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The study of the military Harbour of Brest (France): contribution from a Very High Resolution seismic tool

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Abstract:
Within the framework of the modernisation of the military harbour of Brest, two seismic surveys have been conducted with the Seistec boomer (in 2004 and 2006) to recognize the sedimentary cover and depth of the rock basement. Previous investigations, based on drill holes, have shown the occurrence of vertical offset between geological strata. The "continuous" view acquired with the VHR seismic profiles allows a new approach of these vertical offsets and thus a new interpretation: they could be special undulating structures relative to the phase of sedimentary infilling of the bay. Such a global vision of the sea bottom floor allows to better understand the geomorphologic evolution of the harbour and to go beyond the "punctual" view. Whereas the Penfeld River seemed to be the actual active river, the influence of the Aulne River appears to have been preponderant in the sedimentary dynamics of the bay.

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1. Introduction

The geophysical surveys realized with the Seistec boomer have been programmed to better understand the geological structure of the roadstead of the military harbour of Brest (Brittany, France) to realize new harbour designs. The focus was to complete logs and drilling holes made by the SIF BACHY company (1966) and other ground tests penetration realized *in situ* with the dynamic cone penetrometer by the MENARD society (1967).

In particular, it was very important to answer two questions: what is the depth of the rock base in this part of the harbour and what does the strata offsets described by MENARD (1967) represent: were they faults or other geological structures ?

Seismic acquisition of different profiles gives us the opportunity to have a vertical view of the sediment layers, with a very high resolution (HALLEGOUET, 1989). This approach improves the possibility to understand the sedimentary processes involved in the evolution of the submarine infilling.

2. The Very High Resolution seismic

The IKB Seistec boomer (*www.seistec.ca/boomer.html*) was acquired by the "Laboratoire de Morphologie Continentale et Côtière" of the University of Caen, within the framework of the "Pôle Géophysique de Très Haute Résolution" of Normandy, BALTZER *et al*. (2003).

The principle of the seismic surveys of the submarine domain is based on the study of acoustic rays, artificially emitted and reflected by the different interfaces: the submarine bottom and the limits of the sedimentary layers. Thus an acoustic reflector reveals the occurrence of an interface characterized by a change of acoustic impedance. This happens when the seismic wave passes from a layer characterized by an impedance value Z1 (Z1 = V1 * D1) to a new layer characterized by an impedance Z2 (Z2 = V2 * D2). When this acoustic signal has a high frequency (from 10 to a few 100 kHz), but a low power supply, it cannot penetrate into the sedimentary layers and is totally reflected by the submarine bottom.

The higher the power supply, the lower will be the signal frequency of the acoustic signal (from 10 Hz to a few kHz) and deeper will be the penetration of the acoustic rays within the sedimentary layers. This is the base of the seismic principle. Contrary to the "conventional" seismic used by oil companies and characterized by an important penetration (some kilometres) but a low resolution (a few tens of metres), the seismic used in coastal areas, where the thickness of sediments reaches a maximum of 100 m, is qualified "Very High Resolution". It responds to a double necessity: a very detailed analysis of the sediments (large scale) with a very high resolution (around 25 cm) and tool handling, from small boats, in shallow waters areas.

The IKB Seistec boomer, made in Canada (SIMPKIN & DAVIS, 1993; MOSHER & SIMPKIN 1999; SIMPKIN, 2005) is characterized by an electro-magnetic source: a metal plate (boomer) is deformed by the electric discharge coming from a 4000 Volts power supply. The reflections of the acoustic waves are caught by the hydrophones placed just behind the metal plate. Its emission frequency covers a band from 1 to 10 kHz to obtain a record length of the return signal between 75 ms (4 to 6 shots/second) to 250 ms (3 shots/second), depending on the water depths. We used a "power" supply of 150 J allowing a penetration depth of 20 metres. The survey realized in the roadstead of the military harbour regroups 48 seismic profiles out of which a general view of the sedimentary cover and the substratum have been obtained.

