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Morpho-sedimentological and dynamic patterns in a ria type estuary: the Belon estuary (South Brittany, France)

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ABSTRACT

Ria-type estuaries correspond to complex systems at the transition between the continental and the marine domains, within a context of rocky coastlines. The Belon Estuary, in South Brittanny (France), is described as a typical ria-type estuary characterised by complex morpho-sedimentological facies, strongly influenced by the South Brittany's geological framework. The characterisation of the morpho-sedimentological patterns is sourced from recent multi-data acquisition with acoustic remote sensors coupled to ground truth data. The Main Map synthesises the main results of this study concerning the hydro-morphological and sedimentological characterisation of the Belon estuary. This study adds up to former studies over ria-type estuaries and lay out the base for future studies on the hydrodynamic of complex rias, as the Belon estuary.

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1. Introduction

Regarding the different definitions of ria-type estuaries (Evans & Prego, 2003; Perillo, 1995b, 1995a; Von Richthofen, 1901), the one proposed by Castaing and Guilcher (1995) is the most accurate: 'an incised valley formed by sea flooding of Pleistocene-Holocene river valleys […] developed in medium-high relief coast' with a strong control of the geological and tectonic frameworks. Classified as 'sandy rias' (Castaing & Guilcher, 1995), estuaries such the Belon are characterised by a low mud content, generally lower than 2% in the subtidal zone, and the predominance of sands while the coarse material is usually related to a marine origin, with a carbonate content ranging from 10 to 80%. Rias have been described worldwide (e.g. Spain, Korea, Great-Britain, China and France) (Castaing & Guilcher, 1995). Rias along the coastline of the Iberian Peninsula have been vastly documented in terms of morphology (e.g. Martínez-Carreño et al., 2017), sedimentology (Arnaud-Fassetta et al., 2006; Rubio et al., 2001) and hydrodynamics (Bernabeu et al., 2012; Vilas et al., 2005). However, the rias in South Brittany (France) have been poorly documented in terms of geomorphology and slightly documented in terms of sedimentology (Castaing & Guilcher, 1995). Indeed, most detailed sedimentological studies on the South Brittany rias are sedimentological descriptions associated with benthic ecological habitats studies (Blanchet et al., 2014; O. Fossi Tankoua et al., 2012; Olivia Fossi Tankoua et al., 2011).

The Belon estuary, in South Brittany, is located in the Bay of Biscay, between Bay of Concarneau and Bay of Lorient (Main map, location map). Its history is related to the geological evolution of the South Armorican domain during both Cadomian and Hercynian orogeneses (Gumiaux et al., 2004). The Belon estuary is incised in a metamorphic substratum (Béchennec et al., 1997), composed of three highly competent (Bucher & Grapes, 2011) orthogneiss formations (Béchennec et al., 1996). The first one, the Lanmeur-Saint-Ouraneau orthogneiss, with an age of 498 ± 12 Ma, is derived from a peraluminous granitoid. The second one is the Moëlan orthogneiss with an age of 485 ± 6 Ma also derived from peraluminous granitoid. The last orthogneiss described in the Belon estuary (Béchennec et al., 1996) is the Porz-Manech orthogneiss with an age of 592 ± 10 Ma and is derived from adamellites. Béchennec et al. (1996) also described the Nerly group and Kerfany formation, both composed of micaschists and a foliated (N100–N110) and altered, fine-grained leucocratic and ribboned gneiss. All geological units described are outcropping (Béchennec et al., 1997), especially in the most downstream part by constituting, on both riverside of the Belon, tens of metres high cliffs. These formations are affected by a regional system of strike-slip fault associated with a primary Hercynian event and a relay system of normal fault shaped since Eocene until

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late Oligocene (Béchennec et al., 1996, 1997). Therefore, the distribution of the main geological units and the location of the major tectonic elements strongly influenced the incision of the Belon valley since Pliocene (Béchennec et al., 1996; Pinot, 1974). Moreover, the meanders and the connection of three main inlets to the main estuary: the Keristinec inlet (Jegou, 1974), the Pen-mor inlet and the Lanriot inlet (both last within the study area, cf. Main map, bathymetric map) is always located, either within erodible formations (Nerly and Kerfany groups) or above major tectonic structures. The Gorgen Cove (Main map, bathymetric and geological map) is incised within a erodible Nerly group enclave (Béchennec et al., 1997) and corresponds to the widest section of the estuary, with approximately 450 m width (Jegou, 1974). In terms of hydrodynamics, Belon river flow rate varies between 0.40 and 1.50 m^3/s during low flow and high freshwater flow, respectively (Jegou, 1974). The Belon estuary is submitted to a semi-diurnal mesotidal regime, with a mean tide range of 5.5 m during high spring conditions (SHOM, 2019). At the mouth of the Belon estuary, the maximum surface current speed during mean spring tide is lower than 25 cm/s (SHOM, 1994). The significative height of swell and waves varies between 0.5 and 3 m high (Tessier, 2006).

