Origin of rippled scour depressions associated with cohesive sediments in a shoreface setting (eastern Bay of Seine, France)

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Abstract Side-scan sonar investigations in the eastern part of the macrotidal Bay of Seine have revealed the presence of numerous rippled scour depressions (RSDs) at water depths of 5-9 m. The sediments in these depressions essentially consist of coarse-grained shell hash derived from underlying Holocene sediments dated at roughly 6,500 years BP, and arranged in large wave-generated ripples. The shallow marine area where these features occur consists of a wave-generated ravinement surface produced during the marine flooding of the late Holocene transgression. It can be shown that, during the last twenty years at least, erosion of the muddy sand and sandy seabed has exposed underlying relict sediments. These consist of stiff clays, silts and a layer of shell debris, which, when exposed, cover the bottom of large scour depressions which appear to be in equilibrium with the local hydrodynamic regime. Morphological and hydrodynamic data suggest that the RSDs are generated by strong cross-shore bottom currents flowing parallel to the features in the direction of the prevailing waves, and probably associated with storm-induced downwelling events.

Introduction

The occurrence of sediment filled scour depressions have been reported from a variety of environments around the world, including the inner continental shelves (e.g. Coleman *et al*., 1981; Mann *et al*., 1981; Cacchione *et al*., 1984; Ashley, 1990; Thieler *et al*., 1995; Marlow *et al*., 1999), estuaries (e.g. Dyer, 1970; Flood, 1981) and large lakes (Flood, 1983; Flood and Johnson, 1984). Most of these features have been classified as "rippled scour depressions" (RSDs) by Cacchione *et al.* (1984). The sediments in such depressions are commonly composed of coarse-grained sands, shell hash, or clean gravels fashioned into large wave-generated ripples. In spite of these investigations, the origin, maintenance, and significance of these features in terms of shelf hydrodynamics and morphodynamics are still poorly understood. Cacchione *et al.* (1984) associated these features with areas of intensified cross-shore flows produced by coastal downwelling events, whereas others (e.g. Swift and Freeland, 1978; Swift *et al*., 1979) have suggested that they are created by shore-parallel flows. Based on a numerical model simulating nonlinear dynamic transport of both coarse- and fine-grained sediment fractions, Murray and Thieler (2004) have recently proposed a new mechanism for the formation of RSDs, suggesting self-organization of the sediment.

Although RSDs have been documented mostly from the coasts of North America (see the review in Murray and Thieler, 2004), they are also known to occur on the European continental shelf. On the French continental shelf (Fig. 1), for example, similar sedimentary features have been observed, although they have either been interpreted to be associated with quite different processes to those suggested by American workers, or their origin and formation have remained unclear. Thus, coarse-grained sediments within depressions on the Aquitaine shelf were attributed to the reworking of underlying relict sediments after differential removal of finer surficial sediments (Turcq *et al*., 1986; Cirac *et al*., 2000), whereas alternating tidal currents were considered thought to be responsible for the creation of RSDs in the Bay of Morlaix (described as "gravel furrows" by Auffret *et al*., 1992).

Recent investigations in the eastern part of the Bay of Seine have, for the first time, revealed the widespread occurrence of typical RSDs in shallow water adjacent to the Calvados coast in front of Houlgate beach (Fig. 2), where the seafloor mainly consists of fine-grained and muddy sand (Garnaud *et al.*, 2003). The aim of this paper is twofold: a) to explain the presence of RSDs and their morphodynamics in the context of the eastern part of the Bay of Seine, and b) to clarify whether they have developed only recently, as they were not described from any previous surveys, extending back over 20 years.

Study area

The study area is located in the Bay of Seine on the southern flank of the English Channel, on the north-western coast of France. It covers a surface area of 4,000 km² (Fig. 1) and comprises a shallow depression with a smooth seafloor at water depths of less than 45 m. During the Last Glacial Maximum at 18,000 years BP, this area was subjected to fluvial incision to as much as 30-45 m below the floor of the adjacent shelf (Auffret and d'Ozouville, 1986b; Lesueur *et al.*, 2003a; Garnaud *et al.*, 2003). The present-day morphology results from the infilling of these incised valleys, the palaeo-Seine in particular, by both fluvial and marine sediments which accumulated during the late Weichselian stage and the Holocene transgression. The local Holocene sequence is composed of three distinct units. It began with floodplain fine sediments (Unit 1), then passed into a marsh clay (Unit 2), dating to from 9,200 to 6,800 years BP; inter- and subtidal sedimentation (Unit 3) was finally initiated after marine flooding, around 6,500 years BP (Garnaud *et al.*, 2003).

Major hydrodynamic forcing agents in the study area are strong tides, fluvial discharge of the Seine river, wind-driven currents, and waves. The tidal characteristics in this region are strongly controlled by the general macrotidal English Channel system (SHOM, 1968; Chabert d'Hières and Le Provost, 1978), which has a maximum tidal range of about 7-8 m at Le Havre, in the mouth of the Seine. The tide is semi-diurnal with a high water slack duration of up to three hours during spring tides (SHOM, 1968). The tidal wave becomes asymmetrical in shallower water depths, and the duration of the flood tide is considerably shorter than that of the ebb tide. In the study area, the main tidal currents flow in a SW-NE or NE-SW directions (SHOM, 1996), i.e. parallel to the coastline. Surface tidal currents reach speeds up to 70 cm s^{-1} (Garnaud, 2003). However, the strongest currents in the study area are wave- and wind-generated, although these are still very poorly known (Avoine *et al*., 1986). The Bay of Seine is partly sheltered from the influence of the prevailing western Atlantic swells and is mainly affected by local wind waves (Larsonneur *et al*., 1982). The prevailing winds are from north to north-west, although the strongest winds are offshore (i.e. from the south-west). The local wind-induced waves from the north-western sector have short periods ranging from 3 to 7 s.