3. Interpretation

3.1 General settings

Two reports were realized in 1966 and 1967 on the basis of drilling holes to study the geotechnical characteristics of the harbour bottom: the first one by the SIF BACHY company (1966) and the second one by the MENARD company (1967).
The first report describes 10 drilling holes made in the south west of the roadstead, along the south wave breaker (figure 1). All these drilling holes present a relatively similar succession of two fine and grey sand layers, more or less shelly sand, with a thickness from 3 to 5 m covering the schist substratum which have been reached between 4 and 7.5 m under the sediment interface. A thin layer of black shale, from 30 cm to 2 m of thickness is deposited on all the area. The second report describes 3 drilling holes realized in the north of the roadstead at the "l'épi de la grande rivière" (known as "épi de Laninon" – figure 1). The top of the schist substratum is dipping from East to West, passing from 4.25 m under the sea floor to 8 m. It is covered by a thick layer of sand and gravels varying from 4 to 6 m, overlaid by a thin muddy sand layer.
The MENARD report (1967) shows 7 geological sections based on 58 drilling holes, around the Penfeld promontory (figure 1). In each case we see the schist substratum covered by a layer of old alluvium with a thickness from 1 to 5 m. This deposit is made of schist blocks and quartz and granite blocks included in a clayey sand matrix. A 4 to 5 m thick layer of modern alluvium, composed by muddy sand with gravels, covers the sequence; it exceptionally reaches 10 m and more, on sections 4, 5 and 7.

3.2 Seismic data and interpretation

Figure 1 shows the localization of the 37 seismic profiles (from profile S1 to S37) realized in the roadstead of the military harbour of Brest. These profiles cut the harbour in several directions and enable us to establish the morphological setting.
Within seismic reflection, the travel time of the sound is given in milliseconds two way times (ms TWT) which corresponds to the time necessary for the acoustic ray to go from the seismic source to the sedimentary interface and back to the hydrophone. To obtain the water depth, the travel time value is divided by 2 (one way) and this number

is multiplied by the sound velocity characterizing the sediment layer: 1500 m/s in water and velocities varying up to 2200 m/s for marine superficial sediment depending on the sediment nature (see Table 1).

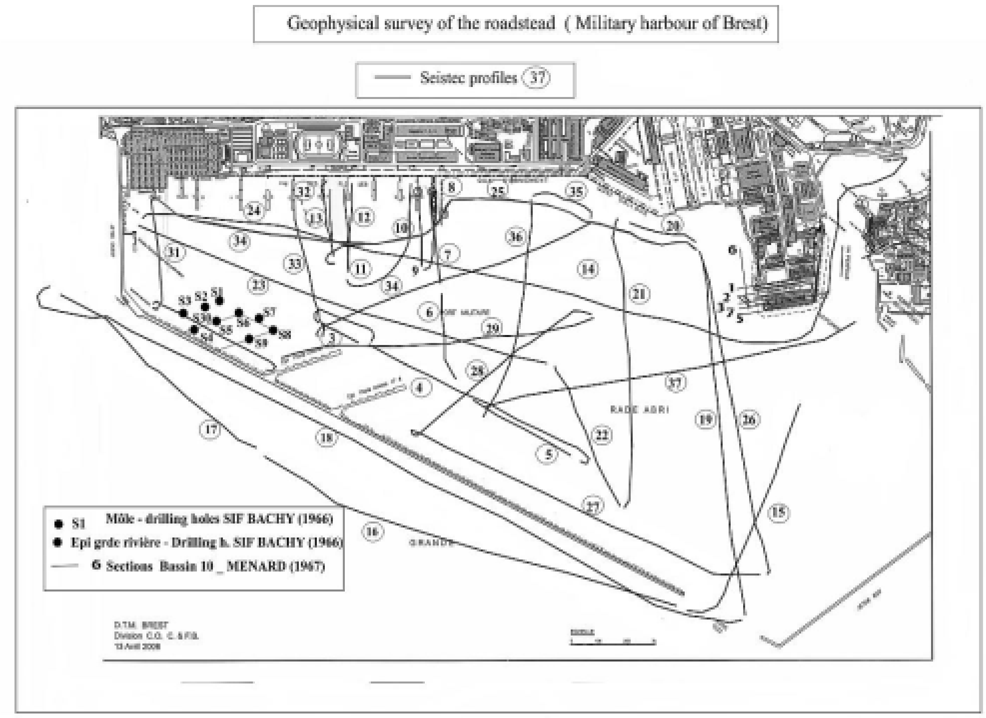

Figure 1. Locations of the drilling holes and seismic profiles.

In the roadstead, most of the profiles are characterized by a maximum penetration of 8 ms TWT, *i.e.* a maximum penetration of 5 m. We focus here on the fact that, depending of the chosen sound velocity (from 1800 m/s to 2200 m/s); it is possible to reach penetration depths from 7.10 m to 8.8 m.

Table 1. Correlation between the seismic velocities and the sedimentary formations based on seismic refraction and cores - FUGRO report (1999).

