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The morpho-sedimentology of an artificial roadstead (Cherbourg, France)

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ABSTRACT

Because of its size and geographical position, the Cherbourg roadstead appears as a favourable site for Marine Renewable Energy (MRE) industry. As a result, Cherbourg harbour has undergone profound changes (2015 and 2016) due to the installation of industrial infrastructures to service the needs of expanding MRE further offshore. However, little is known about the morpho-sedimentary distribution and associated dynamics of seabed sediments before and after harbour transformations. This study focuses on sedimentary dynamics using detailed morphological and sedimentological analyses based on data acquired before changes (2012). The main map includes a unique bathymetric map (1:35,000) and sedimentary maps showing the percentage of the characteristic grain size fractions of 184 seabed samples. Despite the high tidal conditions, the roadstead construction had a significant impact on the sedimentary facies and distribution. This study provides a basis for future investigations on geomorphological evolution linked to the impact of anthropogenic development.

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Morphology; sedimentology; morphodynamic; granulometry; bathymetry; Cherbourg roadstead

1. Introduction

Located between the Atlantic Ocean and the North Sea in the central part of the English Channel, Cherbourg harbour (northern France) and its roadstead are situated near British and French offshore wind and tidal turbine farms (Alderney tide race). By pooling its industrial infrastructure with Caen-Ouistreham harbour, Cherbourg harbour is an essential part of an industrial development plan established by the Normandy region in response to the growing needs of offshore MRE production. The morphology of the Cherbourg harbour has undergone vast changes between March 2015 and July 2016 (Figure 1), involving the extension of the harbour area (39 ha) and the dredging of the main channel in the bay (Egis Eau, 2013).

At present, the roadstead consists of: (1) a commercial port with heavy investment in marine renewable energies (wind and hydro-electric), (2) a military port, which is one of the three naval bases in metropolitan France, (3) a fishing port (fleet of 33 inshore and offshore vessels), and (4) a marina with 1600 mooring berths and 5000 boats a year. It is the port most visited by leisure craft in France (Figure 1). The Cherbourg roadstead also hosts a fish farm, with an annual production of about 800 t of salmon.

Despite the fundamental importance of Cherbourg bay, the morpho-sedimentary patterns and associated

dynamics are poorly known. Only a few bathymetric and sedimentological data are available in the literature (SHOM, 1997, 2014). In this paper, we focus on the sedimentary dynamics occurring in the Cherbourg roadstead before major engineering changes between 2015 and 2016. A new bathymetric map and sedimentological data combined with hydrodynamic characteristics (currents and swell) and biological data (benthic fauna) allow us to determine the sediment trends. Hence, these maps provide a basis and offer an excellent opportunity to (1) study the morphodynamic processes and (2) their evolution after the new harbour development.

2. Study area

2.1. Presentation of the Cherbourg roadstead

Situated halfway along the northern coast of the Cotentin peninsula, the Cherbourg roadstead is located in a morphological depression, with the Cap Levi to the east and the Cap de La Hague to the west (Figure 1 and Main map).

The creation of Cherbourg harbour was favoured by the presence of a geomorphologically well-marked bay. This bay was enclosed by a breakwater creating an ‘inland sea’ (the main roadstead) (in 1853). Later, port development led to the creation of the inner roadstead (Main map). The Cherbourg roadstead (1500 ha) forms the second largest artificial harbour in the world