The study area covers 21 km² and is located 20 km southwest of the mouth of the Seine. It extends offshore to water depths of 9 m below low-tide level. With the exception of the RSDs, the seafloor is generally covered with fine-grained sand and muddy sand (mean grain-size: 200-300 µm) with a very low content of coarse-grained sediments (Garnaud *et al.*, 2002). However, gravel and coarse-grained sand occur further offshore at water depths > 20 m (Avoine, 1986; Garnaud, 2003).

Methods

Side-scan sonar track lines, vibracores, and a large number of grab samples were collected in the eastern part of the Bay of Seine in the course of several cruises between 1999 and 2001 (Garnaud, 2003). Approximately 80 linear km of side-scan sonar data were surveyed during two cruises in 2000 and 2001 (Fig. 2) using an Edgerton model 260 TD operating at 100/500-kHz and set at swatch ranges of 75- or 100- m either side of the ship's track. 90 grab samples and 30 cores (Reineck boxcores, Kullenberg cores, and vibracores) were recovered from the study area (Fig. 2). Accurate positioning of the sampling sites and side-scan sonar track lines (at 15-s intervals) was accomplished by a Trimble Differential Global Positioning System. Several surficial samples were also obtained from within the RSDs using grabs and a Reineck corer. The Reineck boxcores typically penetrated the seafloor to depths of 20 cm, thus only allowed the investigations of the internal structures of the surface sediments. The backscatter of the surface sediments (side-scan sonar data), coupled with the grain-size data of the grab samples, has enabled the distinction of different seafloor lithofacies, and allowed the delineation of their spatial extent. Unfortunately, the acquisition of underwater video data was not possible because of a high turbidity near the bottom. Nevertheless, a sediment profile imaging (SPI; Rhoads and Germano, 1982) system was used with success during previous studies in May-June 1996 (Velegrakis *et al.*, 1999; Garnaud, 2003). Information about the flow field in the study area was provided by the Service Hydrographique et Océanographique de la Marine (SHOM, 1968; SHOM, 1996). In addition, data on near-bottom currents at depths of 8 m off Houlgate beach was published by Avoine *et al.* (1986).

Results

Side-scan data from shallow water off Houlgate Beach revealed a rough and highly variable bottom composed of two major morphologic components: elongated scour depressions (RSDs) aligned normal to the coastline floored by large and long-crested ripples and, very stiff clays cropping out irregularly on the floor of the shoreface at water depths between 5 and 7 m. These were sampled by vibracorer, and have been shown to be relict deposits with ages using peats, woods, and shells as being between 9,250 and 1,260 years BP. The deployment of a SPI system (Velegrakis *et al.*, 1999) showed that outside the area of RSDs and stiff clays, the surficial sands were formed into well-defined oscillatory ripples, which were too small (wavelength: 20-30 cm, height: 1.1-2.9 cm) to be detectable with the side-scan equipment used.

The side-scan sonar records show that the RSDs are flat-floored depressions with the only roughness being caused by the ripples. The RSDs have a maximum depth of 50 cm and are most common in water depths of 5-9 m (Fig. 2). They have been identified at about 150 sites in the study area (Fig. 2) where they form a distinct field. Because of the range of side-scan sonar survey (75-100 m), the knowledge of the detailed cartography of RSDs is incomplete except where intersections of track lines occur, when the total length of RSDs can be seen to be as great as 200-300 m. Due to the large spacing between survey profiles (i.e. more than 2000 m), individual RSDs observed on parallel track lines cannot be connected and have thus been plotted as separate features (Fig. 2).

Individual RSDs are on average 30-200 m wide with spacings ranging from 50 to 100 m (Fig. 3). Their predominant orientation is NNW-SSE, i.e. shore-normal or slightly oblique to the coastline. Grab samples and boxcores from the bottom of the RSDs clearly show that they are covered with coarse-grained debris of winnowed shell hash, composed of shells of mainly *Tellina, Abra, Mytilus, Petricola,* with a mean grain-size > 5 mm; whereas the intervening areas are composed of muddy fine-grained sands (Fig. 3). Within the depressions, the shell debris are arranged in long, straight-crested, symmetric wave-generated ripples with wavelengths of approximately 1 m (mean of 1.2 m) and heights of 0.1-0.2 m (Figs. 3 and 4). The ripple crests are aligned perpendicular to the orientation of the RSDs and are thus oriented roughly parallel to the shoreline.

The side-scan sonar records, numerous cores and grab samples (Fig. 2) have shown that the modern sediments in the area of the RSDs form only a thin veneer with a maximum thickness of 20-30 cm (Garnaud, 2003; Garnaud *et al*., 2003). In contrast to the RSDs, the intervening seafloor is irregular due to numerous elevated outcrops of earlier Holocene stiff clays (Unit 3, Fig. 6a) which attain heights of 0.3-0.6 m above the surrounding seafloor (Fig. 5).

Boxcores from the RSDs show that their bottoms are composed of coarse-grained shelly sand, which are sometimes covered by the modern fine-grained muddy sands. The shelly bed is always observed to be in contact with the underlying stiff relict clays, noted Unit 2 (Fig. 6b).

Discussion

Age and origin of RSDs

The RSDs occur in an extensive erosional area that was first described several decades ago. Based on comparisons of bathymetric surveys from 1834 to 1913, Volmat (1929) showed that the whole area between Le Havre at the mouth of the Seine river (Fig. 1) and Cabourg on the Calvados coast has been subject to widespread erosion. Similar erosional areas are known but of a larger scale in the English Channel where very strong tidal currents and waves occur (Larsonneur *et al*., 1982). The mean increase in the water depth in the study area over this 80-years period was estimated to be 0.68 m, suggesting an average erosion rate of 0.86 cm year^{-1} (Volmat, 1929). This long-term erosional tendency is in good agreement with recent observations which show that the surface area of outcropping earlier Holocene clays has increased during the last three decades (Garnaud *et al*., 2003). The present-day outcrops of relict clays appear to have formed recently since both previous side-scan sonar surveys (1982-1983) did not reveal their presence and, only a few RSDs were described (Auffret and d'Ozouville, 1986a). The mean depth of the studied RSDs (i.e. the maximum difference in level between the bottom of the depressions and the adjacent sandy seabed) is approximately 0.4-0.5 m. In contrast, the earlier work of Auffret and d'Ozouville (1986a) showed that the RSDs observed at the same location were about 1 m deep at the time. The substantial differences in observed RSD depths may be due to the method, i.e. the less accurate sonograms in 1982-1983. Also, it could be explained by: (1) high-frequency variations in the local hydrodynamics, and (2) long-term, erosion of the adjacent seabed.