Velocity (m/s)	***Bed formation***
1480 - 1600 m/s	*Silty or clayey sands* *Possibly some gravels. Unconsolidated state*
1600 – 1800 m/s	*Sand and coarse sand with some gravels and pebbles. Slightly consolidated*
1800 - 2000 m/s	*Dense sand and gravels, gravels with possible pebbles*
2000 - 2200 m/s	*Dense gravels with pebbles*

The profiles show a succession of 5 acoustic facies (figure 2) described from the older one (the deeper one) to the younger one at the surface. These acoustic facies belong to the classification established by MITCHUM *et al*. (1977) for seismic stratigraphy. They constitute 5 seismic units covering the rock substratum, which correspond to the units described in different scientific papers on incised valleys in southern Brittany (PROUST *et al*., 2001; JOUET *et al*., 2003; MENIER *et al*., 2006).

The rock substratum (dark green): this first acoustic facies shows no visible reflector, showing chaotic and discontinuous reflections, corresponding to the top of the rocky substratum (vertical dip of the schist). This is the ground base of all the seismic profiles, described in the north zone with more or less alteration in its upper part but with no alteration in the south part (south breakwater). This facies should correspond to the brioverian schist described by JOUET *et al*. (2003) in the Bay of Douarnenez.

Unit U^r: it corresponds to a chaotic facies, more or less transparent, with a thickness varying from several metres to 5 metres maximum. Strictly localised in the paleovalley of the Aulne, this unit is probably made of heterogeneous and coarse sediments responsible for the chaotic acoustic facies, and would constitute the first phase of the infilling of these valleys, already described by JOUET *et al*. (2003) in the Bay of Douarnenez.

Unit 1B (watered beige): this unit, with a thickness varying from 3 to 5 m, shows a group of continuous, plane and concordant reflectors, deposited on the rocky substratum. It appears in all the harbour, except in the south part, close to the breakwater standing on the sand bank of Saint-Pierre. Thus, this deposit is synchronous or just posterior to the sand bank building. This unit corresponds to the old alluvium described by MENARD (1967): blocks of schist and quartz (continental erosion) included in a matrix of clayey sand. It is possible to see "pockmarks" corresponding to gas or fluid escapes on the profile S19, on the edge of the Aulne paleovalley.

Unit U1A (yellow). This unit reveals a transparent acoustic facies with, only in the southern part of the harbour, some chaotic reflections. At some points, marked reflectors characterized by a sub vertical dip (fore sets) show the progradation of this sedimentary structure. This acoustic signature, almost transparent (profiles S4 & S27) correspond to the occurrence of sand, in agreement with the "fine grey sand, sometimes shelly and muddy deposits" described in the drilling holes realized by BACHY (1966). This Unit U1A constitutes the shallow water area associated to the sandy bank of Saint-Pierre.

Unit U2 (red): this is a layered facies showing numerous and continuous reflectors, on a thickness varying from 5 to 6 m. This facies covers the incisions made in the previous deposit of old alluvium. The top of this unit is eroded and incised. This unit reveals the alternation of muddy sand and gravel layers described by MENARD (1967) and cover the surface of discontinuity, presenting a depression infilling (profiles S37 et S19 (figure 3). This infilling unit is only preserved within a shallow depression, at the west of the rocky promontory, at the Penfeld mouth.

Unit U3 (orange): this acoustic facies presents chaotic reflections and recovers units U1 and U2. It corresponds to modern alluvium (clayey sands and gravely layers) coming from the Aulne river, described by MENARD (1967). This unit has been deposited after a period marked by a stop in sedimentation as shown on all the profiles by an erosion surface. This new phase corresponds to the establishment of tidal marine influence on the sedimentation.

Unit U4 (blue): this more or less layered facies is covering Unit U3 and corresponds to the black mud described in the southern part of the bay (near the breakwater).We could observe a lateral shift of facies, from a muddy facies to a silty sand facies which constitutes the superficial coverage in the northern part of the bay. This difference in surface sediments can probably be explained by the hydrodynamic conditions in the harbour. The southern part, more confined, allows the deposit of silt, while in the northern half, fines are more easily remobilized by currents and the sand is "washed" of its fine.

One can note the presence of the paleovalley of the Aulne River, clearly visible in figure 2, which ran along the cliff in geological times. This paleovalley divides the roadstead into two areas, with Saint-Pierre's bank in its southern part and the alluvium deposits in the northern half.

