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Long term evolution and internal architecture of a high-energy banner ridge from seismic survey of Banc du Four (Western Brittany, France)

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ABSTRACT

The recent completion of a coupled seismic and swath bathymetric survey, conducted across the sand ridge system of the *Banc du Four* located on the Atlantic continental shelf of Brittany (Mer d'Iroise, France), provided new data for the study of the long term evolution of deep tidal sand ridges. Five seismic units are distinguished within the ridge, separated by pronounced major bounding surfaces. The basal unit is interpreted to be shoreface deposits forming the core of the ridge. It is overlaid by a succession of marine sand dunes fields forming the upper units. Sandwave climbing, which combines progradation and accretion, is the major process controlling the growth of the ridge. The elevation of the preserved dune foresets reaches values of about 20–30 m within the ridge. The foresets indicate a combination of giant dunes characterized by numerous steep (up to 20°) clinoforms corresponding to a high-energy depositional environment. Moreover, the presence of scour pits linked to the 3D geometries of giant dunes allow the growth of bedforms migrating oblique to the orientation of giant dune crest lines. All of the radiocarbon ages of the biogenic surficial deposits of the *Banc du Four* range from 10,036 to 2748 cal years B.P. and suggest the *Banc du Four* has grown during the last sea-level rise. The apparent absence of recent surface deposits could be caused by a change in benthic biogenic productivity or the non-conservation of recent deposits. In contrast, the presence of relatively old sands at the top of the ridge could be explained by the reworking and leakage of the lower units that outcrop locally at the seabed across the ridge. Moreover, the long-term evolution of the ridge appears strongly controlled by the morphology of the igneous basement. The multiphase accretion of the ridge is closely linked to the presence of a residual tidal current eddy, consecutive with the progressive flooding of the coastal promontories and straits that structured the igneous basement.

Therefore, the *Banc du Four* should be thought of as a representative example of a large-scale high-energy banner bank.

1. Introduction

Sand ridges (or sand banks) are the most significant bedforms of tidal-dominated continental shelves. These elongated bedforms are flow-parallel or slightly oblique (<30°) to the peak of tidal flow direction (Belderson et al., 1982; Kenyon and Stride, 1970; Kenyon et al., 1981; Le Bot, 2001; Van Veen, 1936). They result from sand-transporting hydrodynamics and typically exhibit kilometric length and decametric height (Berthot and Pattiaratchi, 2006; Trentesaux et al., 1999). In this study the *Banc du Four*, a particular example of sand ridges located at the junction area between the English Channel and the North Atlantic Ocean, is investigated. Numerous types of tidal sand ridges are observed throughout the English Channel and the Celtic Sea. According to the classification system of Dyer and Huntley (1999) (modified by Kenyon and Cooper, 2005), their morphodynamic processes allow us to distinguish (1) open shelf ridges, (2) estuary and delta mouth bars, and (3) banner sand ridges or "banner banks". Open shelf ridges are the largest and deepest sandbanks, oriented at angle to the flow (Deleu et al., 2004). They have been mostly studied on the outer continental shelf of the Celtic Sea (Berné et al., 1998; Bouysse et al., 1975; Marsset et al., 1999; Reynaud, 1996; Tessier, 1997). Estuary mouth bars lie parallel to the flow, and are associated with macrotidal tide-dominated estuaries, for example Mont Saint Michel and the Seine bays on the southern English Channel (Tessier et al., 2010). Finally, banner sand ridges (Neill and Scourse, 2009) are attributed to the presence of residual current eddies generated by the tidal flow passing a coastal irregularity (Davies et al., 1995) or island (Wolanski et al., 1984). They are well illustrated on the Shambles bank along the Dorset coast in the U.K. (Bastos et al., 2003) and on the Schole and Sercq banks on the coast of France (M'Hammdi, 1994; Quesney, 1983; Walker, 2001).

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Moreover, if most of the superficial morphologies of ridges appear to be in equilibrium with the present-day hydrodynamic regime, the timescales of the processes responsible for the formation and evolution of these large bedforms are of the same order as the duration of a high frequency sea-level cycle and most of them are transgressive features (Reynaud and Dalrymple, 2012; Reynaud et al., 2003). Furthermore, physical models have shown the interplay of the substratum with the presence of a small bed perturbation during ridge initiation (Huthnance, 1973, 1982a, 1982b). These models argue for a continuum between juvenile and constructional (fully evolved) ridges as conditions change over a transgression (Snedden and Dalrymple, 1999). This implies that sea-level fluctuation, particularly during the last post-glacial sea-level rise, is one of the main controlling factors of the long-term evolution of tidal ridges, along with nature, source of sediment supply, and paleomorphology. As a consequence of both the long and short-term combined processes involved in tidal ridge development, the understanding of ridge morphodynamics is needed to characterize their internal architecture.

Several previous studies have already dealt with internal ridge architecture on continental shelves (Bastos et al., 2003; Berné et al., 1994, 1998; Houbolt, 1968; M'Hammdi et al., 1992; Marsset et al., 1999; Olariu et al., 2012; Reynaud et al., 1999a, 1999b, 2003; Tessier, 1997; Trentesaux et al., 1999; Vecchi et al., 2013), however most of them focused on shallow waters (0–50 m Lower Astronomical Tide, L.A.T.) or concerned themselves with the moribund ridges located on the outer shelf at depths below that of the Last Glacial Maximum sea-level drop (> − 120 m). Other studies were concerned with tidal ridges at intermediate depths but in specific highly-supplied sedimentary environments such as the Yellow Sea and East China Sea (Berné et al., 2002; Jin and Chough, 2002; Jung et al., 1998).

The lack of studies on the long-term evolution of the sand ridge system of the *Banc du Four*, located on the starved continental shelf of western Brittany, motivated the coupled seismic and swath bathymetric surveys. This tidal sand ridge system is about 45 m thick, settled by depths of 70–105 m L.A.T., and surrounded by straits and islands. Results of a study on its short-term evolution have already been published and have shown that this ridge does not display classic ridge morphology (Franzetti et al., 2013). The aim of this paper is thus to present the results of these surveys. We discuss the relative influences of intrinsic sedimentary parameters and hydro-sedimentary processes, as well as post-glacial transgression and shelf paleomorphology in regards to tidal sand ridge growth.

2. Ages and stratigraphic modelling of tidal ridge growth

There is very little data concerning the dating of tidal ridges, due to the difficulties of coring sand bodies and the fact that the penetration of vibrocorers is usually limited to about 5 m. As a consequence, the timing of tidal ridge genesis remains speculative in most case studies.

Generally, the growth of ridges is believed to be linked to the post-glacial sea-level rise and thus considered to be younger than 20 ka. This assumption is in accordance with the ages (9000–1300 years B.P.) of the detritic gravels and bioclastic sands recovered at the base and top of the tidal ridges of the Western English Channel (Auffret et al., 1980; Hommeril, 1971; M'Hammdi, 1994). Tidal ridges of the southern North Sea also originated at around 8000–7800 years B.P. (Jelgersma, 1979; Trentesaux et al., 1999). They can be considered as linked to the post-glacial sea-level rise and the start of their formation depends on the age of their basement flooding. The deeper ridges are formed early, and seem to record strong ravinement by tidal currents that remove the main part of the early deposits. As the sea level rises, the tidal control becomes weaker and the ridge surface becomes wave dominated above a wave ravinement surface (Huthnance, 1982b; Reynaud et al., 2003). In contrast, the shallower tidal ridges are formed later and may preserve initial lower coastal deposits and tidal-dominated deposits that are located at the upper parts of the ridge (Berné et al., 1994). Alternatively, deeper tidal ridges could also be considered as mainly consisting of lowstand deposits (i.e. older than 20 ka) and only their top could correspond to transgressive deposits fed by erosional process. This interpretation is given by Berné et al. (1998) for the tidal ridges of the Celtic Sea. The ridge itself is assumed to be a partially relict feature created during periods of sea-level lowstand; its surface is still active, exhibiting attached dune fields in accordance with present hydrodynamics. The report on sands dated from MIS2 and recovered by vibrocoring across the Celtic Banks (Evans, 1990) reinforces this hypothesis.

3. Study area and previous results

The study area (Fig. 1A) is located about 10 km off the shore of western Brittany (France) and extends into the northern part of the Iroise Sea (48°30′N, 05°00′W). The water depth ranges from 70–105 m L.A.T. The area is characterized by strong tidal currents and large swells. Indeed, the singular morpho-bathymetry of this segment of Brittany's continental shelf consists of a wide, northward-opened triangular bay that catalyses and amplifies tidal dynamics (Franzetti et al., 2013). It is bound to the east by coastal reefs (plutonic rocks) and to the south and west by the Ushant-Molene Archipelago. This barrier is interrupted by two narrow, shallow straits, the Fromveur strait (60 m L.A.T.) and the Four strait (13 m L.A.T.), whereby tidal current eddies become strong alternating unidirectional currents with surface velocities reaching up to 4 $m.s^{-1}$ (Hinschberger, 1962a, 1970). Moreover, Eulerian residual tidal currents, modelled by Guillou (2007) and the French Operational Coastal Oceanographic Centre PREVIMER, reveal a clockwise current eddy occurring in the western part of the study area where a dominant north-eastward current extends along the coastal Four strait to the east (Fig. 1B). The area is also exposed to Atlantic storm waves coming from the northwest. Their heights regularly exceed 4 m, with wavelengths reaching over 200 m (Dehouck, 2006). The frequent rough seas could explain the limited number of studies devoted to the *Banc du Four*. The first survey was conducted by Hinschberger (1962b) and enabled the definition of the approximate morphology of the area and highlighted the massive volume of sand deposits. It also revealed the carbonate nature of the sediments, which are predominantly composed of organogenic debris with a mean grain size of about 0.8–0.9 mm. A recent study based on the completion of three recent 29-month-spaced swath bathymetric surveys of the area, complemented by a historical data set, enabled the accurate characterization of morphology and the quantification of dune migration rates (Franzetti, 2014; Franzetti et al., 2013).

Concerning the morphology and equilibrium conditions, the recent surveys have shown that the *Banc du Four* bedform field is characterized by offshore sandbodies that define a V shape. More than 500 large dunes exhibit a great diversity of morphologies, ranging from 2D to 3D shapes. The largest dune (over 1000 m in wavelength and over 30 m in height) reaches the maximum size of the sedimentary structures recently described in the Irish Sea (Van Landeghem et al., 2012), where the tidal regime and depths are quite similar to those of Brittany's continental shelf (Figs. 2A, B). Previous results have shown that the outer limits of the *Banc du Four* have remained unchanged during the last 82 years. Despite the fact that the imprecision of the ancient data set prevents the assessment of vertical movement, the comparison of the respective locations of the 50 m isobath shows that the southern flank of the sand ridge has eroded, whereas the eastern part has accreted (Franzetti et al., 2013).