The modern erosion of the shoreface to inner shelf of the south-eastern Bay of Seine (Garnaud *et al*., 2003) exhumed relict sediments, among which coarse-grained shelly sands at the bottom of the Unit 3. This material is analogous to the shelly sediments from the bottom of the RSDs (fig. 6). The latter therefore appears to testify to an earlier period of marine flooding (transgression), between 6,530 ± 110 and 6,360 ± 90 years BP (e.g. fig. 6). In some places, it has been covered by tidal deposits (Unit 3), but was later exhumed and reworked under modern shallow-marine conditions. As a result, the relief of the stiff relict clays may have resulted from differential erosion in places where either shell debris has not been exhumed (then Unit 3 forms the surface), or where the material has been removed (when it is formed of Unit 2).

Factors controlling the evolution of RSDs

The side-scan sonar surveys were carried out in June 2000 and June 2001. Over such a short period, it was not possible to identify any substantial changes in the location and morphology of RSDs. Nevertheless, at some intersections of track lines in the deeper area at water depths of 7-9 m (Fig. 2), the shapes of some individual RSDs had changed between June 2000 and June 2001. This area corresponds to a water depth called a “zone of minimum mean-water motion” between an offshore tide-dominated area and a shoreward wave-dominated fringe (Larsonneur *et al.*, 1982). Because the RSDs are incised in very stiff clays, these features are unlikely to shift position over short-time scales. The apparent inter-annual change in the position of some RSDs is therefore more probable due to changes in the distribution of the overlying surficial muddy sand cover which may temporarily blanket the coarse-grained sediments within the RSDs (Fig. 6b). It has been shown that on a seasonal time-scale, this part of the Bay of Seine is affected by high-frequency variations in the distribution of the surficial sediments which are replenished by mud originating from the Seine estuary during specific events called 'estuarine floods' (Garnaud, 2003; Garnaud *et al.*, 2003). Such a present-day supply of fine-grained material can form a soft mud blanket over the RSDs directly covering the shelly coarse-grained sands. The analysis of some short cores demonstrates that the settlement of such a veneer of mud occurs without its mixing into the underlying coarse-grained shelly material (Fig. 6b).

The occurence of RSDs at the very shallow water depths must in some way be associated with the modern hydrodynamic regime. Because the area is under the general influence of SW-NE currents flowing parallel to the coastline (the "Calvados current"; SHOM, 1996), tidal currents can not be responsible of the formation of these shore-normal features. Moreover, it can be assumed that the fine-grained muddy sands offshore of Cabourg are likely to move for about 85% of the time during neap and spring tide (Avoine *et al.*, 1986). However, the tidal currents are not strong enough to move the shelly coarse-grained sands in the RSDs. Indeed, friction velocity (U*) calculated based on measurements of near-bottom mean flows do not exceed 1.73 cm. s^{-1} during spring tides (Avoine *et al.*, 1986). On the other hand, the conformity of the orientation of all RSDs with the direction of wave approach in the littoral zone of Villers-sur-Mer is very striking (Garnaud, 2003; Lesueur e*t al.*, 2003b); the data show that more than 70% of the waves, including the maximum wave heights, propagate from the N-NW sectors (Levoy *in* Lesueur *et al*., 2003b).

The formation of depressions in the sandy sediments, the erosion of stiff relict clays, and the reworking and the movement of coarse-grained material into the RSDs can therefore only be the result of the action of strong bottom currents associated with large-amplitude, relatively long-period surface waves. The latter are more important during the winter. Symmetrical ripples in the RSDs were probably formed during the waning phase of storms and subsequently maintained by the fair-weather wave climate, preventing fine-grained material to deposit and to be preserved in the depressions.

Shore-normal RSDs similar to those in the study area have been reported from shorefaces and inner shelves in other parts of the world at water depths between 2 and 80 m (see the review in Cacchione *et al.*, 1984). According to the available literature, the initiation of RSDs has variably been attributed to (1) strong scouring rip currents caused by large storm waves (Reimnitz *et al.*, 1976; Morang and McMaster, 1980; Aubrey *et al.*, 1984), (2) wave effects (Hunter *et al.*, 1982), (3) current-parallel features generated by strong bottom currents during storm-induced downwelling effects (Cacchione *et al.*, 1984; Gayes, 1990), and (4) turbidity currents (Reimnitz *et al.*, 1976). Due to a lack of current and wave measurements any of these locations, particularly during storms, there is no general agreement as to the cause of depression formation. An essential feature common to all these different environments is that these depressions are particularly well developed along sediment-starved continental margins (Murray and Thieler, 2004). The presence of RSDs is often associated with erosional sedimentary settings in the presence of rocks outcrops (Cacchione *et al.*, 1984; Auffret *et al.*, 1992; Thieler *et al.*, 1995), or outcrops of relict sediments (Aubrey *et al.*, 1984; Schwab *et al.* 2000, Garnaud *et al.*, 2003). However, Murray and Thieler (2004) have recently shown that pre-existing, cross-shelf-extending coarse-grained material is not a prerequisite for the development of RSDs. In the Bay of Seine, for example, only the presence of underlying earlier Holocene material can explain the existence of the coarse-grained material in the RSDs since the content of this material in the adjacent modern sediments is low. Furthermore, RSDs are only observed in this restricted area of the Bay of Seine where stiff relict sediments crop out.

In the eastern Bay of Seine, tidal currents of incompatible directions and insufficient velocities can be excluded as cause for the present-day active RSDs. The most probable driving force for the generation of these features must therefore be attributed to strong bottom currents flowing parallel to the orientation of the features. This would support the model of storm-induced downwelling events as previously suggested by Cacchione *et al.* (1984).