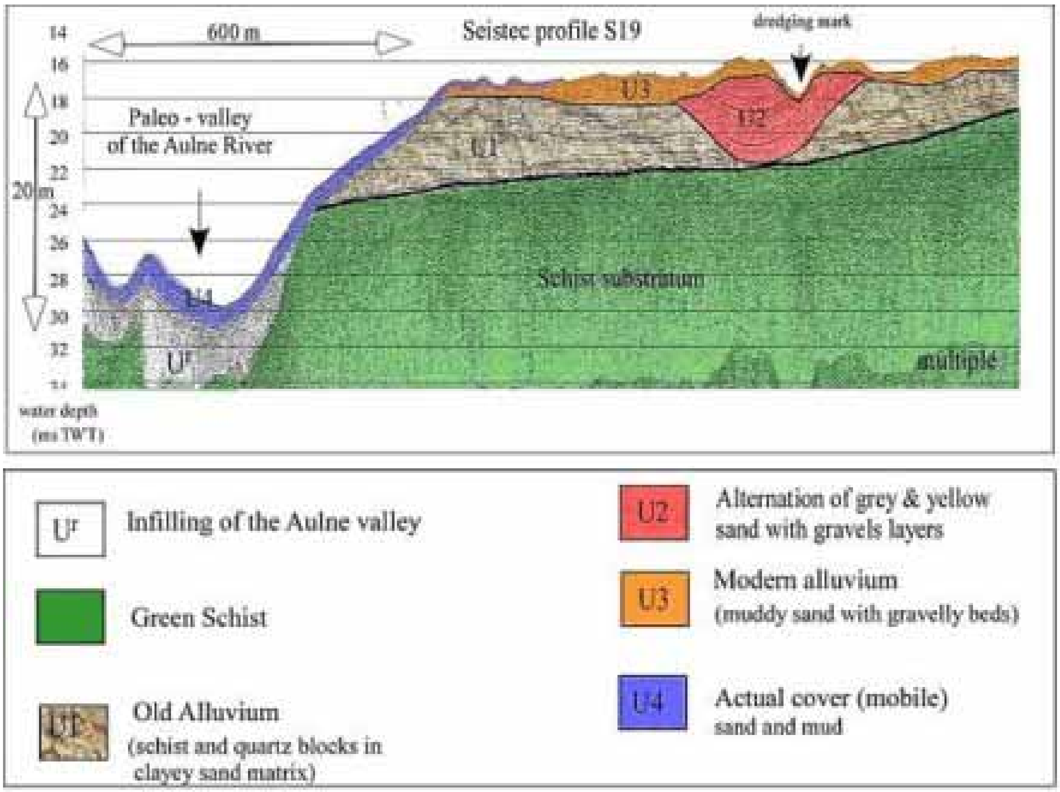

Figure 2. Seistec seismic profiles showing the different acoustic facies.

4. Discussion

Thanks to the vision given by the geophysical survey, it is possible to better describe the morphodynamical evolution of the seabed. It is divided lengthwise, through the passage of a paleovalley, which is not the Penfeld as one might suppose, but the Aulne River (figure 6). The paleovalley Aulne enters into the bay by the South Pass extends into the bottom of the roadstead and exits at the western area of former West Pass. It presents the same morphological characteristics, 600 m wide and 20 m deep, as the incised valleys recognized in south Brittany (JOUET *et al*., 2003). In the south of the paleovalley, the Saint- Pierre's bank (support for the breakwater) is visible on seismic profile S37 (figure 5). To the north, deposits are formed by filling of sedimentary units.

It is possible to interpret the profiles according to 2 scenarios. The only way to choose the good one would be a core allowing the calibration of all the acoustic facies.

We present here the two possible scenarios:

Scenario 1:

Phase 1: a first filling phase (U^r) of the Penfeld paleovalley which corresponds to the filling of the major Armorican system of incised valleys (JOUET *et al*., 2003) during an initial rise in sea level, still a low sea level.

Phase 2: a second phase of filling allows the deposit of the unit U1 (old alluvium) on the banks of Aulne river (MARTY, 1994).This filling attests a net sea level rise and the establishment of a tidal dynamics (building of a sand bar) in the estuarine area. Two hypotheses could be proposed to explain the absence of U1 above U^r on profile 19, either by a non deposit of this unit related to a vigorous current (highly energetic hydrodynamic conditions) or the erosion of the UI deposit relative to a general erosion event observed in the Bay of Brest. Thus, the infilling phase of U1 is interrupted by an event or a phase of erosion which will hack and dig a depression to the top of the rock substratum (figures 3, 4 and 5). This depression or bowl is then filled by a sandy layered deposit (U2).

Again, two hypotheses may explain this phase of erosion:

a) erosion due to a short and catastrophic event: a climate crisis characterized by a system of storms that could have dug deep scars and hollows in the deposition of unit 1;

b) erosion related to a larger event in time such as a drop in sea level. The deepening of the depression is in this case mainly due to its location: the combination of 3 factors that can influence the local hydrodynamics. Figures 5 and 6 show that the erosion depression of this basin is located just at the end of the rocky outcrop of the mole of the military port, at the mouth of the river Penfeld, and in opposite to the sand bank of Saint-Pierre. As there is no other profile showing such a facies, one might imagine that the hydrodynamic conditions in that specific location, have conducted to the erosion of the sediments under the action of a hydraulic jump for example.

