JOURNAL OF MAPS, 2016
VOL. 12, NO. 5, 1152–1159
http://dx.doi.org/10.1080/17445647.2016.1139514

Taylor & Francis
Taylor & Francis Group

SCIENCE

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

Gwendoline Gregoire[a,b], Axel Ehrhold[b], Pascal Le Roy[a], Gwenael Jouet[b] and Thierry Garlan[c]

[a]Institut Universitaire Européen de la Mer, Plouzané, France; [b]IFREMER, Géosciences Marines, Centre de Brest, Plouzané, France; [c]SHOM, Centre Hydrographique, Brest, France

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.

ARTICLE HISTORY
Received 6 October 2015
Revised 4 January 2016
Accepted 5 January 2016

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 (Dalrymple, Knight, Zaitlin, & Middleton, 1990; Dalrymple, Mackay, Ichaso, & Choi, 2012; Dalrymple & Zaitlin, 1994; Davis & Hayes, 1984; Ryan et al., 2007; Tessier, Delsinne, & Sorrel, 2010). At the estuary entrance, the accelerated tidal 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 scour 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 be deposited in sheltered areas. Nevertheless, not much is known about the detailed facies and the patterns of morphological change controlling the balance between erosion and sedimentation. This knowledge is essential for understanding sedimentary exchanges between continental and marine domains and is of utmost importance in deciphering human influence from natural controls. The Bay of Brest offers 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 km^2) 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 60 m below sea-level) where tidal currents are subjected to the venturi effect and reach speeds up to 9 m/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 a third of the mean water volume of the bay (Fichaut, 1984). The strait also marks the transition between (1) the oceanward extent 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

CONTACT Gwendoline Gregoire gwendoline.gregoire@ifremer.fr

and Elorn) with a total annual load of about 1×10^4 T, and marine sources due to the tidal 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 work 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 and based on the 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 backscatter imagery based on interferometric 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 (Main Map).

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 *Simrad EM 1000* and *EM 2040* multibeam systems, working at frequencies of 93–98 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 to 50 m of resolution. The 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 to LAT using Esri ArcGIS and Circee (© IGN) software. For emergant terrain, data were obtained from the IGN (Institut Geographique National) with the NGF93 datum. Surveys, LIDAR, and continental elevation grid data were merged using FLEDERMAUS (© IVS) software to a resolution of 5 m. The identification and mapping of geometric features were carried out using ArcGIS with a variety of resolution grids (1–5 m) in order to be able to the differentiate features at different scales.

2.2. Backscattering imagery and sedimentological analyses

The side-scan sonar signatures result from backscatter variation (imagery) that depends on the seabed material and its macro-morphology (Augustin & Lurton, 2005; Augustin et al., 1996; 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 using 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 (25,000–40 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 using the *Manche Code* classification adopted for English Channel sedimentological mapping (Larsonneur, Bouysse, & Auffret, 1982).

The final sedimentary map produced from 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, 3 and Main Map).

3. Results and interpretation

The new morpho-sedimentological map highlights the partitioning of the estuary system in to 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 towards the bay up to a virtual line joining the *Longue* and *Ronde* islands; and (3) An inner domain characterised by