Conclusions

Side-scan sonar investigations in the shallow south-eastern part of the macrotidal Bay of Seine have revealed the existence of rippled scour depressions (RSDs) at more than 150 sites. They are probably much more widespread, considering that side-scan surveys were not undertaken with the purpose of a complete mosaic mapping. These features are floored by coarse-grained shell hash arranged in large wave-generated ripples having wavelengths of about 1 m oriented perpendicularly to the axes of the RSDs. Their presence on this shoreface is rather surprising because (1) they contrast sharply with the surrounding surficial muddy fine-grained sands, (2) they occur in a very limited area of the Bay of Seine, (3) their predominant orientation is shore-normal or slightly oblique to the coastline, whereas tidal currents are roughly alongshore, and (4) there is clear evidence for their recent formation and a recent substantial increase in depth of scouring (only a few RSDs having been described 20 years ago from the same area).

The reconstruction of the Holocene sedimentary sequence (Garnaud *et al.*, 2003) suggests that the most likely source for the very coarse-grained material found in the RSD is the erosion of exhumed relict coarse shelly sediments dated at 6,500 years BP, which formed during the postglacial marine flooding of the area. This material was formed into currently active wave-generated ripples in the RSDs. In intervening areas, stiff relict clays of mid-late Holocene age form an irregularly topography. These have enlarged and the magnitude of their relief has increased over past decades. These observations are compatible with the present-day erosive nature of the shallower part of the open eastern Bay of Seine which represents a wave-ravinement surface. Morphological observations and current evaluations suggest that the RSDs are the result of strong bottom currents generated during northerly to north-westerly storm events which, more generally, are also responsible for the erosion of the larger part of the sandy and cliff-bordered Calvados shoreline. Moreover, the results of this study are in accordance with the model proposed by Cacchione *et al*. (1984).

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Figure captions

Figure 1: Location of the study area in the eastern part of the Bay of Seine; boxed area indicates the only region in the Bay of Seine from where rippled scour depressions (RSDs) have been described. Î Other locations on the French continental shelf where bathymetric depressions floored by coarse-grained sediments have been recorded are: Bay of Morlaix (Auffret *et al.*, 1992); Morbihan Gulf (Augris, personal communication); Grande Vasière (Bourillet *et al*., 2003); Aquitain shelf (Turcq *et al*., 1986; Cirac *et al*., 2000).

Figure 2: Detail of rippled scour depression distribution in the study area, and location of sediment samples (grab and cores) and side-scan track lines (heavy line). Shaded subtidal areas between 5 to 9 m water depths are interpreted as being characterized by the presence of RSDs. Geophysical surveys of this area were conducted in 2000 and 2001.

Figure 3: Sonogram illustrating rippled scour depression bedforms in the eastern Bay of Seine (water depth of 8 m; 500 kHz). Areas of high backscatter consist of coarse-grained sediment in depressions surrounded by muddy fine-grained sand (low backscatter). In the other parts of the eastern Bay of the Seine, the side-scan sonar survey reveals an essentially featureless homogeneous seafloor only interrupted by bottom trawling marks (see Fig. 5). Location of sonogram, see Fig. 2.

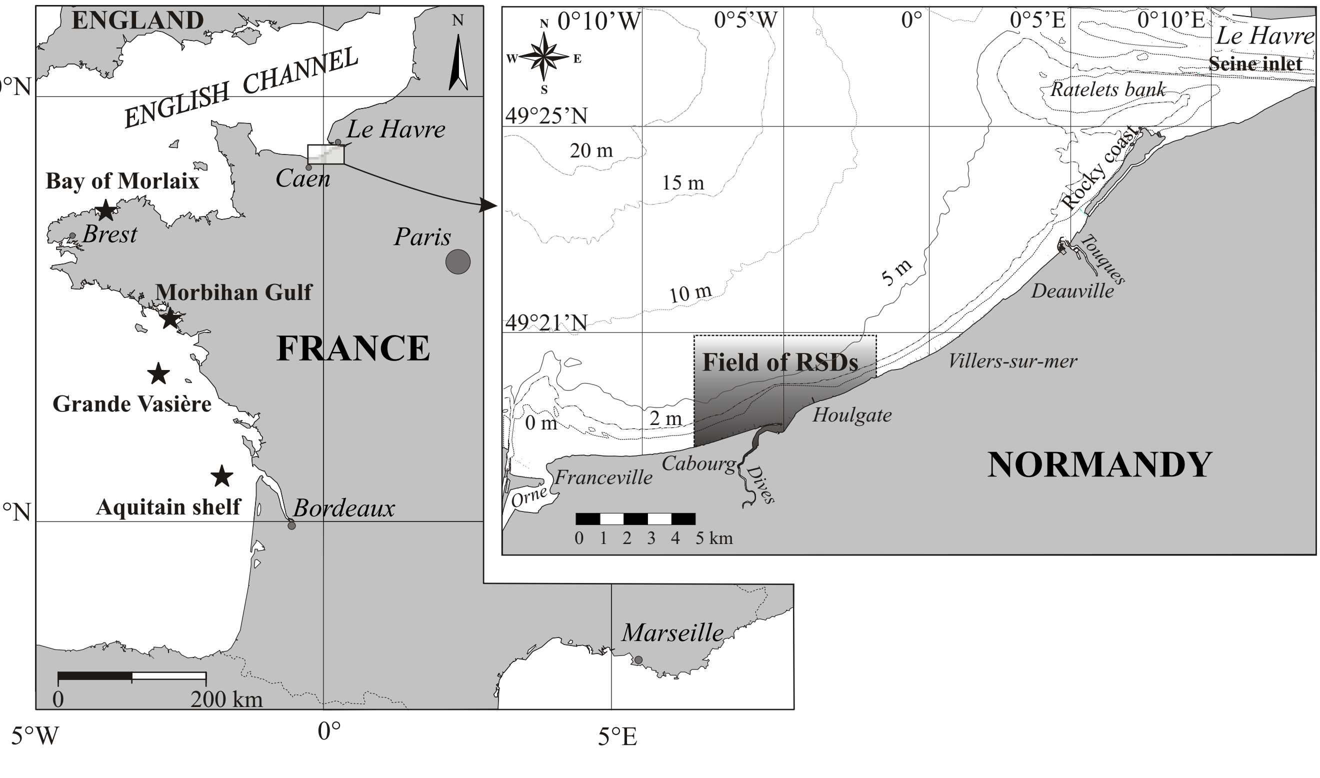
Figure 4: Detail of a typical side-scan sonar image of a part of a single rippled scour depression covered with wave-generated ripples (water depth of 7 m; 500 kHz). The boundary with the surrounding muddy fine-grained sand is sharp and steep. Location of sonogram, see Fig. 2.

