (dark blue). Red lines show the location of the profiles selected in figures 4, 5, 6 and 7.
The white line represents the Haploops area limits: it has been drawn on the side scan imagery, where black grey facies corresponds to *Haploops* tubes (see photos) and light grey facies corresponds to mud with no *Haploops* tubes present. The white frames represent the focus zones from 1 to 5.

Figure 3: For Focus 1, Focus 2, Focus 3 and Focus 4 zones, (white frames in figure 1), an extraction of bathymetric maps was realised in 2011 and 2014. The comparison of the two bathymetric extractions reveals the almost perfect superimposition of pockmarks from 2014 and 2011. Focus 5 shows a detailed bathymetry map with large and small pockmarks. Large pockmarks (> 20 m) usually occur very clearly on the bathymetry, such as the Alpha pockmark indicated, but may sometimes

present smoother contours.

Figure 4: Area 1: chirp profile 82 was realised in 2011and was replicated in 2014 (profile 72), exactly at the same location (see location on figure 2). Interpretation of Profile 82 reveals the presence of gas intercalated in the different valley branches. Gas pathways issued from the bottom of the palaeo-valleys occurred at the same places in 2011 and 2014 (whereas the 2014 data quality is poor, because of the weather).
The sea-bottom reflector appears to be continuous and highly reflective in the absence of *Haploops* tubes, whereas it presents a serrated shape when *Haploops* tubes are present.

Figure 5: Area 2: chirp profile 68 was realised in 2011 and was replicated in 2014 (profile 32), exactly at the same location (see location on figure 2). Interpretation of Profile 68 reveals the presence of gas within the main valley. Gas issued from the bottom of this paleo-valley followed the same pathways in 2011 and 2014, materialised by chimney pipes (red circles), and creating pockmarks (red circles) on the sea floor. A flare occurs on profile 68, which was not present in 2014.

Figure 6: Area 3: chirp profile 41 was realised in 2011 and was replicated in 2014 (profile 178), exactly at the same location (see location on figure 2). Interpretation of Profile 41 reveals the presence of gas within the main valley, and the absence of gas within the small buried valley on the left. There are no *Haplooops* tubes above the small buried valley. Gas issued from the bottom of the paleo-valley followed the same pathways in 2011 and 2014, materialised by chimney pipes (red circles), and creating pockmarks on the sea floor surface.

Figure 7: Area 4: chirp profile 30 was realised in 2011 and was replicated in 2014 (profile 122), exactly at the same location (see location on figure 2). Interpretation of Profile 30 reveals the presence of gas within the main valley, and the absence of gas within the small buried valley on the left. There are no *Haplooops* tubes above the small buried valley. Gas issued from the bottom of the paleo-valley followed the same pathways in 2011 and 2014, materialised by chimney pipes (red circles), and creating pockmarks on the sea floor surface.

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Figure 8A: Pockmark distribution merged from 2011 and 2014 data. All the pockmarks have been manually plotted (resolution of 50 cm).

Figure 8B: Superimposition of the geological map (1:250 000 vectorised map from BRGM) with the map of pockmark density. The black lines delimit the *Haploops nirae* area. The light brown line delimits the eocene outcrop (e5-6), coloured in yellow on the geological map. Faults are underlined by a black line and the paleo-valleys are represented by blue lines.

Figure 9: Two sketches illustrating the possible pathways for gas migration are presented in this paper: the upper block diagram shows a "bottom-up" model and the second diagram shows a "top-down" model for gas along preferential pathways.

Figure 9A: The "bottom-up" model shows the gas, issued from the buried organic matter at the bottom of the buried valley, migrating along preferential pathways in U2. Gas is stopped and stored just under the EGR (Enhanced Gas Reflector) at the top of U2. A second network of pathways may conduct gas through U3 up to the base of U4. Consequently, gas is able to migrate up to the sea floor surface, via tidal pumping processes, creating the large pockmarks. Note the presence of chimney pipes within the unit U4.

Figure 9B: The "top-down" model illustrates the specific case of the trawl-scour pockmarks. These pockmarks have been triggered by the trawls of fishing boats on the sea floor. The digging action initiates a preferential pathway for gas escape, resembling iceberg-scours.