Concerning dune migration, the rates calculated for the eastern part of the *Banc du Four* range from 3 $m.a^{-1}$ to 20 $m.a^{-1}$. Such velocities have never before been previously recorded on deep continental shelves (>70 m) and attest to the existing morphodynamic equilibrium of the large dunes (Franzetti et al., 2013). Actually, the non-consistent

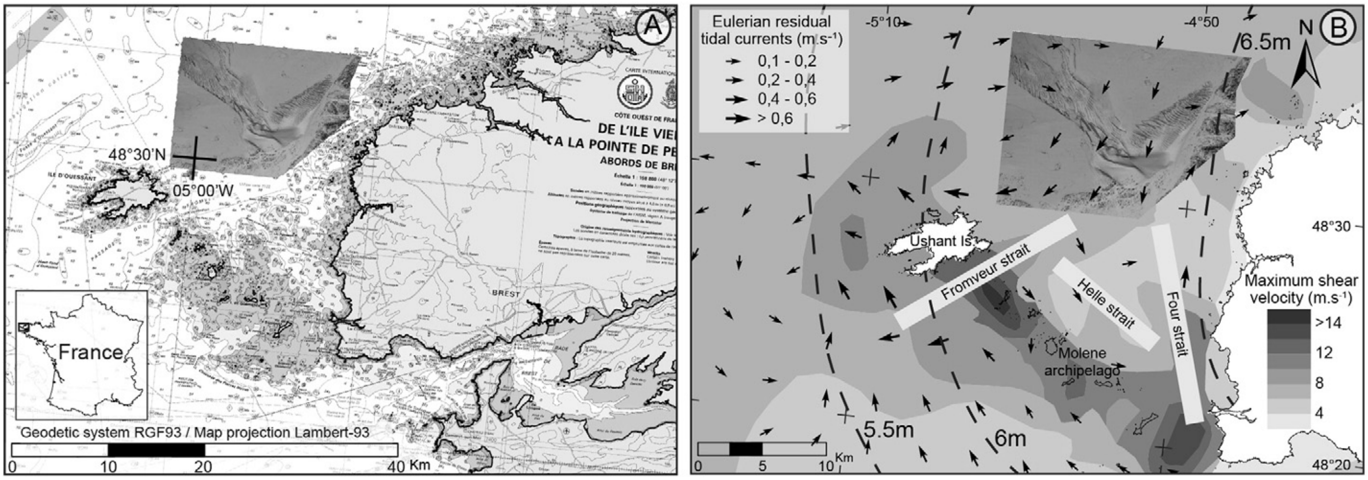

Fig. 1. (A) Map of the Iroise sea (situated between the French Brittany coast and the Ushant-Molene Archipelago), showing the location of the *Banc du Four* (from the DTM acquired during the EvalHydro 2009 survey). This ridge system is defined by offshore bedforms which define a V shape. The water depth of the basement ranges from 70 to 105 m below Lower Astrononomical Tide. (B) Eulerian residual tidal currents and maximum shear velocities at seabed according to the French Coastal Oceanograhic Centre (Previmer) for a tidal range of 90. Pecked lines are co-range lines joining points of the same tidal range.

morphology and orientation of the sand ridge could be partially explained if it is considered as being inherited and shaped by different hydrodynamic settings during the last post-glacial stage.

4. Data and methods

The *Banc du Four* sand ridge was investigated by a series of High and Very High Resolution seismic surveys (GeoBrest 2003, 2005, 2006, 2010, 2012, and 2013) carried out by the "Institut Universitaire Européen de la Mer" (IUEM, UBO) from onboard the oceanographic research vessel (R/V) "Côtes de la Manche". The seismic energy sources were a 250 J SIG™ mille® supplying a SIG™ EDL1020® spark-array with 200 strands, and a 50 J SIG™ENERGOS supplying a 50 strand spark-array. Seismic receivers were composed of a monochannel streamer for GeoBrest 2012 and a 6-channel streamer, SIG™ 16 for the other surveys. The seismic grid consisted of 47 seismic profiles with a variable spacing of 100–1000 m (Fig. 3). IXSEA™ Delph2.1® software was used to acquire and process the data. Interpretation was performed using SMT™ KINGDOM®. Time-depth conversions are estimated in the text using a seismic velocity of 1600 $m.s^{-1}$ in porous sands.

The superficial sedimentology of the sand ridge was studied by the analysis of 50 Shipek grab samples taken during the GeoBrest 2010 survey. Samples were washed and dried before analysis. Sedimentological parameters (mean grain size, sorting, and skewness) according to Folk and Ward (1957) have been calculated by weighing different fractions split by vibro-sieving. Carbonate content was measured with a Bernard calcimeter using the volumetric calcimetric method. The radiocarbon method was used to date seven shells originating from five samples. AMS ^{14}C dating was performed on shells by the Poznan Laboratory (Table 1; Fig. 4).

Absolute dates have been calibrated using the programme Calib Rev7.1. We used the marine radiocarbon calibration curve "Marine09" for marine shell samples (Reimer et al., 2009). These calibrations yield ages with 1 standard deviation (1 sigma, 68.3% confidence level; 2 sigma, 95.4% confidence level). We applied a regional deviation ΔR of -40 ± 42 years corresponding to the nearby Sein Island (Marine reservoir correction database: http://intcal.qub.ac.uk/marine/).

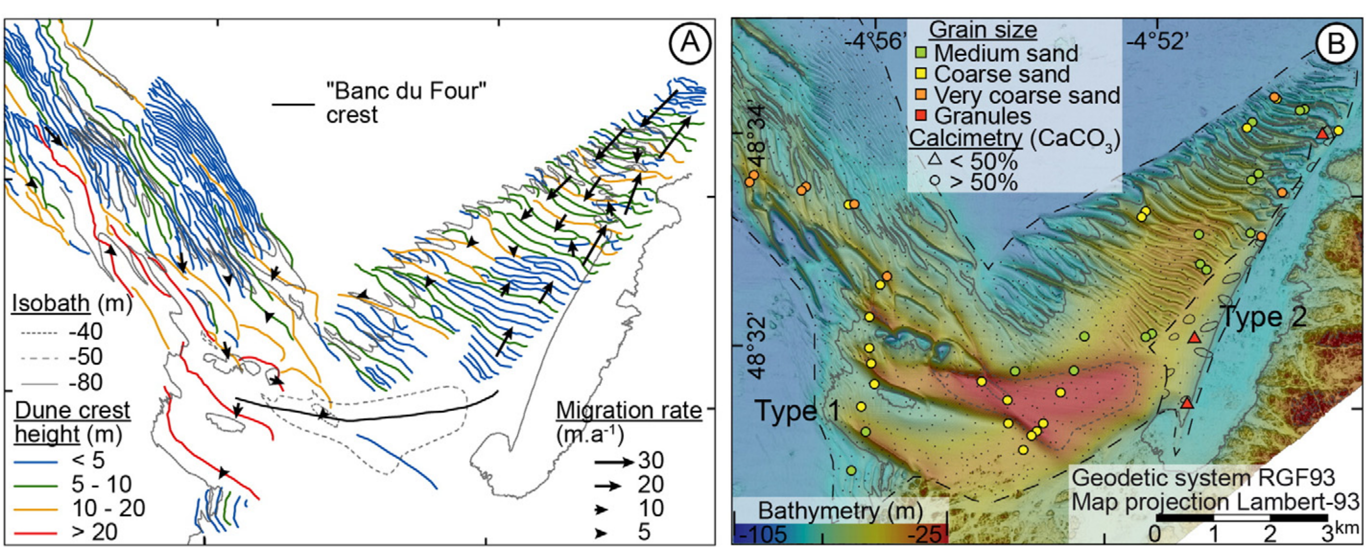

Fig. 2. (A) Detailed view of the *Banc du Four* system with crest heights and migration rates. From Franzetti et al. (2013). (B) Bathymetry of the Banc du Four from DTM 2009 with locations of the Shipeck grab samples. There are two types of sediment on the ridge system: type 1 is composed of medium to coarse bioclastic sands, while type 2 is characterized by siliciclastic gravels.

5. Results and interpretation

5.1. Samples

The surface of the *Banc du Four* is composed of slightly gravelly (Folk and Ward, 1957) bioclastic sands (Fig. 2B). The mean grain size (M) varies between 0.27 and 4.3 mm with an average value of 0.89 mm. The calcimetry analyses show that the sand consists of 80% carbonates, with values ranging from 16–95%. The carbonate fraction is composed of shell ash and the shells of bivalves (20%, belonging to the familiaes Arcidae, Glycymeridae, and Veneridae, urchin spicules (27%), gastropods (3%), bryozoan (5%, mostly Cellaria), Polychet (2%), crab carapaces debris (2%), and algae (1%)). Undetermined bioclastic debris makes up 40%. The terrigenous fraction (20%) is composed of gravels, including granite clasts, quartz, and flint. There are two sediment types on the sand ridge: Type 1 corresponds to the majority of samples, and is characterized by medium to coarse (M between 0.25 and 1 mm) sand, moderately sorted (σ_1 between 0.5 and 1). The carbonate fraction is largely dominant (higher than 85%). Type 2 is in the minority and corresponds to samples 8 and 9 located in the east. Type 2 samples are characterized by siliciclastic gravel (M between 2 and 4 mm), including granitic large pebbles. This sediment is poorly sorted (σ_I between 1.5 and 2). The carbonate fraction is lower than 25%, characterized by large, well-preserved bivalve shells.

5.2. Seismic

The architecture of the *Banc du Four* was principally examined using VHR sparker surveys.

Three seismic units (U_{S1} to U_{S3}) are identified within the substratum of the sand bedforms, and five (U_{B1} to U_{B5}) are identified within the ridge. They are separated by pronounced, regional-scale erosional unconformities distinguished on the seismic lines at the scale of the ridge. They are shown by selected representative sections (Fig. 3). These unit boundaries can be considered to be major bounding boundaries or first-order discontinuities within the ridge by comparison to previous works on eolian dunes (Brookfield, 1977), tidal sand dunes (Berné et al., 1988, 1989, 1993; Ferret et al., 2010; Le Bot and Trentesaux, 2004), and sand ridges (Marsset et al., 1999; Trentesaux et al., 1999). The corresponding reflectors are labelled on the seismic lines (R_{B1} to R_{B4}) and mark the respective upper limits of the seismic units U_{B1} to U_{B4}.

Each unit shows local geometric and facies variations and can be described as an assemblage of subunits, each composed of migrating or aggrading bedforms with internal medium bounding surfaces that can only be locally followed (second order discontinuities) within the ridge. The seismic reflectors within the sub-units are assumed to be the isochronous surfaces of short-term sediment transport. They roughly correspond to reactivation surfaces, i.e., discontinuities in the lateral

