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Dynamics of inner-shelf, multi-scale bedforms off the south Aquitaine coast over three decades (Southeast Bay of Biscay, France)

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ABSTRACT

This paper aims to investigate the seabed morphodynamics of the south Aquitaine inner shelf in the area known as “La Salie” (150 km^2, Atlantic ocean, west coast of France), through a descriptive and comparative analysis (time lapse of 29 years) of geophysical and sedimentological datasets.

At a water depth of 24–50 m, four orders of sedimentary body types were observed at different scales. The first order are large cross-shore “morphological ridges,” corresponding with the properties of very large sorted bedforms. The second order consisted in patchy sorted bedforms, composed of alternately medium to fine sand patches (0.5–2 m in thickness), cut by smaller, elongated coarse sediment depressions. In particular, the data from the sub-bottom profiler revealed that sand patches predominantly overlayed the coarse-grained blankets on the eastern (shoreward) extremities, while coarse-grained blanket wedges were found in front of the sand patches (southwestward) or locally overlying them on the southwestern extremities. The third order of bedforms involved groups of dune-like features (fine/medium sand), lying in wide areas of coarse-grained sediment. Finally, in the fouth order, the entire inner shelf was covered with wave-generated ripples, oriented N15°, that were larger where sediments were coarse (wavelengths of 2.2 m) than where sediments were fine (wavelengths of 0.3 m). Over the past 29 years, at a large scale of observation, patchy sorted bedforms have remained remarkably persistent, as has their overall appearance. However, at a smaller scale, weak but constant movements were observed. The coarse depressions have become elongated at their extremities (by a maximum of 300 m over 15 years), and certain coarse/fine sediment boundaries have moved toward the northeast and southeast (by a maximum of 75 m over 12 years). The general movement has been shoreward as has the migration of third-order submarine dune-like features. The persistence of sorted bedforms thus appears to be the consequence of sediment sorting feedback and recurrent storm events.

1. Introduction

The inner continental shelf constitutes an area in which sediments can be permanently or temporarily stored. The sediments can experience alongshore transportation and/or be exchanged with the littoral zone or permanently lost toward the continental slope and deep basin. In the present context of the eustatic rise and erosion of sandy coasts, improving our knowledge of these exchanges and their associated processes appears to be of primary importance. As a first step, a better understanding of the morphodynamics of the inner continental shelf can help shed light on cross-shelf dynamics.

Some continental shelves with siliciclastic superficial sedimentary cover subject to intense hydrodynamic processes (storms or tides) display alternating bathymetric lows, such as coarse depressions or erosion furrows (coarse sand, gravel, and pebbles), and bathymetric highs, such as sand patches (medium to fine sand). These sedimentary structures have a relatively low topographic relief (1–2 m) (Murray et al., 2014; Murray and Thieler, 2004).

These sedimentary features, known as “sorted bedforms” (Murray and Thieler, 2004) or “rippled scour depressions” (Cacchione et al., 1984), are ubiquitously observed throughout the world. They do not always display a regular pattern (Ferrini and Flood, 2005) and exhibit a broad range of characteristics. Several

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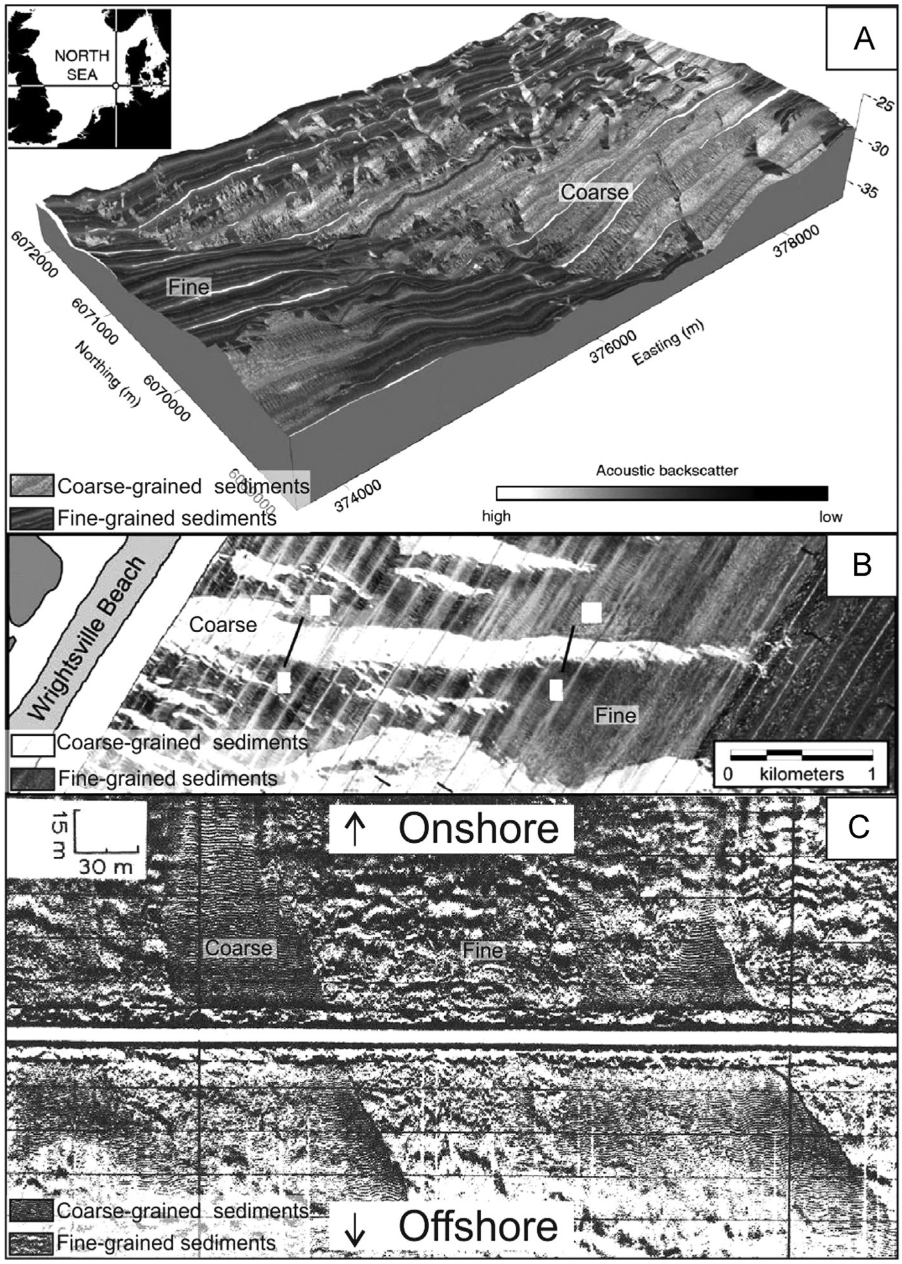

Fig. 1. Classification of sorted bedforms (Coco et al., 2007b). (A) Patchy (Diesing et al. 2006); (B) linear (Thieler et al., 2001); and (C) V-shaped (Morang and McMaster, 1980).

publications have proposed classifications for sorted bedforms (Coco et al., 2007b; Ferrini and Flood, 2005). Coco et al. (2007b) suggest that these seabed features can be classified into three types according to their shape: (1) patchy, (2) linear, and (3) offshore widening (or V-shaped) (Fig. 1). In this paper, we use this terminology, with a specific focus on patchy sorted bedforms.

Patchy sorted bedforms have been identified in numerous studies of continental shelves off the coast of Alaska (Hunter et al., 1982), the west coast of the United States (Davis et al., 2013; Eittreim et al., 2002; Ferrini and Flood, 2005; Hunter et al., 1988), the east coast of the United States (Thieler et al., 1999), the coast of New Zealand (Black and Healy, 1988; Hume et al., 2000; Trembanis and Hume, 2011), the coast of Germany (Diesing et al., 2006), the southern Baltic Sea (Schwarzer et al., 2003; Tauber and Emeis, 2005) and the French Aquitaine coast (Berné, 1999; Cirac et al., 1997, 2000; Turcq et al., 1986). These patchy sorted bedforms are found at a water depth of 4–90 m and have a low topographic relief with a vertical amplitude of under 2 m. Their spacing is very irregular, ranging from meters to kilometers, and their asymmetry and orientation also remain highly variable. Migration varies from site to site and grain size ranges from fine sand to pebbles. Moreover, Schwab et al. (2014) recently demonstrated on the northeast american inner shelf (offshore of Fire Island, New York) that such modern thin bedforms can lie uncomformably atop the Holocene ravinment surface and thus propose that such sediment starved seabed features can illustrate formation of a marine transgressive erosion surface.