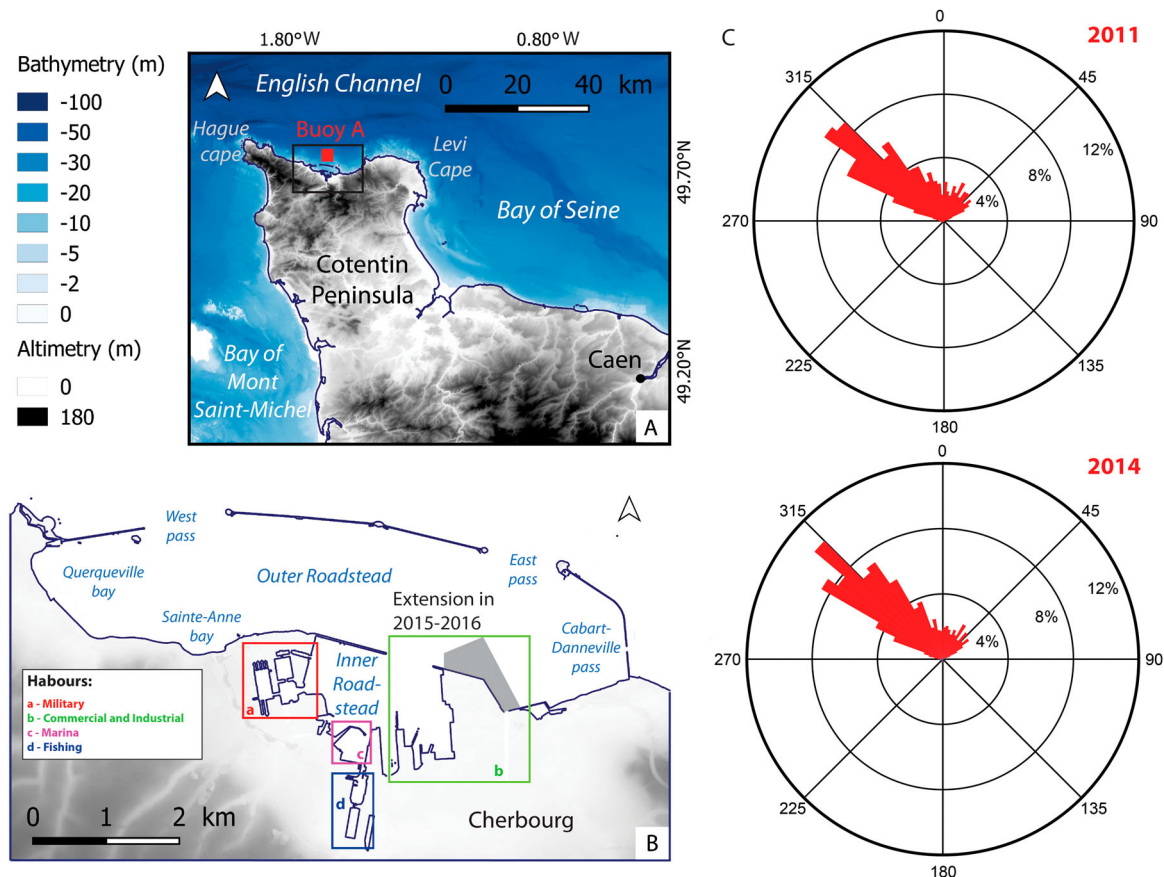


Figure 1. (A) Location map of Cotentin (northern France), (B) location map of Cherbourg roadstead and (C) two wind roses (2011 and 2014) based on data acquired at the buoy A.

after Ras Laffan (Qatar). It is separated from the waters of the English Channel by three breakwaters 6 km in length, with an average width of 100 m at their base, 12 m at their summit and an overall elevation of about 27 m (Main map). Three passes allow the circulation of currents which ensure a connection with the English Channel. The ‘West’ and ‘East’ passes have a width of 1100 and 700 m, respectively. The ‘East’ breakwater is interrupted by the ‘Cabart-Danneville’ pass with a width of 80 m (Figure 1).

2.2. Geology and sedimentology

Most of the bedrock in Cherbourg bay is made up of Precambrian and Cambrian chlorite schists forming promontories on either side of the bay (Graindor, 1964). The Cherbourg area is a sheltered enclave where fine sediment can be deposited in contrast to the otherwise highly exposed north Cotentin coast, which is typified by coarse heterogenous sediment (Baux et al., 2017). The fine particulates are either of marine origin (Boust, Hairie, Fraizier, & Baron, 1995) or continental origin linked to the inputs of small rivers such as ‘La Divette’ and ‘Le Lucas’, the former being the most important with an average flow of 1.28 m³ s. Based on a synthesis of sedimentological data carried out by Larsonneur (1971), Vaslet, Larsonneur, and

Auffret (1978) and later supplemented by the SHOM (1997), the sedimentary cover of the Cherbourg roadstead appears highly heterogeneous.

2.3. Hydrodynamics

Three main wind directions are identified: 40% are westerly, 20% north-westerly and 20% north-easterly (Bellessort & Migniot, 1987). The major swell comes from the west to northwest (290°–350°) with periods of about 10 s (Figure 1(C)). Swell from the west enters the English Channel and becomes diffracted by the Cap de la Hague. Even with winds coming from the southwest, the swell direction is close to northwest. North-easterly swell lies between 10° and 70°, showing shorter wavelengths with a period not exceeding 8 s. For both swell directions, the significant wave height is around 2.1 m and the average height is 1.4 m (SOGREAH, 1986). Periods of flat calm occur 22% of the time.