Figure 5: a) Side-scan sonar record showing the relationships between elevated relict earlier Holocene clays and the rippled scour depressions (water depth of 6.5 m; 500 kHz).

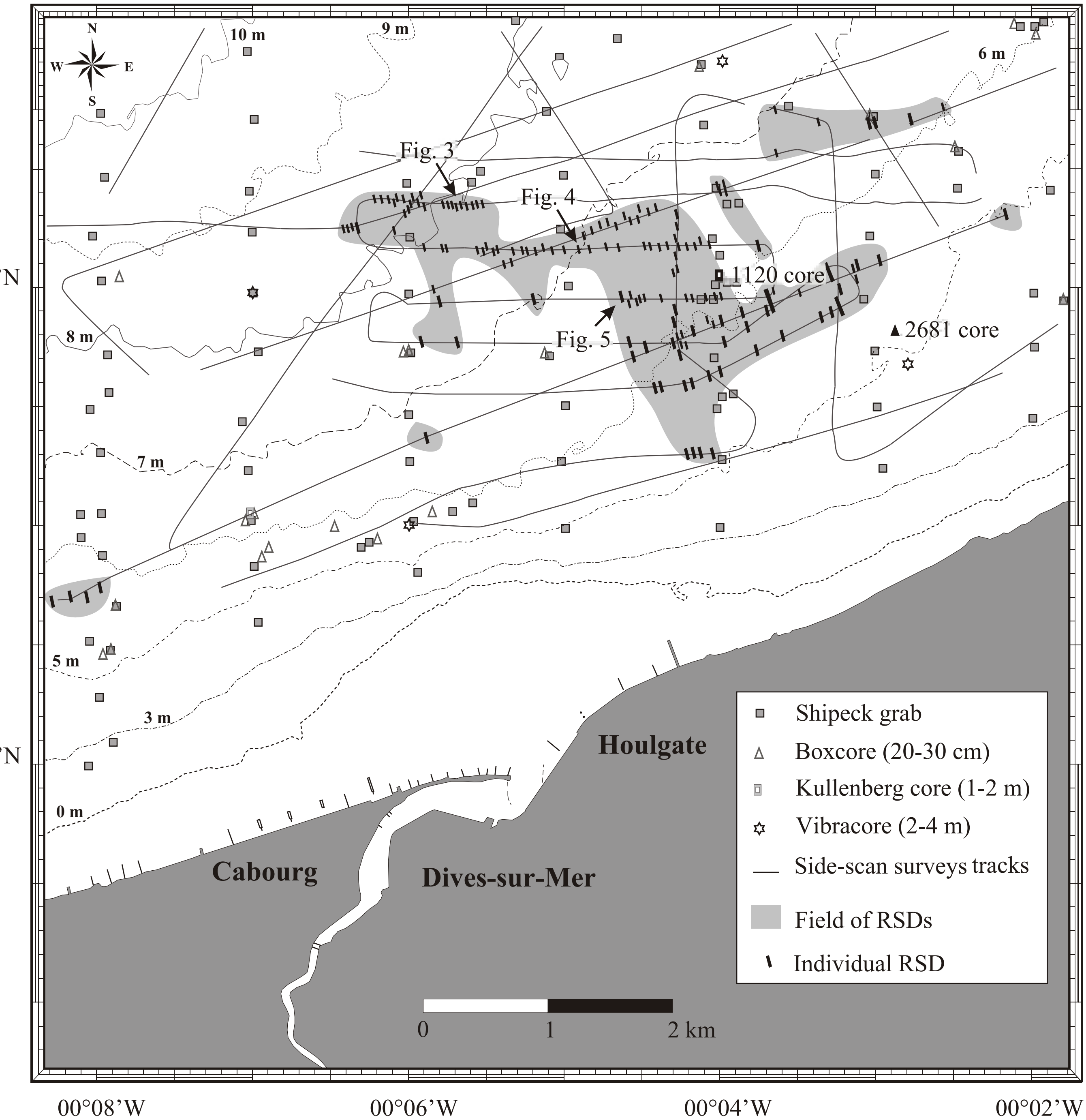
Even within some RSDs, earlier Holocene stiff clays crop out with clearly elevated relief above the surrounding seafloor. In some places, these relict clays constrain the RSD direction (i.e. diversion) or even stop them (see an example in the lower left corner). Location of sonogram, see fig. 2.