This second hypothesis, which does not call for a catastrophic event but only special

and localized hydrodynamic conditions which probably occurred when the sea level was back down below a certain threshold, seems more realistic. It seems reinforced by two points: the unique location of this depression and its depth that reaches 4.5 m. It seems to us unlikely to reach 5 m of erosion in a single storm in such a protected environment. And if, would be the case, then to observe only one depression over the entire harbour.
Phase 3: the infilling of unit U2 is observed within the depression so it is difficult to draw conclusions regarding the mode of deposition of this unit. Figures 3, 4 and 5 show that this unit is made up of alternating beds of sand and gravel (MENARD, 1967) following the shape of the depression. It presents undulations highlighted by the strong vertical exaggeration (x 25). These "undulations" cause shifts of 2 to 4 m, which are located exactly in the same area as the faults mentioned by MENARD (1967).
Phase 4: the fourth phase of filling itself, recognized across the bay is composed by modern alluvial deposits described by MENARD (U3) is up to a few meters thick. It corresponds to the establishment of the actual hydrodynamic system related to the latter phase of rising sea level, probably around 6000 years BP, dominated by tidal influence.
Eventually, a superficial deposit of sand and mobile mud coverage (U4) with a thickness of 30 to 150 cm drapes the units. This coverage corresponds to the present sedimentation and is cut by several dredging (figure 6).

Scenario 2:
Unit U1 would be deposited prior to unit U^r and would be assimilated to a fluvial terrace built by the Aulne river before the sea level fall (40 000 years ?). During the following rise of the sea level (since 18 000 years BP), U^r could be deposited. Thus U^r would be of the same age as unit U2 or deposited between U1 and U2. Nevertheless, it would be difficult to link the U1 facies to the Penfeld paleovalley, as this one is well known for its low supply of sediment (MUSSET, 1934).