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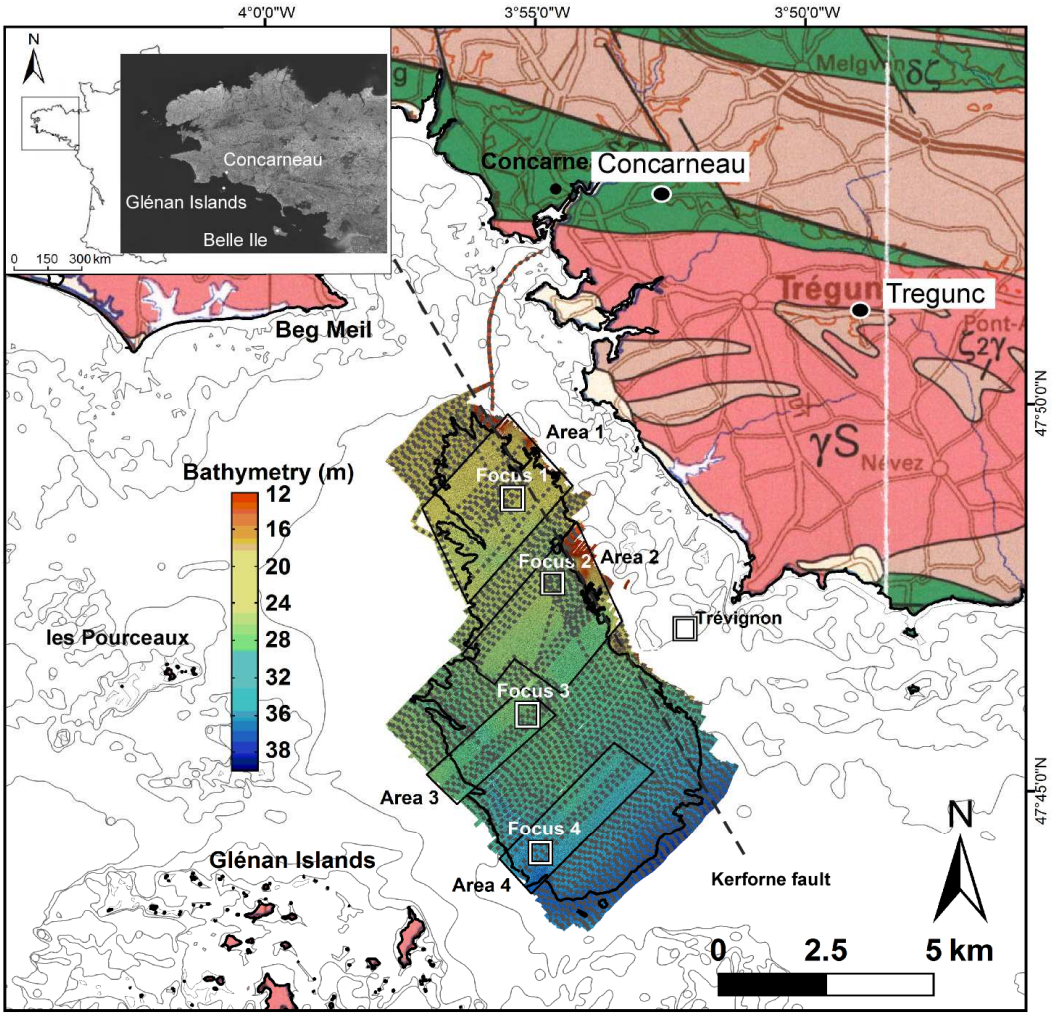
Figure 1



Data acquired during Pock & Ploops (2011) : Areas 1, 2, 3 and 4

Data acquired during Pock & Tide (2014)

Haploops nirae area limits

Selected focus 1, 2, 3 and 4 (profiles acquired in 2011 and 2014)