The node of the tidal pulse coming from the Atlantic and entering the Channel is located at the level of Cherbourg. The tidal range is 5.30 m at mean spring tides and 2.50 m at mean water neaps (Lower Astronomic Tide L.A.T) (Salomon & Breton, 1990). In addition to sea-level fluctuations due to the tide, the atmospheric and oceanographic conditions can also lead to raising

and lowering of the sea surface. In bad weather conditions, with winds coming from the West, the surges can reach 1 m (Merceron, Bentley, Le Grand, Lamort-Datin, & Kempf, 1997). Tidal currents in the main roadstead can range from a maximum of 2 m s^{-1} at neap tide, to up to 4 m s^{-1} during spring tide (Merceron et al., 1997).

3. Methods

3.1. Bathymetric map

The bathymetric map was produced by processing and interpolating interferometric sidescan sonar data for the deeper parts of the roadstead (from 2 m to 18 m related to L.A.T) and from aerial LIDAR (Light Detection and Ranging) for the shallower part (from the emerged land to 2 m depth in relation to L.A.T).

High-resolution shallow-water bathymetric data were obtained from a geophysical survey on board the R/V *Haliotis* (IFREMER), during spring (from 3 to 17 May 2009), equipped with a Geoacoustics Geoswath system. Its phase measuring sonar system, working at frequency of 250 kHz, allowed the acquisition of backscatter (cannot be used in this study due to acquisition complications) and bathymetric data in very shallow water depths (but deeper than 2 m) with a vertical resolution of around 20 cm for the considered water depths. Vessel navigation was carried out by DGPS-RTK (Differential Global Positioning System – Real Time Kinematic) using a reference station located at a short distance on the coast, providing a positioning accuracy better than 10 cm. The RTK system allowed us to correct for tide variations. The bathymetric survey consisted of 330 bathymetric profiles. To correct for refraction errors, acoustic velocity profiles were repeated every day before the start of the daily survey.

Sonar data were treated manually using the CAR-AIBES software (©IFREMER) to clean aberrant soundings (40%) and correct data for tide variations. These data allowed us to create a 1-m grid bathymetric Digital Elevation Model (DEM), edited with ©QGIS software.

LiDAR data were from the Litto3D Digital Elevation Model (DEM) distributed by ROL (Reseau d'Observatoire du Littoral Normandie – Haut de France) and SHOM (Service Hydrographique et Océanographique de la Marine) (Shom-ROL, 2018). The source data were acquired between 2016 and 2017 with respectively vertical and horizontal accuracies of 2 and 20 cm. This DEM using the French altimeter system IGN69 was converted into L.A.T. LiDAR and interferometric data were merged to create a unique DEM with a horizontal resolution of 1 m.

3.2. Sedimentological analysis

A Shipek grab sampler (400 cm^2) was used to collect sediments during the autumn of 2012 (20–25 October). Each of the 184 samples (Main map) was then described, photographed and immediately stored in PE (polyethylene) bags at -18°C . Sediment laboratory analyses involved desalination of sediments and wet-sieving through 2000 μm sieve, in order to separate the mud and sand fractions from the gravel. Weight percentages for gravel ($>2000 \mu\text{m}$) could thus be calculated. The Grain Size Distribution (GSD) of the $<2000 \mu\text{m}$ fraction was determined using a Horiba Partica LA-950v2 laser scattering particle-size analyzer. The LA-950v2 analyses the GSD by calculating the percentage size frequency of 96 classes over a size range of 0.011–3000 μm (error $<2\%$). Each sample was measured following the Lorenz-Mie theory (complex refractive index: Fluid RI: 1.33; Sample RI: 1.55; Imaginary RI: 0.1). The GRADISTAT statistical Excel package (Blott & Pye, 2001) was used to obtain statistical parameters using the Folk and Ward (1957) method.

The final sedimentary maps (Main map) were produced by Principal Component Analysis (PCA) using R language (R Core Team, 2016). The interpretation of the properties of sub-populations is based on the calculated eigenvectors and relative weighting of the scalar quantities of these eigenvalues.