On the Aquitaine continental shelf (Fig. 2B), patchy sorted bedforms have been the subject of numerous studies. Turcq et al. (1986) and Berné (1999) have described them as a sedimentary succession of sand patches, based on a coarse substrate, at a water depth of 30–90 m. The sand patches, which are irregularly shaped, are composed of fine to medium sand. They are rarely greater than 2 m in height and display a relatively flat surface with slightly asymmetric stoss and lee sides (Cirac et al., 1997, 2000). The coarse substrate is composed of coarse sand, gravel, and pebbles and

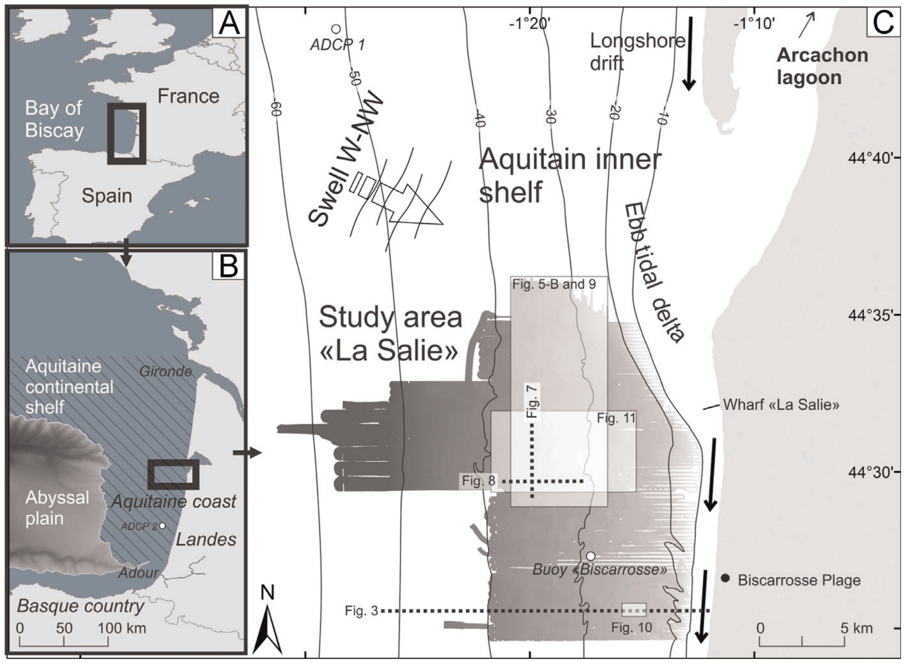

Fig. 2. (A)–(C) Location of the study area in the Bay of Biscay on the south Aquitaine inner shelf.

forms a continuous body under the sand patches. It is visible in areas where recent sedimentary cover is absent or eroded, known as “erosional windows.” Coarse sediments are considered topographic anomalies or erosive furrows.

At a smaller scale, subaqueous dunes and wave ripples are usually found on siliciclastic continental shelves. Subaqueous dunes are granular deposits submitted to unidirectional currents that migrate in the direction of the current, with the crest largely oriented perpendicular to the current (flow-transverse figure) (Berné, 1999). The size and shape of the dunes varies widely: wavelengths range from 0.6 m to 100 m and heights range from 0.05 m to several dozen meters (Reynaud and Dalrymple, 2012). The wave ripples are undulating geometric features generated by the interaction of the waves with the bed sediments. Their size varies from a few centimeters to several meters (Ardhuin et al., 2002; Cummings et al., 2009; Traykovski et al., 1999) and their crests tend to run perpendicular to the direction of flow (Nelson and Voulgaris, 2014).

Unlike subaqueous dunes or wave ripples that develop exclusively as the result of the interaction between bathymetry and flow, recent numerical studies have suggested that in addition to these usual concepts, the development of “sorted bedforms” involves a mechanism of sorting feedback (Coco et al., 2007a, 2007b; Murray and Thieler, 2004; Van Oyen et al., 2010, 2011). This sorting feedback is initiated by large wave-generated ripples in coarse sediments that act as relief-generating local turbulent motion. This turbulence initiates the sorting feedback mechanism, by suspending fine sediments or preventing their deposition. Thus, fine sediments settle in less turbulent areas formed by smaller ripples develop over the fine domains.

This paper focuses on the dynamics of patchy sorted bedforms on the south Aquitaine inner shelf and is based on in-situ measurements. The paper begins by describing the study site, known as “La Salie”, and the methodology and data used (Section 2). In Section 3, a descriptive and comparative analysis is provided of the geophysical and sedimentological datasets in the area. Section 4 is devoted to discussion, focusing on the morphology and evolution of sorted bedforms.

2. Study site description, methodology, and data

2.1. Physiographic context

The southeast of the Bay of Biscay forms a right angle with the Aquitaine coast (France) oriented on a north–south axis (N10°) and the Basque Country (Spain) oriented on an east–west axis (Fig. 2A and B). The Aquitaine continental shelf is narrow off the coast of Landes (50 km wide) and extends up to 175 km wide to the north, off the Gironde fluvial-estuarine system. Water depth at the shelf break is approximately 160 m.

The study area, known as “La Salie”, is located on the south Aquitaine inner shelf, to the south of the Arcachon lagoon tidal inlet (Fig. 2C). The northeastern section of the study area is bordered by the ebb tidal delta of this inlet. Fig. 3 provides a cross-shore profile of the part of the inner shelf studied. The beaches are composed of homogeneous quartz sands, with mean sizes ranging from 200 to 400 μm (Pedreros et al., 1996). The sandy coast exhibits two distinct rhythmic sedimentary systems: (1) ridge and runnel systems found in the intertidal zone (Figs. 3 and 2) a crescent outer-bar appearing at approximately 500 m offshore in the subtidal zone (Fig. 3; Lafon et al., 2005). Immediately seaward of this outer sand bar, the slope increases by 1–1.5°, plunging from 5 m to 24 m in depth. Beyond 24 m water depth, the slope decreases significantly (0.15°) and remains constant for almost 10 km down to 45 m water depth. This zone constitutes the study area. The slope then steepens again from 45 to 55 m water depth. This topographic anomaly has been interpreted as a paleo-shoreline (Arbouille, 1987).

2.2. Hydrodynamic context

The Aquitaine coast is a wave-dominated environment exposed to high-energy North Atlantic swells, traveling mainly from the west–northwest (Butel et al., 2002). Near the coast, these conditions generate a southward longshore drift, with an annual sediment transport estimated at 38,000 m^3 to 657,000 m^3 (Fig. 2C) (Idier et al., 2013). On the inner shelf, swells do not play the same role in the transit of sediment, where it is generally limited to

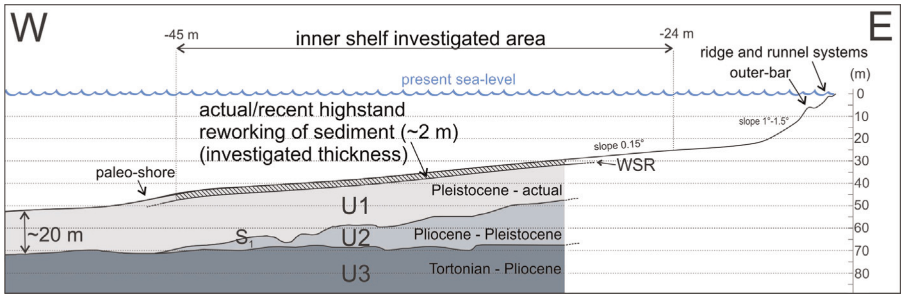

Fig. 3. East–west cross-shore bathymetric profile of our study area. Interpretation of the seismic line of the sedimentary cover (adaptation from the work of Cirac et al. (1997), Bellec et al. (2010) and Féniès and Lericolais (2005). U1, U2, and U3 correspond to the different sequences of deposition over time, S1 is an erosional unconformity and WRS the wave ravinement surface. See Fig. 2 for location.

sediment remobilization (Idier et al., 2006). The "Biscarrosse" buoy (Fig. 2C) recorded an annual mean significant wave height of 1.36 m, with a mean duration of around 6.5 s over the 1980–2000 period (Butel et al., 2002). During this period, severe storm wave heights reached 9.7 m and their corresponding duration was around 15 s. Regarding the 1958–2001 period, Charles et al. (2012) have underlined the strong correlation between seasonal wave characteristics and North Atlantic Oscillation (NAO) and East Atlantic (EA) patterns in the Bay of Biscay (Biscay buoy).

The hydrodynamics of the Aquitaine shelf, particularly the inner shelf, are considered to be dominated by processes related to wave and storm-induced currents (Barthe and Castaing, 1989; Castaing, 1981; Cirac et al., 2000; Idier et al., 2006, 2010).

Over the Aquitaine shelf, recent measurements based on acoustic Doppler current profilers (ADCPs) were made in the summers of 2002, 2008, and 2009 respectively, just north of the study area (44°39.1′N, 1°26.8′W; 54 m depth; site ADCP 1 in Fig. 2C) (Batifoulier et al., 2012, 2013) and for about one year between 2009 and 2010 to the south of the study area (44°N, 1°31′W; 54 m depth; site ADCP 2 Fig. 2B) (Kersalé et al., 2014; Le Boyer et al., 2013). These studies revealed 7- to 22-day northward alongshore current pulses reaching up to 50 cm (on average, 38 cm) two or three times per year in the summer or autumn over the entire water column. These events are related to wind forcing and/or surface cooling, which induces downslope bottom currents transporting coastal waters offshore and generating horizontal density gradients on the bottom and strong northward currents (Batifoulier et al., 2012, 2013; Kersalé et al., 2014; Le Boyer et al., 2013).

2.3. Geological and sedimentary context

The sedimentary cover of the Aquitaine shelf has been investigated by many authors (Allen and Castaing, 1977; Arbouille, 1987; Cirac et al., 1997, 2000; Dalrymple, 1984; Turcq, 1984). Bellec and Cirac (2010) reveal the presence of three units (Fig. 3): a bedrock unit (U3) forms the basal unconsolidated substratum, with units U2 and U1 lying above it. U2 and U1 are the most recent units, composed of sediments brought by the rivers during successive glacio-eustatic regressions in the Quaternary. Seismic surveys have demonstrated that U1 corresponds to a single 20-meter-thick sequence, involving: (1) an erosional unconformity (S1) corresponding to a fluvial incision at low sea level; (2) a transgressive deposit, representing the majority of the unit (~20 m); and (3) a superficial reworked cover, about 2 m thick that lies on the transgressive Wave Ravinement Surface (WSR; Féniès and Lericolais, 2005). This superficial cover is investigated in this paper.