Base map: 1/250 000 vectorised geological map from BRGM

Figure 2

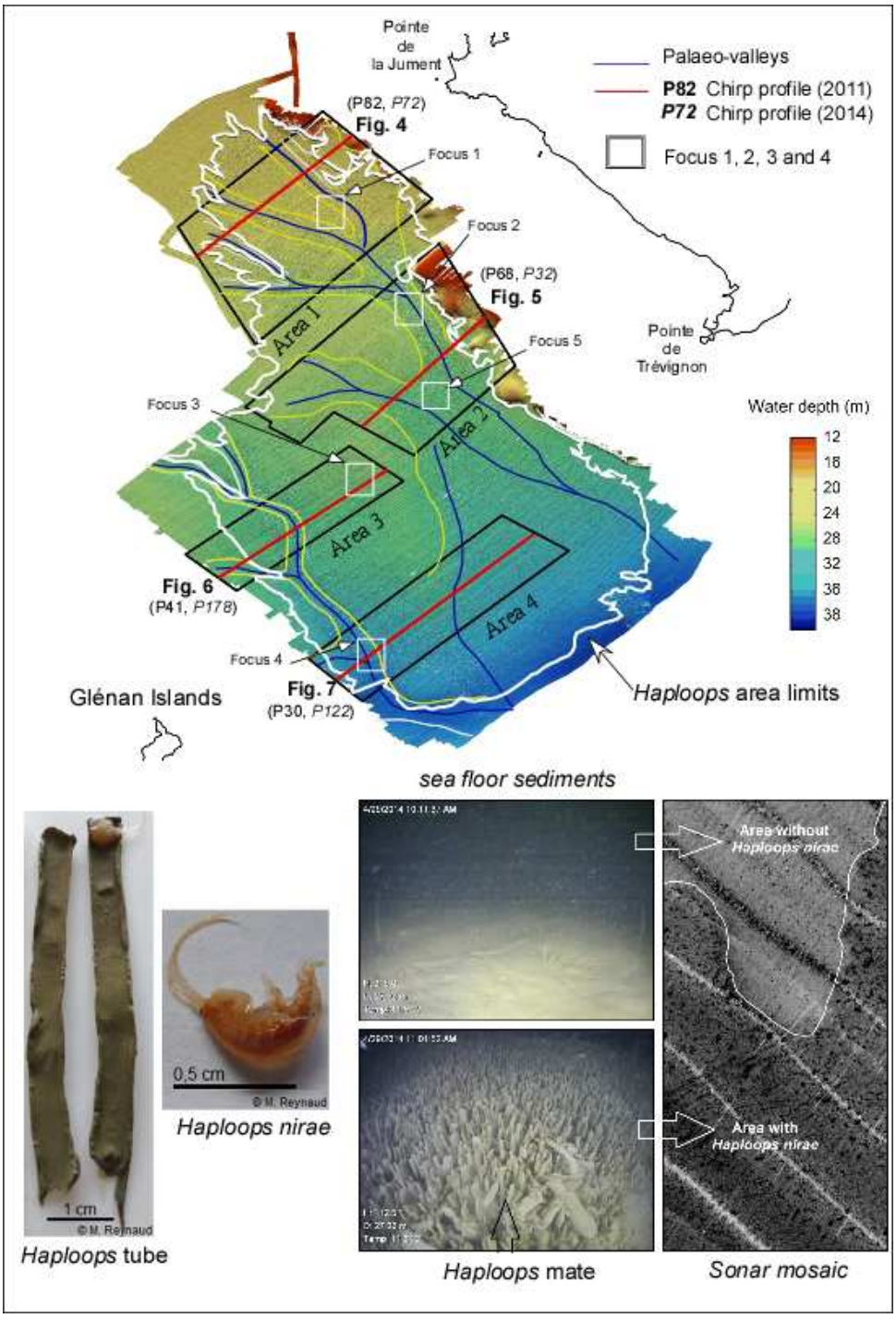

Pointe de la Jument
(P82, P72)
Fig. 4
Palaeo-valleys
P82 Chirp profile (2011)
P72 Chirp profile (2014)
Focus 1, 2, 3 and 4
Focus 1
Focus 2
(P68, P32)
Fig. 5
Area 1
Focus 5
Pointe de Trévignon
Focus 3
Area 2
Water depth (m)
12
16
20
24
28
32
36
38
Area 3
Fig. 6
(P41, P178)
Area 4
Focus 4
