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Modern morpho-sedimentological patterns in a tide-dominated estuary system: the Bay of Brest (west Britanny, France)

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Abstract :

Long-studied with respect to its sedimentological features (1897), the Bay of Brest (Western Britanny, France) is a textbook example of a tide-dominated estuary. Characterised by macrotidal conditions, this estuary system is sheltered from the open sea (Iroise Sea) by a narrow strait that partitions the wave tide influences and continental/marine inputs. Sediments are supplied to the bay both by rivers (the Aulne and Elorn rivers) and by marine tidal currents. This study presents new analyses of detailed facies and morphological patterns, based on the integration of multisource data compiling seabed sampling, swath and LIDAR bathymetry, and backscatter imagery. The Main Map, at a scale of 1:90,000, contains (1) a sedimentological distribution using the 'Code Manche' classification, (2) a morphological map, and (3) bathymetric mapping which presents the morphology of marine and terrestrial landforms. This work may lay the foundation for a future study on sedimentary transport in a unique and confined coastal environment.

Keywords : Morpho-sedimentological cartography, tide-dominated, estuary system, estuarine sedimentation, backscatter imagery, Bay of Brest

1. Introduction

According to the definition by Dalrymple, Zaitlin and Boyd (1992), tide-dominated estuaries are characterised by funnel shaped morphologies and highly dynamic environments dominated by strong tidal currents, with lesser influence from waves and river currents. Numerous studies have been devoted to these environments in recent years and the morphology and sedimentary partitioning of tide-dominated estuaries are predictable in general terms (Davis and Hayes, 1984; Dalrymple, Knight, Zaitlin, & Middleton, 1990; Dalrymple & Zaitlin 1994; Dalrymple, Mackay, Ichaso, & Choi, 2012; Tessier, Delsinne, & Sorrel, 2010; Ryan et al., 2007). At the estuary entrance, the accelerated tide currents shape the seafloor into many bedforms such as dune fields as observed in the San Fransisco Bay (Barnard, Erikson, Elias & Dartnell, 2012) or large scours features as reported in the Minas Basin in the Bay of Fundy (Shaw, Todd & Li, 2014). The gradual decrease in current intensity allows sediments to deposit in sheltered areas. Nevertheless, not much is known about the detailed facies and the patterns of morphological changes controlling the balance between erosion and sedimentation. This knowledge is essential for understanding the sedimentary exchanges between continental and marine domains and is of utmost importance in deciphering human influence from natural controls. The Bay of Brest offers us the opportunity to examine these points and to compare them with previous studies. Located at the western-most part of Brittany (France) it is a large tide-dominated estuary system (about 230 km2) with macrotidal conditions. The estuary system is sheltered from the open sea (Iroise Sea) by a narrow, one nautical mile wide, strait (the *Goulet*) formed of Brioverian (end of Precambrian) rocks and controlled by an inherited Hercynian fault system. This N70°E trending fault system separates two regional geological domains composed of Hercynian granitic rocks to the North of the main fault and sedimentary rocks to the south (Brioverian and Paleozoic) which form the whole rocky basement of the bay (Babin, Didier, Moign, & Plusquellec, 1969; Ballèvre, Bosse, Ducassou, & Pitra, 2009; Ballèvre et al., 2014; Garreau, 1980). The strait corresponds to a relatively enclosed channel (about 60m below sea level) where tidal currents are subjected to venturi effect and reach speeds up to 9m/s during spring tides. This allows the exchange of about 700×10^6 to 1×10^9 m^3 of seawater at each tidal cycle which corresponds to about the third of the mean water volume of the bay (Fichaut, 1984). The strait also marks the transition between 1) the oceanward extension of the estuary system to the west which can be dominated by the swell mostly during south-west storm events and 2) a large (180 km^2) semi-enclosed bay to the east (the Rade de Brest *s.s*). In this last internal domain, wave action has a limited influence and marine hydrodynamics are clearly dominated by tidal currents ranging from 0.25 to 2 m/s (SHOM, 1994). Sediments are supplied to the bay both from continental sources, fed by two main rivers (Aulne and Elorn) with a total annual load of about 1×10^4 T, and marine sources due to the flood currents (Auffret, 1983; Bassoulet, 1979). The first sedimentary map of the Bay of Brest, published in 1897, by the French hydrological department (SHOM) is believed to be one of the oldest representative map in the world (*in* Garlan, 2012). Successive works devoted to studying the sedimentation of the bay were based on interpolation of sediment sampling over time (Auffret, 1983; Fichaut, 1984; Guérin, 2004; Guilcher & Pruleau, 1962; Hallégouët, Moign & Lambert, 1979; Hinschberger, Guilcher, Pruleau, Moign & Moign, 1968; Moign, 1967). In this study, a new sedimentary map is made based on integration of multisource data combining seabed sampling, with bathymetric data collected by the SHOM and the French Institute for marine studies (IFREMER), with the integration of surveys conducted for the benthic fauna habitat mapping program (REseau BENThique, Ehrhold, Hamon & Guillaumont, 2006) by the European Institute for Marine Studies (IUEM). Additional side-scan backscattering imagery based on interferometry sonar conducted by IFREMER was also used to evaluate the nature of the seabed. Using this, geomorphic and sedimentary maps are presented to highlight the type of sediment characterising the different depositional environments through the estuary system.