In this study, new morphological and sediment maps (Main Map) are compiled based on the integration of acoustic and ground truth data. The detailed description of the Belon estuary, hydro-morphological and sedimentological characteristics with information on bedforms, allows to propose a segmentation of the estuary in accordance with the ria morpho-type (Castaing & Guilcher, 1995; Evans & Prego, 2003) and a general flow circulation scheme. An additional mapping of the anthropised features based on a side-scan sonar mosaics highlights the human impact onto the estuarine dynamics (Reid & Church, 2015).

2. Methods

2.1. Data acquisition

During the AUPASED-3 survey (18th to 20th March 2019 (Lesourd, 2019)), acoustic and ground truth data have been collected in the Belon estuary. Bathymetric and seafloor backscatter data (Main map) have been acquired onboard the R/V ‘Haliotis’ using a GeoSwath Plus interferometric sonar (©Kongsberg GeoAcoustic), working at a frequency of 250 kHz. Side-scan sonar mosaics have been acquired onboard the R/V ‘Monod’ with a pole-mounted CMAX-CM2 Digital Towfish side-scan sonar (©C-MAX Ltd.), operated at a frequency of 325 kHz. A total of 52 grab samples has been collected using Van veen and Shipek grabs (Michel et al., 2020). A total of 31 seabed video profiles has been recorded with a weighted GoPro©.

2.2. Morphological analysis

Bathymetric data have been: (i) processed using Globe software (IFREMER©) with the application of attitude correction (pitch, roll and heave), noise reduction filter (manual and automatic filtering), sound velocity corrections, tide corrections, and (ii) gridded at 1 m resolution. The CMAX-CM2 side-scan sonar mosaics have been processed using HYPACK® 2018 Software with the application of manual altitude corrections and gridded at 10 cm resolution. Side-scan sonar mosaics have been exploited to map anthropic features (ripraps, oyster farms) and (sub-)outcropping substratum.

Intertidal and subtidal domain differentiation (Main Map) has been carried out by classifying tide corrected bathymetric data (ArcMap 10.6 ©ESRI, Spatial Analyst, Arctoolbox/Reclassify), based on the French hydrographic datum (SHOM, 2019). Estuarine morphologies mapping is based on the interpretation of bathymetric and derived data (slope and curvature from Spatial Analyst Toolbox in ArcMap 10.6; ©ESRI) (Dolan et al., 2011). Estuarine morphologies have been manually delimited by identifying slope breaks and seafloor textures, from smooth to rough, within both intertidal and subtidal domains. Regarding bathymetric data resolution, only the dunes characterised by a wavelength longer than 3 m have been studied. Dune polarity is defined by characterising the position of their long and short flanks; dune polarity is then compared to the global orientation of the ebb and flood tidal currents in order to define the dominant tidal current phase for sediment transport (Ferret et al., 2010; Le Bot & Trentesaux, 2004). The final morphological map (Main map, Hydro-morphological map) synthesises the delimitation of estuarine morphologies and estuarine dynamics.

2.3. Seafloor backscatter interpretation

Seafloor backscatter data have been processed using SonarScope software (IFREMER©), with the application of attitude correction (pitch, roll and heave), noise reduction filter (automatic filtering) and amplitude compensation for each profile. Backscatter data were gridded at 30 cm resolution with automatic interpolation of specular backscattering beneath the vessel (nadir).