Fig. 7
(P30, P122)
Glénan Islands
Haploops area limits
sea floor sediments
1 cm
© M. Reynaud
Haploops tube
0,5 cm
© M. Reynaud
Haploops nirae
Area without Haploops nirae
Area with Haploops nirae
Haploops mate
Sonar mosaic

Figure 3

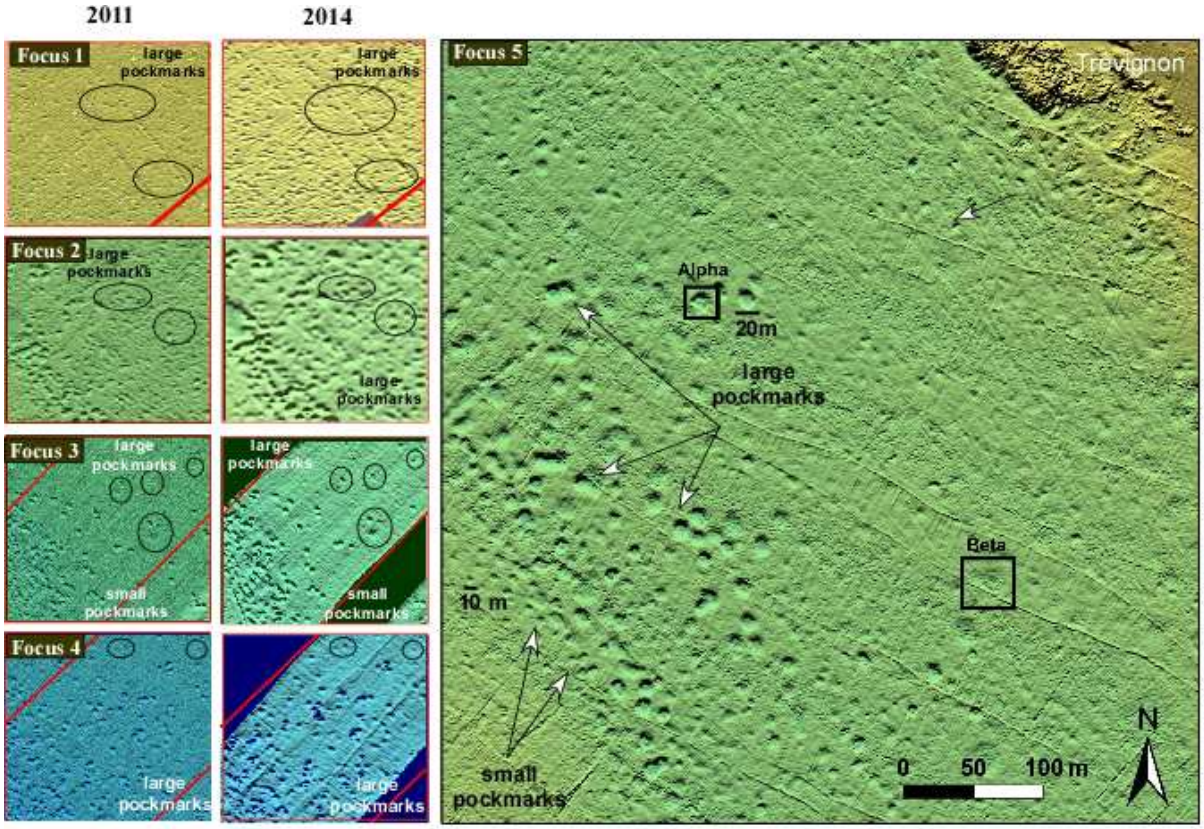
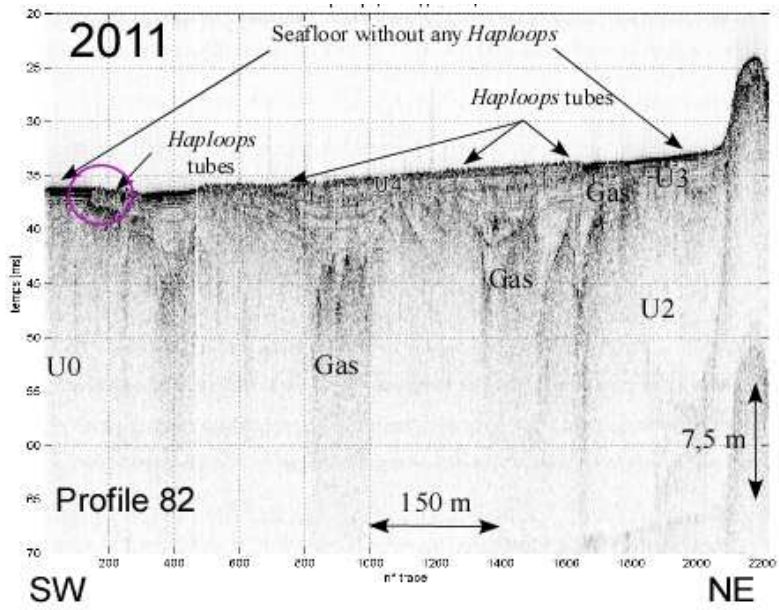
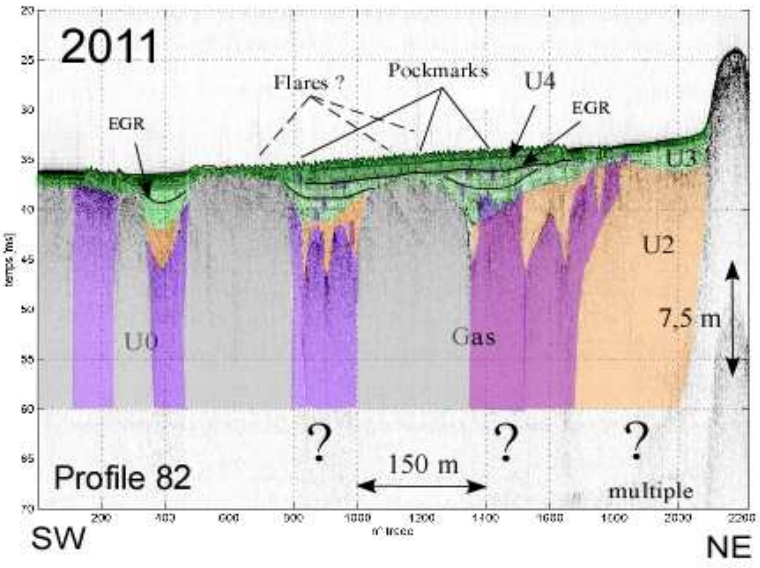
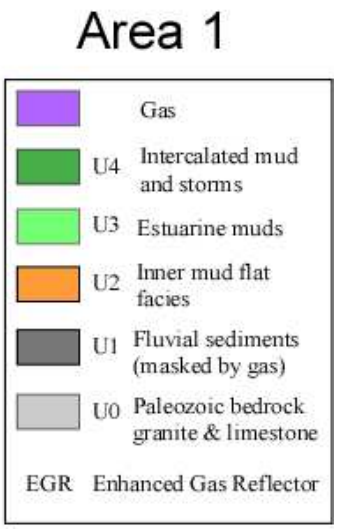