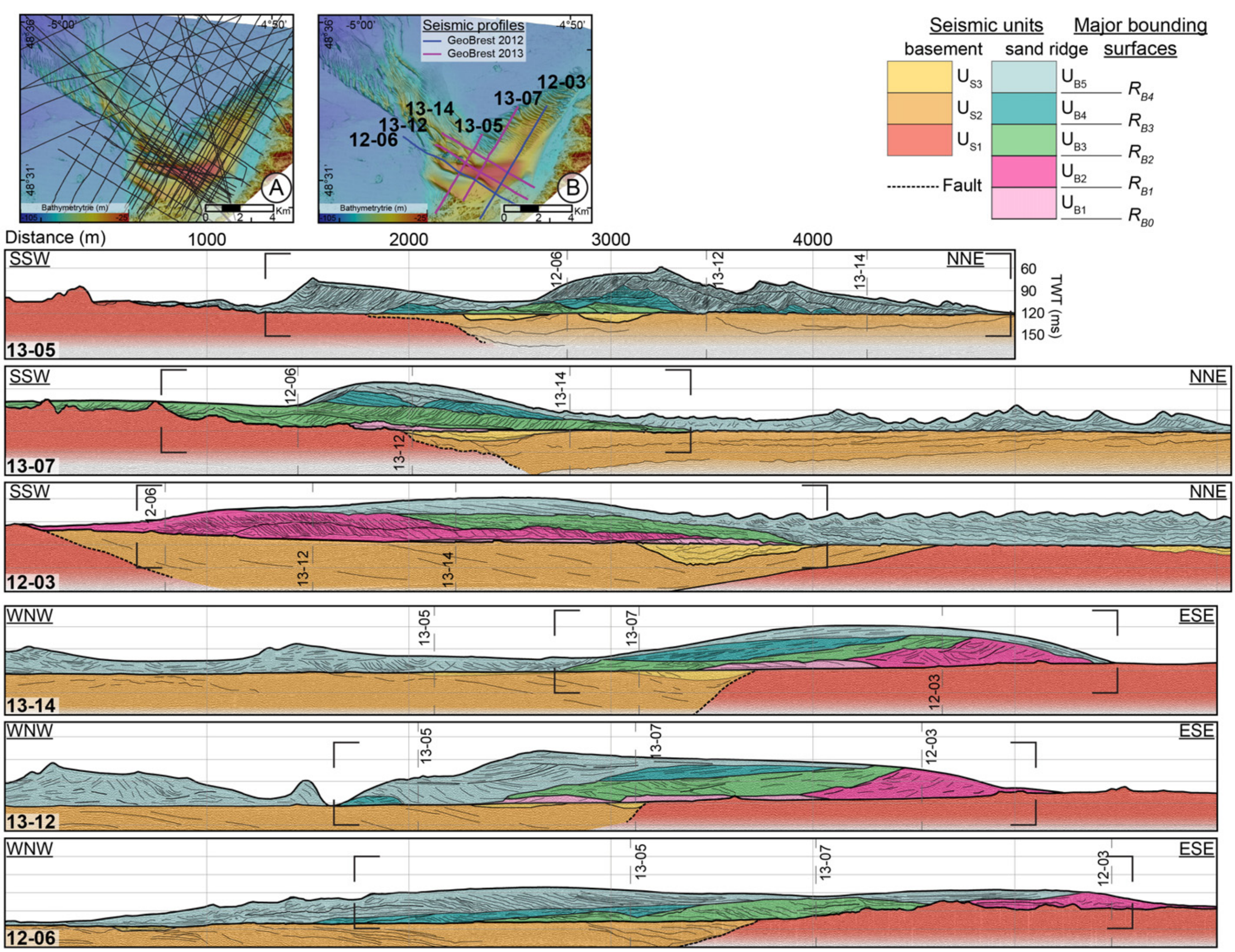

Fig. 3. A: Location of the sparker seismic lines used in this study. B: Interpretative line drawings of several representative seismic lines. C: Extracts of representative seismic lines corresponding to selected sections of previous line drawings (location on Fig. 3B). Three seismic units (U_{S1} to U_{S3}) are distinguished within the substratum and five within the ridge (U_{B1} to U_{B5}).

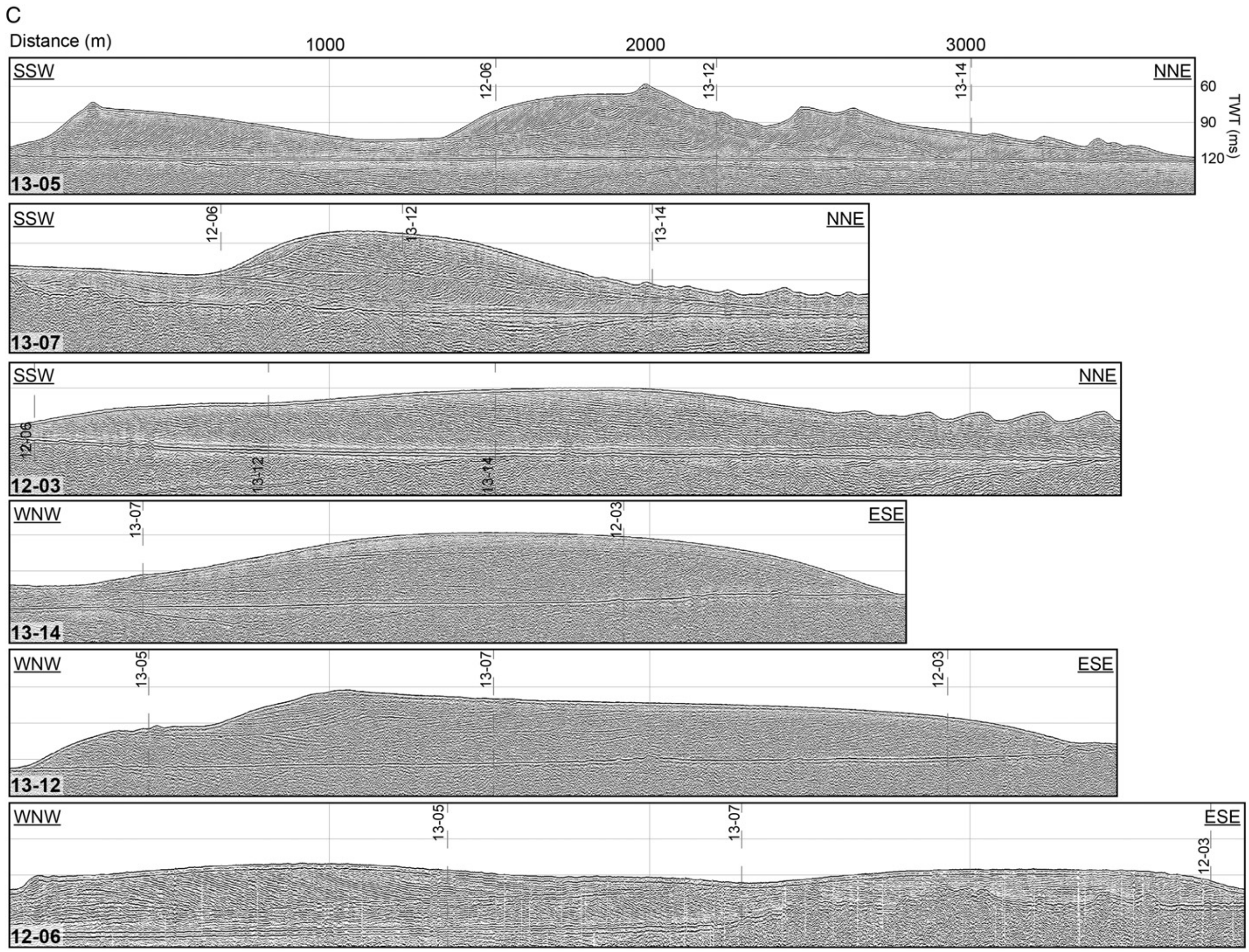

Fig. 3 (*continued*).

sequence of cross-strata within the unit, with either a planar or convex up erosion surface. They are representative of the lithology and energy variations. The spatial distributions of the sand ridge seismic units are shown on the isopach maps (Fig. 5). Correlation of the seismic units described below and the sediment samples are shown in Fig. 4.

5.2.1. Basement

The basal unit U_{S1} is characterized by a chaotic seismic facies interpreted as being representative of the Hercynian crystalline rocks that outcrop along the nearby Ushant-Molene Archipelago (Fig. 3). This crystalline basement is structured by regional-scale faults marked on the bathymetry by a succession of straits (Fromveur and Four, see §3), where morphologic thresholds communicate with deeper domains along the Ushant-Molene Archipelago. Above, the spatial arrangement of the reflectors of the U_{S2} unit defines complex oblique-parallel-to-

Table 1
Radiocarbon datations of the surficial deposits of the Banc du Four. Calibrations yield ages with 1 standard deviation. We applied a regional deviation ΔR of −40 ± 42 years corresponding to the nearby Sein Island (Marine reservoir correction database: http://intcal.qub.ac.uk/marine/).

Sample reference	Shell valve preservation (*Macoma* sp. *Glycimeris* sp.)	Age AMS C^{14} years B.P.	Calibration 1σ ($\Delta_R = -40 \pm 42$) cal years B.P.
10-08 J	Very well preserved	6855 ± 40	7288-7401
10-08 V	Normal	9175 ± 35	978,91,036
1024	Normal	5815 ± 30	6156-6268
10-32	Normal	5010 ± 40	5265-5417
10-32 J	Very well preserved	5440 ± 40	5708-5857
10-42 V	Normal	6740 ± 30	7168-7277
12-03	Normal	3085 ± 30	2748-2861

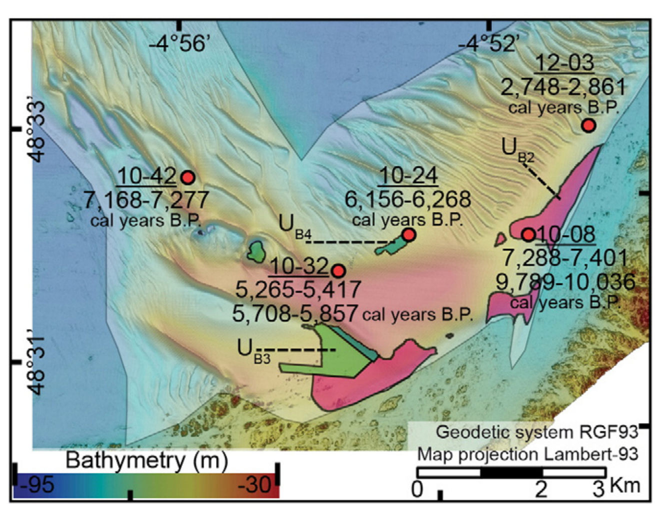

Fig. 4. Spatial extension of the ridge's seismic units merging at seabed and correlation with the surficial sediments. Locations of the samples with radiocarbon datations (ages cal years B.P.). See Table 1 for details.