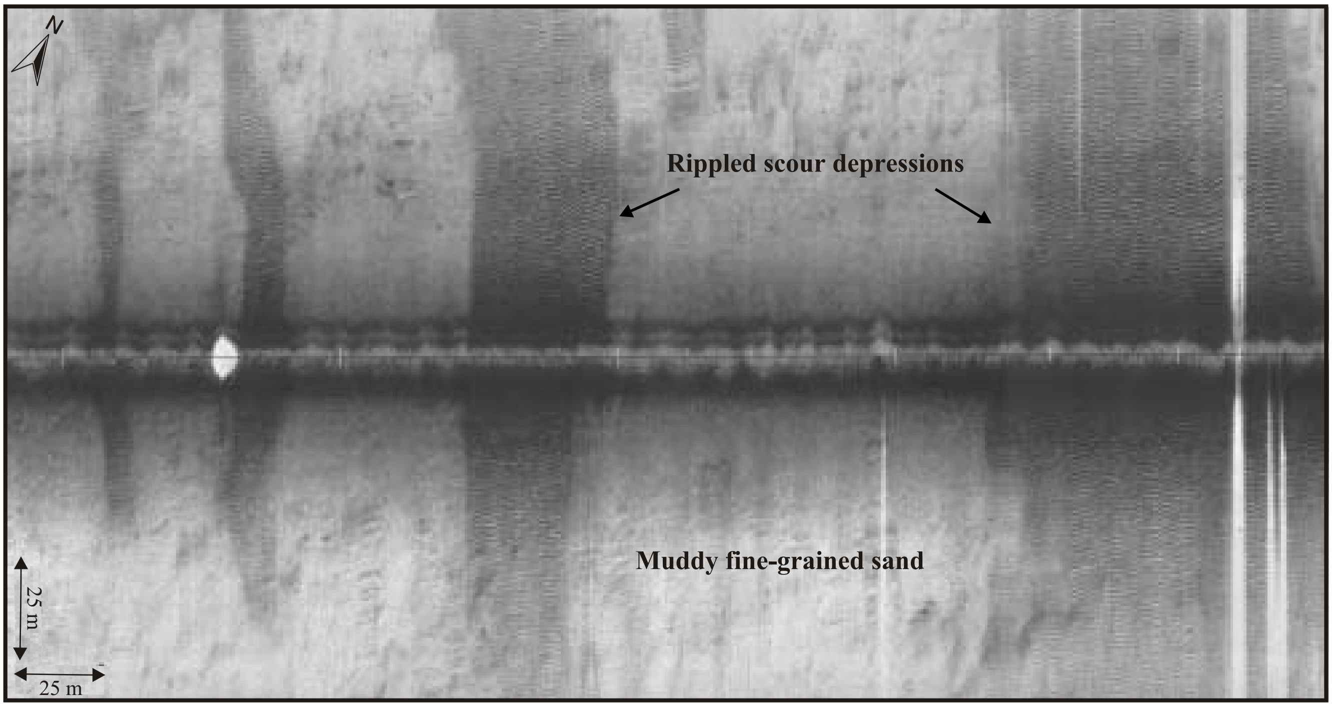
b) Perspective view of a sedimentary model of the inner shelf of the south-eastern Bay of Seine, showing the main sediment bodies and the interpretation of their geometrical relations in the area of the RSDs.

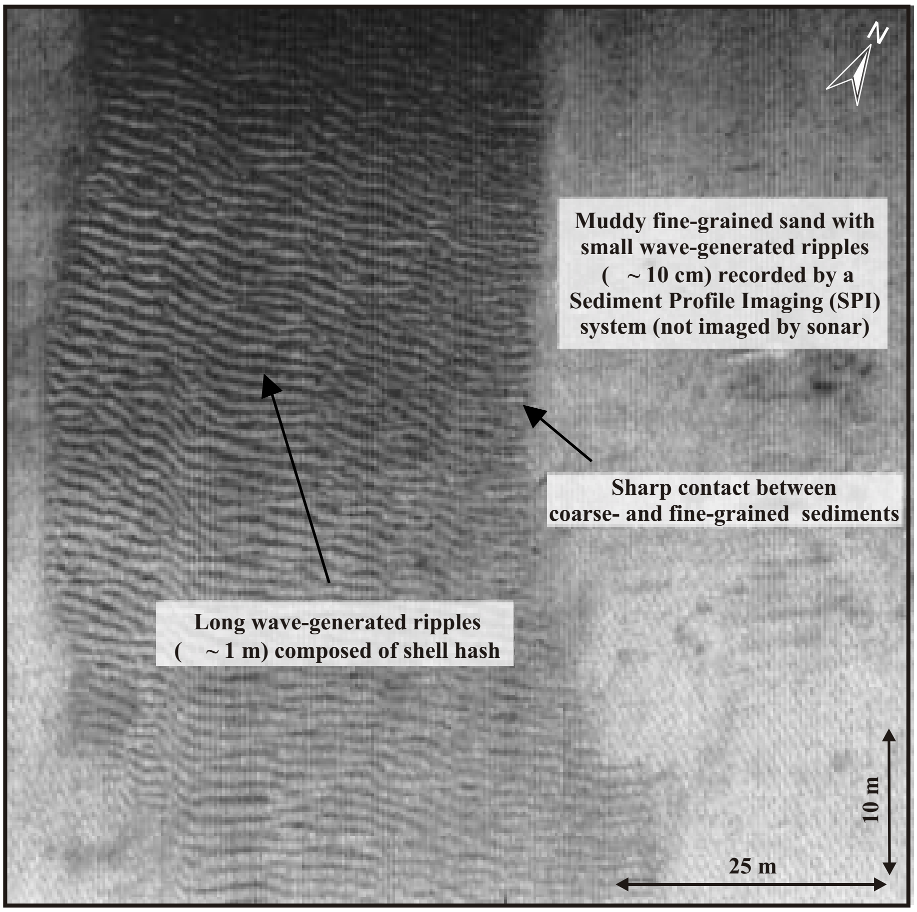
Figure 6: Details of two cores displaying the various modern and relict lithofacies in the study area in the form of distinct sedimentary units. a) Positive of X-radiograph (Scopix system, University Bordeaux I) and detailed photography of a vibracore taken in the vicinity of RSDs at a water depth of 6 m (1120 core); analogous coarse-grained relict layers can be distinguished in some cores. b) Photograph of a boxcore taken in the region of RSDs at a water depth of 5 m (2681 core). For location of cores, see Fig. 3.