2.4. Methodology and data

Our study was based on seven coastal surveys carried out between 1984 and 2013 in the area of "La Salie" (Table 1). Geophysical (acoustic data, including multibeam echo-sounders, side-scan sonars, and sub-bottom profilers) and sedimentological datasets (cores, Shipek grabs) were collected successively in the years of 1984, 1989, 1998, 2010, 2012, and 2013. Bathymetric data were collected and processed using CARAIBES (©IFREMER) and Caris (©HIPS) software, including manual-cleaning, automated-filter tide corrections, in order to obtain a digital elevation model (DEM). Sidescan backscatter signals were processed using SonarScope software (©IFREMER) in order to compensate artefacts related to seafloor properties, beam reception, and signal transmission angles. Seismic data collected from the SBP120 (2013) sub-bottom profilers were processed using ©MATLAB and analyzed using ©KINGDOM and ©ArcGIS software in order to obtain an isopach map of the sand patches. The two-way travel times between the seafloor and the unconformities were converted to thicknesses in meters using a constant velocity of 1600 m/s. Sedimentological analyses were performed by the sedimentology laboratory at Bordeaux University, including grain-size measurement (sieving and measurements using a Malvern Mastersizer S, which measured particle size using laser diffraction). The Wentworth grain size nomenclature is used in this paper (Wentworth, 1922). Because recent vibrocoring attempts have failed, our study used old unpublished vibrocore data, collected and described in 1989. We consider that the correlation of these past vibrocore data with our modern seismic data is acceptable because the related sampling areas did not undergo any strong evolution during the period studied.

Table 1
List of surveys conducted between 1984 and 2013 (N.C.: not concerned).

Year	Month	Name	Multibeam echosounder, with resolution	Sidescan	Sub-bottom profiler	Sampling
1984	July	FASEC 84	N.C.	Sidescan	N.C.	N.C.
1989	October	GEODEP 3	N.C.	N.C.	N.C.	Vibro-core
1998	July	ITSAS 1	EM1000, 5 m	N.C.	N.C.	N.C.
2010	June	SEDYMAQ 2	EM1000, 5 m	DF1000	N.C.	Shipek grab
2012	June	SEDYMAQ 3	EM2040, 1.5 m	Sidescan	N.C.	Shipek grab
2013	September	PROTEVS DUNE	EM1002, 1 m	N.C.	SBP120	N.C.

3. Results

Multibeam and sidescan sonar backscatter values revealed three acoustic facies: (1) high reflectivity, (2) medium or "wispy" reflectivity, and (3) low reflectivity (Fig. 4A). The results of the grain-size analysis of the Shipek grab samples revealed nine distinct sediment facies (Fig. 4A). These nine sediment facies were simplified and merged into three groups in order to correlate them with the acoustic facies (Fig. 4B). This correlation showed that: (1) high reflectivity could be correlated with coarse-grained sediments (D50=2.36 mm), (2) medium or "wispy" reflectivity could be correlated with mixed sediments (D50=0.64 mm), and (3) low reflectivity could be correlated with fine-grained sediments (D50=0.24 mm). Coarse-grained sediments included pebbles, gravel, very coarse sand, and coarse sand. Fine-grained sediments included medium and fine sand. Mixed sediments were usually collected in grab samples showing a combination of coarse- and fine-grained sediments. Coarse and fine-grained sediment distribution was unimodal and well sorted (Fig. 4F and G, respectively), whereas mixed sediment distribution was clearly bimodal (Fig. 4E). In water depths of 24–40 m, the sediments were composed of 63%, 33%, and 4% of fine-grained, coarse-grained, and mixed sediments, respectively.

The analysis of the 3D bathymetric view (with ×100 vertical exaggeration) revealed the presence of first-order morphological features: large cross-shore "morphological ridges" (Fig. 5). The vertical amplitude of these sedimentary bodies does not exceed 2 m. They are 2–3 km wide, 5–10 km long, and run perpendicular to the coast on an east–west axis (N80°).

These morphological ridges are covered by second-order sedimentary bodies corresponding to patchy sorted bedforms. Indeed, the sand patches (fine-grained sediment domains) are generally located on the northeastern side of the first-order morphological ridges and are alternated with coarse sediment domains, generally lying on the southwestern side of the morphological ridges (Fig. 5B and C). The sand patches correspond to bathymetric highs (up to 2 m in vertical amplitude). They are usually asymmetrical in shape, with a crest separating the lee (westward) and stoss (eastward) sides (red line; Fig. 5B and C). Unlike submarine dunes however, these sand patches generally exhibit steeper slopes on both sides upon contact with the coarse sediment domains. They are themselves incised by smaller elongated depressions (yellow line; Fig. 5B and C), several kilometers long and 100–500 m wide. These depressions generally cut the sand patches from the south on a north–south axis (N15°–N30°) (Fig. 5) and are typically floored by coarse sediments (Figs. 4 and 5B).

Vibrocore VK8909 (Fig. 6A) was collected in a sand patch and was composed of three stacked sandy beds. These beds began with an erosive base covered with coarse sediments made of gravel and pebbles in a sandy matrix. The sequences ranged from coarse to medium sand, showing oblique planar-tangential or sigmoidal bedding with an apparent dip ranging from 5° to 20°.

Vibrocore VK8910 was collected in a depression. It involved a bed that was 10–30 cm thick, alternately composed of fine

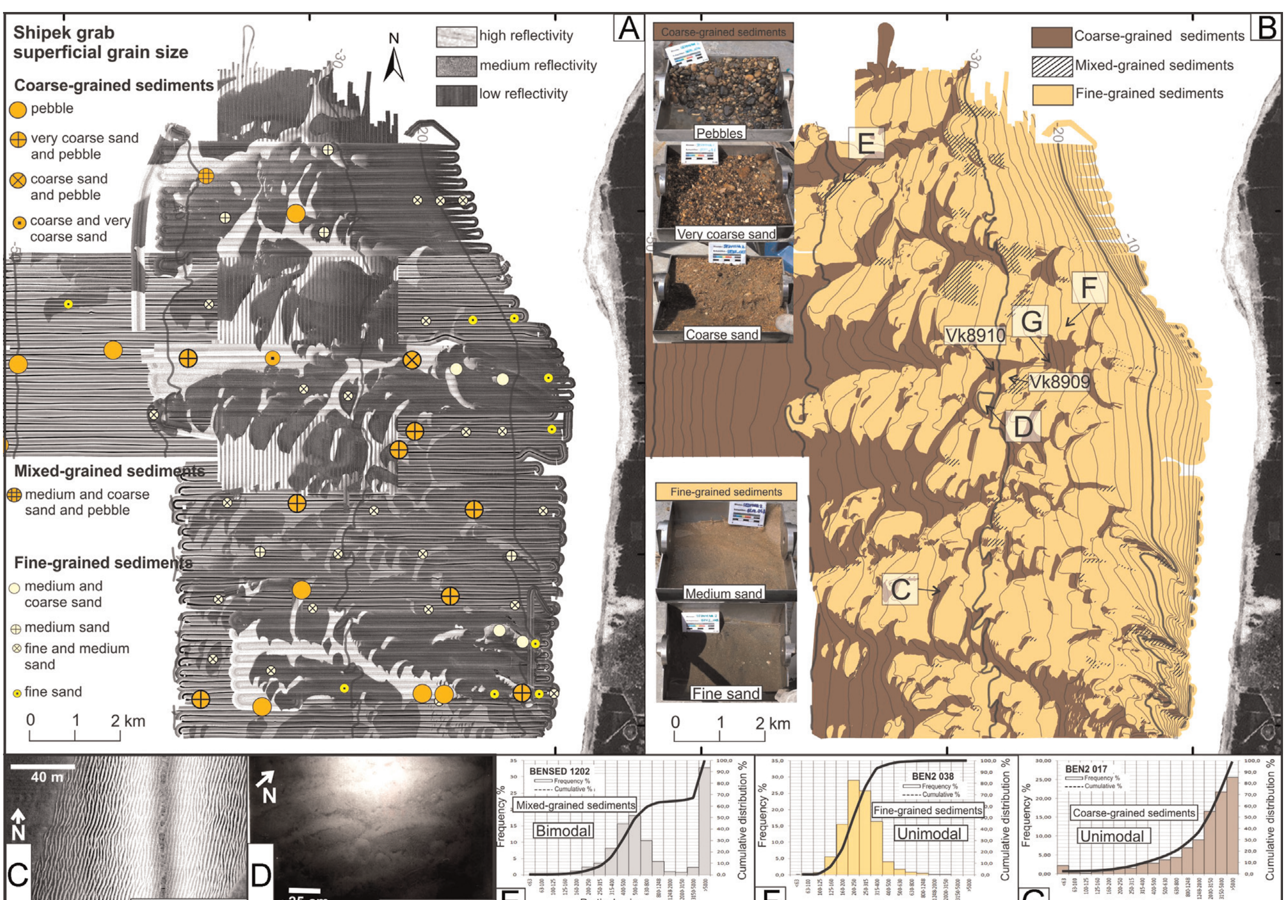

Fig. 4. (A) Map of multibeam and sidescan sonar backscatter data and grain-size analysis of Shipeck grab samples (please note that tone-matching anomalies are the result of the mosaic of different surveys and not of sediment textural changes). (B) Map of seabed sediment facies at "La Salie" (interpreted from [A]). (C) Sidescan sonar: large wave-generated ripples, in 33 m water depth, D50=3.4 mm, amplitude <20 cm and wavelengths=~2.2 m. (D) Photographs of the seabed: wave-generated ripples, D50=0.23 mm, amplitude =~15 cm and wavelengths =~30 cm. (E) Bimodal sediment distribution. (F and G) Unimodal sediment distribution.