4. Results and interpretation

4.1. Morphological analysis

The morphology of the outer roadstead of Cherbourg is characterised by a main channel extending from the 'West' pass to the entrance of the inner roadstead (Main map). This channel marks the separation between the SW and NE sectors of the bay, which are characterised by two different morphologies. Trending NW-SE, the channel is bordered by a sandy prism in the NE and well-developed outcrops of chlorite micaschist in the SW (Graindor, 1964). With a length of 3000 m and an average width of 1000 m, this channel is characterised by a V-shape with gentle slopes (2%). The depth of the channel decreases from 15 m at the west to 12 m at the entrance to the inner roadstead, and is locally interrupted by rocky outcrops rising up to 1–4 m above the surrounding seabed (central outcrop, Main map). These outcrops are mainly located close to the 'West' pass. Toward the east, the sedimentary cover is formed of small symmetric sand ripples characterised by an average height of 10 cm and a wavelength about 10 m. These ripples are produced by the swell action which crests are armed by invasive benthic species (American slipper limpet *Crepidula fornicata*) forming chains (Blanchard, 1995; Le Gall, 1980; Retière, 1980). In this area grabs are often filled with shells.

The sandy prism covers 35% of the roadstead area, lying at an average depth of 6 m and occupying the entire eastern part of the Cherbourg roadstead. The north-western extremity of this prism is arrow-shaped and extends up to the foot of the central breakwater (Main map). The crest of the prism runs along the south side (at 5 m depth) and shows asymmetrical flanks: steeply sloping in the south (2%) and gentle in the north (0.6%).

The sandy prism is incised in many places, either by natural or by anthropogenic processes. Troughs are located at the level of the 'East' and 'Cabart-Danneville' passes, and can be interpreted as secondary channels created by the acceleration of tidal currents after construction of the breakwaters. The deeper trough occupies the narrow entrance of the 'East' pass. Here, the water depth shallows rapidly from 12 m to 6 m, at the immediate entrance of the roadstead, where the slope is about 2%. This channel is highly asymmetric and is bounded by abrupt flanks at the foot of the 'East fort' promontory (86%). On its other side, the slope is more gentle (1.7%).

A large field of dunes and ripples (Ashley, 1990) is developed close to the East pass associated with the acceleration of currents in the channel (Figure 2(B)). Barchan dunes are distributed over the northern part of the field, while the southern part is characterised by asymmetric transverse ripples. Barchans dunes show a mean height of 1 m. Their gentle slopes (60 m wide) were oriented toward the east and steep slopes (20 m wide) toward the east. Asymmetric transverse ripples have a height of 0.2 m and a wavelength of 10 m, with gently sloping flanks (6 m wide) oriented toward the east and steep flanks (1 m wide) toward the west.

A sedimentary bedform, oriented almost perpendicular to the pass, occupies the centre of the 'East' pass channel (Figure 2(A)). Rising up to 2 m above the bottom, 400 m long and 160 m wide, it is characterised by a steep east flank (8%) and a gentle west flank (1.7%) (profiles A-B on Figure 2). Due to its elongate morphology, asymmetry on either side and its location behind the breakwater, acting as promontory, this sedimentary bedform can be considered as a banner bank (Belderson, Johnson, & Kenyon, 1982; Dyer & Huntley, 1999). The formation of this bank is linked to the action of alternating tidal currents (ebb and flood) which create residual eddies (Berthot & Pattiaratchi, 2006; Dyer & Huntley, 1999; Neill & Scourse, 2009). The southern part of the bank is covered by three sedimentary bedforms equivalent to symmetric dunes (50 cm in height and wavelength of 25 m). A field of symmetric ripples extends from SE to NW at the base of the east flank, characterised by an average height of 20 cm and a wavelength of 15 m.

The channel connected to the 'Cabart-Danneville' pass is very shallow with a constant depth of about 3 m. A ripple field is well-developed along the bottom

on its northern side (Figure 2(D)). The ripples are symmetric, ranging in height from 10 to 20 cm high with a regular wavelength of 10 m.

Dredging operations carried out during previous port developments have created three deep depressions (Figure 2(E)). The two widest are located in the sandy prism (Main map). These depressions have the same depth (14 m), very abrupt flanks (30%) and type of morphology linked to the dredge method (suction dredge), but they differ by their shape. The depression nearest to the coast is rectangular in shape and covers an area of 4×10^5 m², whereas the northern depression covers an irregular area of 2×10^5 m². The third depression is located at the entrance to the inner roadstead and has a very small extent. With a depth of 17 m, this represents the deepest zone in the entire Cherbourg roadstead. The dredging operations have extracted a total of 8×10^6 m³ of sediment. Sediments have contributed to extension backfill during the creation of the inner roadstead.