2. Methods

2.1 Geomorphological analysis

The bathymetric map was created by processing and interpolating data from multibeam echosounder surveys for the deepest domains (from 10 m to 50 m in Lower Astronomical Tide L.A.T) and from aerial LIDAR (Light Detection and Ranging) for the shallowest part (from land to 10 m in LAT). Data provided from five geophysical surveys (Rebent 14, 17, 20, 2013 and Esstech) were compiled to obtain the deepest bathymetry of the marine landform map. Swath bathymetry data were mainly acquired on board the *R/V La Thalia* using the *Simrad EM 1000* and *EM 2040* multibeam systems, working at frequencies of 93-98 kHz and 200-400 kHz, respectively. The intermediate deep waters were surveyed by the launch *Haliotis*, equipped with an interferometric system Geoacoustics Geoswath, working at a frequency of 250 kHz. Data processing was performed using *Caraibes* subsea mapping software developed by IFREMER, which included the correction of attitude sensor data (roll, pitch, and heave), the application of sound velocity profiles and tide corrections, and the use of statistical and geometrical filters to remove any unorganised noise. Processed data were gridded in order to obtain diverse Digital Terrain Models with cell-size varying from 1 m to 50 m of resolution. The laser detection or LIDAR, acquired by plane, is provided by the SHOM and IGN (© Litto3D) using the French altimeter system IGN69 with a resolution of 1 m. These data were converted in LAT with ARCGIS (© ESRI) and Circee (© IGN) software. For the emerged part, data were obtained from the I.G.N (Institut Geographique National) with an elevation reference in NGF93. Surveys, LIDAR, and continental elevation grid data were merged using the FLEDERMAUS (© IVS) software to a resolution of 5 m. The identification and mapping of geometric features was carried out using ARCGIS software with a variety of resolution grids (1-5 m) in order to be able to the differentiate the features at different scales.

2.2 Backscattering imagery and Sedimentological analyses

The sidescan sonar signatures result from backscatter variation (imagery) that depends on the seabed material and it is macro-morphology (Augustin et al., 1996; Augustin & Lurton, 2005; Lamarche, Lurton, Verdier, & Augustin, 2011; Le Chenadec, Boucher, & Lurton, 2007; Lurton, 2003). Their identification relies on the interpretation of shades of grey and apparent textures in the mosaic. The ensuing geological interpretation of the area requires correlations between surficial sediment characteristics and the mosaic backscatter interpretation, and thus depends on ground-truth. Accordingly, 148 samples were analysed by the sieving method: sediments were passed through sieve columns of different sizes [Figure 1]. Fourteen sieves of square mesh were used in order to characterise the grain size repartition for the heterogeneous sediment (25,000 μm to 40 μm) [Figure 1]. The wet sieving method was used for the finest samples along with a *Coulter LS200* diffraction laser microgranulometer. Carbonate content was measured with a Bernard calcimeter using the volumetric calcimetric method. Both analyses allowed us to define 19 sediment types in the *Manche Code* classification adopted for English Channel sedimentological mapping (Larsonneur, Bouysse & Auffret, 1982).