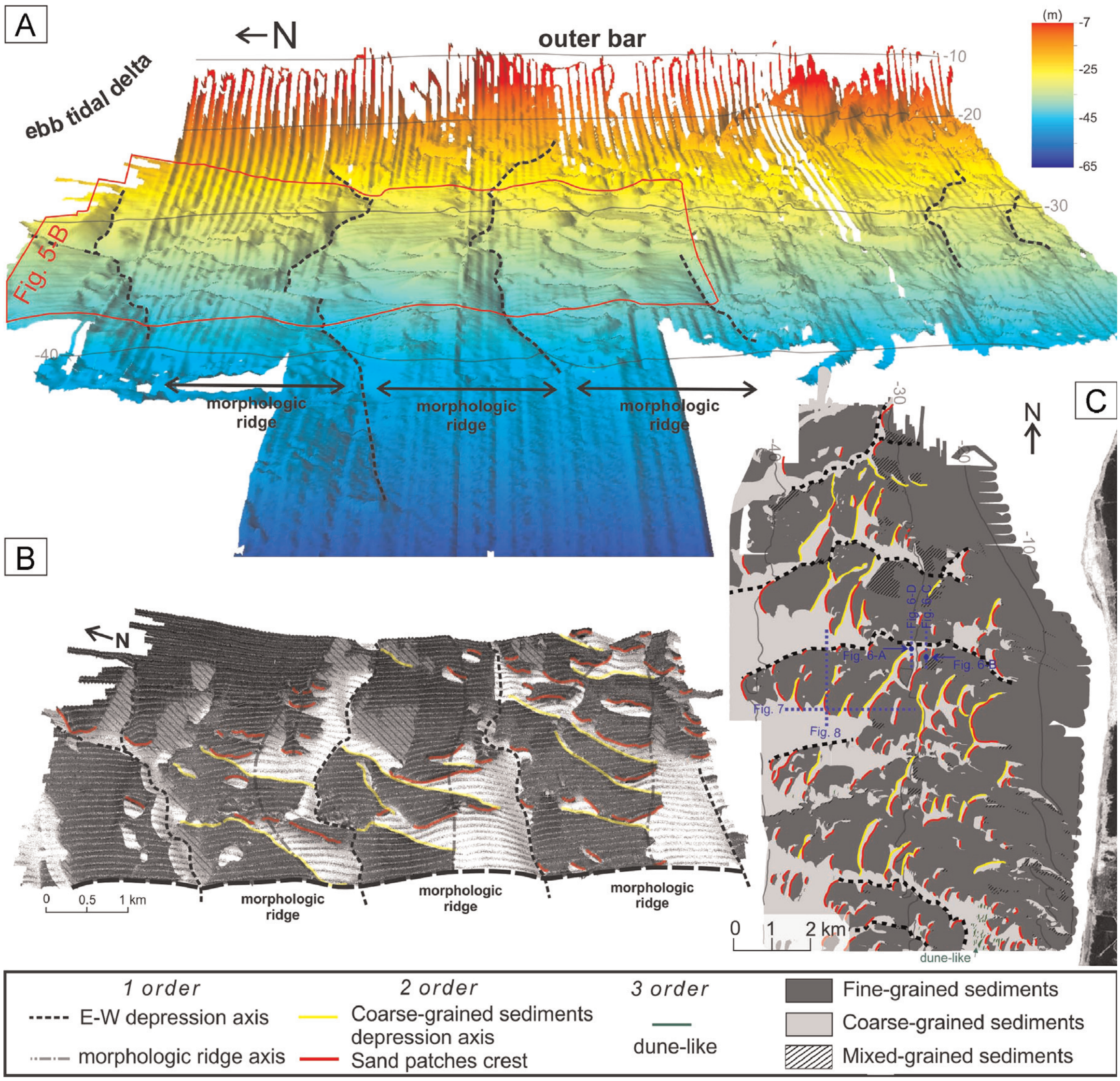

Fig. 5. (A) 3D views of the bathymetry looking landward (mosaic of the last three cruises: 2010, 2012, and 2013) (vertical exaggeration is × 100). (B) Sea-floor images of acoustic backscatter draped over bathymetry (vertical exaggeration is × 100) (See Figs. 5A or 2 for location). (C) Map of seabed sediment facies at "La Salie" and morphological features. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

(medium sand or mud) and coarse sediments (gravel and pebbles; Fig. 6B) and capped with coarse sediments.

These two vibrocores allowed for the calibration of the sub-bottom profiler data (very high resolution seismics). Three acoustic facies were observed. (1) High-amplitude chaotic facies corresponding to coarse-grained seabed sediments (Fig. 6D). The amplitude of the seabed reflector was not high, and the alternation of fine and coarse-grained sediments evidenced on the cores did not appear on the acoustic facies (Fig. 6C and D). (2) Low-amplitude facies corresponding to the fine sand unit (sand patches; Fig. 6C). The reflector corresponding to the sandy seafloor was well defined and involved a continuous high-amplitude sand patch top reflector. Because of the signal reflection on the coarse-grained sea floor, the sub-bottom resolution was too low to allow the identification of internal structure units, such as the stacked sandy "elementary sequences" seen in core VK8909 (Fig. 6A). (3) Very low-amplitude discontinuous reflectors unit corresponding to the top of the non-reworked "substratum." This facies became sub-transparent at greater depth due to signal attenuation. The top of this substratum was visible at the bottom of core VK8909 (Fig. 6A). This facies is locally topped by a medium amplitude discontinuous reflector (D-reflector) and everywhere else drastically contrasts (acoustic discontinuity) with the overlying coarse-grained seabed sediments unit (high amplitude chaotic facies).

The strike sub-bottom profile (N–S) was located at a water depth of 36 m and crossed two "large morphological ridges" (Fig. 7). The morphology of the sand patches did not appear to be influenced by the underlying coarse substrate. The coarse deposits forming the sub-bottom sediments appeared as coarse decimeter-thick blankets that could locally overlie the southern extremities of the sand patches. Very high resolution seismic analysis also confirmed the morphobathymetric analysis that highlighted the sand patch crests. The limit of the sand patches and coarse sediments generally showed a sharp transition with a steep slope. The northern limit between two morphological ridges was ill-defined, with a gentle slope and finer-grained sedimentary bodies.

The dip profile (E–W), located at a water depth of 30–40 m, intersected several second-order sand patches and a depression floored with coarse deposits (Fig. 8). The tops of the sand patches appeared to be somewhat concave and were still marked by the presence of crests to their western extremities. They had an asymmetrical form that was thicker in the west and that was

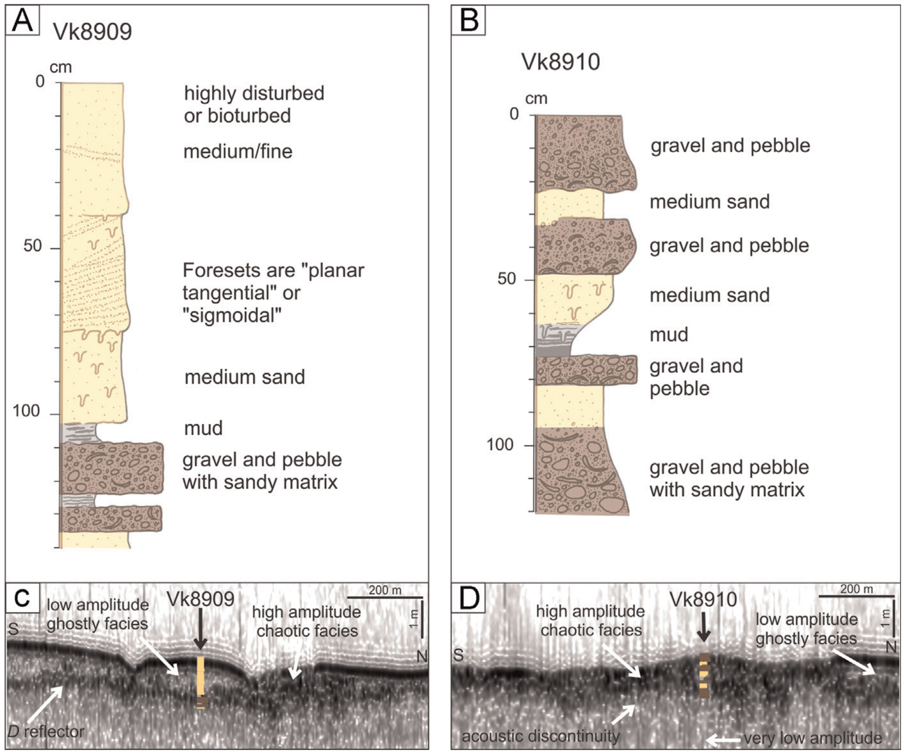

Fig. 6. (A) Vibrocore 8909 (1.4 m long) collected in fine-grained sediments. (B) The 1.2-m-long vibrocore 8910 was collected in coarse-grained sediments. (C and D) Calibration of sub-bottom profiler data. Three acoustic facies were observed. See Fig. 5C for location.

interbedded with the adjacent coarse blanket. Thus, the coarse-grained blankets appeared to be lying in front of the sand patches (wedge-shaped coarse blankets) or, as above, locally overlying the southern extremities of the sand patches, whereas the sand patches were found systematically overlying the coarse blankets on their eastern (shoreward) extremities. This whole superficial reworked cover lay on the non-reworked coarse unconsolidated substratum (U1, Fig. 3).