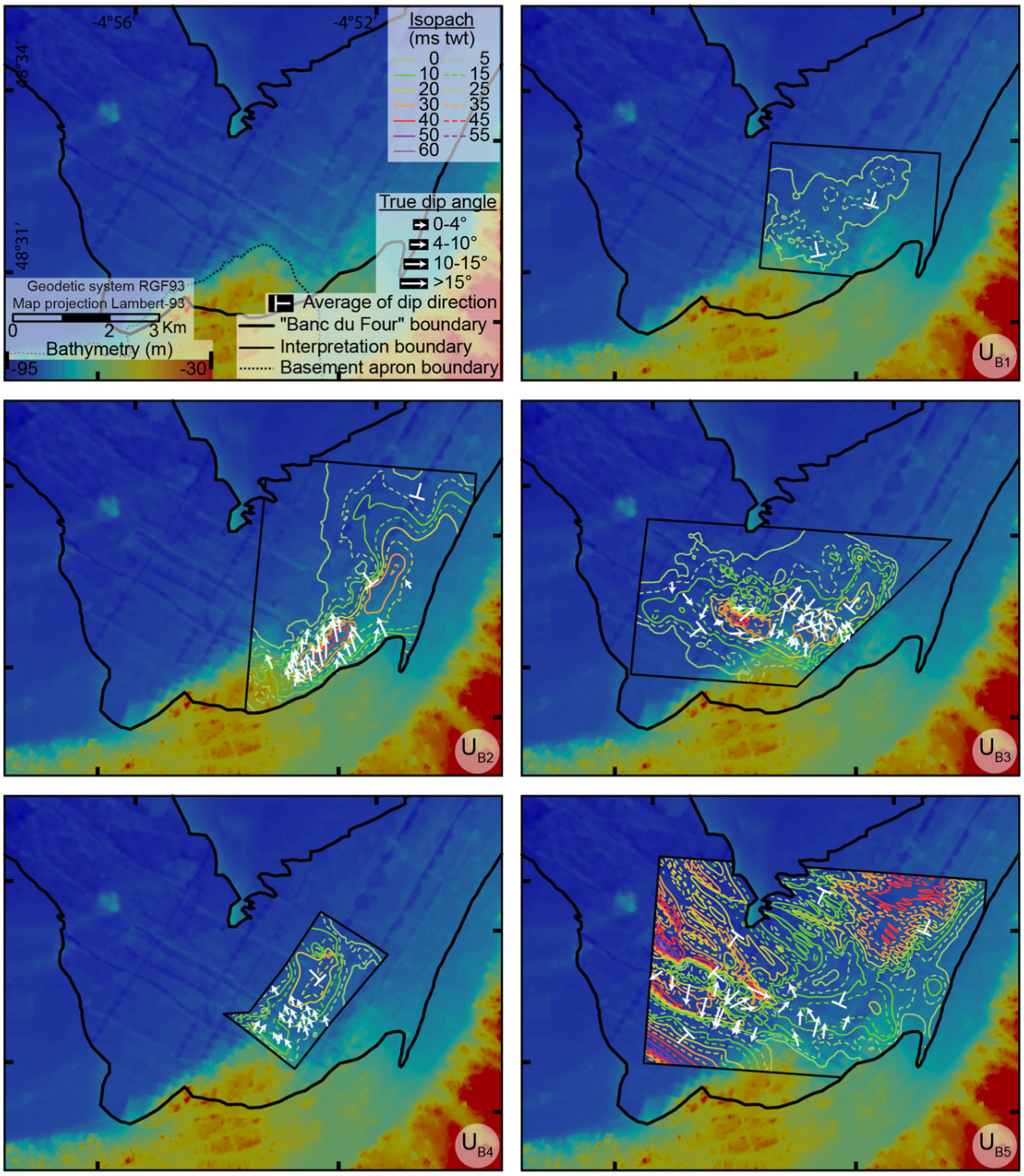

Fig. 5. Isopach maps (in ms TWT two way travel time) of the ridge seismic units U_{B1} to U_{B5}. The present ridge system has been removed from the bathymetric DTM shown backward and only its outline is shown (black line, insert up left). The polylines correspond to the extension of the interpolation areas.

sigmoidal patterns with numerous imbricated erosional surfaces. The U_{S2} unit merges at the seabed towards the northeast and chrono-stratigraphic identification of the deposits is possible from previous studies conducted along the continental shelf (Andreieff et al., 1972; Lapierre and Bouysse, 1975). They are considered to be biogenic Miocene deposits and could correspond with the calcarenites from the

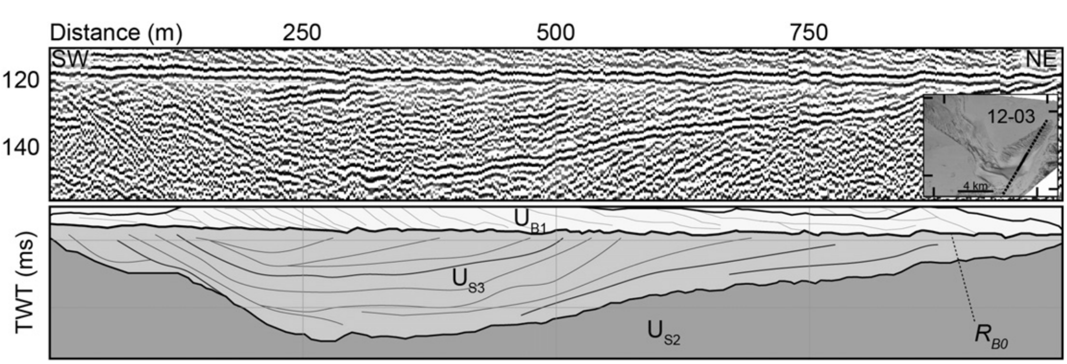

Fig. 6. Extract and interpretative line drawing of the seismic line 12–03 showing the geometry of the U_{S3} substratum seismic unit. It is interpreted as the infilling of a fluvial paleo-valley incised at the top of the Neogene basin (U_{S2}).

Cockburn Formation identified along the Western Approaches (Evans, 1990; Le Roy et al., 2011). The upper unit U_{S3} exhibits reflectors ranging from chaotic to oblique clinoforms, suggesting a channel-fill geometry (Fig. 6). The corresponding deposits define the infill of a deep paleovalley 200–400 m wide and 30 m deep, located along the previous bounding fault, its geometry seems to be controlled by the topography of the bedrock (U_{S1}). The valley was probably the outer segment of a fluvial network that has drained the coastal rias of NW Brittany and was extended further offshore up to the 200 m deep Ushant Trough. As in the other case studies done along the French Atlantic margin (Chaumillon et al., 2011), the valley fill is assumed to correspond to the Pleistocene sequence (Fig. 7).

5.2.2. Sand ridge

5.2.2.1. Unit U_{B1}

5.2.2.1.1. Description. The basal unit (U_{B1}) is located at the sole of the present-day sand ridge. It settled over the Neogene deposits and the igneous basement topped by the R_{B0} reflector. Its lower boundary lies at about 110 and 120 ms TWT (i.e. about 85–95 m b.s.l.). It consists of several small patchy deposits, lenticularly-shaped, and connected with each other forming a basal sole lying over the basement units. Its thickness is generally lower than 10 ms (about 8 m) and it extends to the north of the crystalline rock aprons (U_{B1}), showing an elevation of about 20 m above the surrounding seabed (Fig. 5, U_{B1}). Where the unit is thick enough, the internal reflectors show an oblique parallel pattern dipping up to 5° northward (NNE to NNW), (Fig. 8).

5.2.2.1.2. Interpretation. The northwest dip of the bedding planes, the low elevation of the unit above the basement, and its elongation toward the NNE all suggest that these deposits nucleated behind the rock aprons. These types of sediment arrangements showing through cross beddings are well-matched with shoreface deposits and we interpret the corresponding deposits as being representative of high energy coastal deposits

5.2.2.2. Unit U_{B2}

5.2.2.2.1. Description. This unit constitutes the bulk of the south-eastern side of the sand ridge. The correlation of seabed samples with the seismic units that outcrop at the seabed show that the U_{B2} unit mainly corresponds to siliciclastic gravels. It extends north-eastward and delineates an elongated prism parallel to the eastern dune field of the *Banc du Four*. Its southern termination is anchored along the rocky apron. Its maximum thickness is 45 ms TWT (about 35 m), and its top is at about 60 m (below sea level, b.s.l.) Its eastern and southern flanks outcrop directly at the seabed, while its northern and western ridges are buried by units U_{B3}–U_{B5}. The geometries of the medium-to-high amplitude reflectors are imbricated sets showing clinoform profiles (Fig. 3). Two sets are clearly individualized along the SW-NE and exhibit high angle reflectors (from 5° to 15° to the northeast).

5.2.2.2.2. Interpretation. The current direction is indicated by the northward elongated shape of the unit and the presence of stacked sets of high angle cross-stratification assumed to be formed by dunes that migrate in this direction. The sets delineate stacked, lens-shaped bodies bounded by gently undulating concave bounding surfaces. The

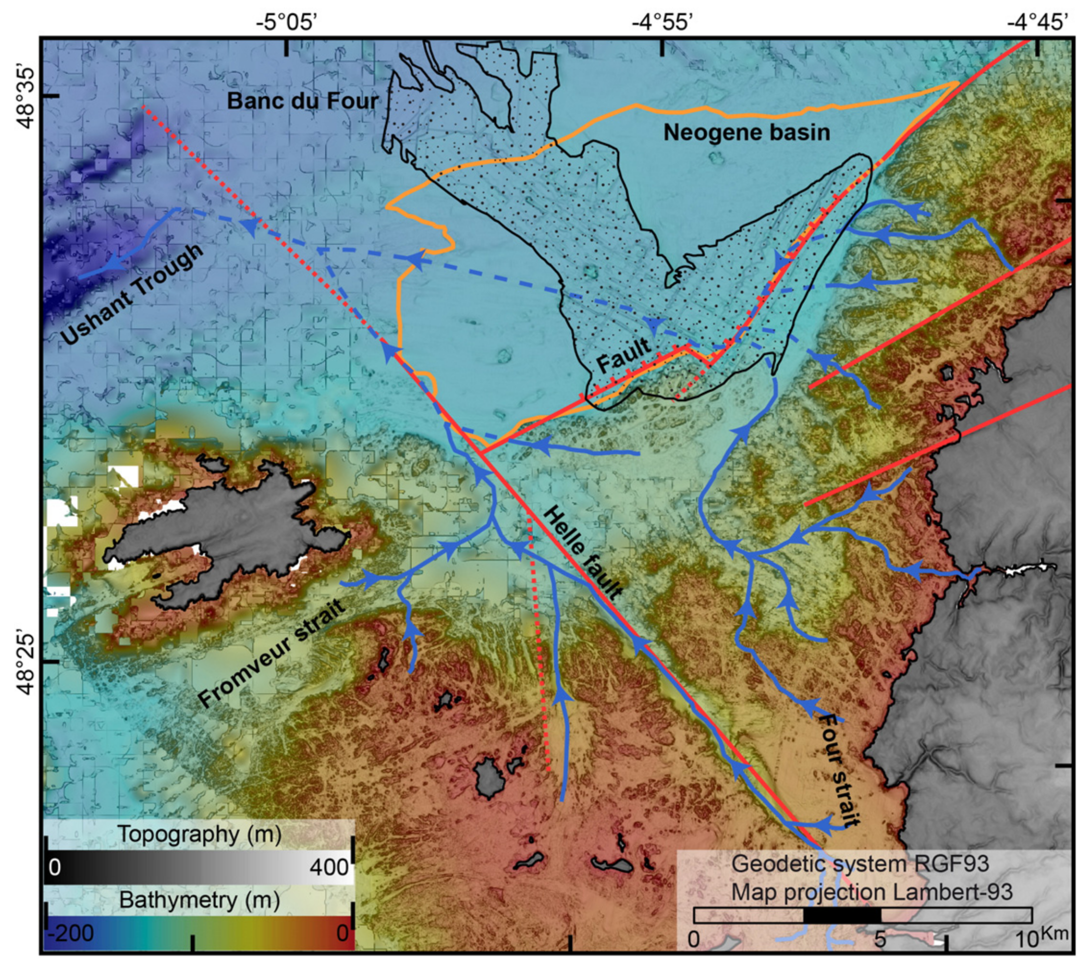

Fig. 7. Extension of the Neogene basin corresponding to the substratum seismic unit U_{S2} (orange line). The geometry of the structure, bounded by northwestward-dipping normal faults (red lines), delineates a faulted block (modified from Le Gall et al., 2014). In blue: reconstruction of the probable paleovalley network around the *Banc du Four* drawn from the morphology of the crystalline basement and extension of the U_{S3} seismic unit.