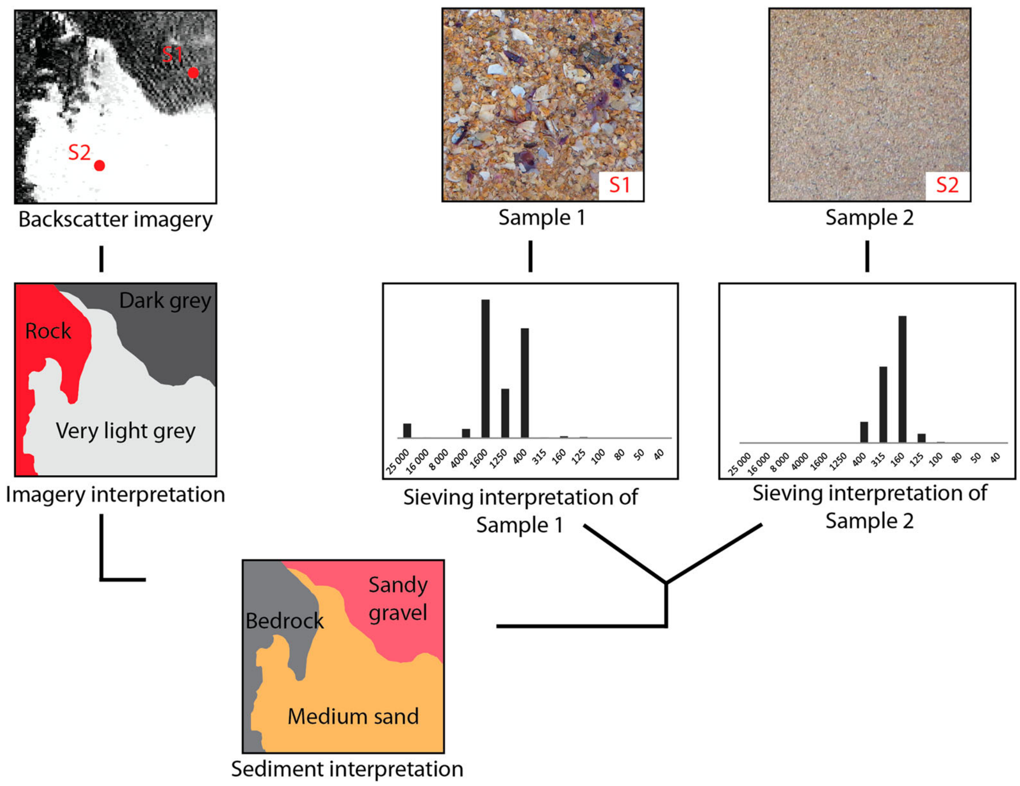

Figure 1. Methods for the creation of the sedimentological map of the Bay of Brest: in the left top corner the side-scan sonar (1:5000) analysis allowed us to define the backscatter variations (grey nuances); in the right top, sample analysis by the sieving method is translated into a histogram for each sieve and shows the final sedimentary interpretation.

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 on both sides of the channel.

The channels extend from the coastal river mouths and incise 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 m) and are V-shaped with a depth ranging from 20 to 25 m below sea-level (b.s.l.) (Figure 2). The channel geometries evolved in relation to the bedrock geology and differ between the two channel systems related to the rivers Aulne and Elorn. For the latter, 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 as a result of the sedimentary basement. The channels appear discontinuous in several places with the creation of 'blind' tidal channels. The origin of these discontinuities appear linked to structural control of the fluvial paleo-valleys rather than process of dichotomy of tidal channels found in estuaries (Robinson, 1960). Along the meanders, the channels widen (1500 m) and paleo-terraces are visible on both sides with depths 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 the main paleo-valley connected to the deep strait extending to the external domain. Here, the U-shape channel narrows 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 shallower before narrowing 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 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 bedform 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