The isopach map (Fig. 9), which was made using only the SBP120 data, represents the thickness of the sand patches. The thickest areas (3–6 m), visible on the northeastern part of the map, correspond to the offshore edge of the neighboring Arcachon inlet ebb delta and are not representative of the study area. On the inner shelf, the average thickness of the studied sand patches ranges from 0.5 to 2 m. As suggested by their morphology, the sand patches are anisopach. They are generally thicker at the western and southern extremities on a vertical axis from their crests. Excluding the ebb tidal delta, a total fine sand volume of 22,000,000 m^3 for a surface area of 24,000,000 m^2 was estimated at a water depth of 28–38 m (1 m thick on average, if this fine sand stock were uniformly spread). The gray scale lines represent the thickness of the sand patches where they are overlaid by a coarse

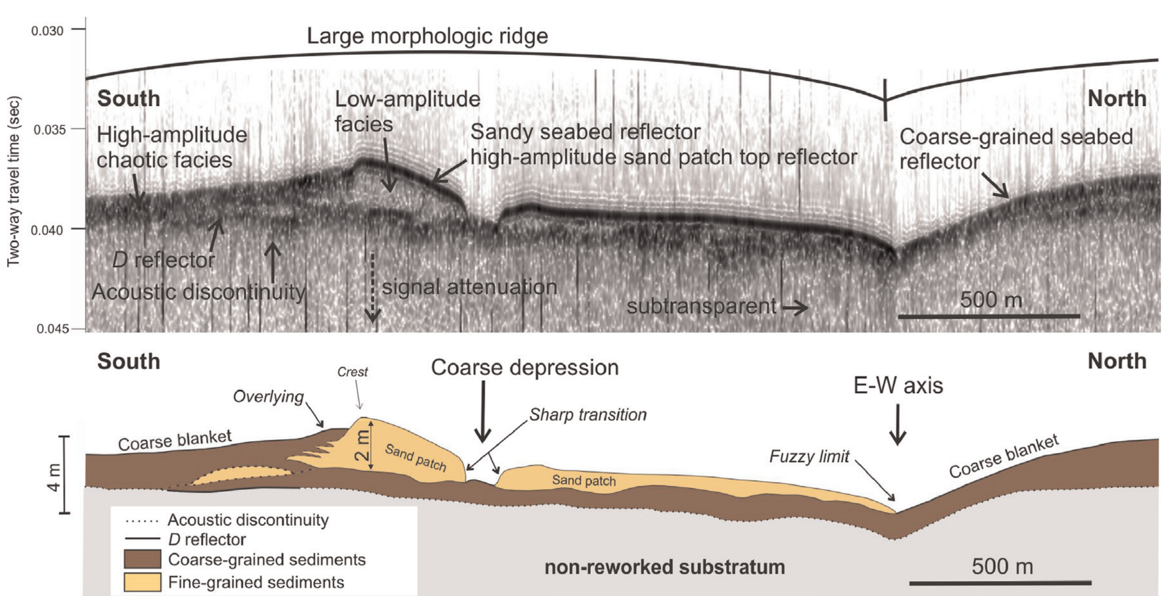

Fig. 7. Sub-bottom very high resolution seismic profile analysis collected by the SBP120 profiler. North–south profile at a water depth of 36 m. See Figs. 2, 4, or 5C for location.

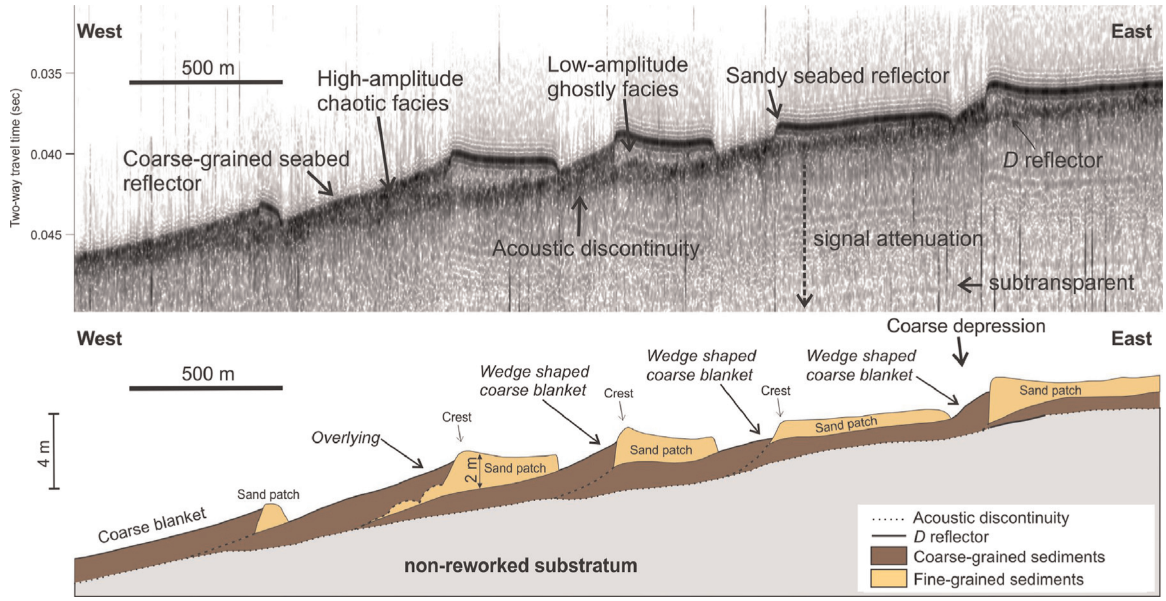

Fig. 8. Sub-bottom very high resolution seismic profile analysis collected by the SBP120 profiler. East–west profile at a water depth of 30–40 m. See Figs. 2, 4, or 5C for location.

sediment blanket. The map clearly shows that this particular kind of overlaying usually concerns the southwestern termination of the affected sand patches (Fig. 9B–E).

Third-order sedimentary bodies corresponding to groups of dune-like features lie in areas of wide, coarse sediment and are isolated from neighboring sand patches (Fig. 10A and C), similar to those observed by Cacchione et al. (1987). Because these features were nearing the resolution limit of most of our bathymetric data, the shape of their transversal cross-section was difficult to determine. According to the highest-resolution bathymetric data

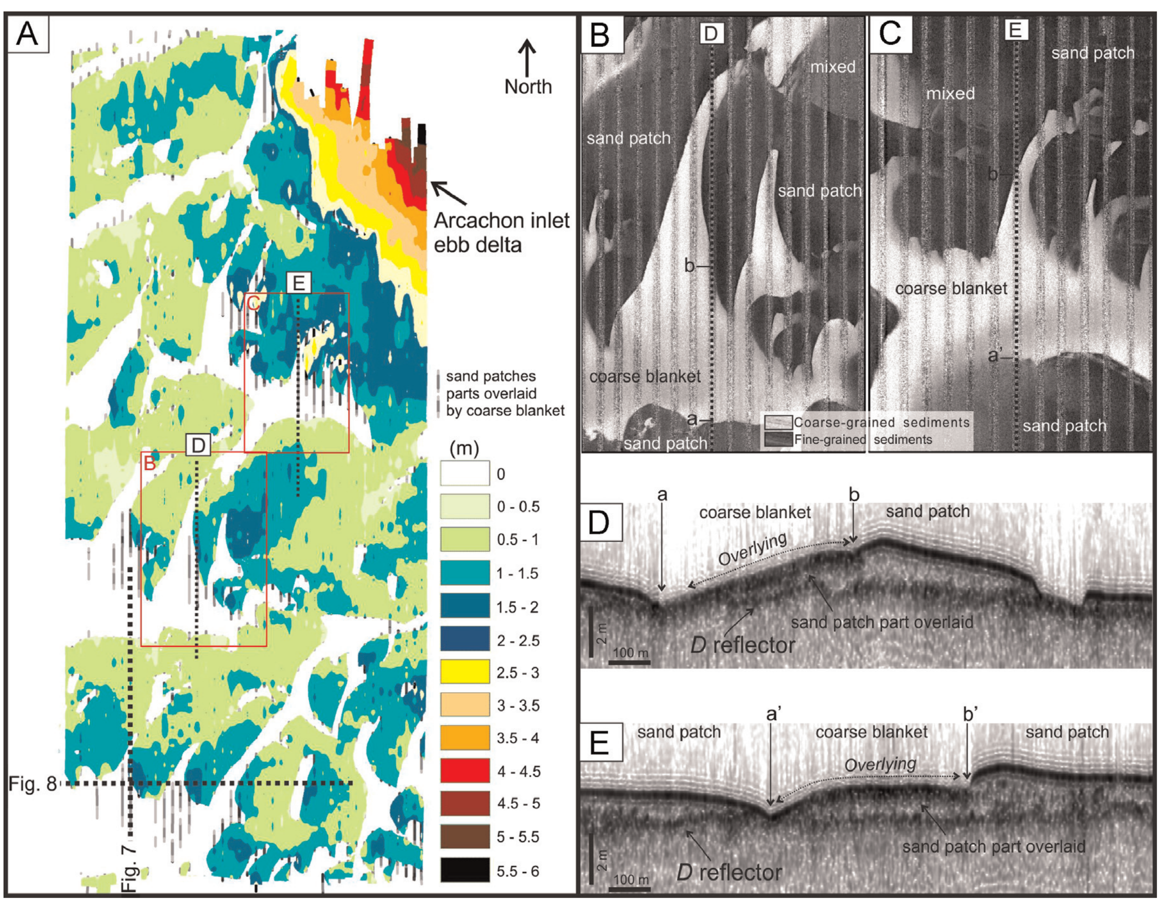

Fig. 9. (A) Isopach map of sand patches (m). Gray scale lines represent the thickness of the sand patches where they are overlayed by coarse-grained sediments (see Fig. 2 for location). (B and C) Seafloor images of acoustic backscatter (See Fig. 9A for location). (D and E) Sub-bottom very high resolution seismic profile analysis collected by the SBP120 profiler (See Fig. 9A–C for location).