Bedrock is well-developed along the coastline to the west of the Cherbourg roadstead. These outcrops have a relief of 3–5 m, showing many faults mainly oriented NE-SW, and lie within areas mapped as Hercynian metamorphic rocks (chlorite schists) by Graindor (1964). These rocky outcrops separate sheltered pocket beaches whose depth gradually decreases towards the coastline. The western beaches show erosional structures with different morphologies. Elongate scours extending behind rocky outcrops in Querqueville bay are characterised by a narrow channel, about 10 m wide and with a depth of between 30 and 50 cm (Figure 2(F)). As previously shown in other contexts (Nichols, 2009; Picard & High, 1973; Reineck & Singh, 1975), these scours appear to be linked with rocky outcrops which would allow the creation of local turbulent currents. Scours of a more circular shape, with a diameter of 20 m, are found in Querqueville bay, without any apparent link with obstacles of possible anthropogenic origin causing a modification of local hydrodynamic conditions.

4.2. Sedimentological distribution

Sedimentary maps show the areal distribution of four grain-size fractions, from the finest down to the coarsest (Main map), which correspond to the four sediment type groups determined by PCA analysis (Figure 3); the population is made up of 184 individual sediment samples and the variables correspond to the grain-size modal classes described by Wentworth (1922) and modified by Blott and Pye (2001).

The finest grained sediment type (group 1) is formed of mud (<63 µm) and very fine sand (63–125 µm), closely associated together (Figure 3). Group 2 is composed of fine sand (125–250 µm), while group 3 comprises medium sand (250–500 µm) (Figure 3). Group 4 includes fractions coarser than 500 µm. The percentage