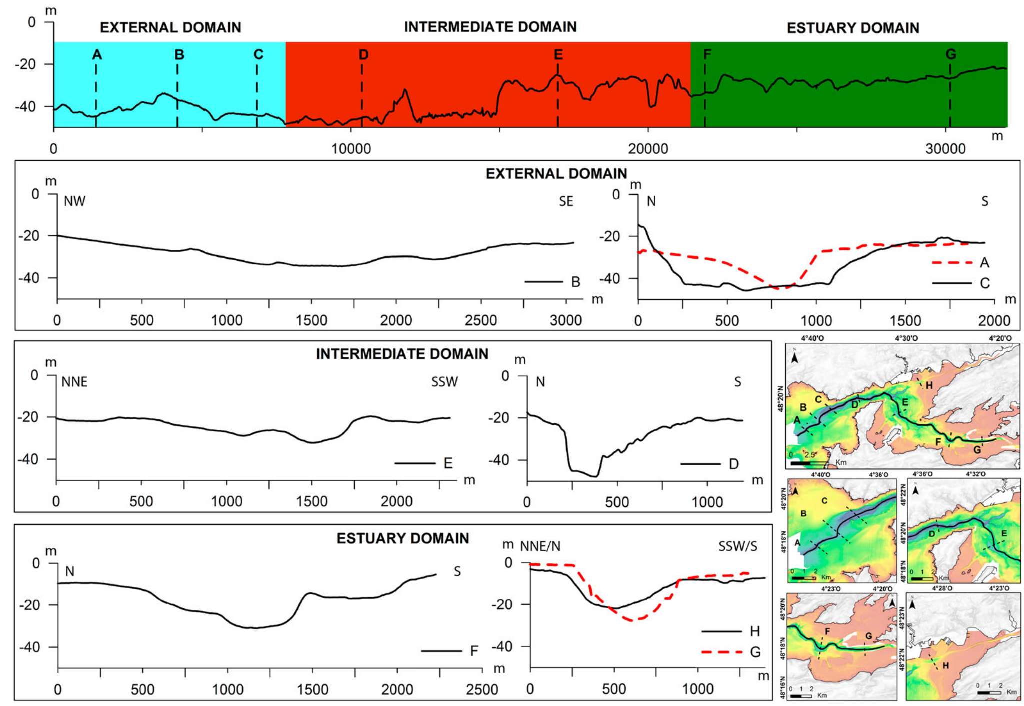

Figure 2. Shape of the paleo-footprints and their location on the maps on the right lower corner (scale of 1:90,000 and 1:30,000). On the top this is the profile that follows the channel from the Iroise Sea to the Aulne estuary divided in three main domains: external (blue), intermediate (red), estuary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