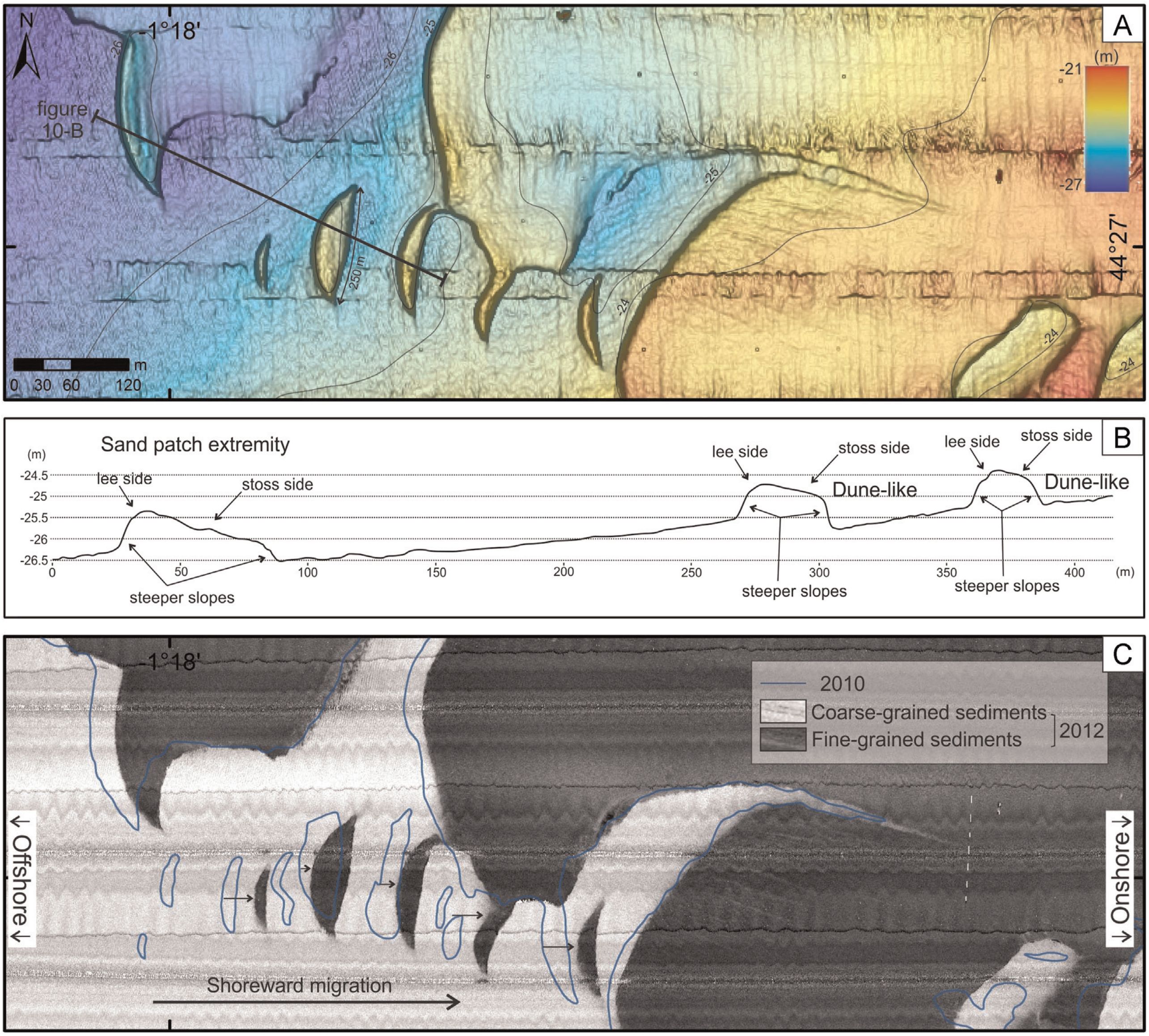

Fig. 10. (A) Sea-floor images of multibeam bathymetry (data from 2012). (B) East–west cross-shore topographic sections derived from the bathymetric maps (see Fig. 10A for location). (C) Seafloor images of acoustic backscatter (2012) and comparison of third-order data between 2010 (blue) and 2012 (black and white shading). See Fig. 2 for location. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(EM2040, 1.5 m resolution), however, at least one of these dune-like features is asymmetrical in shape, with a westward lee side and eastward stoss side (Fig. 10B), both of which exhibit a steep slope upon contact with the coarse sediment domain. Their sub-linear crests are oriented N10°–N30° (subparallel to the shore), and they range from 50 to 250 m in length, 20–50 m in width, and 0.5–2 m in thickness. These dune-like features share morphological and lithological similarities with the extremities of the sand patches previously described. In particular, both sedimentary bodies are composed of medium and fine sand (Fig. 10C).

Fourth-order sedimentary bodies are located in areas covered with both coarse and fine sediments. In areas covered with coarse sediments (deposits with a D50 of 3.4 mm), side-scan sonar data (Fig. 4C, 33 m water depth) showed large ripples that are usually straight, sometimes bifurcated and that have the same northeast–southwest orientation (N15°). Their estimated amplitude was under 25 cm and their mean wavelength was 2.2 m. In areas covered with fine-grained sediments, wave-generated ripples did not appear on the side-scan sonar, due to the low resolution of the device. Photographs of the sea-floor revealed symmetrical ripples, however, that are oriented northeast–southwest (Fig. 4D) in these areas. Their dimensions are smaller than those found in areas covered with coarse-grained sediment, with amplitudes of about 15 cm and mean wavelengths of about 30 cm. It should be noted that the presence of these two types of ripples is widespread on the Aquitaine shelf, regardless of water depth (Cirac et al., 2000). The morphology of these ripples (symmetrical) and their orientation (N15°, i.e. perpendicular to mean swell direction) leads us to view them as large wave-generated orbital ripples, as observed by Traykovski et al. (1999) and Ardhuin et al. (2002) on continental shelves.

The time-lapse side-scan sonar and imagery database allowed the movement of the limits of the patchy sorted bedforms to be studied over the period of 1984–2013, at a water depth of 25 m–39 m. For this purpose, only clear-cut and well-contrasted boundaries between the fine (low reflectance) and coarse (high reflectance) sediments were used. Ragged or ill-defined boundaries were not included in this investigation (Fig. 11).

Over the past 29 years, at the largest scales, the location of second-order sedimentary bodies (patchy sorted bedforms) has