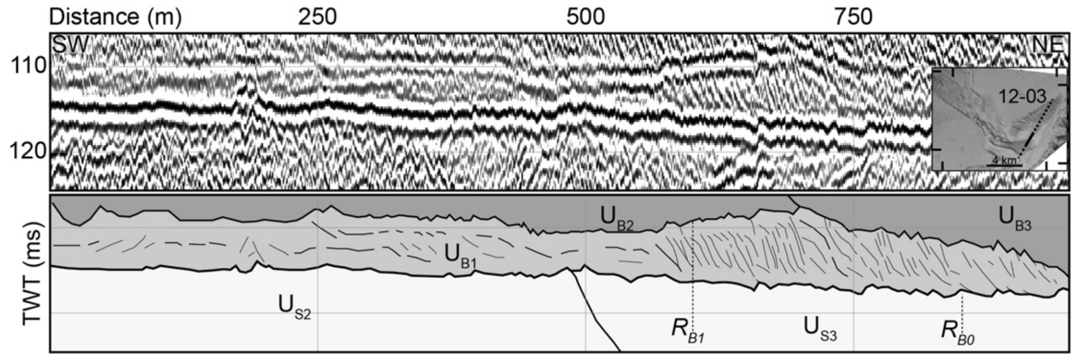

Fig. 8. Extract and interpretative line drawing of seismic line 12–03 showing the geometry of the U_{B1} ridge seismic unit. The location corresponds to the solid black line. The internal reflectors are sub-horizontal to the south, and grade to northwestward gently-dipping clinoforms to the north.

top sets are absent along the erosional upper unit-bounding surface (R_{B2}) that outcrops at the seabed to the south. Along the WWN-EES transverse seismic profiles, the medium bounding surfaces are slightly concave upwards (Fig. 9). The U_{B2} unit is thus interpreted to be downstream-accreting large-scale compound dunes (Dalrymple and Rhodes, 1995). The transverse WWN dipping concave surfaces produced scallop-shaped sets of cross-beds (Rubin and Hunter, 1982). They are assumed to represent the progressive infilling of space between dunes that approach each other and for which both sides of the hollow are the stoss and lee sides of the two facing bedforms. The elevation of the preserved dune foresets is about 15–20 m. If we consider the present day Brittany shelf to be where the highest dunes (30 m) tend to scale to flow depth at a ratio of about 1:3 (Franzetti, 2014; Franzetti et al., 2013), it is probable that the water would have been about 45–60 m deep during the deposition of U_{B2}. These deducted values are much less than what is predicted by the equation of Yalin (1964) which stated a ratio of 6:1 between water depth and dune height.

5.2.2.3. Unit U_{B3}

5.2.2.3.1. Description. It forms a large part of the western section of the sand ridge (Fig. 10). It outcrops at the seabed over a small surface at the south of the ridge (Fig. 4). The correlation of sediment samples with seismic units show that U_{B3}, like the upper units, corresponds to bioclastic sands. The U_{B3} unit lies over the basement, or over units U_{B1} and U_{B2} toward the southwest. Its WWN-EES orientation contrasts with the U_{B2} unit, even if its eastern termination trends to parallel to the NNE-SSW orientation of the U_{B2} unit. Its maximum thickness is comparable to the previous unit and its upper boundary is a sharp erosional surface. The unit is made up of numerous superposed sets with thicknesses ranging from 10 to 40 ms, bounded by well-marked medium bounding surfaces (Fig. 10). Here, again, geometries consist of oblique-parallel to oblique-tangential profiles with moderate angle dipping reflectors (5–10°). The direction of the progradation enables the distinction of two zones within the sand ridge: (1) in the western section the orientation is mostly south-westward; (2) in the eastern section it is north-westward. The basal progradation surfaces separating the overlying clinoforms themselves dip to the north with variable angles (0–3°).

5.2.2.3.2. Interpretation. We interpret the geometry of U_{B3} as corresponding to large superimposed dunes. The dipping reflectors in each set are conformable to the lee side of the large dunes and indicate the net migration of large subtidal dunes. The basal progradation surfaces separating cross-beddings delineate climbing dunes with no stoss side preservation, and various angles of climb. They correspond to structures deposited by two-dimensional bedforms climbing at a stoss-erosional, lee-depositional, net-positive angle of climb as defined by Rubin and Carter (2006), and corresponding to A-type or subcritical from Jopling and Walker (1968) and Allen (1970).

Another remarkable pattern is observed within the U_{B3} unit. It consists of a large concave-up surface marking the base of a 100 m wide and 25 ms (about 20 m) deep elongated trough observed along the SW-NE seismic sections. Its lateral extension is limited and does not exceed several hundred meters, as deduced from parallel sections. It is filled by south-eastward prograding reflectors with tangential basal

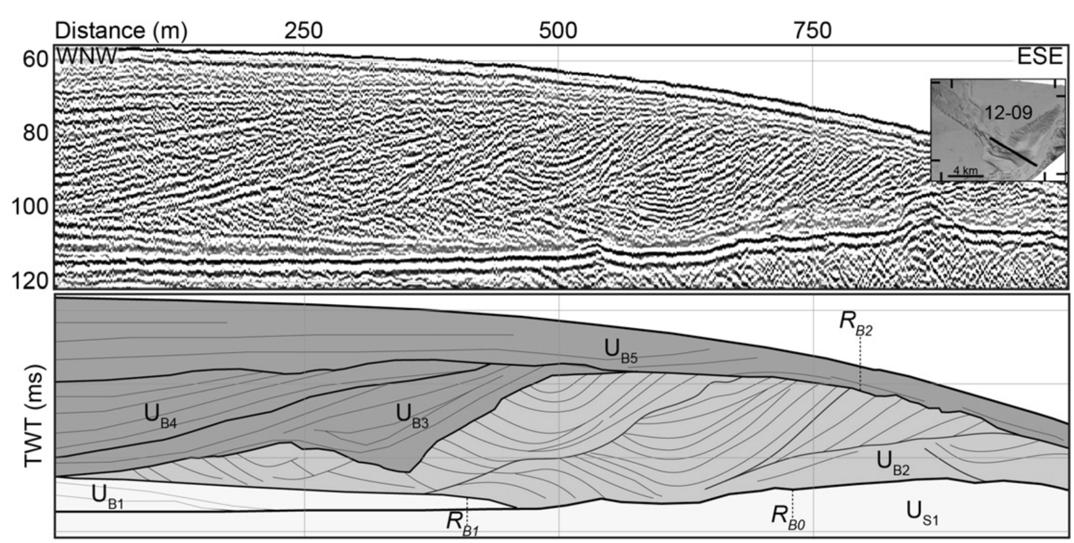

Fig. 9. Extract and interpretative line drawing of the seismic line 12–09 showing the geometry of the U_{B2} ridge seismic unit.

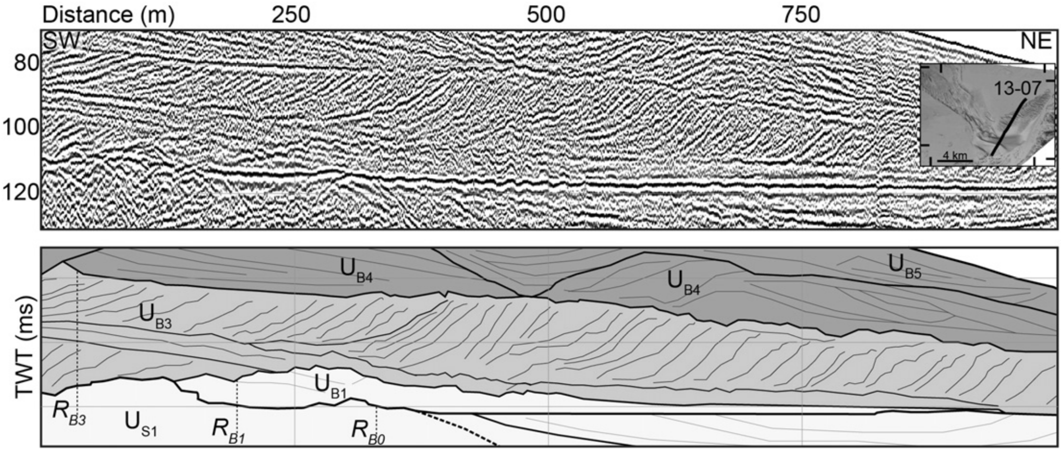

Fig. 10. Extracts and interpretative line drawing of seismic line 13–07 showing the geometry of the U_{B3} ridge seismic unit. The unit is composed of superimposed sets with the geometry of the reflectors consisting of oblique-parallel to oblique-tangential profiles. It is interpreted as corresponding to large climbing dunes with no stoss-side preservation.

contacts that define a perpendicular orientation with respect to the troughs. Its interpretation is discussed later in the text (§2.1).

5.2.2.4. Unit U_{B4}

5.2.2.4.1. Description. The U_{B4} seismic unit forms a 20 m thick prism which has accreted up to the U_{B2} and U_{B3} units (Figs. 3 and 11). It is characterized by large (several hundred meters of extension), low angle clinoforms (3–4°) dipping to the northwest and slightly to the NNE at the southern termination of the unit. The high continuity moderate-to-low amplitude and frequency reflectors downlap over the basal boundary and are truncated at the top. Some local variations of geometry are observed at the western termination of the ridge (line 13–05, Fig. 3) but the pattern of the entire unit is quite consistent over the sand ridge.

5.2.2.4.2. Interpretation. The reflectors of the U_{B4} unit are thus considered to be formed by lateral accretion of the ridge surface. They migrate laterally toward the northwest relative to the ridge axis (NE-SW)

5.2.2.5. Unit U_{B5}

5.2.2.5.1. Description. The uppermost seismic unit, U_{B5}, nearly covers the entire ridge, and corresponds to its present shape (Fig. 12). Its thickness reaches up to about 50 ms TWT (about 40 m) along the northeast area, and is absent in the southeast. The lower bounding surface of the unit is an erosional unconformity that marks a change in the architecture of the deposits. Medium bounding surfaces are frequent within the unit and their characteristics allow us to distinguish two different zones characterized by their geometries. To the west of the ridge, unit U_{B5} corresponds to a succession of aggrading and prograding deposits dipping to an overall southwest direction at angles ranging between 0° and 15°. The thickest sets reach about 30 m. Examination of the western part of the ridge also reveals the presence of deep troughs showing similar sizes to those of unit U_{B3}, and showing an WWN-EES orientation. Their infill consists of large (20–30 m) and high-angle (15–20°) clinoforms prograding to the EES and climbing along the western flank of the ridge over the U_{B3} and U_{B4} units. At the eastern section of the ridge, the U_{B5} unit forms a blanket that extends to the NNE. The seismic pattern consists of slightly (1–3°) dipping reflectors with the lateral extent reaching 250 m and oriented toward the NNE at the top of the ridge. The NNE extension corresponds to the eastern dune field of the *Banc du Four*. The field is characterized by numerous reactivation surfaces and the directions of the dipping reflectors reflect the present day migration of dunes at the seabed.

5.2.2.5.2. Interpretation. Except for the nature of the troughs discussed below, the pattern of the western part of unit U_{B5} is a continuation of that of the U_{B3} deposits. The U_{B5} deposits are interpreted as a succession of stacked dunes migrating to the southwest and climbing along downlap basal surfaces. These basal surfaces dip 1 - 5° to the NNE. The thickness of the preserved dune foresets is about 20–30 m, similar to the giant dunes located southwest of the ridge. The underlying units progressively disappear westward, where a succession of giant asymmetric dunes marks the edge of the ridge. The stratigraphic pattern of these climbing giant dunes shows that the southern deposits are older than the northern dunes. Here again, as for unit U_{B3}, the morphology of the progradation basal surface controls the angle of the lee-side and the bottom set pattern of the superimposed dunes. The angles are more pronounced and the internal reflectors show an oblique parallel pattern where the basal surfaces are flat and horizontal. In contrast, they become sub-horizontal with tangential terminations

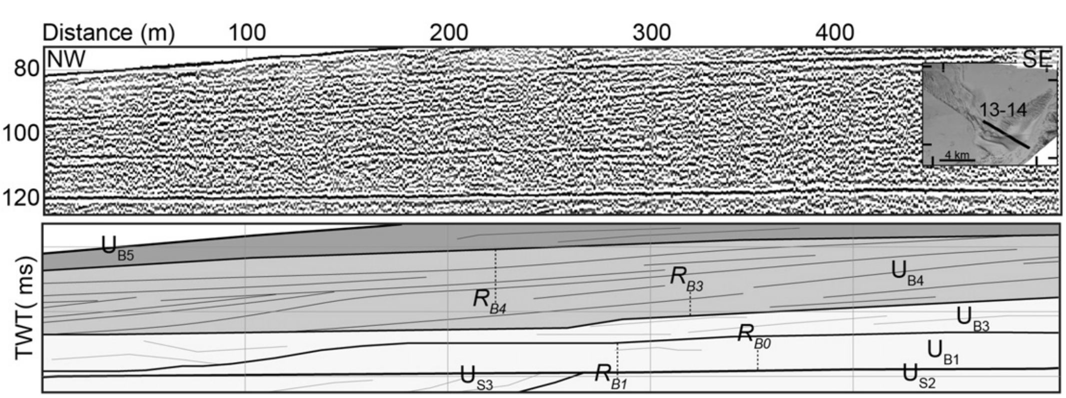

Fig. 11. Extracts and interpretative line drawing of seismic line 13–14 showing the geometry of the U_{B4} ridge seismic unit. The unit is characterized by large and slightly oblique clinoforms. The reflectors are considered to be formed by lateral accretion of the ridge surface.