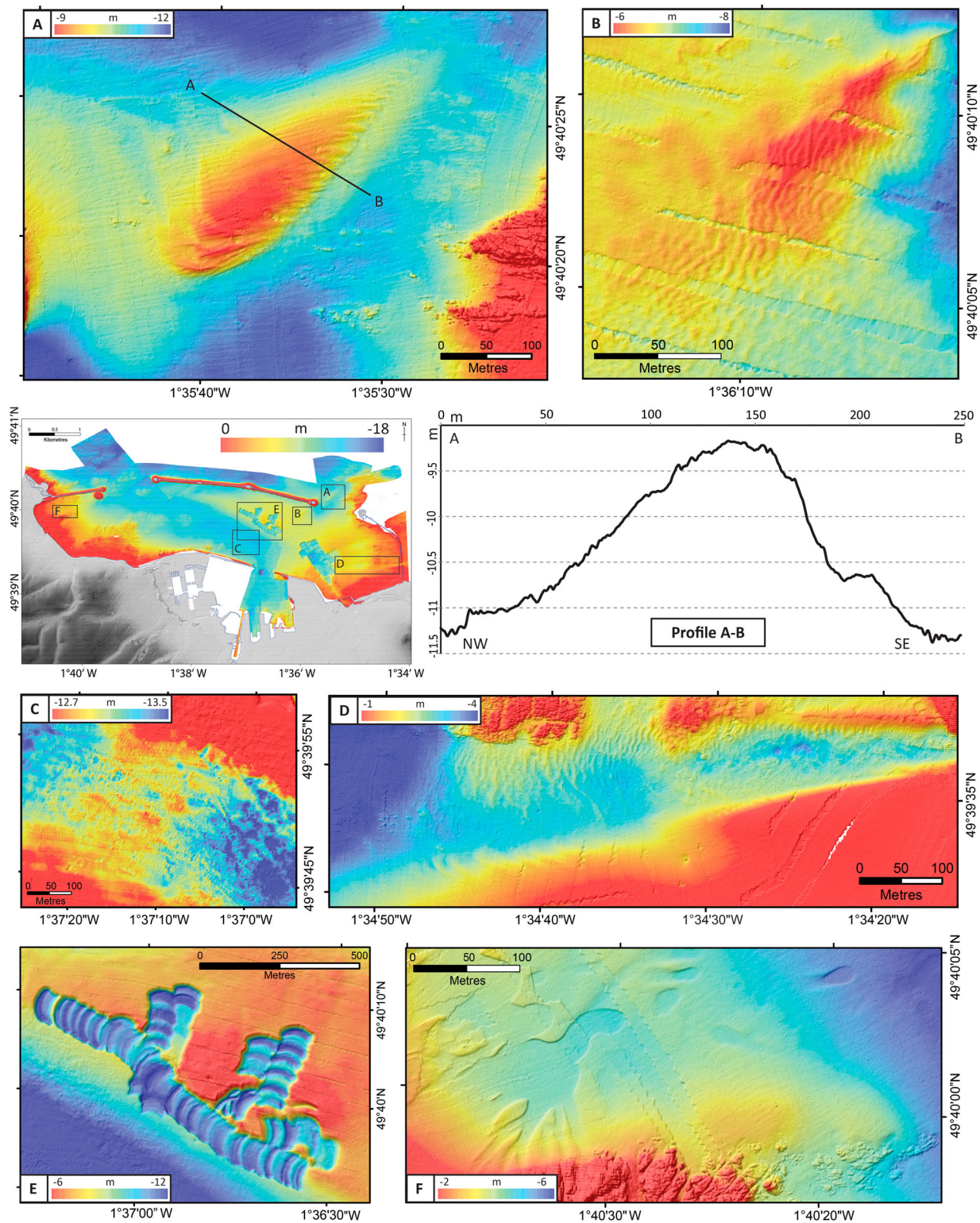


Figure 2. Sedimentary bedforms in the Cherbourg roadstead: (A) banner bank in the east pass, with 2D profile (A-B lateral), (B) dunes located close to the east pass, (C) ripples associated with American slipper limpet, (D) ripples and dunes in the channel of the ‘Cabart-Danneville’ pass, (E) Dredgin marks and (F) scours.

of each group is represented on the sedimentary map (main map), with red dots indicating a strong concentration of sediments belonging to a given modal class.

Finer samples with a high concentration of grain-size classes belonging to group 1 (75–100%) are located in the western part of the Cherbourg roadstead, more precisely to the south of the ‘Querqueville’ breakwater, in the central area of the roadstead from the central

rocky outcrop to the entrance of the inner roadstead and from the ‘Homet’ breakwater northward to the fish farm. Patches of group 1 samples extend laterally on both sides of the entrance of the inner roadstead, i.e. along the ‘Homet’ breakwater and ‘Flamands’ jetty (main map). Sediments covering the bottom of dredge depressions also show a high percentage of this modal group (50–75%).