(Main Map). 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

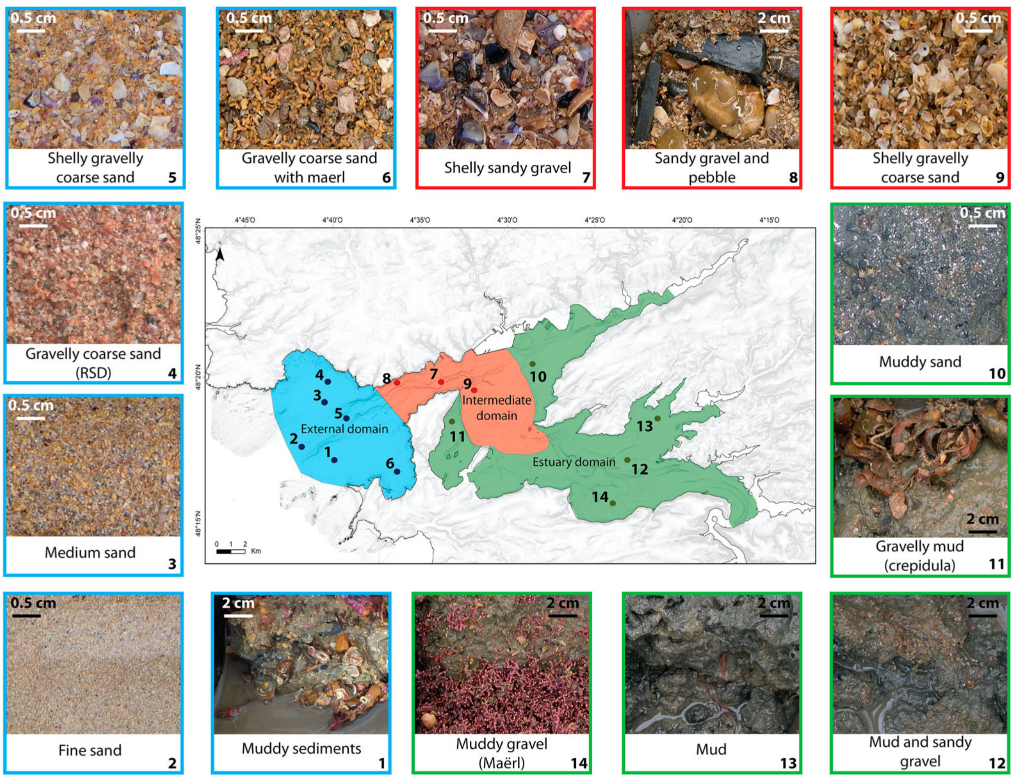

Figure 3. The location of the three main domains of the study area and facies samples; the external domains (in blue) are characterised by sand (fine to gravelly) and shelly sand, the gravelly coarse sediment located in the RSD (Ripple Scour Depression) is observable for the north and south; the intermediate 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.

ripples' (Cacchione, Drake, Grant, & Tate, 1984) are observed on the shelf surrounding the channel at depths between 20 and 10 m (b.s.l). Off the bay of Bertheaume, the RSDs are formed from bedrock outcrop and extend about 4500 m towards the North-North-East. 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 South-South-East. 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.

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 m) in the western part where coarse grains are associated with at least 5% mud (Figure 3). The intermediate domain and the *goulet* collect 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 *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 at least 25% mud (blue on the Main Map) and sediments that contain between 5% and 25% mud (green on the Main 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 et al., 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 deposition. In the intermediate domain, the many outcrops reflect the strong intensity of tidal currents preventing the sedimentary deposition. The tidal sand ridges located in the centre of the main channel seem to be indicative 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 tidal currents. The presence of RSD, 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 continental muddy sediments sourced from the Bay of Brest may be deposited and this deepest portion of the basin should have limited effect from the swell during exceptional storms.

4. Conclusion

The refined high-resolution morpho-sedimentological map of the Bay of Brest combining sediment sampling, bathymetry, and backscatter imagery allows us to provide 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 estuarine 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 deep water areas, which preserve the inherited shape and terraces associated with paleo-valley activity during successive sea-level lowstands, and by fluvial inputs in the most remote shallowest area. The external domain is controlled both by tidal currents with the main stream canalised in the paleo-valley and by the Atlantic swell affecting the large exposed shelves which are shallower. The resultant map illustrates the main hydrodynamic processes which impact sediment distribution at the land–sea transition. Several studies have already used the methods presented in this paper to understand how the dynamic processes impact on the geomorphology and sedimentary partitioning in tide-dominated estuaries (Barnard, Erikson, Elias, et al., 2012; Barnard, Erikson, Rubin, Dartnell, & Kvitek, 2012; Garcia-Gíl, Durán, & Vilas, 2000; Shaw et al., 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 finer-grain sedimentation in the well-constrained geomorphology of an original estuary system.

Software

Esri ArcMap 10.2 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.

Acknowledgements

We would like to thank IFREMER, in particular the organiser of the Rebent program and the University of Western Brittany (UBO), for collecting data. We would like to thank SHOM and IGN for providing the LIDAR data (litto3D©). We would also like to thank the boarding staff and technicians. The authors are very grateful to Chris Orton, to Luisa Sabato, to Thomas S.N. Oliver and the associate editor Wayne Stephenson for their careful examination of previous versions of this paper and for their helpful comments.

Disclosure statement

This work was supported by the Laboratoire d'Excellence, LabexMer [ANR-10-LABX-19-01], and by a grant from the Regional Council of Brittany.

Funding

The authors acknowledge financial support by Labex Mer and the Britanny Region.

ORCID

Gwendoline Gregoire http://orcid.org/0000-0003-3369-8639

References

Auffret, G. A. (1983). *Dynamique sédimentaire de la marge continentale celtique-Evolution Cénozoïque-Spécificité du Pleistocène supérieur et de l'Holocène* (Doctoral dissertation), Université de Bordeaux I, Bordeaux.