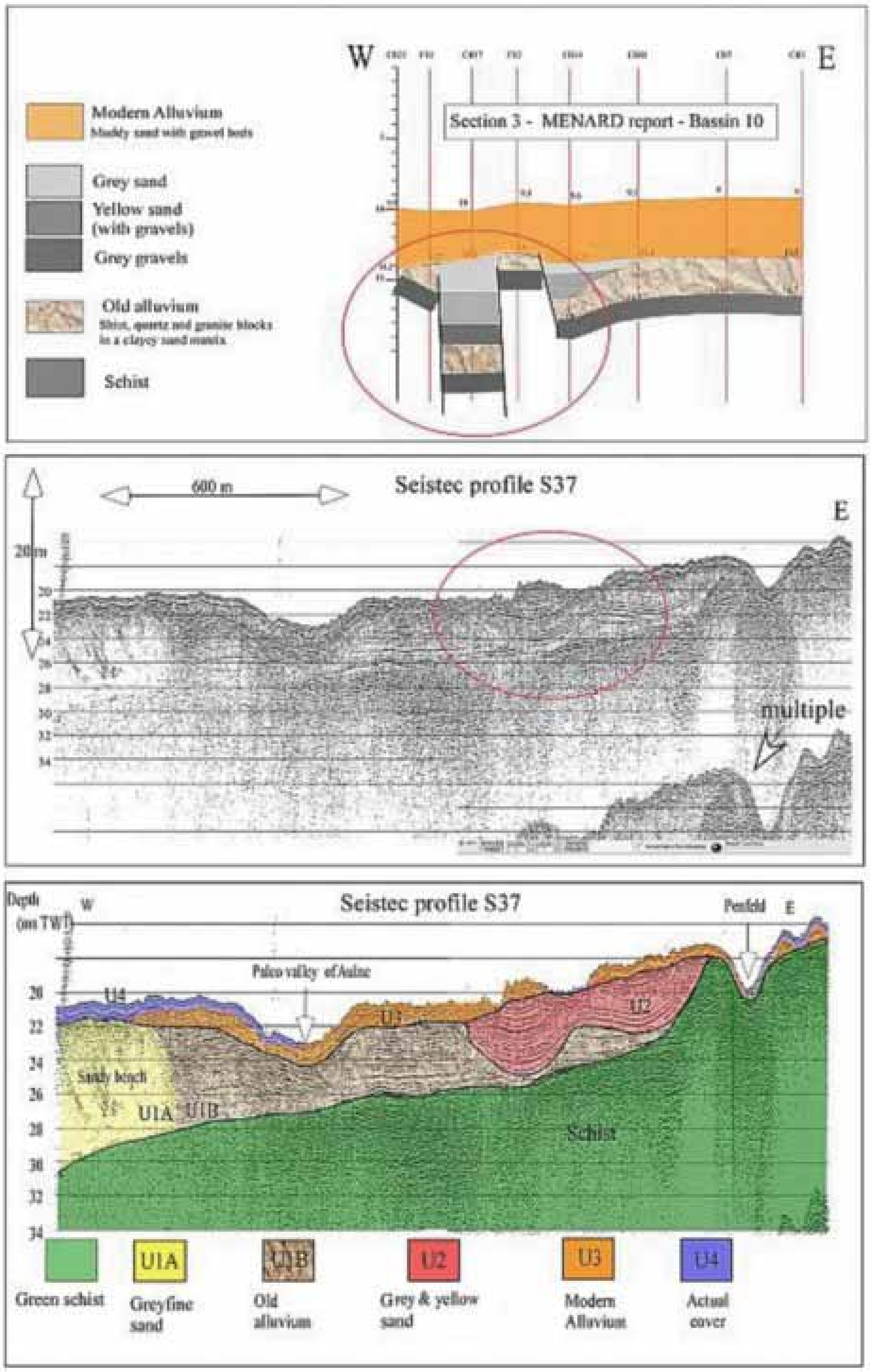

Figure 3. Comparison of the Seistec profile S37 with the geological section 3 (MENARD, 1967).

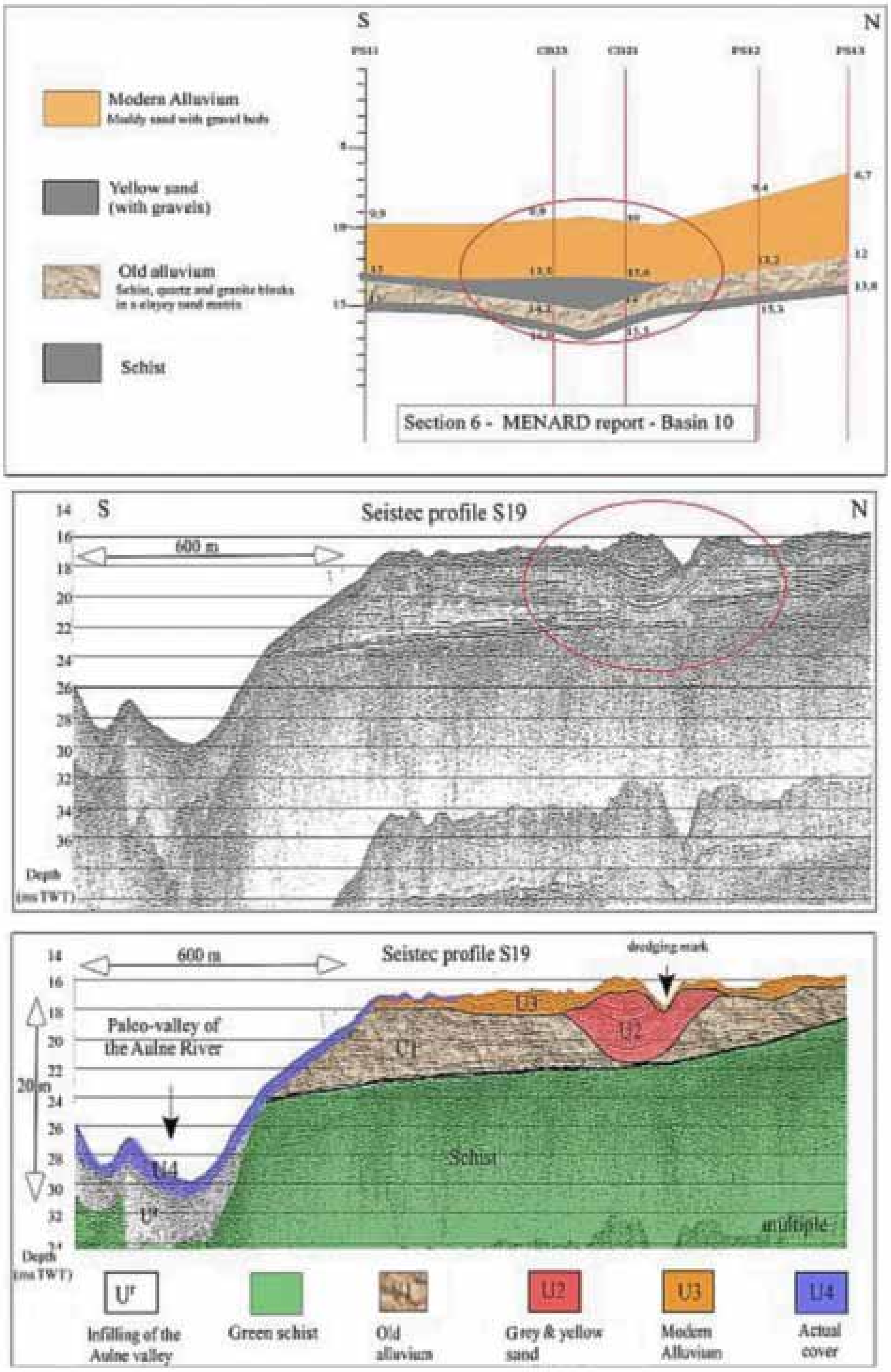

Figure 4. Comparison of the Seistec profile S19 with the geological section 6 (MENARD, 1967).