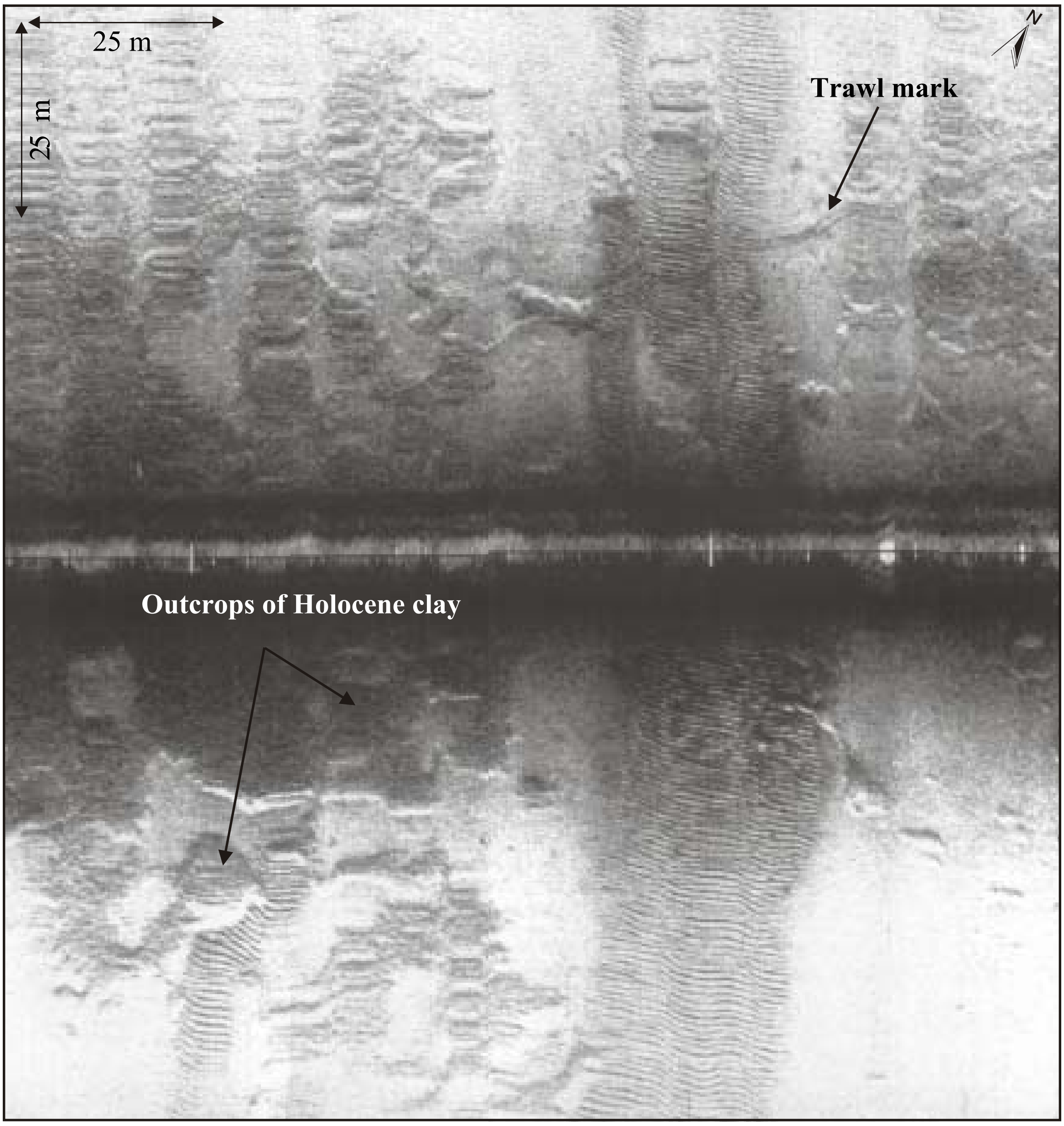
ENGLAND
ENGLISH CHANNEL
N
50°N
Le Havre
Caen
Bay of Morlaix
Brest
Paris
Morbihan Gulf
FRANCE
Grande Vasière
Aquitain shelf
Bordeaux
45°N
Marseille
0
200 km
5°W
0°
5°E
0°10'W
0°5'W
0°
0°5'E
0°10'E
Le Havre
Seine inlet
Ratelets bank
49°25'N
20 m
15 m
Rocky coast
Touques
5 m
10 m
Deauville
49°21'N
Field of RSDs
Villers-sur-mer
0 m
2 m
Houlgate
Cabourg
Dives
Franceville
Orne
NORMANDY
0 1 2 3 4 5 km


N
W
E
S
10 m
9 m
6 m
8 m
7 m
5 m
3 m
0 m
Fig. 3
Fig. 4
Fig. 5
1120 core
2681 core
Houlgate
Cabourg
Dives-sur-Mer
Shipeck grab
Boxcore (20-30 cm)
Kullenberg core (1-2 m)
Vibracore (2-4 m)
Side-scan surveys tracks
Field of RSDs
Individual RSD
0
1
2 km
49°20'N
49°18'N
00°08'W
00°06'W
00°04'W
00°02'W