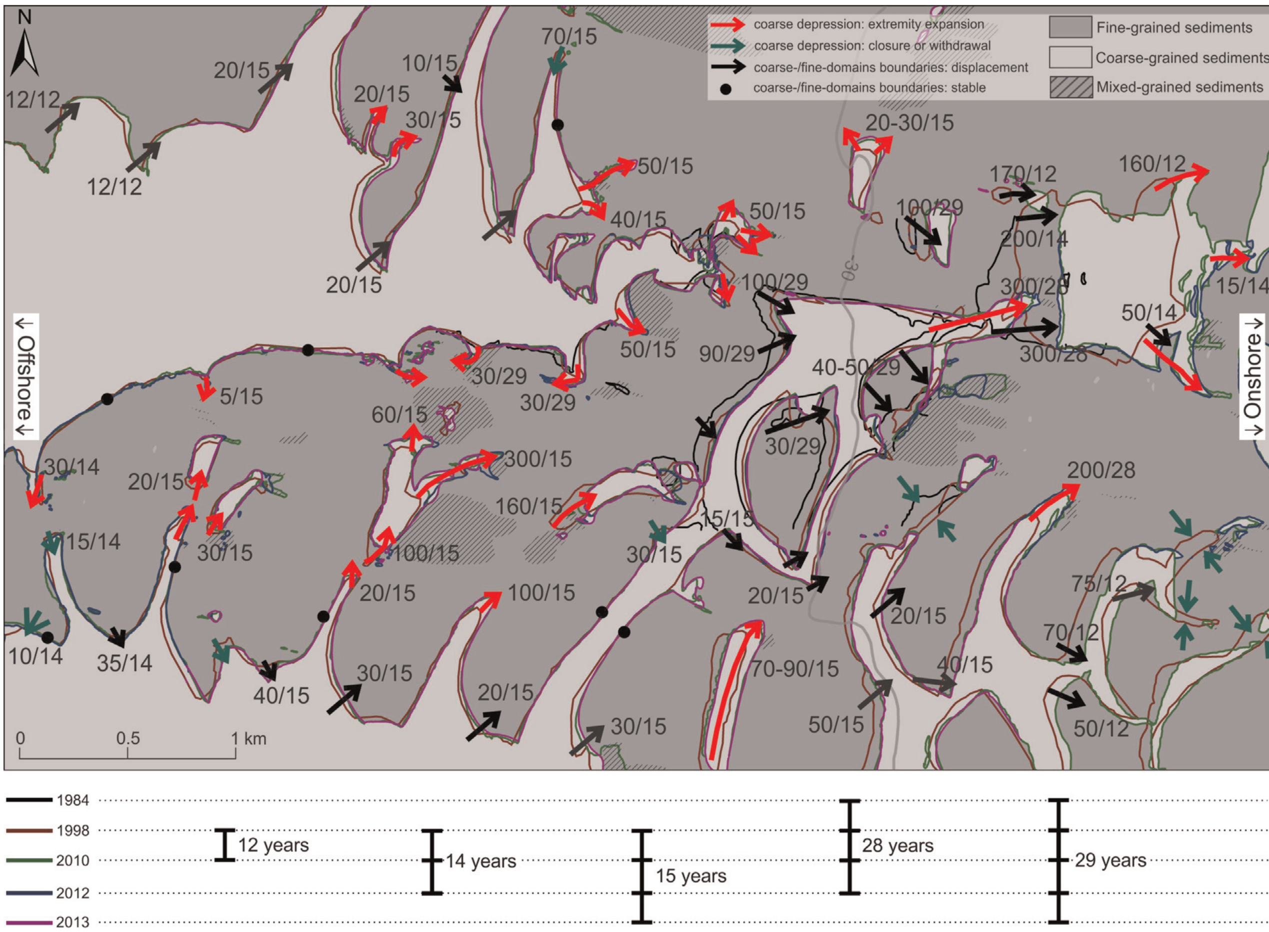

Fig. 11. Analysis of the movement of well-defined limits on reflectivity data between 1984, 1998, 2010, 2012, and 2013, at a water depth of 25–39 m: "movement in meters/ gap in years between the first and last mission." See Fig. 2 for location. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

remained remarkably stable, as has their overall appearance. However, at the second-order scale, three small but constant movements have been observed: (1) the majority of second-order elongated coarse depressions have been expanding at their extremities (red arrow; Fig. 11) (up to 300 m over 15 years); (2) some second-order depressions have closed or retreated (green arrows; Fig. 11); (3) some coarse-/fine-grained sediment boundaries have moved toward the northeast or southeast (black arrows; Fig. 11) (up to 75 m over 12 years). A few boundaries have remained stable over the 29 years (black dots; Fig. 11), while others have moved by about 300 m over 15 years. Comparison of data related to third-order bedforms between 2010 and 2012 (Fig. 10C) showed submarine dune-like features migrating shoreward with displacements ranging from 14 to 66 m over these two years.

4. Discussion

4.1. Morphosedimentary evolution

The high-resolution dataset (1–5 m) covered 150 km^2 and allowed observations at different scales. We highlight the presence of large "morphological ridges" perpendicular (N80°) to the shoreline (Fig. 5). Prior to the present study, descriptive analyses of the Aquitaine inner shelf had only covered a surface area of 40 km^2 (Cirac et al., 1997, 2000). This area was too restricted to detect the large-scale morphological features we observed in the present dataset (Fig. 5). The largest bedforms found along the inner shelf, excluding the tidal sandbanks, were shoreface-connected ridges (Stride, 1982). These shoreface-connected ridges were elongated, periodic undulations of the seafloor with wavelengths in the order of a few kilometers, ridge heights reaching 7 m, and crest lengths ranging from 5 to 50 km. They were connected to the shoreface and extended seaward with an oblique orientation in respect to the shoreline (Thieler et al., 2014; van de Meene and van Rijn, 2000). In our study area, the large morphological ridges had a similar wavelength, in the order of a few kilometers, and a crest length in the order of 10 km. Their orientation remained perpendicular to the shoreline, however, the ridge height did not exceed 2 m. The presence of shoreface-connected ridges suggests a relatively high sediment supply whereas sorted bedforms are characterized by a relatively low sediment supply (Thieler et al., 2014). It therefore seems unlikely that shoreface-connected ridges can coexist (in time and place) with sorted bedforms. Our large "morphological ridges" were covered by patchy sorted bedforms. Moreover, the relief was very low (less than 2 m) and they appeared to have a clear sediment sorting pattern related to bathymetry (sediment sorting at the updrift, and downdrift edges seem to be "sharp" and not degraded or reworked, suggesting active sorting). Fig. 7 shows coarse sediment on the southern flanks and fine sediment on the northern flanks. The measured currents (ADCP) were directed northward (i.e. coarse sediment on the updraft flank and fine sediment on the downdraft flank). They had all the characteristics of sorted bedforms of a scale (wavelength) larger than any sorted bedforms previously observed (in comparison with the classification by Coco et al. 2007b). Recent models

(Coco et al., 2007a, 2007b; Goldstein et al., 2014; Murray and Thieler, 2004) show, however, that sorted bedform size does not saturate when currents are asymmetrical (in this case the currents measured by the ADCP), suggesting that bedforms can continue to grow in size and become quite large.

At a second-order scale, our patchy sorted bedforms alternately involve fine-grained sediment (medium to fine sand), known as sand patches, and depressions blanketed with coarse-grained sediments (coarse sand and pebbles) (Figs. 4 and 5). These sedimentary features have a low relief in our study area, with a vertical amplitude of under 2 m and very irregular spacing, ranging from meters to kilometers (Fig. 9). The average grain-size distribution varies significantly (Fig. 4), both for coarse (D50, 0.5–5 mm) and fine-grained sediments (D50, 0.16–0.4 mm). Nevertheless, each sediment sample exhibits unimodal and well-sorted distribution. Only sediments considered “mixed” have a bimodal distribution. A comparison of the bedforms of the Aquitaine inner shelf with equivalent sorted bedforms reported worldwide (see Section 1) shows similar shapes, dimensions, and grain-size distributions (Diesing et al., 2006; Goff et al., 2005; Green et al., 2004; Gutierrez et al., 2005).

This study brings a new understanding of the sorted bedforms along the Aquitaine inner shelf, thanks to sub-bottom data (chirp; Figs. 7 and 8). Three new characteristics have been identified: (1) the morphology of the sand patches does not appear to be inherited from the underlying coarse substrate paleo-topography. (2) The thickness of the sand patches varies from 0.5 m to 2 m. This is consistent with the results of Cirac et al. (2000), showing a maximum thickness of 2 m for such sand patches over the north Aquitaine shelf. These observations suggest that the thickness of the sand patches should be similar over the entire Aquitaine inner shelf. (3) The seabed succession of coarse- and fine-grained domains corresponds in a cross-section to a lateral succession of wedge-shaped coarse-grained blankets lying in front (southwestward) of slightly thicker sand patches (Figs. 7 and 8). The sand patches usually overlie the following northeastward wedge-shaped coarse blankets (Figs. 7 and 8). In turn, the coarse blankets can occasionally overlie the southwestern extremity of the sand patches (Figs. 7–9D and 9E). Fig. 12 illustrates this complex succession and the local interbedding of the sand patches and coarse blankets. Coarse sediments are visible on the sea floor and no longer appear to correspond to a restricted area of erosion. In several works of related literature on sorted bedforms (Bellec et al., 2010; Goff et al., 2005; Schwab et al., 1996, 2013; Siringan and Anderson, 1994; Tauber and Emeis, 2005), very high-resolution seismic (Chirp) profiles present similarities with the present dataset. In these studies, three units have been identified: (1) the substratum, (2) coarse-grained sediments, and (3) fine-grained sediments (fine sands or levees containing sandy sediment). The overlying of the sand patches by coarse-grained sediment blankets is less common and cannot be explained by such a simple process as an interaction between bathymetry and flow. It appears to involve a sorting feedback mechanism, as described by Green et al. (2004), in which coarse sand is found in suspension with fine sand when waves are highest, suggesting that coarse sand (resuspended from the coarse domain) can be dispersed onto the adjacent fine-sand plain (at least along the same isobath). Such imbrication could correspond to the fine/coarse sand interbedding described in cores by Trembanis and Hume (2011) in a sorted bedform area.

All the sedimentary features described in this study (sand patches and coarse blankets) were located above the acoustic discontinuity and D reflector (when present). The wave ravinement surface (WRS) described on the Aquitaine continental shelf (about 5 km northward of our study area) off the “Cap Ferret” littoral spit (Féniès and Lericolais, 2005), was studied using a single trace sparker. This WRS, which erodes the upper part of the transgressive system tract of the Leyre-incised valley, corresponded with the sparker signal thickness, ranging from 2 to 3 twt ms under the seabed. The acoustic discontinuity and D reflector were both observed on our sub-bottom data in the same depth range under the seabed (2–3 twt ms). Accordingly, our acoustic discontinuity and D reflector (when present) could be interpreted as corresponding to the WRS described northerward. Such an interpretation is consistent with (1) the correlation of core VK8909 and the sub-bottom profile (Fig. 7A and C), where the D reflector correlates with the lithological unit of gravel and pebbles that may correspond to the “lag deposit” associated with a WRS, (2) the similarity of our data and geometry with that of Schwab et al. (2014) on the north American shelf, which clearly identified a Holocene WRS just below the modern reworked deposit in the same environment. However, unlike Féniès and Lericolais (2005) (Aquitaine shelf/Sparker) and Schwab et al. (2014) (Northeast American shelf/Chirp), we did not clearly identify an erosional truncation at the top of unit U1. The rapid signal attenuation beneath the acoustic discontinuity/D reflector prevented such observation. The erosive nature of the acoustic discontinuity could not be clearly established and its interpretation as a Wave Ravinement Surface therefore remains subject to discussion.