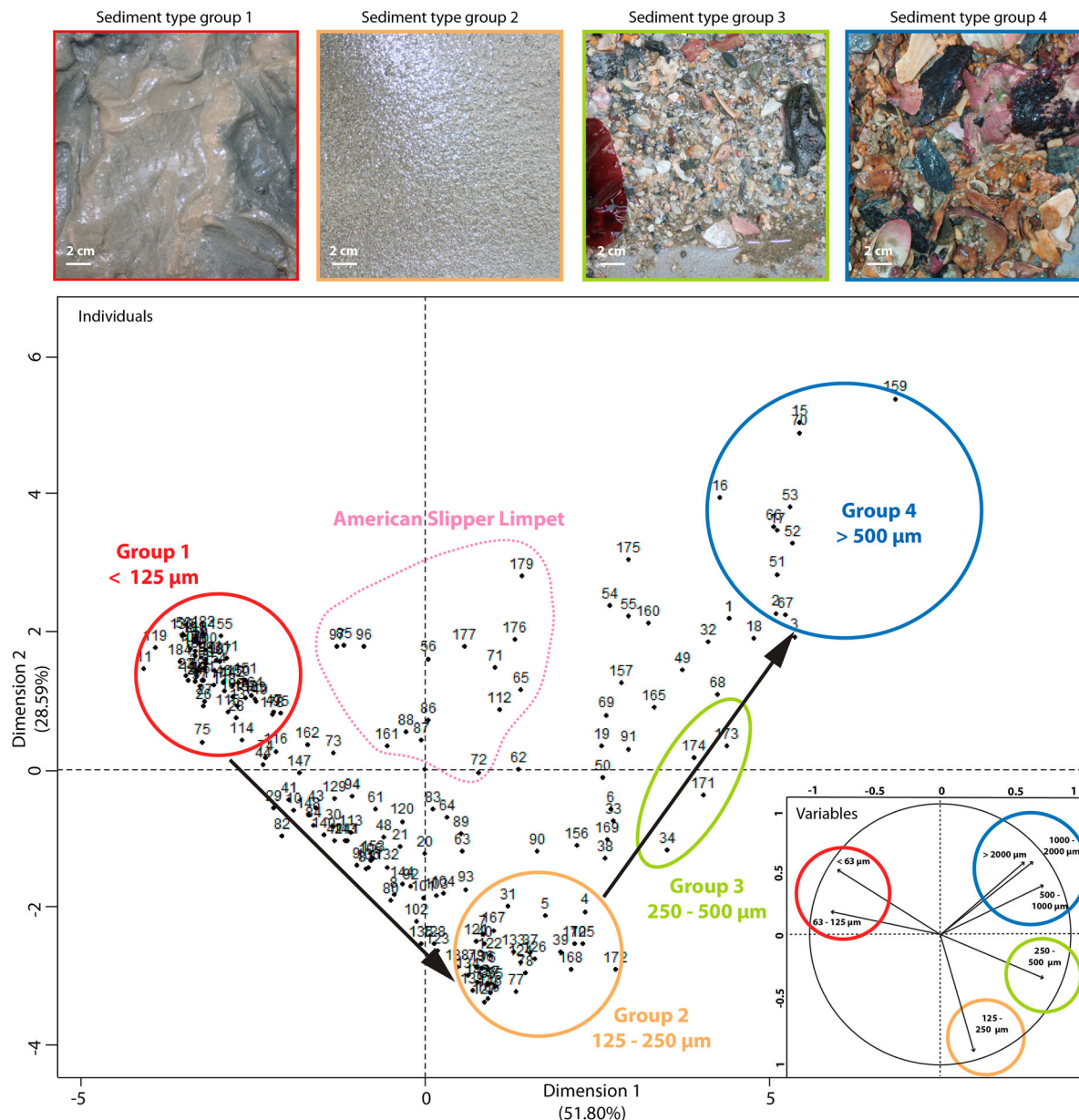


Figure 3. In the centre, plots of the principal component analyses (PCA) based on 184 samples, and, in the right-hand lower corner, granulometric fractions (variables) described by Wentworth (1922) and modified by Blott and Pye (2001). On both plots, the sedimentary groups are illustrated in different colours: red for group 1, orange for group 2, green for group 3 and blue for group 4. At top, photograph of a 'typical' sample from each of the groups.

Group 2 is largely dominated (50–75%) by samples located in the eastern part of the Cherbourg roadstead (Main map). Predominant homogeneous very fine grey sand (Figure 3) forms the sandy body previously described and covers the bottom of the 'East' pass. It is also present in the pocket beaches in Querqueville bay (Main map). At the scale of the entire Cherbourg roadstead, group 2 is ubiquitous with a percentage of at least 5% of this sediment type in each sample.

Group 3 samples, with a high concentration (50–75%) of medium sand, are rare and only found in the 'East' pass (Main map). Here, the calcareous coarse fraction is significant (Figure 3). The area immediately surrounding the pass shows a lower but non-negligible concentration (25–50%) of this group, but shell debris is very scarce. In this area, the 250–500 µm fraction is gradually replaced

by a finer modal class (125–250 µm) toward the south and east. The 'West' pass shows the same concentration of sediments belonging to group 3 (25–50%).

Group 4 is strongly concentrated between the 'West' pass and the central rocky outcrop (Main map). Near this pass, the coarsest particles are mainly represented by shell debris (Figure 3). Closer to the central rocky outcrop, coarse lithoclastic particles make up sheets of gravels derived from the erosion of outcrops.

4.3. Sedimentary provenance and transport modes

PCA analysis allows to determination sediments transport trends (Figure 3). Two significant components can be distinguished accounting for 80.4% of the variance,

with the more important component 1 accounting for more of the half of the variance (51.8%). According to these components, the previously described groups form a V-shaped pattern (Figure 3) which reflect: (1) the sedimentary provenance, (2) the transport mode, according to the Passega diagram (1963), and (3) the hydrodynamic agents (swell, tide or river flood). Thus, it makes it possible to determine the sedimentary dynamics in the Cherbourg roadstead in accordance with the main groups previously described.