Auffret, J. P., Augris, C., Cabioch, L., & Koch, P. (1992). Sillons graveleux aux abords de la Baie de Morlaix [Furrows gravel near the Bay of Morlaix]. *Annates de la Societe Geologique du Nord*, *1*, 143–147. Retrieved from https://scholar.google.fr/scholar?q = auffret + 1992 + augris&btnG=&hl = fr&as_sdt = 0%2C5

Augustin, J. M., Le Suave, R., Lurton, X., Voisset, M., Dugelay, S., & Satra, C. (1996). Contribution of the multibeam acoustic imagery to the exploration of the sea-bottom. *Marine Geophysical Researches*, *18*(2–4), 459–486. doi:10.1007/BF00286090

Augustin, J. M., & Lurton, X. (2005). Image amplitude calibration and processing for seafloor mapping sonars. *Oceans 2005-Europe, IEEE*, *1*, 698–701. doi:10.1109/OCEANSE.2005.1511799

Babin, C., Didier, J., Moign, A., Plusquellec, Y. (1969). Goulet et rade de Brest : Essai de géologie sous-marine [Goulet and bay of Brest : Submarine geology test]. *Revue de géographie physique et de geologie dynamique*, *XI*(2), 55–63. Retrieved from http://etudes.bretagne-environnement.org/index.php?lvl = notice_display&id = 15957

Ballèvre, M., Bosse, V., Ducassou, C., & Pitra, P. (2009). Palaeozoic history of the Armorican Massif: Models for the tectonic evolution of the suture zones. *Comptes Rendus Geoscience*, *341*(2), 174–201. doi:10.1016/j.crte.2008.11.009

Ballèvre, M., Catalán, J. R. M., López-Carmona, A., Pitra, P., Abati, J., Fernández, R. D., & Martínez, S. S. (2014). Correlation of the nappe stack in the Ibero-Armorican arc across the Bay of Biscay: A joint French–Spanish project. *Geological Society, London, Special Publications*, *405*(1), 77–113. doi:10.1144/SP405.13

Barnard, P. L., Erikson, L. H., Elias, E. P. L., & Dartnell, P. (2012). Sediment transport patterns in the San Fransisco Bay coastal system from cross-validation of bedform asymmetry and modelled residual flux. *Marine Geology*, *345*, 72–95. doi:10.1016/j.margeo.2012.10.011

Barnard, P. L., Erikson, L. H., Rubin, D., Dartnell, P., & Kvitek, R. G. (2012). Analyzing bedforms mapped using multibeam sonar to determine regional bedload sediment transport patterns in the San Francisco Bay coastal system. Sedimentology. In M. Z. Li, C. R. Sherwood, & P. R. Hill (Eds.), *Sediments, morphology and sedimentary processes on continental shelves: Advances in technologies, research and application* (pp. 273–294). Special Publication of the International Association of Sedimentologists (IAS), 44 Retrieved from: http://eu.wiley.com/WileyCDA/WileyTitle/productCd-144435082X.html.

Bassoulet, P. (1979). *Etude de la dynamique des sédiments en suspension dans l'estuaire de l'Aulne: Rade de Brest* (Doctoral dissertation). Université de Bretagne occidentale, Brest.

Beudin, A. (2014). *Dynamique et échanges sédimentaires en rade de Brest impactés par l'invasion de crépidules* (Doctoral dissertation). Université de Bretagne Occidentale, Brest.

Cacchione, D. A., Drake, D. E., Grant, W. D., & Tate, G. B. (1984). Rippled scour depressions on the inner continental shelf off central California. *Journal of Sedimentary Research*, *54*(4), 1280–1291. Retrieved from http://