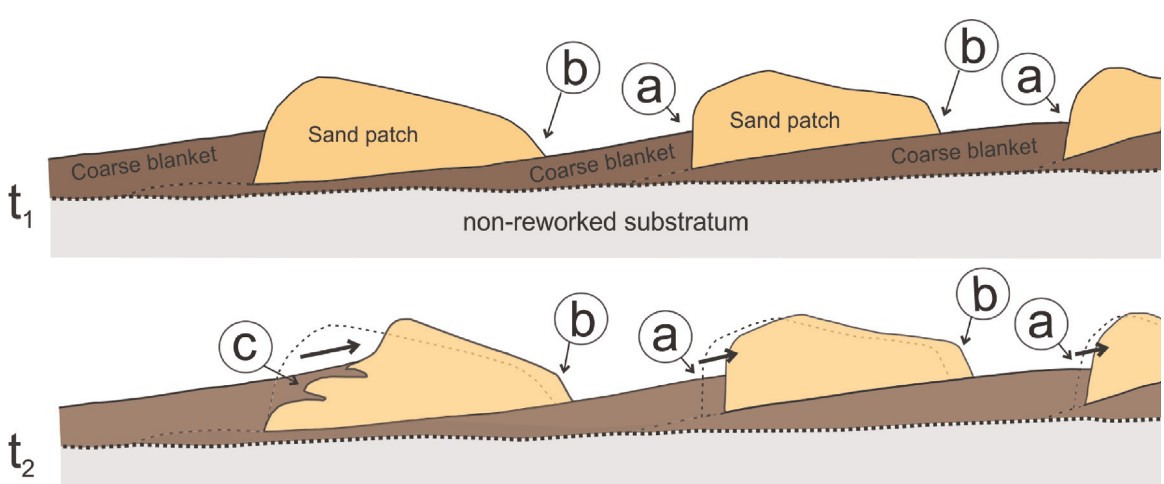

Fig. 12. A two-panel conceptual model showing idealized cross sections, illustrating the imbrications of the sand patches and coarse blankets over time: (a) wedge-shaped coarse-grained blankets lying in front (southwestward) of slightly thicker sand patches; (b) sand patches overlying the following norteastward wedge-shaped coarse blankets; and (c) coarse blankets overlying the southwestern extremities of the sand patches.

This study has shown the reduction or absence of sorted bedforms toward the northeastern part of the study area, close to the Arcachon ebb tidal delta. At present, the north of the study area, constituted by the ebb tidal delta area, contains a large quantity of medium and fine sand (deposit thickness > 6 m). The influence of the ebb tidal delta remains poorly understood, however referring to the work of Thieler et al. (2014), a large-sediment supply could inhibit the development of sorted bedforms.

4.2. Time lapse analysis

Seven reflectivity surveys were performed between 1984 and 2013 in the study area, at water depths ranging from 24 to 50 m. These surveys allowed for the analysis of the evolution of sorted bedform shape over time (Fig. 11), bringing a new outlook to the dynamics of the Aquitaine shelf. Patchy sorted bedforms have remained remarkably persistent throughout the period studied and over a large surface area, and the general patterns of the sorted bedforms have not shown any major evolution: the overall shape of the sorted bedforms has remained the same and the particular features can be easily recognized from one survey to another. However, at a smaller scale, two points can be highlighted: (1) second-order coarse depressions have become longer and correspond to the regions with the most significant sediment dynamics (red arrows in Fig. 11: with a maximum of 300 m over 15 years). These depressions seem to grow mostly in length and to almost “bisect” the sand patches, generally with a northeastward trend (parallel to their lengthening), but their width has remained relatively constant. (2) The limits of the coarse/fine-grained sediments have mainly been shifting toward the east (black and yellow arrows in Fig. 11: with a maximum of 75 m over 12 years, and an overall shoreward movement).

At an annual timescale, some studies have focused on the migration of patchy sorted bedforms (Diesing et al., 2006; Harrison, 2003; Tauber and Emeis, 2005), and all of them have concluded that large-scale morphologies are stable over time. However, high-resolution analysis has revealed some tiny changes in the shape or appearance of new features. The present results support previous studies reporting both the stability and persistence of sorted bedforms over a large surface area as well as the frequent remobilization of fine and coarse-grained sediments at a smaller-scale. Previous studies on the Aquitaine inner shelf have been based on morphological observations, however, and have never included any comparison of the same area at different periods in time (Berné, 1999; Cirac et al., 2000). The asymmetry of the sand patches with a seaward lee side and a shoreward stoss side had previously suggested a seaward migration. In contrast, we observed an overall shoreward migration (Fig. 11) for the patchy sorted bedforms over the last 29 years. The similar lee- and stoss-side orientation in submarine dune-like features also revealed an onshore migration (of up to 66 m) between 2010 and 2012, which was a counter-intuitive migration as observed by Franzetti et al. (2013) (Fig. 10C).

Thus, over the past 29 years, our study has shown the persistence of patchy sorted bedforms, with generally no appearance or loss of coarse- and fine-grained domains at least in a range of 24–50 m water depth (Fig. 11). As previously indicated, the hydrodynamics of the Aquitaine inner shelf are dominated by processes related to wave- and storm-induced currents (Barthe and Castaing, 1989; Castaing, 1981). This is coherent with the model of Green et al. (2004) who presented the idea that storms strengthen sorting feedback and expel fine grains from coarse domains, contributing to the persistence of sorted bedforms. Our study area also included a very large area of coarse-grained sediments, which was a necessary feature in sustaining the sorted bedform fields (Goldstein et al., 2011).

Seismic analysis has shown wedge-shaped coarse-grained blankets lying in front of the sand patches or locally overlying the southern extremities of the sand patches, whereas sand patches systematically overlie the coarse blankets on their eastern (shoreward) extremities. Such northeastern imbrication suggests a synchronous migration of these two second-order features toward the northeast. The movement of sediment bodies suggested by the sub-bottom profiler data (Figs. 7–9) confirms the movements evidenced on the map showing evolution over time (weak northeastward migration over the last 29 years) (Fig. 11). These results suggest a coastward/northeastward “dynamic” with the persistence or recurrence of (current) forcing conditions in this direction. The northward component of this “dynamic” corresponds to the summer and autumn shelf northward current pulses (up to 50 cm/s) described by Batifoulier et al. (2012, 2013), Le Boyer et al. (2013), and Kersalé et al. (2014). Neverthless, to date, no in-situ bottom-current meter records have corresponded with the eastward component of this dynamic. Among the known Aquitaine shelf hydrodynamic processes, high-energy North-Atlantic swells, traveling mainly from the west–northwest sector (Butel et al., 2002) and producing large wave-generated ripples in the area (orientation: N15°; Fig. 2), appear as a potential forcing factor for this eastward (shoreward) component of the weak migration of the sorted bedforms. However, further investigation is needed to argue for such bedform migration swell control.

5. Conclusions

The descriptive and comparative analysis of the geophysical and sedimentological datasets in the area known as “La Salie” on the Aquitaine inner shelf of the French Atlantic coast has lead to the following key results:

(1) At a water depth of 24–50 m, sorted bedforms have been observed with different morphologies depending on the scale of observation. These sedimentary bodies have been characterized at a first-order scale by large cross-shore “morphological ridges” conform to the properties of very large sorted bedforms. Second-order sedimentary bodies are composed of medium to fine sand patches, with a thickness of 0.5–2 m, cut by smaller elongated coarse sediment-blanketed depressions. This second-order pattern corresponds to the patchy sorted bedforms largely described in the literature. In particular, the sub-bottom profiler data has revealed that sand patches predominantly overlie the coarse-grained blankets on their eastern (shoreward) extremities and that coarse-grained blanket wedges are found in front of the sand patches (southwestward) or locally overlying the southwestern extremities of the sand patches. Third-order sedimentary bodies, corresponding to groups of dune-like features, lie in wide areas of coarse sediment and are isolated from the neighboring sand patches. Finally, the entire inner shelf is covered by wave-generated ripples that are larger where sediments are coarse-grained than where sediments are fine-grained.

(2) Over the past 29 years, over a large surface area, the location of patchy sorted bedforms has remained remarkably stable, as has their overall appearance (shape). However, at a smaller scale, small but persistent second-order movements have been observed: the elongation of coarse depressions at their extremities (with a maximum of 300 m over 15 years) and the movement of coarse-/fine-grained sediment boundaries toward the northeast and southeast (with a maximum of 75 m over 12 years). The general movement has remained shoreward oriented as has the migration of third-order submarine dune-like features.

(3) Our study has shown the persistence of sorted bedforms in a storm-dominated environment, supporting previous observational approaches (Green et al., 2004) that have demontrated the importance of recurrent storms in maintaining sorted bedforms.

We should point out, however, that from a water depth of 24–50 m, the available sedimentary stock appears to have been migrating shoreward, both in the reflectivity time-lapse survey (29 years) and the sub-bottom profiler data (no time calibration). This study does not address the question of cross-shore sediment exchange between the beach and the inner shelf. More research is needed at a water depth of 10–24 m, where the absence of large datasets does not allow conclusions to be drawn on this point. Nevertheless, the present observations confirm that the Aquitaine inner shelf constitutes an area where remobilized non-cohesive sediments are stored (1 m^3 per m^2 on average on the inner shelf).

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