According to Boust et al. (1995) muddy sediment is transported from the English Channel into the Cherbourg roadstead and deposited in Querqueville bay behind the breakwater. From our study and the analysis of maps (Main map), it appears that muddy sediments (group 1) come from the 'Divette' river via the inner roadstead and are immediately redistributed in suspension by tidal currents. During the ebb tide, sediments are transported toward the west, whereas, during the flood, sediments are redistributed toward the eastern part (Main map). Sediments accumulating along the Flamands jetty during the flood tide, can be reworked by swell action during extreme wind events. In this situation, sediments might be either expelled from the roadstead through the 'Cabart-Danneville' pass (flood) or redistributed within the roadstead (ebb) (Main map).

Sandy sediments belonging to group 2 are characteristic of the North Cotentin (Baux et al., 2017) and contributed to clastic supply in the studied area before the creation of the roadstead. At present, these sediments are very stable except in and close to the main passes. According to Passega (1963), the sand particles are transported by saltation into the Cherbourg roadstead from the English Channel by swell and tidal currents (Main map). Many samples plot on a straight line connecting groups 1 and 2 (Figure 3). The sediments are more or less enriched in two fractions (<63 µm and 63–125 µm). The middle of axis 1 intersecting this straight line (characterised by 0) marks the limit between samples transported in suspension on the left and by saltation on the right (Figure 3).

Groups 3 and 4 are composed of marine sediments brought in through the passes by swell (mainly 'West' pass) (Main map). The particles are transported by rolling as far as the central outcrops. Samples intermediate between groups 2 and 4 represent an increase in the intensity of swell energy.

Component 2 accounts for 28.59% of the variance, modulating the relative distribution of groups and influencing the samples located in the centre of the V-shaped pattern outlined by the four groups (Figure 3). This set of samples is characterised by the presence of the American slipper limpet (*Crepidula fornicata*) forming ripples, as observed in grab samples. In contrast to the situation along the coast from Cherbourg to Brest, where American slipper limpets are accumulated in

banks, thick mats or superficial patches (Baux et al., 2017; Beudin, Chapalain, & Guillou, 2013; Ehrhold, 1999; Ehrhold, Blanchard, Auffret, & Garlan, 1998; Guérin, 2004), the formation of *Crepidula fornicata* ripple structures in the Cherbourg roadstead seems to be favoured by strong currents which allow the colonies to remain in balance with environmental conditions.

5. Conclusions

Despite its economic importance and strategic position, the Cherbourg roadstead lacks any precise bathymetric or sedimentological maps. Our study fills this gap and proposes an interpretation of the sedimentary dynamics. It appears that the main structures (central channel and sand body) are inherited features that were already in place before construction of the breakwaters and harbour. The banner sand body and rocky outcrops have served as an anchor for the central structure of the breakwaters. On the other hand, smaller sedimentary features (banks, dunes and ripples) were formed after breakwater construction in response to the establishment of the new hydrodynamic regime. The sediments initially deposited in the bay of Cherbourg were unimodal fine sands (PCA Group 2) typical of the north Cotentin coast (tidal currents). Profound anthropogenic changes, produced by roadstead development, have led to modifications of the sedimentary cover. Muddy sediments coming from both Divette river and open sea are trapped in the roadstead and deposited in calm hydrodynamic areas. Coarse bioclastic sediments are imported through the passes and main channel which induce channelling of tidal currents and swell concentration. Furthermore, establishment of the American slipper limpet has also led to modifications in the local hydrodynamics. The accumulation of these colonies in the centre of the main channel creates a stronger porosity and rugosity on the bottom. The rugosity generates turbulence which then allows filling of interstitial spaces by fine sediments. The slipper limpet accumulations are associated with ripple structures mainly generated by swell, which are then sealed by the trapping of muddy sediments. Monitoring carried out by our research team since the 1980s reveals a state of sedimentary equilibrium. However, recent harbour expansion developments (dredging and land reclamation) have changed this equilibrium. Thus, our study offers a reference for future research and will serve as a basis for modelling the volumes of sediment in transit, which are either supplied to or exported from the Cherbourg roadstead.

Software

Software ©QGIS 2.18.13 (Las Palmas) was used to create the bathymetric map and sedimentological data

maps. Map layout and final editing was performed using ©Adobe Illustrator CS 6. PCA has been produced thanks to ©RStudio software.

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No potential conflict of interest was reported by the authors.

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