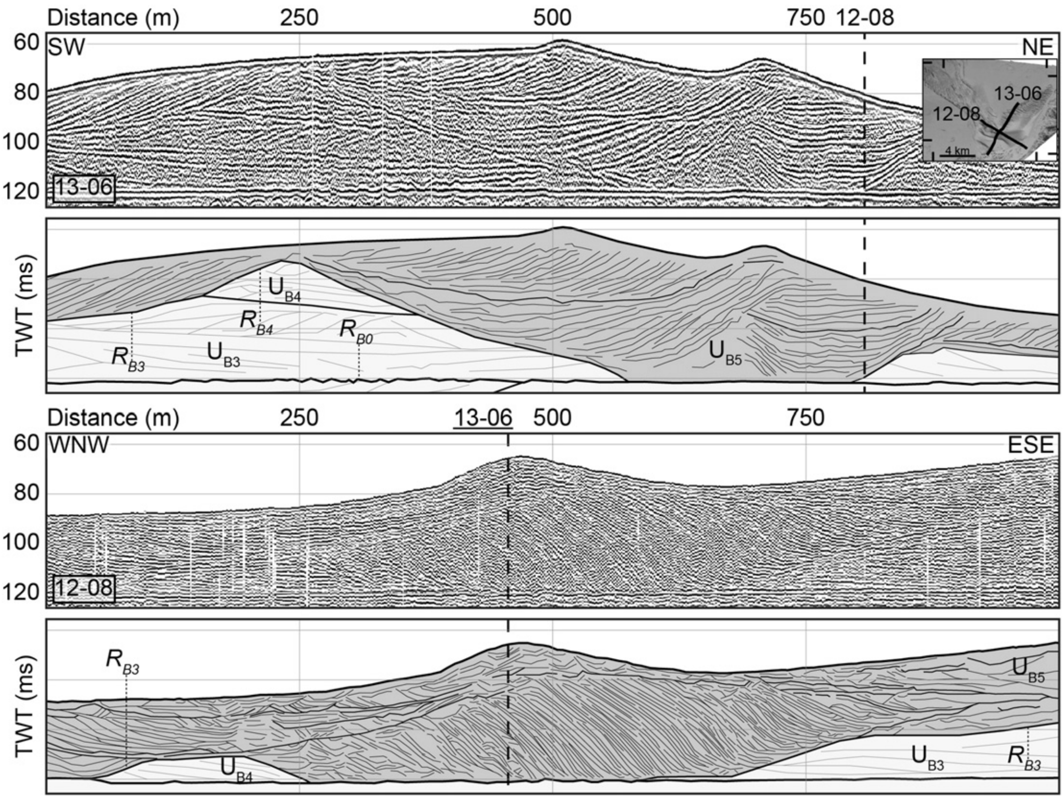

Fig. 12. Extracts and interpretative line drawings of the two secant seismic lines 13–06 and 12–08, showing the geometry of the U_{B5} ridge seismic unit. The geometry of the unit is characterized by a succession of aggrading and prograding climbing sets of reflectors. They are interpreted as massive climbing dunes.

where the angles of the basal surfaces are higher. On the eastern part of the ridge, the geometry of unit U_{B5} suggests an intense reworking of the ridge crest and a residual north-eastward sediment transport toward the attached dune fields. The transport is in accordance with present hydrodynamics and attests to the active state of the *Banc du Four*.

Another remarkable feature is the presence of deep troughs within units U_{B3} and U_{B5} (Figs. 12 and 13). These structures are only located along the western flank of the ridge. Examination of parallel seismic lines indicate that these troughs are quite short (500 m in length), about 200–300 m wide, oriented roughly W-E, and pinching out toward the western flank of the ridge. Their shapes are ovoid. The lowest position of the depression is about 90 m b.s.l. and corresponds to the basement where the entirety of the sandy bedforms has been removed by erosion. They are interpreted as pits with local scouring separating a giant three-dimensional dune (Reynaud et al., 1999b; Rubin, 1987). Their infill consists of oblique reflectors (angle of dip about 10°, up to 15°) prograding to the EES. They are perpendicular to the pit's flanks and considered to be the bedding of giant tidal dunes. Three to four sets separated by medium bounding can be distinguished within the pit's infills. Crossbedding directions are similar within each set, and downlap over the bounding surfaces. These boundaries correspond to migration surfaces, and the dune foresets show offshoots passing the troughs and reaching the flank of the adjoining dune. This type of

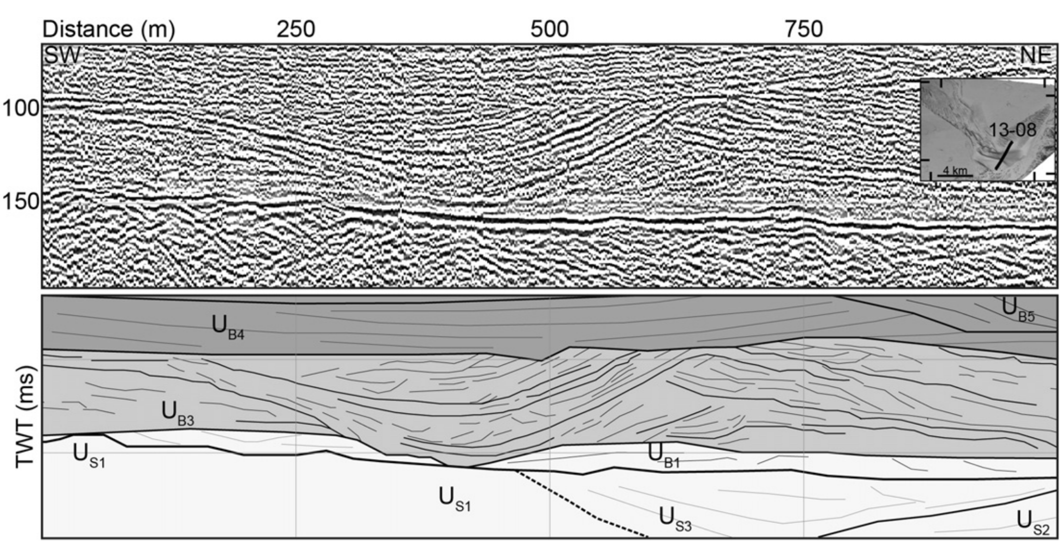

Fig. 13. Extract and interpretative line drawing of seismic line 13–08 showing the presence of large concave-up geometries within the U_{B3} ridge seismic unit.

bedding feature is quite similar to minor scale, asymmetric, wave ripple cross bedding (Boersma, 1970).

This interpretation of the pit's infills leads us to consider the occurrence of a subordinate eastward paleo-current, normal to the polarity of the giant dunes. This is consistent with recent current measurements taken at the seabed along the nearby eastern dune field, from 10/11/2011 to 20/11/2011 during the PROTEVS DUNES Cruise operated by the S.H.O.M. Results show the occurrence of a minor eastward current component able to mobilize middle sands and reaching up to 0.5 $m.s^{-1}$ at medium tidal range. Therefore it makes sense to consider that sediment transfer is still today partially controlled by a subordinate E-W tidal current along the scour pits area and to look for sedimentary structures related to this direction of sediment transport. Examination of multibeam bathymetric images provided from the 2010 Daurade cruise (Fig. 14) reveal that such structures are located at the junction of the western giant dunes and the sand ridge. Four to five unfilled pits with sizes similar to the structures observed on seismic lines are identified along the troughs separating the giant dunes. They correspond to erosive structures where the basement outcrops at the seabed in the center of the troughs. They are separated one from another by sinuous and oblique dune crests and oriented in a NNW-SSE direction. They are partially connected to the main giant dunes showing sinuous and bifurcated crests. The polarities of the bedforms enable identification of the current pattern, which shows a succession of antagonist gyres and a migration of dunes toward the EES (Fig. 14).

The divergence of the oblique bedforms relative to the mean current normal to the orientation of giant dune crest lines is thus controlled by the presence of residual eddies. This situation was demonstrated by flume experiments where bidirectional flows were applied to subaqueous dunes with a divergence angle greater than 90° (Rubin and Ikeda, 1990). It is thus consistent with the consideration of an eastward subordinate residual current mentioned above.

6. Discussion

6.1. Architecture of the sand ridge

One of the most remarkable morphological features of the *Banc du Four* is the presence of two large sand dune fields oblique to one another and intersecting around the sand ridge depicted by seismic investigation. This pattern is quite different from the typical shapes of sand ridges proposed by Dyer and Huntley (1999). It reflects the convergence of two tidal bedload transport pathways. One is parallel to the coast and orientated NW-SE, the second corresponds to a gyre generated by the Ushant promontory. Though this tidal-transport path is complex, the *Banc du Four* is clearly anchored by coastal eddies and the sandwaves display a convergent pattern toward its western flank, favouring accretion.

Its smooth and rounded crest is perceptible to the east, and its roughly W–E extension is neither parallel nor perpendicular to the