[Figure 1 near here]

The final sedimentary map produced by the correlation between backscatter imagery facies and the dominant sediment type-class allowed us to establish a reference nomenclature for domains of the study area – such as external, internal, estuaries – to be applied to the whole bay [Figure 1 and 3].

3. Results and interpretation

The new morpho-sedimentological map highlights the partitioning of the estuary system study in three main areas [Figure 3]: (1) A western outer domain open to the ocean (Iroise Sea); (2) An intermediate domain comprising the *strait* and extending toward the bay until a virtual line joining the *Longue* and *Ronde* islands; and (3) An inner domain characterised by the benches, tidal flats, and coastal river mouths (Aulne, Elorn and Daoulas rivers).

3.1 Morphological description

The main morphological features are the presence of a well-marked channel network spread out along the seafloor and extended bench/tidal flat covering more than half of the surface of the bay and started on both sides of the channel.

[Figure 2 near here]

The channels extend from the coastal river mouths and incises the Palaeozoic basement of the bay. They correspond to fluvial paleo-valleys formed during successive Quaternary sea level lowstands (Hallégouët, 1994) and evolved as tidal inlets after the settling of the present-day high sea-level. In the vicinity of the river mouths, the thalwegs of the paleo-valleys are narrow (500 meters) and are V-shaped with a depth ranging from 20 to 25 meters below sea-level (b.s.l.)[Figure 2]. The channel geometries evolved in relation with the bedrock geology and differ between the two channel systems related to the two rivers Aulne and Elorn. For this last one, the relatively straight channel, oriented from the NE to the SW, is clearly controlled by the regional Elorn fault system, while the NW trending Aulne estuary meanders further thanks to the sedimentary basement. The channels appear discontinuous at several places with the individualisation of 'blind' tidal channels. The origin of this discontinuity seems more linked to the structural control of the fluvial paleo-valleys rather than process of dichotomy of tidal channels as described for estuaries (Robinson, 1960). Along the meanders, the channels widen (1500 meters) and paleo-terraces are visible on both sides with depth of 20 m b.s.l to the south rim and 15 m b.s.l. to the north. Both channels converge at the centre of the bay to form a main paleo-valley connected to the deep strait extending to the external domain. Here, the U-shape channel tightens and is bounded by abrupt cliffs [Figure 2]. At the *goulet* end, the thalweg shows a large 750 m wide flat bottom and preserves its abrupt rim to the North. In the central part of the external area the vein widens and becomes shallowest before tightening in the most downstream portion of the system [Figure 2].

Sedimentary bedforms are mostly established in the external and intermediate domains. Long NE-SW trending tidal sand ridges are located at each termination of the strait and along the main channel of the central part of the bay. Most of them appear linked to the presence of residual current eddies generated by the tidal flow upon entry in the bay and are therefore considered to be representative of banner sand ridges (Davis & Balson, 1992, Dyer & Huntley, 1999, Neill & Scourse, 2009).

The most significant of them is the *Cormorandière* ridge (length: 1.8 km, width: 0.8 km, height: 3 m) extending to the east of the *Espagnols* headland and occurring along the western rim of a channel segment. In the external domain there is a banner bank found in the *Capucine* headland from the NE to SW, while dunes and megaripple fields have been identified in the paleo-valley. Rippled scour depressions (RSD) that are "channel-like depressions of low, negative relief […], containing large sand ripples" (Cacchione, Drake, Grant, & Tate, 1984) are observed on the shelf surrounding the channel at depths between 20 and 10 meters (b.s.l). Off the bay of Bertheaume, the RSDs are formed from bedrock outcrop and they extend about 4,500 meters towards the NNE. They are characterised by an alternation of negative relief furrows, containing symmetric and regular ripples following the same orientation, and positive relief bands of a similar width. In the south, RSDs cover the main part of the Bay of Camaret and form a large depression filled by symmetric and regular ripples oriented towards the SSE. A megaripple field occurs in the central part of the external domain where the thalweg is the widest and presents many types of features characterised by different wave length, symmetry, and orientation. Dunes cover the north rim of the thalweg at the exit of the *goulet* and are oriented towards the NE.