archives.datapages.com/data/sepm/journals/v51–54/data/054/054004/1280.htm
Dalrymple, R. W., Knight, R., Zaitlin, B. A., & Middleton, G. V. (1990). Dynamics and facies model of a macrotidal sand-bar complex, Cobequid Bay-Salmon River Estuary (Bay of Fundy). *Sedimentology*, *37*(4), 577–612. doi:10.1111/j.1365-3091.1990.tb00624.x
Dalrymple, R. W., Mackay, D. A., Ichaso, A. A., & Choi, K. S. (2012). Processes, morphodynamics, and facies of tide-dominated estuaries. In R. A. Davis, R. W. Dalrymple, & W. Robert (Eds.), *Principles of tidal sedimentology* (pp. 79–107). Springer. Retrieved from: http://www.springer.com/gb/book/9789400701229.
Dalrymple, R. W., & Zaitlin, B. A. (1994). High-resolution sequence stratigraphy of a complex, incised valley succession, Cobequid Bay—Salmon River estuary, Bay of Fundy, Canada. *Sedimentology*, *41*(6), 1069–1091. doi:10.1111/j.1365-3091.1994.tb01442.x
Dalrymple, R. W., Zaitlin, B. A., & Boyd, R. (1992). Estuarine facies models: conceptual basis and stratigraphic implications: Perspective. *Journal of Sedimentary Research*, *62*(6), 1130–1146. Retrieved from http://archives.datapages.com/data/sepm/journals/v59-62/data/062/062006/1130.htm
Davis, R. A., & Balson, P. S. (1992). Stratigraphy of a North Sea tidal sand ridge. *Journal of Sedimentary Research*, *62*(1), 116–121. Retrieved from http://archives.datapages.com/data/sepm/journals/v59-62/data/062/062001/0116.htm
Davis, R. A., & Hayes, M. O. (1984). What is a wave-dominated coast? *Marine Geology*, *60*(1), 313–329. doi: 10.1016/0025-3227(84)90155-5
Dyer, K. R., & Huntley, D. A. (1999). The origin, classification and modelling of sand banks and ridges. *Continental Shelf Research*, *19*(10), 1285–1330. doi:10.1016/S0278-4343(99)00028-X
Ehrhold, A., Hamon, D., & Guillaumont, B. (2006). The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore macrobenthic habitats: Application to the Bay of Concarneau (South Brittany, France). *ICES Journal of Marine Science: Journal du Conseil*, *63*(9), 1604–1615. doi:10.1016/j.icesjms.2006.06.010
Fichaut, B. (1984). *Réactualisation de la sédimentologie de la rade de Brest* (Doctoral dissertation). Université de Bretagne Occidentale, Brest.
Garcia-Gíl, S., Durán, R., & Vilas, F. (2000). Side scan sonar image and geologic interpretation of the Ria de Pontevedra seafloor (Galicia, NW, Spain). *Scientia Marina*, *64*(4), 393–402. doi:10.3989/scimar.2000.64n4393
Garlan, T. (2012). Deux siècles de cartographie des sédiments marins [Two centuries of marine sediments cartography]. *Revue Le monde des cartes, Bulletin*, *210*, 2011–2012. Retrieved from http://cat.inist.fr/?aModele = afficheN&cpsidt = 25935938
Garreau, J. (1980). Structure et relief de la région de Brest [Structure and relief of the Brest area]. *Norois*, *108*(1), 541–548. Retrieved from http://www.persee.fr/doc/noroi_0029-182x_1980_num_108_1_3925
Grall, J., & Hall-Spencer, J. M. (2003). Problems facing maerl conservation in Brittany. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *13*(S1), 55–64. doi:10.1002/aqc.568
Grall, J., & Hily, C. (2002). Evaluation de la santé des bancs de maerl de la pointe de Bretagne (*Rapport Direction Régional des Espaces Naturels de Bretagne*). DIREN.
Guérin, L. (2004). *La crépidule en rade de Brest: un modèle biologique d'espèce introduite proliférante en réponse aux fluctuations de l'environnement* (Doctoral dissertation). Université de Bretagne occidentale, Brest.