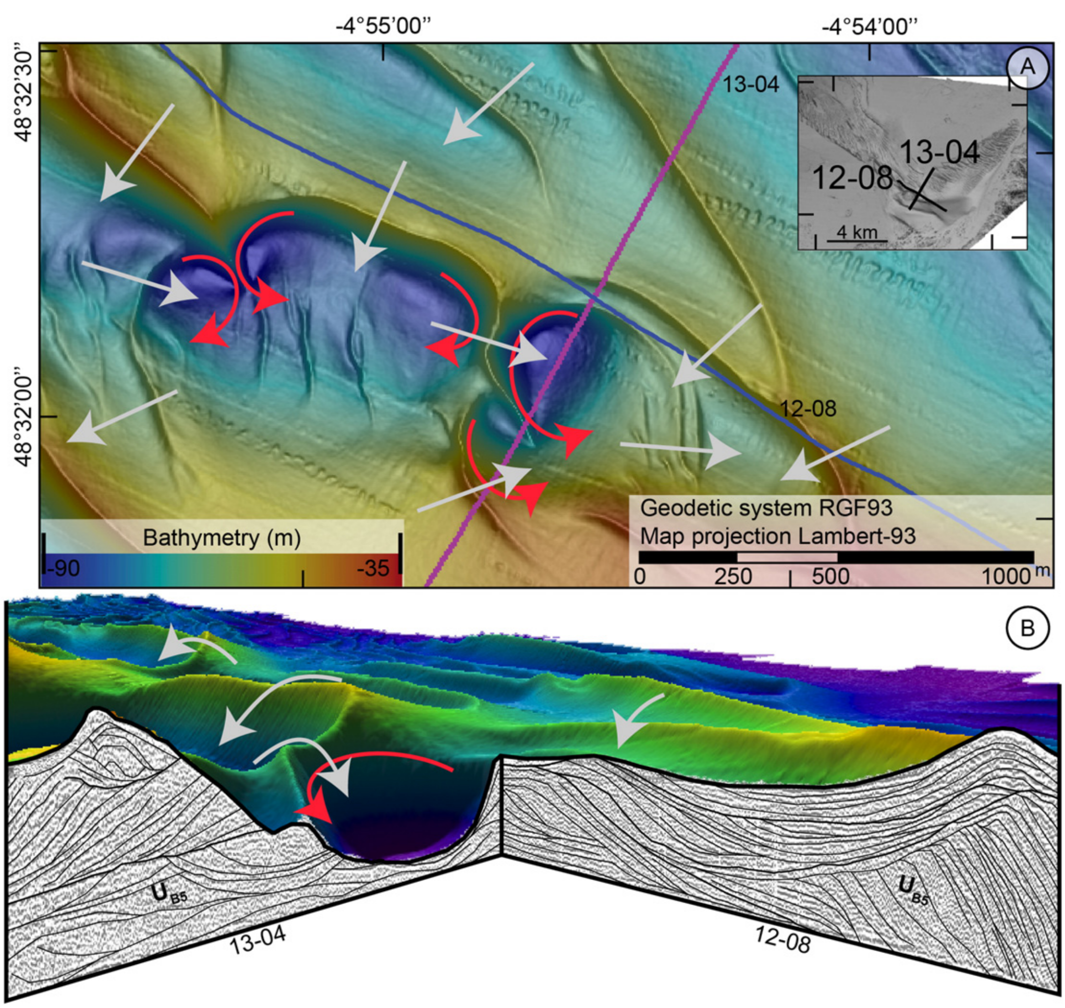

Fig. 14. Bathymetry map (Daurade 2010 survey) of the western border of the *Banc du Four* and corresponding 3D view showing the internal geometry of the U_{B5} seismic unit through extracts 12–08 and 13–04. It shows the succession of scour pits between giant dunes. The deposits have been removed within the troughs. White arrows represent the direction of dune migrations deducted from the asymmetry of the bedforms. Red arrows represent deducted orientations of erosive currents.

residual current, which is oriented towards the northeast (Fig. 2). This morphology means that it cannot be considered representative of an open shelf ridge, normally marked by straight to slightly sinuous crests with orientations at a small oblique angle (about 7–15°) to the peak tidal flow direction. However, banner sand ridges are commonly attributed to the presence of a tidal residual current eddy, such as observed here. The *Banc du Four* could be thus considered representative of this type of ridge, even if numerous banner ridges exhibit associated parallel sand ridges (Dyer and Huntley, 1999).

6.1.1. Internal structure

The vertical succession of the internal structure of the *Banc du Four* is interpreted to be lower coastal deposits grading to offshore deposits and records a sea-level rise. The combination of sandwave climbing processes combining progradation and accretion is the major parameter controlling the growth process of the ridge, as previously described by Reynaud et al. (1999b), Bastos et al. (2003) and Reynaud and Dalrymple (2012). The elevation of the preserved dune foresets is about 20–30 m within the ridge and indicates a combination of giant dunes fields as early deposits of the U_{B2} unit. They are characterized by numerous steep (up to 20°) clinoforms that attest to the high-energy depositional environment of this banner bank. Moreover, the presence of scour pits created by the 3D geometries of the giant dunes allow the growth of bedforms migrating oblique to the orientation of the giant dune crest lines.

This compound architecture of the *Banc du Four* is different from the first seismic records of the Well Bank and Smith's Knoll (southern North Sea), presented by Houbolt (1968) and for a long time considered representative of the internal structures of sand ridges. This initial model is characterized by slightly inclined reflectors (2–4°) related to the migration of the ridge and lying above a flat basal surface. These ridges migrated laterally relative to their axis, due to the obliqueness of the dominant tidal residual flow. Houbolt's theory is effectively validated by more recently studies in the North Sea in relatively shallow waters (<50 m b.s.l.), and on tidal and storm dominated shelves (Cameron et al., 1992; Davis and Balson, 1992; van de Meene, 1994). It is also representative of the shoals located around coastal headlands in southern England, where sand streams formed by large sandwaves do not show a convergent pattern toward their crests (Bastos et al., 2003).

Nevertheless, the internal structure of the *Banc du Four*, with a sedimentary core forming the lower units and overlain by sandwaves, is also reported in previous studies (Bastos et al., 2003; Berné et al., 1994; D'Olier, 1981; Laban and Schüttenhelm, 1981; Marsset et al., 1999; Trentesaux et al., 1999; Yang and Sun, 1988). The lower units are characterized in these studies by variable seismic facies: deep-angle prograding reflectors (Bastos et al., 2003), low-angle clinoforms (Reynaud et al., 1999b), or sub-horizontal aggrading deposits (Berné et al., 1994; Trentesaux et al., 1999). They are interpreted as markers of sea-level lowstands. In some cases the basal units also developed above erosional structures such as inlets or paleo-valley fills (Berné et al., 1998; Reynaud et al., 1999b; Snedden and Dalrymple, 1999; Trentesaux et al., 1999). As observed for the deep Celtic ridges (Reynaud et al., 1999b) or the shallow Flemish ridges (Trentesaux et al., 1999), the presence of a paleo-valley located at the base of the structure could correspond to the initial source of material removed by erosion, which triggered the initiation of the ridge growth. Moreover, a basal pebble lag (coastal storm deposits), comparable to coarse deposits constituting U_{B1} in this study, is also indicated for the Sercq banner ridge located in the southern English Channel (M'Hammdi, 1994) at a depth of about 50 m. However, the lagoonal or estuarine deposits recovered and found in several ridges located on sheltered or shallow shelves (Berné, 1999, 2002; Trentesaux et al., 1999) are absent in the *Banc du Four*. It is more representative of an evolved stage of sand ridges where lower coastal deposits are partially preserved (see §2).

Moreover, very few previous studies dealing with the internal architecture of ridges have mentioned the presence of steep and large clinoforms as observed for the *Banc du Four*. The studies of the ridges of the North Sea (Middlkerke ridge, Berné et al., 1993; Trentesaux et al., 1999) and the Southern Celtic Sea (Berné et al., 1998; Marsset et al., 1999; Reynaud, 1996) mentioned reflector foresets with a maximum dip of 10°. No higher values are reported for the banner ridge of the Shambles bank along the Dorset coast where the amplitude of tides does not exceed 2 m (much lower than the 7 m for the Four Bank during spring tides) (Bastos et al., 2003). The only other example reporting similar dip angle clinoforms is the Sercq ridge located along the French Cotentin Peninsula towards the south of the English Channel (M'Hammdi, 1994). The hydrodynamical setting of this banner ridge is quite similar to that of the *Banc du Four* (macro-tidal regime and exposed to storm waves). Nevertheless, the total thickness of this ridge is about 25 m with a shallower basement depth (50 m) and the elevation of preserved clinoforms does not exceed 10 m. As a consequence the *Banc du Four* appears to be, despite its significant depth, a representative example of a large-scale high-energy banner bank where large and steep clinoforms are depicted in a modern environment. Similar sand-prone clinoforms have also been described in the stratigraphic record. Generally found in association with fluvial and deltaic systems, they have often been the subject of divergent interpretations (SEPM's Research Conference, 2008). The *Banc du Four* shows that the internal structure of a banner ridge must also be considered representative of such bedding structures.

6.2. Age model

Another significant result of this study concerns the radiocarbon ages of the surficial deposits of the *Banc du Four*. Most of the dating was performed on well-preserved to very well-preserved shells, with the exception of samples 10-8 V and 10–42, which suggests limited transport and alteration. The calibrated ages range from 10,036 (10-8 V) to 2748 (12-3 J) cal years B.P. (Fig. 4). Though normally the oldest age logically corresponds to the most altered sample, some bivalves, such as sample 10-42 J, are quite old (7401-7288 cal years B.P.), despite their juvenile appearance. All of the measurements that suggest the *Banc du Four* dates from the Holocene were obtained from the seven analysed shells.

The correlation of seabed samples to the seismic units that outcrop at the seabed show that the U_{B2} unit, located along the eastern flank of the ridge, corresponds to the oldest deposits. The samples consist of siliciclastic gravel with a low biogenic content, as described above. Their age is then contemporaneous with, or older than the shells included (10,036–9789 cal years B.P.). Ages of the upper units (U_{B3}–U_{B5}) are less indicative of the sampled units; they range from 7288 to 2861 cal years B.P. The siliciclastic facies fit with the peri-Armorican pebbly strip ("cailloutis") and the quartzitic sands previously described off Devon and Cornwall (Bouysse et al., 1979; Evans, 1990). They are considered to be produced by coastal erosion, and most have been brought into the areas by periglacial processes. The examination of heavy minerals contained in these siliciclastic gravels and sands do not reveal gradients or significant transport toward the axis of the Western Channel Basin (Bouysse et al., 1979). In the present study, the granitic pebbles collected in the Shipeck grab can be correlated with the *Granite à deux micas and Toumaline* and the *granite migmatique prorphyroïde de Landunvez* that outcrop at a distance of 10–20 km from the ridge along the NW Brittany coast. The sedimentary source of the U_{B2} unit is thus considered to be local, with minor transport. A similar interpretation could be done for the U_{B1} unit, also shown to be composed of coarse siliciclastic deposits, with regards to its coastal deposit architecture. The biogenic fraction forming the main part of the *Banc du Four* area shows a biological assemblage commonly reported on the Channel continental shelf for the last transgressive cycle (Bouysse et al., 1979; Reynaud et al., 1999b; Wilson, 1982). More specifically, it is representative of fresh coastal thanatocaenoses (Raffin, 2003), however its spatial distribution is widespread across the shallow depths of the Western Channel (Larsonneur et al., 1982). We find that Bryozoans do not form the main component of the bioclastic debris of the ridge, as was reported for the bulk of the sediments off the Brittany coast (Bouysse et al., 1979). The winnowing effects of tidal and wave induced currents that increase on the relatively shallow waters over the ridge and giant dunes could explain this difference. One also notices that convergent tidal transport pathways and peak bed-stress vectors deduced from paelo-tidal modelling increase around 9000 years B.P. across NW Brittany (Reynaud and Dalrymple, 2012; Uehara et al., 2006) and favour ridge formation in agreement with our observations.

Moreover, the westward residual ebb-dominant regional tidal currents (Auffret, 1983; Bouysse et al., 1979; Evans, 1990) are able to transport the bioclastic sands through the NW Brittany continental shelf, and contribute to supply the *Banc du Four*. Nevertheless, this sediment supply is probably not significant, rather the good preservation of juvenile shells suggests a local autochthon origin of the bioclastic sands linked to the tidal gyres that occur around the ridge. It is also difficult to explain the broad spectrum of ages and absence of recent or present surficial deposits. The presence of relatively old sands at the top of the ridge could be explained by the alteration and leakage of the lower units that locally outcrop at the seabed across the ridge. It is also possible that the deep scouring exposed above contributes to the mixing of the bioclastic sands and allows them to rise from the lower units. The absence of bioclastic sands younger than 2748 cal years B.P. suggests that the sand ridge and proximal dune fields correspond to a fossilized sand reservoir reworked by tidal and wave dynamics. Even if this result needs to be confirmed by complementary data, two hypotheses can be put forth to explain the absence of recent bioclastic sands. First, the absence could be linked to a relative collapse of biological productivity around 3000 years B.P. Indeed, in contrast to the Holocene transgression that progressively reached the hard floor of the present coast around 7000 years B.P. and triggered the production of epifauna (Bouysse et al., 1979; Larsonneur et al., 1982), a change in climatic and oceanographic regimes occurring around 3000 years B.P. is sufficient to explain the absence of recent shells. It matches with the cooling in the NE Atlantic from a significant Arctic glacier event following the Minoan Thermal Optimum (Denton and Karlén, 1973; Nesje et al., 2008; Van Vliet-Lanoë et al., 2014b). In a second hypothesis, the absence of recent shells could be induced by the non-conservation of deposits. The age of 3000 years B.P. also matches with the timing of the beginning of storminess maxima records along the two coastal sedimentary systems of the Seine Estuary and Mont-Saint-Michel Bay located along the southern coast of the English Channel in northwestern France (Sorrel et al., 2012). These events are also recorded by the onset of coastal barrier degradation from 2400 years B.P. in the Bay of Audierne along SW Brittany (Van Vliet-Lanoë et al., 2014a), and from 4300 years B.P. in other coastal environments in north and northwest Europe (Sorrel et al., 2012). These modifications would have been sufficient to drive the non-conservation of recent deposits.