N
Rippled scour depressions
Muddy fine-grained sand
25 m
25 m

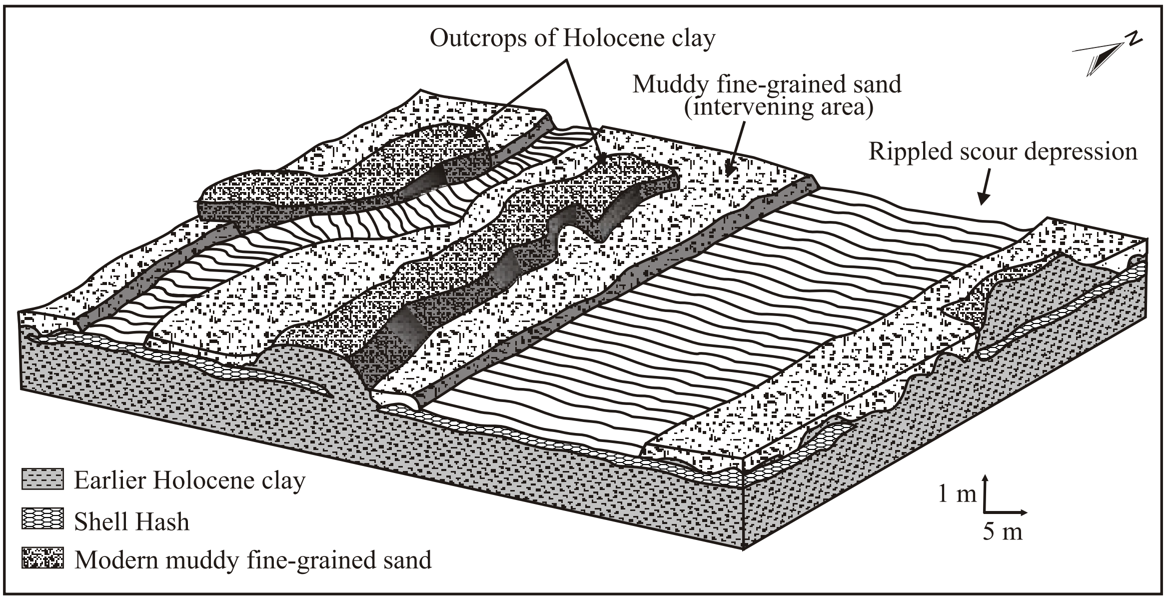

N
Muddy fine-grained sand with
small wave-generated ripples
(~ 10 cm) recorded by a
Sediment Profile Imaging (SPI)
system (not imaged by sonar)
Sharp contact between
coarse- and fine-grained sediments
Long wave-generated ripples
(~ 1 m) composed of shell hash
10 m
25 m

a

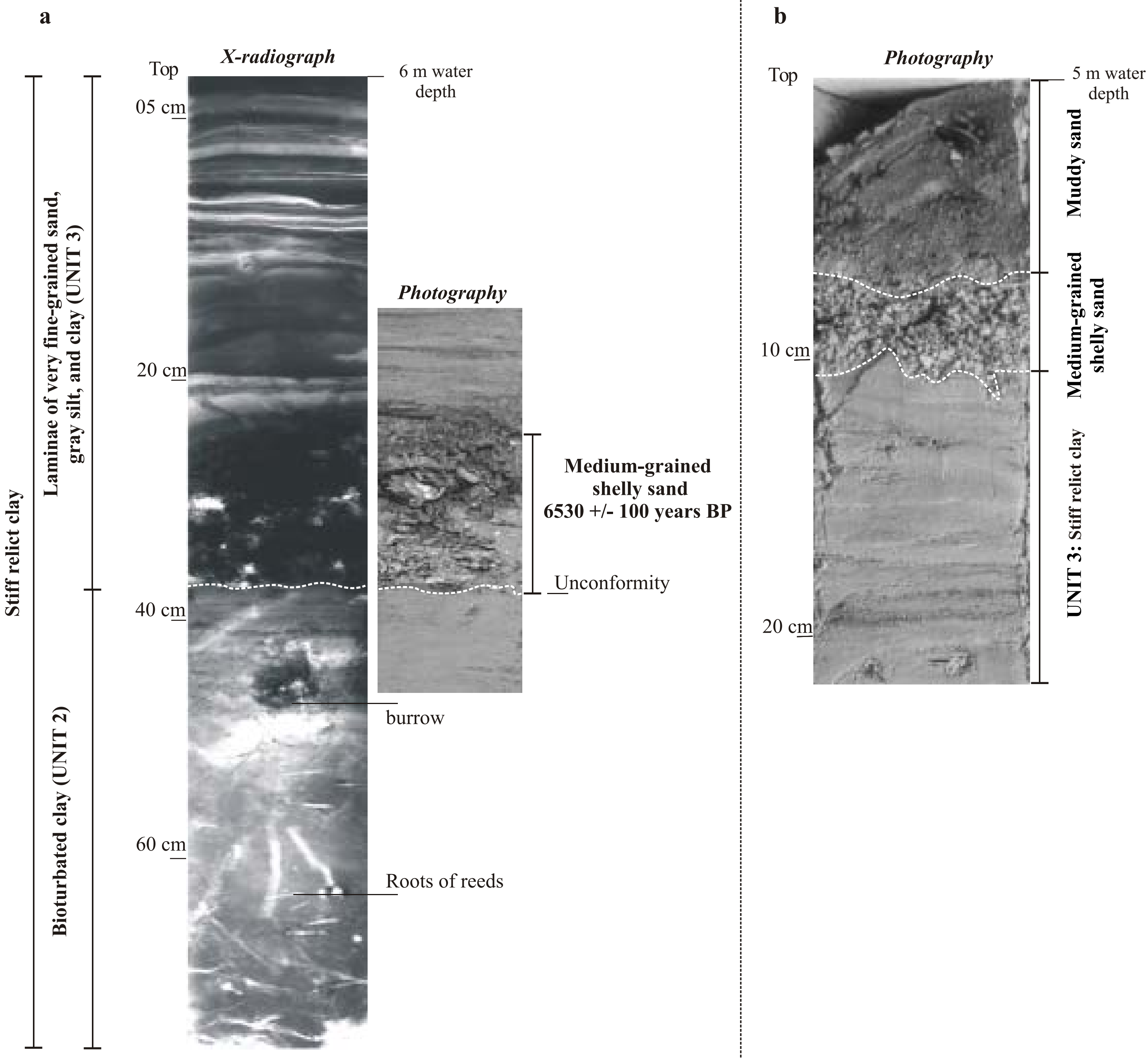


25 m
25 m
Trawl mark
Outcrops of Holocene clay

b



Outcrops of Holocene clay
Muddy fine-grained sand
(intervening area)
Rippled scour depression
Earlier Holocene clay
Shell Hash
Modern muddy fine-grained sand
1 m
5 m


a
X-radiograph
Top
6 m water depth
05 cm
20 cm
40 cm
60 cm
Photography
Medium-grained shelly sand
6530 +/- 100 years BP
Unconformity
burrow
Roots of reeds
Stiff relict clay
Laminae of very fine-grained sand, gray silt, and clay (UNIT 3)
Bioturbated clay (UNIT 2)
b
Photography
Top
5 m water depth
10 cm
20 cm
Muddy sand
Medium-grained shelly sand
UNIT 3: Stiff relict clay