Guilcher, A., & Pruleau, M. (1962). Morphologie et sédimentologie sous-marines de la partie orientale de la rade de Brest [Morphology and sedimentology submarine of the eastern part of the Bay of Brest]. *Com. Trav. Hist. Sci., Bull. Sect. Géograph., Géographie de la Mer*, *75*, 81–116.
Hallégouët, B. (1994). Formation de la rade de Brest. In J. P. Corlaix (Ed.), *Atlas permanent du littoral* (p. 22). Editmar.
Hallégouët, B., Moign, A., Lambert, M. L. (1979). Carte géomorphologique détaillé de la France 1:50 000 IV-17, Brest [Detailed geomorphological map of France 1:50 000 IV-17, Brest]. Retrieved from http://bgi-prodig.inist.fr/notice/12718589
Hinschberger, F., Guilcher, A., Pruleau, M., Moign, A., & Moign, Y. (1968). Carte sédimentologique sous-marine des côtes de France [Submarine sedimentary cartography of the coast of France]. *Feuille de Brest. Echelle*, *1*, 100000. Retrieved from http://www.persee.fr/doc/noroi_0029-182182x_1970_num_66_1_1709_t1_0275_0000_1
Lamarche, G., Lurton, X., Verdier, A. L., & Augustin, J. M. (2011). Quantitative characterisation of seafloor substrate and bedforms using advanced processing of multibeam backscatter – Application to Cook Strait, New Zealand. *Continental Shelf Research*, *31*(2), 93–109. doi: 10.1016/j.csr.2010.06.001
Larsonneur, C., Bouysse, P., & Auffret, J. P. (1982). The superficial sediments of the English Channel and its western approaches. *Sedimentology*, *29*(6), 851–864. doi:10.1111/j.1365-3091.1982.tb00088.x
Le Chenadec, G. L., Boucher, J. M., & Lurton, X. (2007). Angular dependence of-distributed sonar data. *Geoscience and Remote Sensing, IEEE Transactions on*, *45*(5), 1224–1235. doi:10.1109/TGRS.2006.888454
Lurton, X. (2003). Theoretical modelling of acoustical measurement accuracy for swath bathymetric sonars. *The International Hydrographic Review*, *4*(2), 17–30. Retrieved from http://cat.inist.fr/?aModele = afficheN&cpsidt = 15204452
Mazières, A., Gillet, H., Idier, D., Mulder, T., Garlan, T., Mallet, C., & Hanquiez, V. (2015). Dynamics of inner-shelf, multi-scale bedforms off the south Aquitaine coast over three decades (Southeast Bay of Biscay, France). *Continental Shelf Research*, *92*, 23–36. doi: 10.1016/j.csr.2014.11.002
Moign, Y. (1967). *Contribution à l'Etude Sédimentologique de la Rade et du Goulet de Brest* (Doctoral dissertation). Ecole pratique des hautes études, Dinard.
Neill, S. P., & Scourse, J. D. (2009). The formation of headland/island sandbanks. *Continental Shelf Research*, *29*(18), 2167–2177. doi:10.1016/j.csr.2009.08.008
Robinson, A. H. W. (1960). Ebb-flood channel systems in sandy bays and estuaries. *Geography*, 183–199. Retrieved from http://www.jstor.org/stable/40565158
Ryan, D. A., Brooke, B. P., Bostock, H. C., Radke, L. C., Siwabessy, P. J., Margvelashvili, N., & Skene, D. (2007). Bedload sediment transport dynamics in a macrotidal embayment, and implications for export to the southern Great Barrier Reef shelf. *Marine Geology*, *240*(1), 197–215. doi:10.1016/j.margeo.2007.02.014
Service Hydrographique et Océanographique de la Marine, SHOM. (1994). *Atlas des courants de marée* : Courants

de marée de la côte Ouest de Bretagne [Tidal currents of the west Britain coast] (vol. 560).

Shaw, J., Todd, B. J., & Li, M. Z. (2014). Geologic insights from multibeam bathymetry and seascape maps of the Bay of Fundy, Canada. *Continental Shelf Research*, *83*, 53–63. doi:10.1016/j.csr.2013.12.015

Tessier, B., Delsinne, N., & Sorrel, P. (2010). Holocene sedimentary infilling of a tide-dominated estuarine mouth. The example of the macrotidal Seine estuary (NW France). *Bulletin de la Societe Geologique de France*, *181*(2), 87–98. doi:10.2113/gssgfbull.181.2.87