3.2 Sedimentological description

To complete the morphological analysis, the sedimentological map is divided into three main areas corresponding to the geomorphologic domains.

[Figure 3 near here]

The external domain is characterised by contrasting sediments between the north and south side of the main channel. The northern part is defined by a shelf where the RSDs formed by gravelly coarse sand are inserted in an alternation of shelly sandy stripes ranging from coarse gravelly sand to fine sand [Figure 3]. The channel limit on the south side is defined by the last strip of medium sand, while the megarippled field is constituted by fine sand and the dunes by shelly gravelly coarse sand. Beyond this limit the sedimentary repartition is more heterogeneous. The south area is composed of coarse lithoclastic sediment (gravelly sand to pebble) occasionally mixed with a finer matrix, as in the example of the slight depression (40 meters) in the western part where coarse grains are associated with at least 5% mud [Figure 3]. The intermediate domain and the *goulet* collects the coarser sediments, most of 30% is composed of outcrops surrounded by pebbles stemming from the erosion of the nearby sedimentary rocks or gelivation (schist plaques). Some places are coated by a thin cover of shelly gravelly coarse sand [Figure 3]. In the central part of the Bay of Brest, deposits from the central outcrops become finer until the *Ronde Island*. However the *Cormorandière* bank cover is locally formed by shelly sandy gravel and has disrupted the grain size sorting [Figure 3].

A muddy fraction characterises the estuarine domain; all the benches and tidal flats are covered by mixed sediments containing a more and less concentrated matrix of mud [Figure 3]. Two main types of sediment characterised by the mud content are observable: the muddy sediments that contain a minimum 25% mud (blue in the map) and sediments that contain between 5 and 25%

mud (green in the map). The concentration increases around estuaries mainly in the Elorn and Daoulas river mouths. In this study this difference is assumed to be induced by the presence of macrobenthic communities composed mainly of shells (Crepidula) and maërl, whose development has provided the coarse fraction of the sediment (Grall & Hall-Spencer, 2003; Hinschberger, Guilcher, Pruleau, Moign & Moign, 1968) [Figure 3].

3.3 Sediment dynamics interpretation

The estuarine internal domain is characterised by shallow benches and tidal flats that are covered by mud inputs principally fed by the Aulne River (Bassoulet, 1979; Beudin, 2014). The marine fauna and flora species development indicates that the turbidity is relatively low and that currents are moderate (Grall & Hily, 2002). Thus, this estuarine domain has a sedimentary partitioning mainly controlled by the continental fluvial inputs that are weakly reworked after the sediment deposits. In the intermediate domain, the many outcrops reflect the strong intensity of tidal currents preventing the sedimentary deposits. The tidal sand ridges located in the centre of the main channel seem to be an indication of confrontation between ebb and flux currents, and decreasing grain size sorting deposits in the central part of the bay reveal the reduction in tidal current speed. In the outer domain the dune and megaripple fields, characterised by a gravelly shelly sand, reflect the impact of the tidal currents. The presence of rippled scour depressions, including symmetric megaripples, suggests that sedimentation in the outer area is more affected by the swells oriented principally in the same direction as these structures (Auffret, Augris, Cabioch, & Koch, 1992; Mazières et al., 2015). Finally, the patch of muddy sediment in the western part is interpreted as a "sink" depositional area where the continental muddy sediments sourced from the Bay of Brest may be deposited and this deepest portion of the basin should have been spared the effect of swell except in case of exceptional storms.

Conclusion

The refined high-resolution morpho-sedimentological map of the Bay of Brest combining sediment sampling, bathymetry, and backscatter imagery allows us to provide a new accurate mapping of the sedimentary partitioning in accordance with seabed morphology analysis. It highlights the detailed facies distribution and morphology patterns useful for understanding the estuary processes and aids characterisation of the hydrodynamic conditions occurring in the open sea and confined domains. It appears that the Bay of Brest *s.s*, should be categorised as confined estuary controlled by tidal currents in the deep water areas, which preserve the inherited shape and terraces associated with paleo-valley activity during successive sea-level lowstands, and by the fluvial inputs in the most remote shallowest area. The external domain is controlled both by tidal currents with the main stream canalized in the paleo-valley and by the Atlantic swell affecting the large exposed shelves where the depth is less profound. The resulted map illustrates the main hydrodynamic processes which impact the sediment distribution at the land-sea transition.