2011
2014
Focus 1
large pockmarks
large pockmarks
Focus 2
large pockmarks
large pockmarks
Focus 3
large pockmarks
small pockmarks
large pockmarks
small pockmarks
Focus 4
large pockmarks
large pockmarks
Focus 5
Trevignon
Alpha
20m
large pockmarks
Beta
10 m
small pockmarks
0 50 100 m
N

Figure 4


2011
Seafloor without any *Haploops*
Haploops tubes
Haploops tubes
U4
Gas
U3
Gas
U2
U0
Gas
7,5 m
Profile 82
150 m
SW
NE


2011
Flares ?
Pockmarks
U4
EGR
EGR
U3
U2
U0
Gas
7,5 m
?
?
?
150 m
multiple
Profile 82
SW
NE


Area 1
Gas
U4 Intercalated mud and storms
U3 Estuarine muds
U2 Inner mud flat facies
U1 Fluvial sediments (masked by gas)
U0 Paleozoic bedrock granite & limestone
EGR Enhanced Gas Reflector

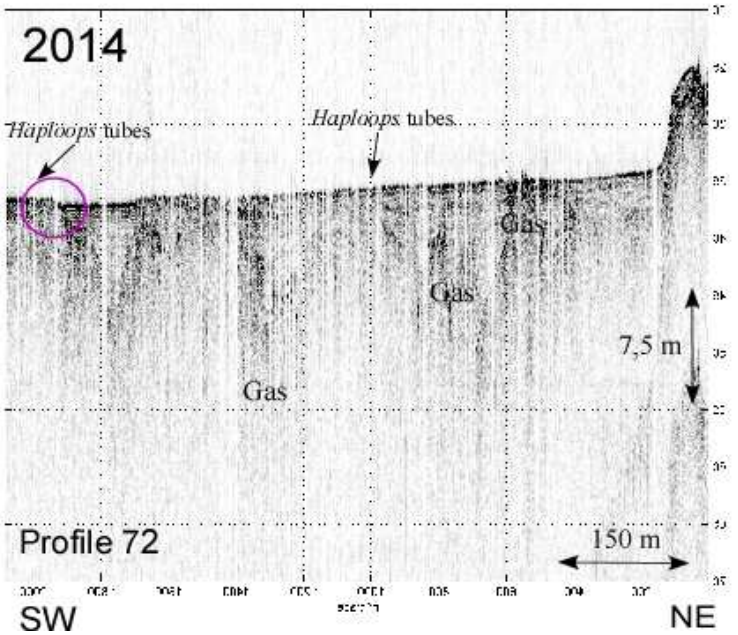

2014
Haploops tubes
Haploops tubes
Gas
Gas
7,5 m
Gas
Profile 72
150 m
SW
NE

Figure 5

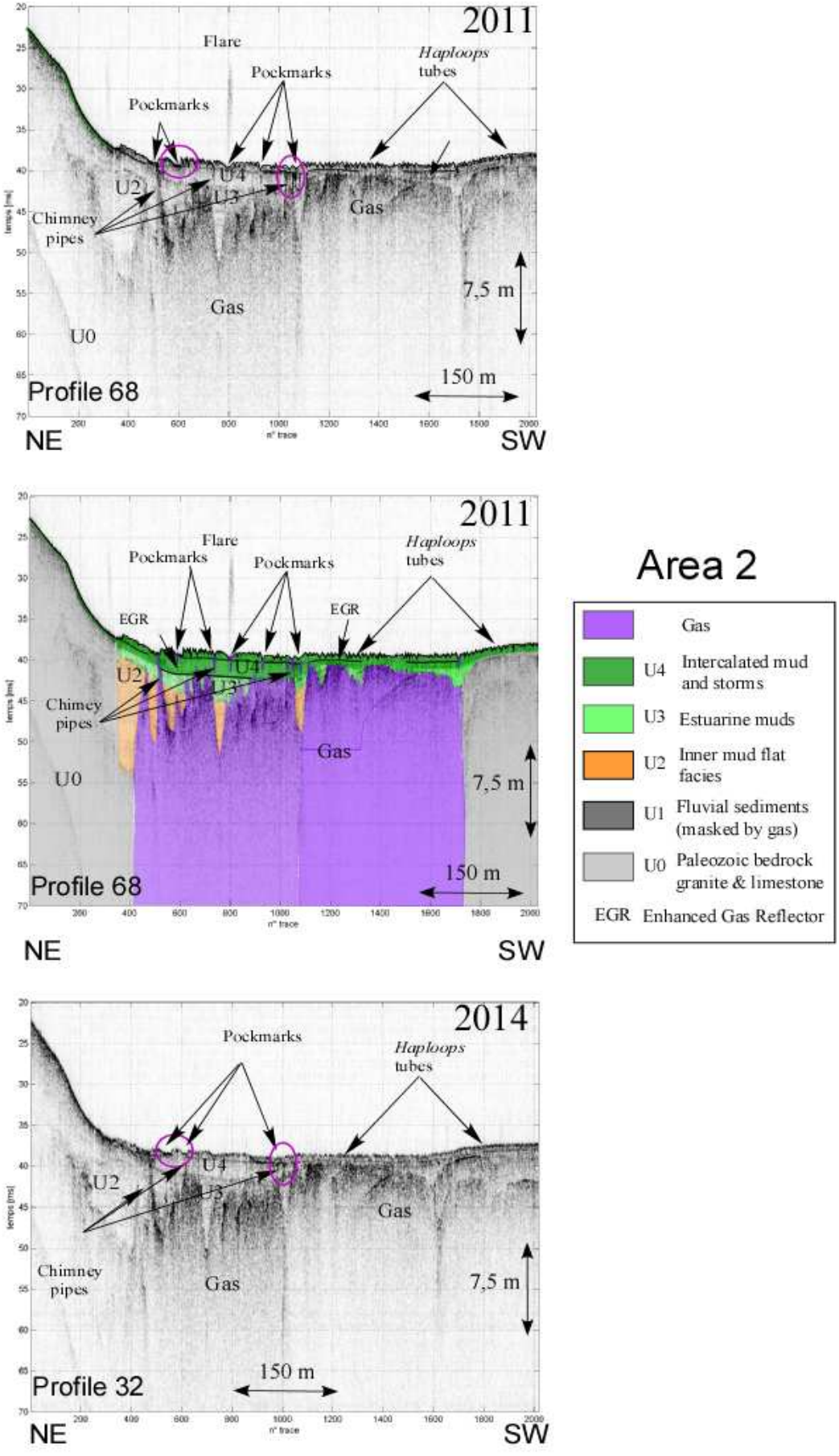
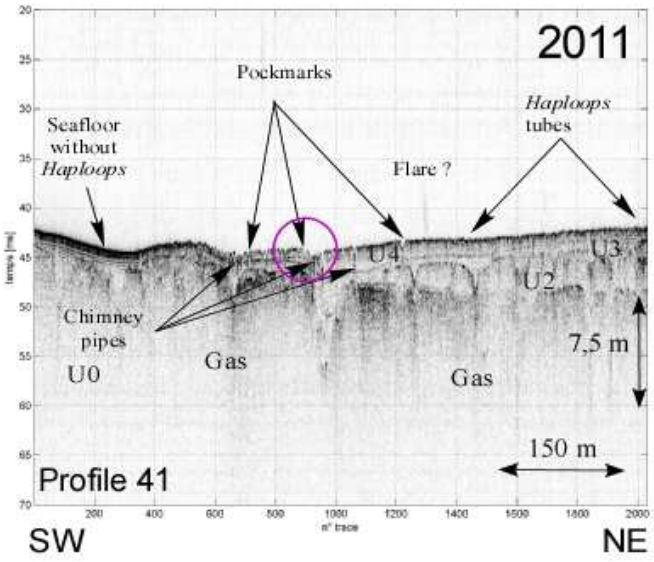
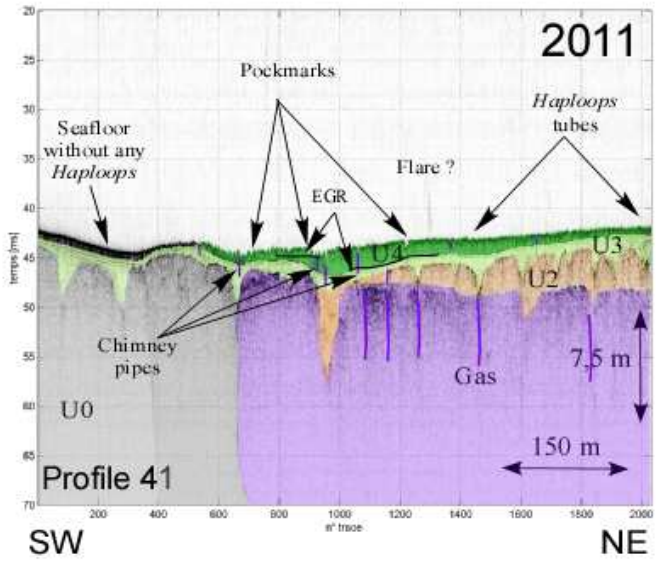
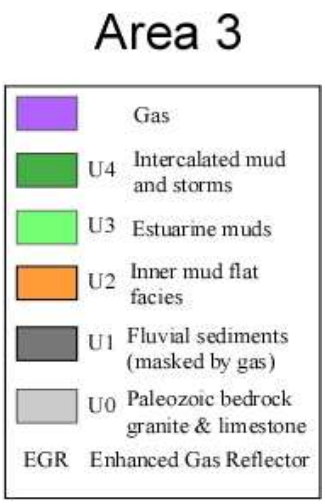