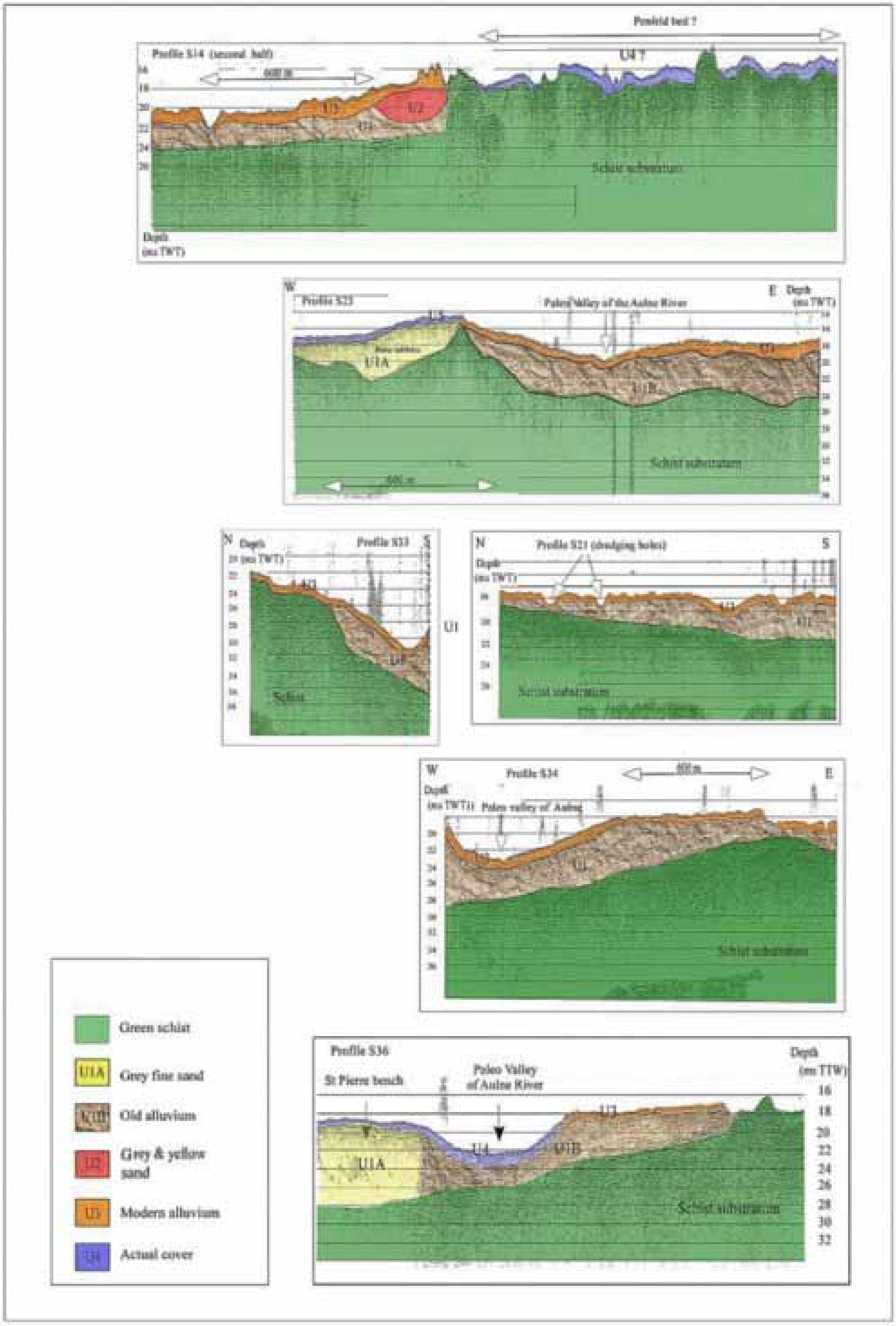

Figure 5. Interpretation of Seistec profiles in the harbour (see location in figure 1).