6.3. Morphologic control

The few available dates allow us to somewhat constrain the timing of the building of the *Banc du Four*, and we find that ridge growth was mainly accomplished during the last deglaciation and sea level rise. An older age cannot reasonably be presumed, indeed if the preservation of previously emerged bedforms could be considered to occur by early diagenetic cementation, the seismic records should display a pronounced contrast in impedance between the old ridge core made of preserved calcarenites at the base of more recent biogenic sands. This is not observed and the *Banc du Four* is thus assumed to be transgressive in origin. The progressive flooding of the crystalline basement and sills bounding the present location of the sand ridge has induced drastic modifications in this hydrodynamic setting. Consideration of the seismic stratigraphy and morphology of the seafloor basement, together with the ages of the sea-level fluctuations during the Holocene, enables us to suggest an evolutionary scenario for the *Banc du Four* (Fig. 15). The Holocene sea-level change along the French Atlantic and southern English coast continues to be a matter of debate in regards to the response of the continental crust to glacio- and hydro-isostatic effects and regional subsidence, but also regarding the interpretation of coastal markers and palaeo-shorelines as storm deposits (Flemming, 1998; Goslin et al., 2013; Lambeck, 1997; Leorri et al., 2012; Wingfield, 1995). Nevertheless, the recent physical models (Flemming, 1998) do not indicate a significant difference with respect to global sea-level curves (Alley et al., 2005; Deschamps et al., 2012; Waelbroeck et al., 2002). We have thus considered these last reconstructions, except for the last 8 ka for which we have also used the recent local curve of Goslin et al. (2013) that updates the Western Brittany Holocene relative sea-level data. This reconstruction is based on basal peat and compaction-free deposits that have accumulated on top of the Pleistocene formations along Western Brittany, which were recovered during the early-Holocene stages of the post-glacial transgression.

According to these studies, the first building stage of the ridge corresponding to the deposits of unit U_{B1} probably started at about 14,000 ($\pm$1000) years B.P., when the sea level reached the basement of the ridge at 90 m b.s.l. All of the straits and channels bounding the present ridge had emerged by this time and the first deposits settled in a wide shallow bay open to the northwest. This environment supports the interpretation of the basal unit U_{B1} as shoreface deposits.

The depths of the preserved part of unit U_{B2} range between 88 and 60 m b.s.l. The unit was formed by large to giant dunes that imply a water depth of 60 m to 45 m (see above §5.2). This paleobathymetry implies that the SSW-NNE ridge U_{B2} started to grow when the Fromveur strait located west of the ridge, and which is lined up with the U_{B2} ridge, was flooded (Fig. 15). It explains the change in the internal structure of the ridge that records a dominant progradation northward. The rock basement located to the south of the ridge remains emerged.

The geometry of the U_{B3} unit, ranging between 90 and 55 m b.s.l., reveals another significant change in the hydrodynamics of the area. New giant tidal dunes rise onto the previous ridge core to the west, and with the exception of small scale fluctuations, the directions of migration are south-westward to the west and northeastward to the east. This apparent residual tidal circulation is similar to present day hydrodynamics across the *Banc du Four* and the Ushant-Molene Archipelago. It suggests that the coastline was close to its present location during the formation of U_{B3}. One may also note that U_{B2} is eroded along the eastern flank of the ridge. This can be interpreted as the consequence of the advent of a new pattern of tidal currents including a residual northward trending flow along the eastern edge of the ridge. It correlates with the opening of the Four strait located south of the ridge, where the basal depth is 13 m b.s.l. These elements combine to place the formation of U_{B3} after 8000 ($\pm$500) years B.P. with reference to the sea-level curve. It is comparable with the oldest deposits recovered at the top of the shelly sands (7300 cal years B.P.). Moreover, the interpretation of the U_{B2} and U_{B3} units linked to the flooding of the straits suggests considering them as a kind of tidal deltaic sedimentation due to deceleration of flow at the outlets of the straits; nevertheless, the orientations of net sand transport in both lithosomes are not compatible with deltaic lobe-shaped deposits.

The relation of the upper units U_{B4} to U_{B5} to flooding steps are not so obvious, even if the last flooding stages of the shallow minor sills (maximum depths 6 m b.s.l.) surrounding the Molene Archipelago could have modified local tidal currents. However, the geometries of units do not lined up with the numerous orientations of the sills (Fig. 5). The stages from U_{B3} to U_{B5} are probably more gradational, corresponding to an overall extension of the ridge to the west, where it enters in the increasing influence of the tidal gyre of the Ushant Island. In this way, U_{B4} could be the stratigraphic expression of the dune intergroup area preserved at the same place and visible in the modern bathymetric map. The superimposed units U_{B3} to U_{B5}, and major bounding surfaces R_{B3} and R_{B4}, would thus predominantly be produced by an autocyclic

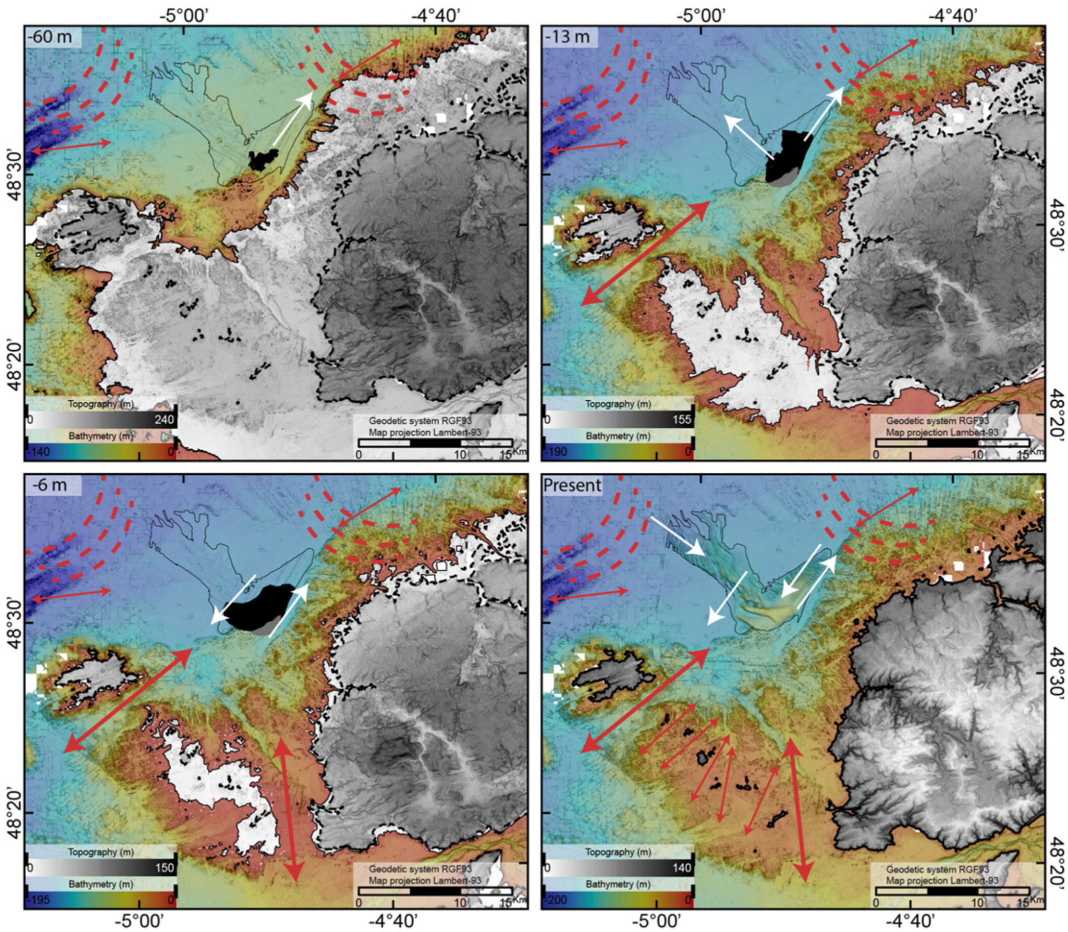

Fig. 15. Reconstruction of the last post-glacial sea-level rise through the study area showing the progressive steps of the ridge growth at −60, −13, −6 and 0 m below the present sea-level. The emerged lands are in grey scale. The extension of the paleo-ridge is shown in black and the outline of the present ridge in fine solid black line. The area in grey around the ridge is expectative and considered as removed by erosion. The tidal connections are marked by red arrows and the main swell orientations by red dotted lines. The directions of main sedimentary transport are shown by white arrows.

process of sand ridge development. Such an interpretation has been made for the internal architecture of tidal sand ridges in the East China Sea (Liu et al., 2007).

However, external parameters as storm waves may also have partially contributed to shape the bounding surfaces. The flattened top of the U_{B5} blanket-shaped (Line 13–14, Fig. 3) is effectively exposed to storm waves as shown by the comparison of recent swath bathymetric surveys (Franzetti et al., 2013).

7. Conclusion

The seismic survey of the *Banc du Four* located offshore Brittany enabled us to characterize the long-term evolution and internal architecture of this deep tidal ridge.

Five seismic units have been distinguished within the ridge, separated by major bounding surfaces and revealing that the ridge construction evolved in stages. The ridge growth was made possible by the presence of a nucleus forming a juvenile ridge interpreted as shoreface deposits. They progressively grade upwards to offshore deposits composed of large-scale tidal dunes. Sandwave climbing, which combines progradation and accretion, is the major process controlling the growth of the ridge. The elevation of the preserved dune foresets reaches values of about 20–30 m within the ridge and indicates a combination of giant dunes characterized by numerous steep (until 20°) clinoforms that denote a high-energy depositional environment. Moreover, the presence of scour pits linked to the 3D geometries of giant dunes allow the growth of bedforms migrating oblique to the orientation of the giant dune crest lines. All of the radiocarbon ages of the biogenic surficial deposits of the *Banc du Four* range from 10,036 to 2748 cal years B.P. and suggest that the *Banc du Four* has grown during the last sea-level rise, as well its morphology reveals it is still active. Moreover, the long-term evolution of the ridge appears strongly controlled by the morphology of the igneous basement. The multiphase accretion of the ridge is closely linked to the presence of a residual tidal current eddy, subsequent to the progressive flooding of the coastal promontories and straits that structured the igneous basement.

The *Banc du Four* is thus representative of an evolved stage of tidal sand ridge, and is still active. It should be referred to as representative of a large-scale high-energy banner bank where large and steep clinoforms are depicted in a modern environment.

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