2011
Flare
Pockmarks
Pockmarks
Haploops tubes
U4
U2
U3
Gas
Chimney pipes
Gas
7,5 m
U0
150 m
Profile 68
NE
SW
2011
Flare
Pockmarks
Pockmarks
Haploops tubes
EGR
EGR
U4
U2
U3
Chimney pipes
Gas
U0
7,5 m
150 m
Profile 68
NE
SW
Area 2
Gas
U4 Intercalated mud and storms
U3 Estuarine muds
U2 Inner mud flat facies
U1 Fluvial sediments (masked by gas)
U0 Paleozoic bedrock granite & limestone
EGR Enhanced Gas Reflector
2014
Pockmarks
Haploops tubes
U4
U2
U3
Gas
Chimney pipes
Gas
7,5 m
150 m
Profile 32
NE
SW

Figure 6


2011
Pockmarks
Haploops tubes
Seafloor without Haploops
Flare ?
U4
U3
U2
Chimney pipes
U0
Gas
Gas
7,5 m
150 m
Profile 41
SW
NE


2011
Pockmarks
Haploops tubes
Seafloor without any Haploops
Flare ?
EGR
U4
U3
U2
Chimney pipes
U0
Gas
7,5 m
150 m
Profile 41
SW
NE


Area 3
Gas
U4 Intercalated mud and storms
U3 Estuarine muds
U2 Inner mud flat facies
U1 Fluvial sediments (masked by gas)
U0 Paleozoic bedrock granite & limestone
EGR Enhanced Gas Reflector