Several studies have already used the methods presented in this paper to understand the dynamics processes impact in the geomorphology and sedimentary partitioning in a tide dominated estuaries (Barnard, Erikson, Rubin, Dartnell & Kvitek, 2012; Barnard, Erikson, Elias & Dartnell, 2012; Garcia-Gíl, Durán & Vilas, 2000; Shaw, Todd & Li, 2014). This new study will allow detailed comparison of scale facies distribution with other confined estuaries. Further modelling will allow the quantification of these processes and estimation of their relative contribution to the finer-grain sedimentation in the well-constrained geomorphology of an original estuary system.

Software

ESRI ArcMap 10.2 software was used for digitising backscatter variation and sediment type-class. Fledermaus and Circee© were used to create the bathymetric map. Map layout and final editing was performed using Adobe Illustrator CS5.

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Figures

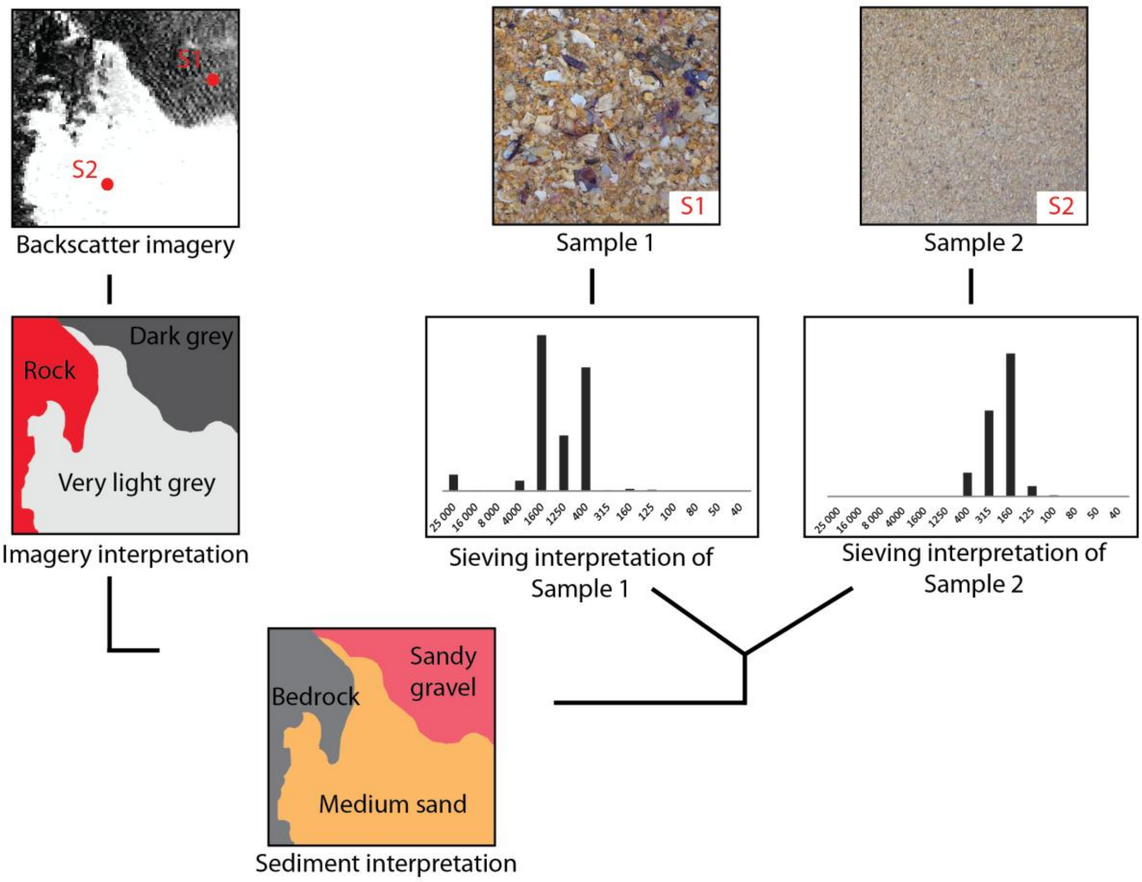

Figure 1 : Methods for the creation of the sedimentological map of the Bay of Brest: In the left top corner the side scan sonar (1:5,000) analysis allowed us to define the backscatter variations (grey nuances); in the right top, sample analysis by the sieving method is translated into a histogram for each sieve and shows the final sedimentary interpretation.

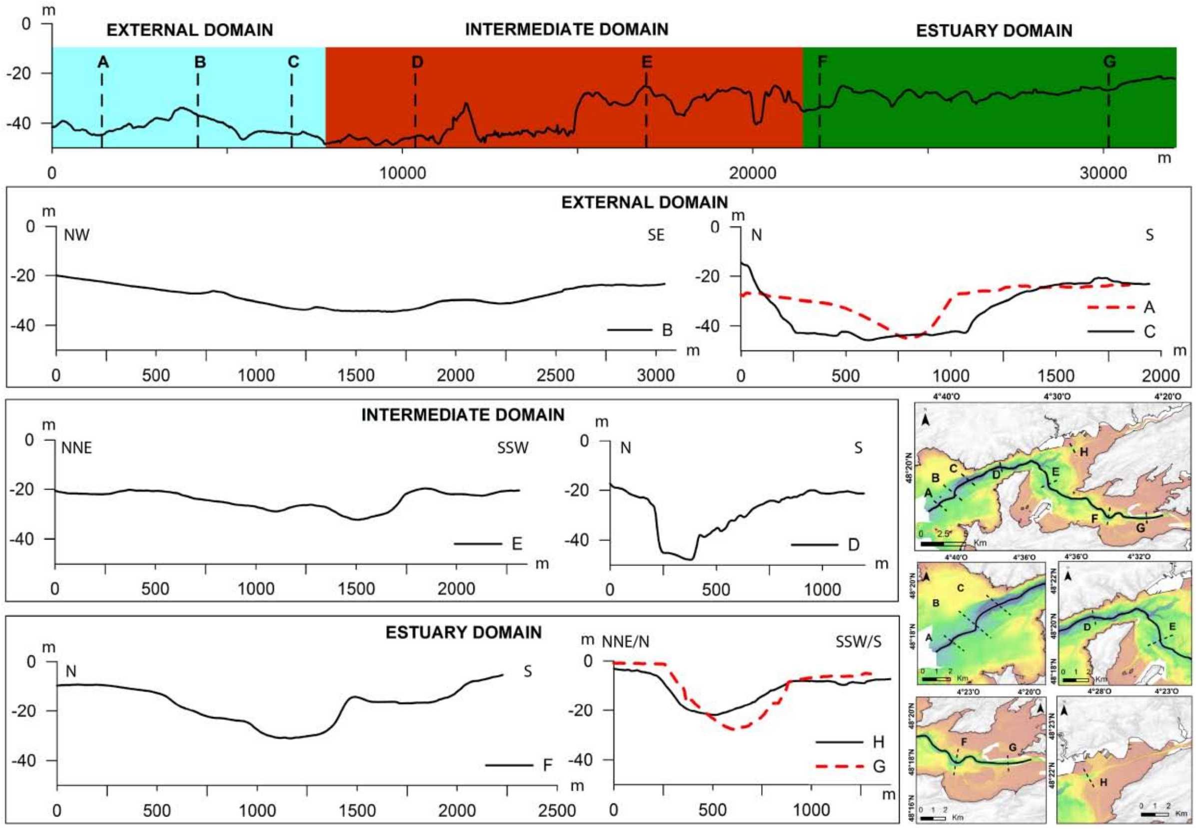

Figure 2: Shape of the paleo-footprints and their localisation on the maps on the right lower corner (scale of 1:90,000 and 1:30,000). On the top this is the profile that follows the channel from the Iroise Sea to the Aulne estuary divided in three main domains: external (blue), (intermediate (red), estuary (green); shapes of each domain are illustrated.