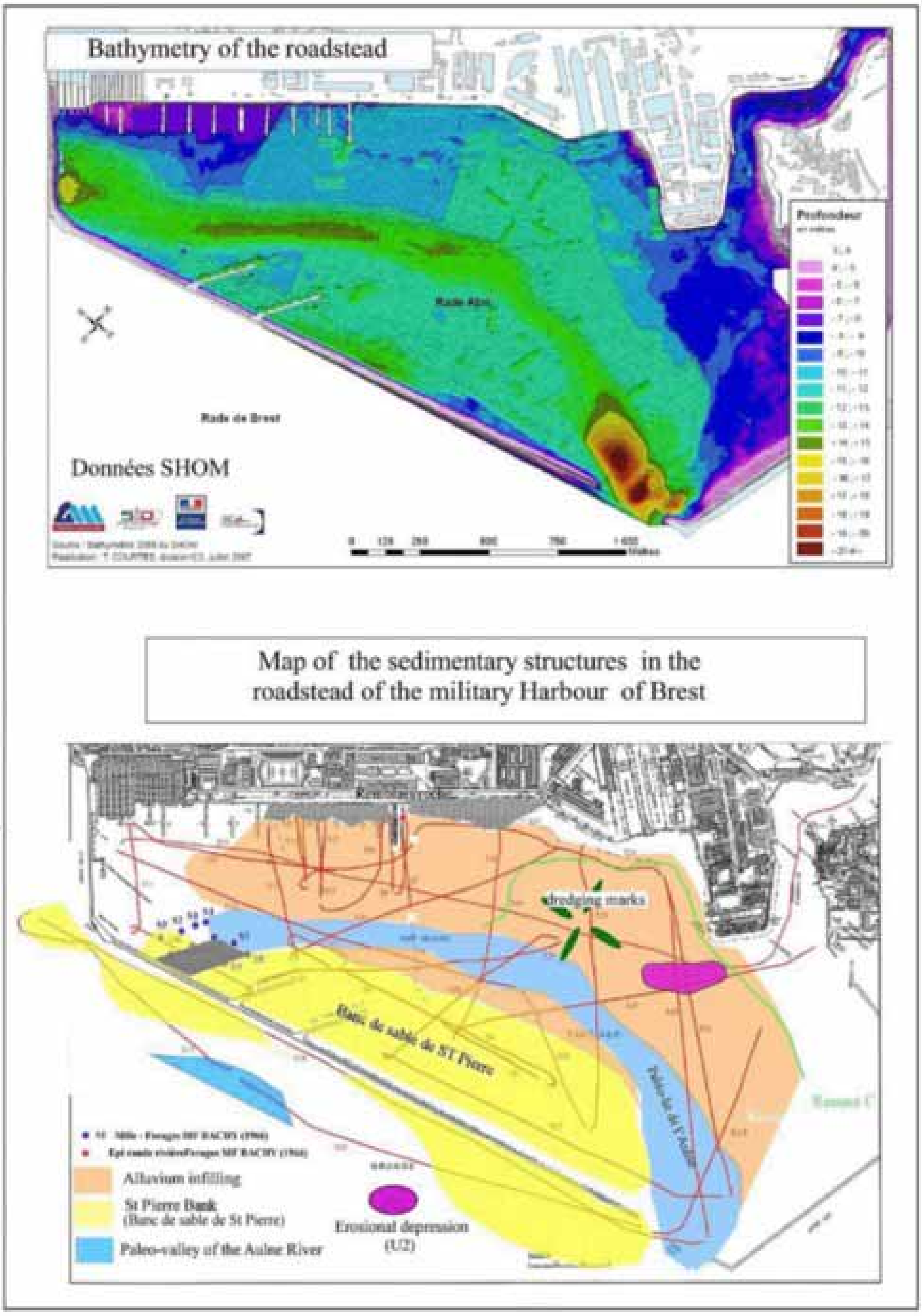

Figure 6. Interpretation of the sedimentary structures.

5. Conclusions

The completion of this geophysical survey using the Seistec boomer allowed us to propose a reconstruction of the sedimentary evolution of the roadstead of the military port of Brest. For example, the influence of the Aulne River, and not the Penfeld River as suggested by its present location, has been predominant in the sediment dynamics of the bay. The sedimentary infilling was held in 4 phases of deposition, and was interrupted by a phase of marked erosion probably during an episode of falling sea level.

The geophysical survey has enabled us to understand how different structures attributed to geological faults, could be re interpreted as a particular infilling of an erosion depression. The depression reached the schist top (re-excavate to a depth of almost 5 metres) and is located in one area, characterized by a combination of special hydraulic factors. This depression was filled during a new phase of rising sea level. The combination of two approaches involving a "continuous" vision and a "punctual" vision has made possible the understanding of this particular structure.

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