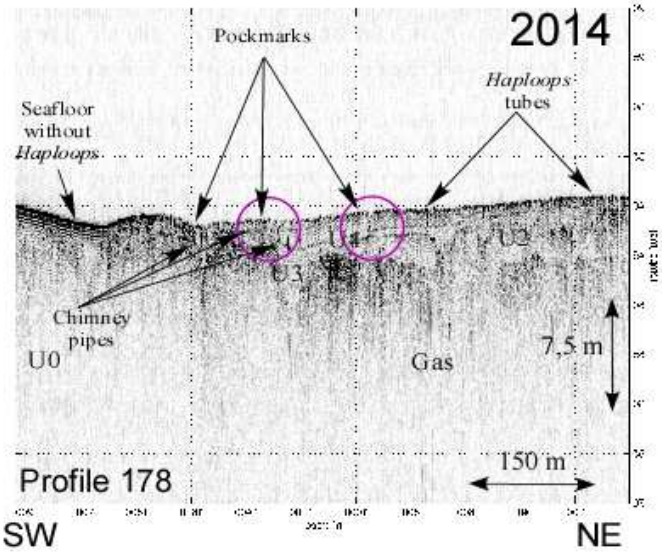

2014
Pockmarks
Haploops tubes
Seafloor without Haploops
U4
U3
U2
Chimney pipes
U0
Gas
7,5 m
150 m
Profile 178
SW
NE

Figure 7

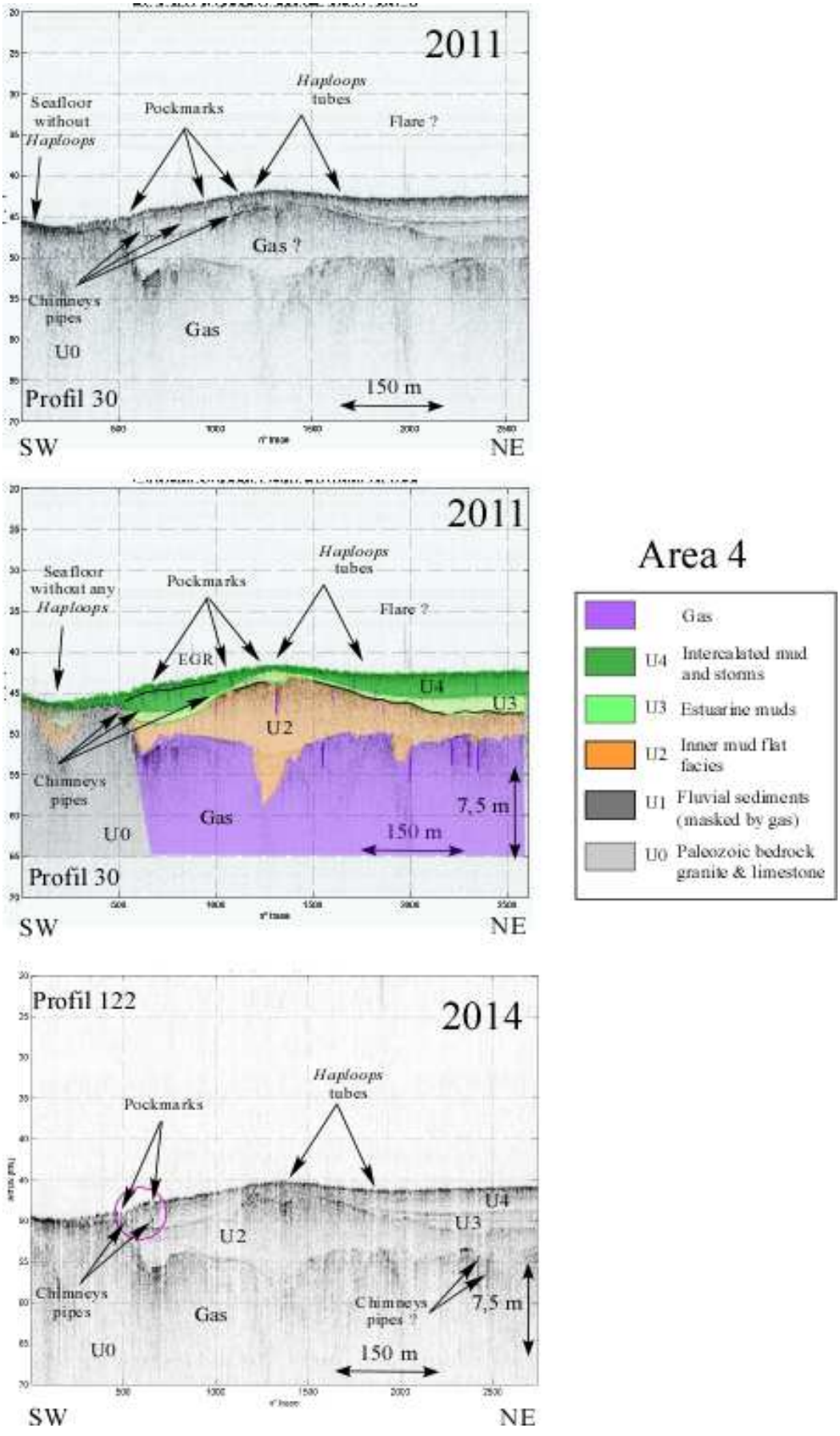

2011
Seafloor without Haploops
Pockmarks
Haploops tubes
Flare ?
Gas ?
Chimneys pipes
Gas
U0
Profil 30
150 m
SW
NE
2011
Seafloor without any Haploops
Pockmarks
Haploops tubes
Flare ?
EGR
U4
U3
U2
Chimneys pipes
Gas
7,5 m
U0
150 m
Profil 30
SW
NE
Area 4
Gas
U4 Intercalated mud and storms
U3 Estuarine muds
U2 Inner mud flat facies
U1 Fluvial sediments (masked by gas)
U0 Paleozoic bedrock granite & limestone
Profil 122
2014
Haploops tubes
Pockmarks
U4
U3
U2
Chimneys pipes
Gas
Chimneys pipes ?
7,5 m
U0
150 m
SW
NE