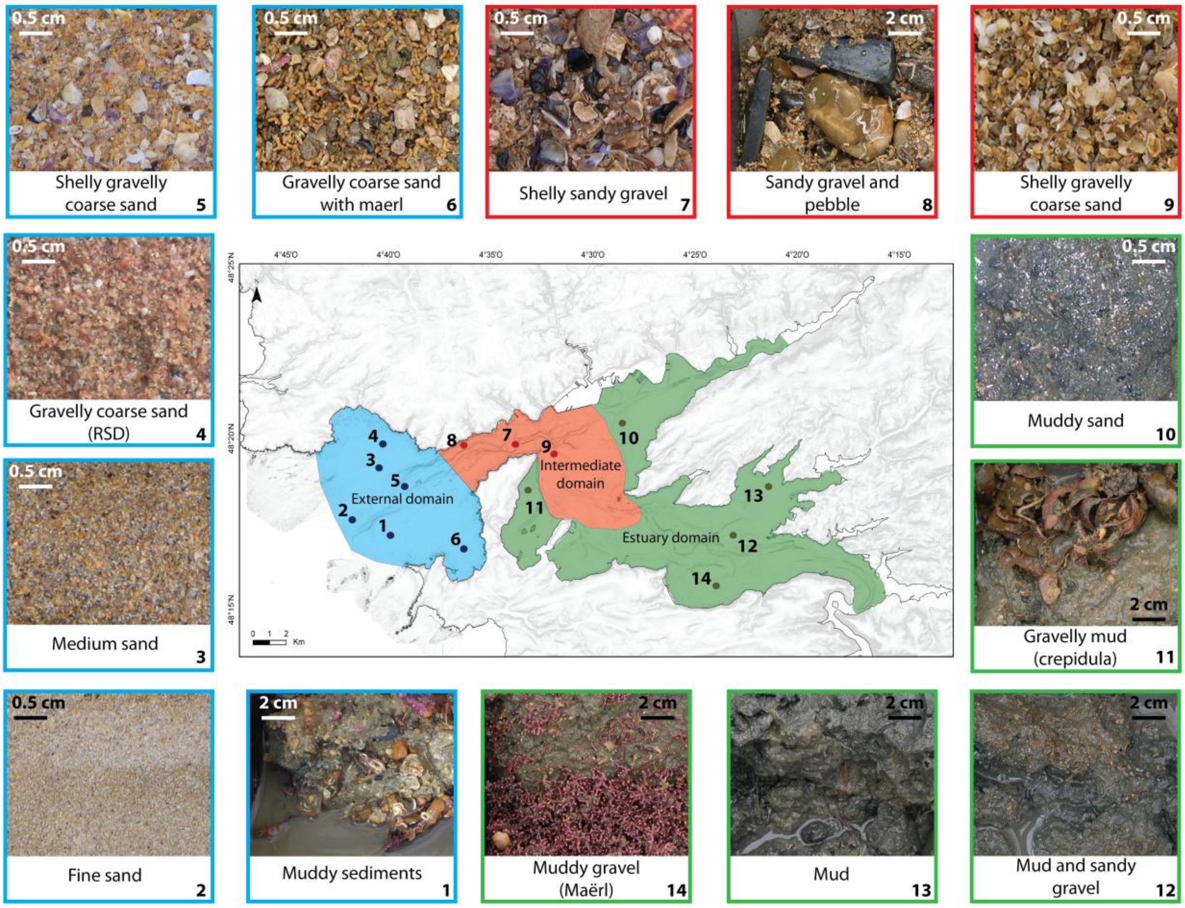

Figure 3 : The location of three main domains of the study area and facies samples; the external domain (in blue) is characterised by sand (fine to gravelly) and shelly sand, the gravelly coarse sediment located in the RSD (Ripple Scour Depression) is observable for the north and south; the intermediate domain (in red) by shelly sandy gravel and pebbles; the external domain (in green) defined by mud mixed in different proportions with other calcareous sediments like crepidula of maërl.

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