Figure 8

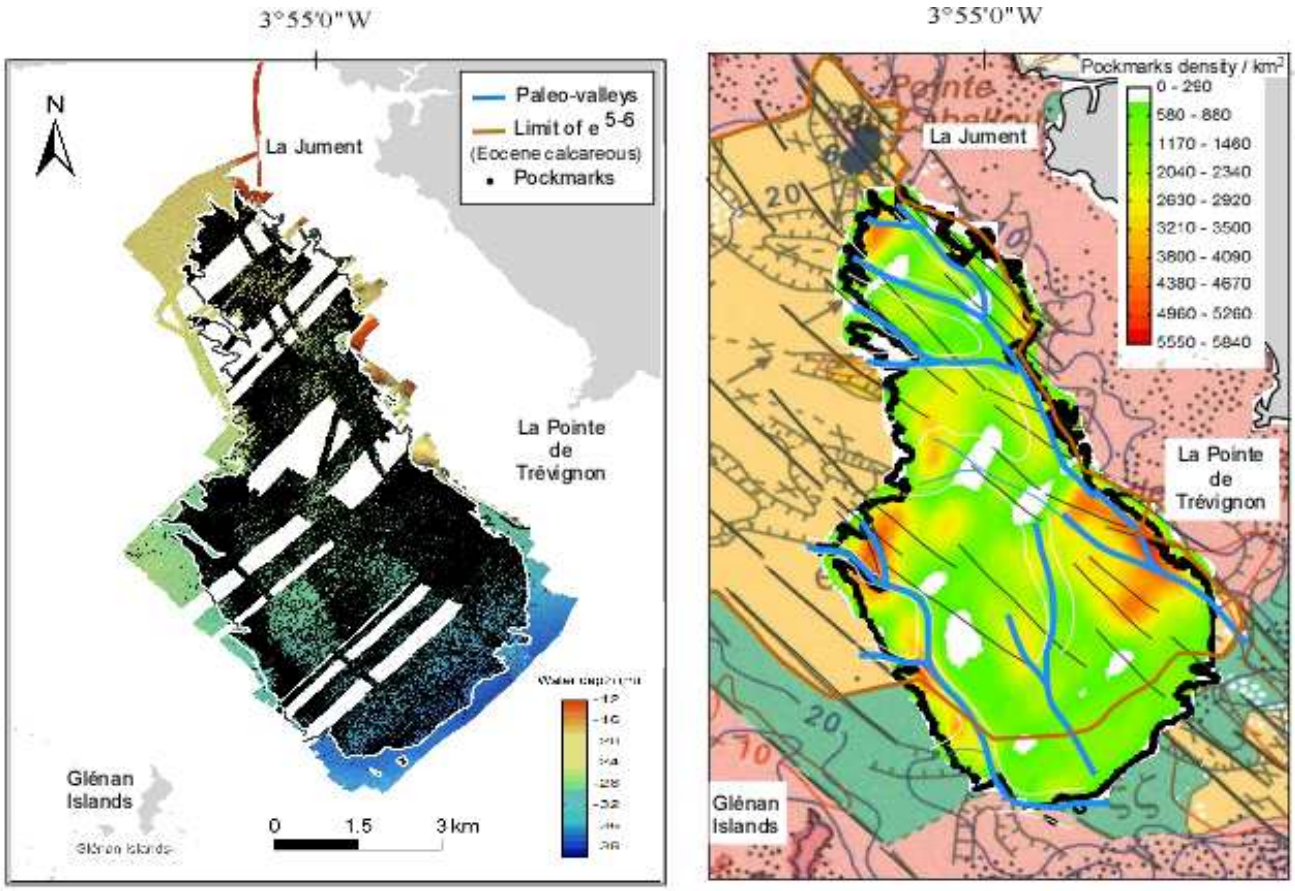
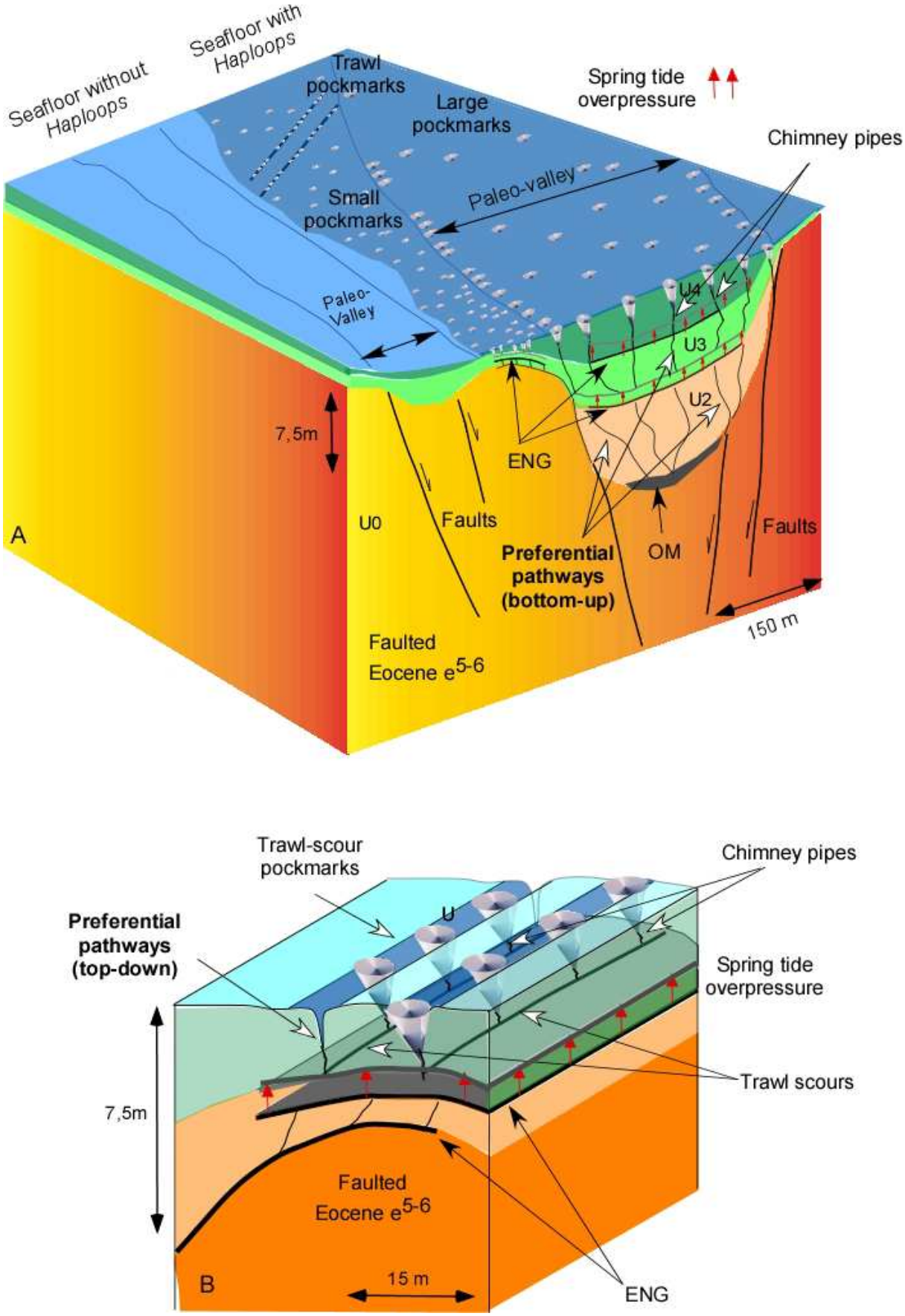

3°55'0"W
N
La Jument
Paleo-valleys
Limit of e 5-6
(Eocene calcareous)
Pockmarks
La Pointe
de
Trévignon
Glénan
Islands
0
1.5
3 km
3°55'0"W
Pockmarks density / km²
0 - 290
580 - 880
1170 - 1460
2040 - 2340
2630 - 2920
3210 - 3500
3800 - 4090
4380 - 4670
4960 - 5260
5550 - 5840
La Jument
La Pointe
de
Trévignon
Glénan
Islands

Figure 9


Seafloor without Haploops
Seafloor with Haploops
Trawl pockmarks
Large pockmarks
Small pockmarks
Spring tide overpressure
Chimney pipes
Paleo-valley
Paleo-Valley
U4
U3
U2
U0
7,5m
ENG
Faults
Preferential pathways (bottom-up)
OM
Faults
150 m
Faulted Eocene e5-6
A
Trawl-scour pockmarks
Chimney pipes
Preferential pathways (top-down)
U
Spring tide overpressure
Trawl scours
7,5m
Faulted Eocene e5-6
B
15 m
ENG