Interpretation of seabed acoustic facies has been carried out by manually delimiting areas of distinct patterns of grey levels, corresponding to seafloor backscatter intensities (Figure 1). These areas correspond

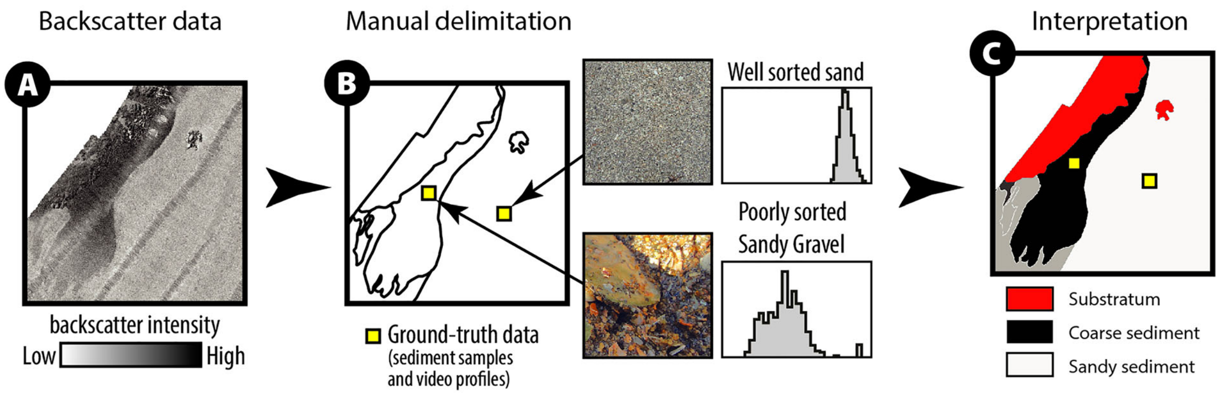


Figure 1. Production process of the sediment map based on: (A) the backscatter data, and (B) the manual delimitation of the acoustic facies and their characterisation using sediment samples and videos, to (C) interpret the sediment classes.

to homogenous or heterogeneous (high spatial variability) patterns of grey levels. Interpretation of seabed acoustic facies has been performed by spatially associating acoustic facies with ground-truthing from video profiles and sediment samples (Figure 1).

2.4. Granulometric data from seabed sediment samples

The 52 sediment samples have been analysed with both mechanical sieving and laser granulometry (Michel et al., 2020). Sediment textural groups (Michel et al., 2020) (Sample location map, Main Map) were defined from GRADISTAT (Blott & Pye, 2001) by following the Udden (1914) and Wentworth (1922) sedimentological scales and the Folk (1954) classification.

Sediment classes of the sediment map (Main Map, Sedimentological map) are based on an adaptation of the EUNIS classification (Long, 2006) derived from the Folk one (1954). The 'Coarse sediment' class characterised sediment samples with a gravel content higher than 5%. The 'Sandy sediment' class (adapted from the 'Sand and Muddy Sand' class of Long, 2006) includes the sandy samples (with Sand:Mud ratio higher than 4:1). The 'Mixed Coarse and Sandy sediments' class has been created to gather complex mixing of sediments from the 'Coarse sediment' and 'Sandy sediment' classes. Sediment samples outside the acoustic coverage are only displayed on the sample location map (Main Map) and are not included within the definition of the sediment classes for seafloor backscatter interpretation. However, they are considered as local information for the overall description of the sediment distribution.

Granulometric data from sediment samples have been used to interpret the acoustic facies (Figure 1). When there is no sediment sample associated with a zone of acoustic facies, the latter have been interpreted based on sediment classes characterised by the same grey scale level observed in other parts of the estuary.

3. Results

3.1. Estuarine morphology and morphological features

The general morphology of the Belon estuary (Main Map, Hydro-morphological map) is characterised by a unique channel meandering within the erodible Nerly and Kerfany groups, and following the main direction of the foliation (N100–N110). Along the Lanmeur and Moëlan orthogneiss formations, the valley follows a NE-SW direction and is strongly controlled by the tectonic features, as illustrated by the NE-SW fault crossing the Porscouric inlet (Main Map, Bathymetry and geology). The channel geometry, width and depth, vary from upstream to downstream (Figure 2 and Table 1). The channel is narrower and more sinuous when the substratum, evidenced by the presence of rocky spurs is outcropping. This is especially observed in the Belon harbour and close to the Porscouric Inlet (Figure 2, P2). The channel flank geometry varies between steep slopes (30–45°) and gentle transition with tidal flats (Figure 2). Tidal flats located on each side of the channel constitute a transitional area between the channel and the rocky banks. The extension of the tidal flats varies largely (Table 1) from upstream to downstream. Tidal flats upstream the Belon Harbour are wide and extend outside the acoustic cover while being narrower downstream the Belon Harbour (Table 1), because of the relative width of the channel and the proximity of the rocky banks (Figure 2). Near the Gorgen Cove, shoals connected to the rocky banks (Figure 2, P4) are observed on both riversides, with a wide terrace on the right riverside. Moreover, four scour holes (Figure 2, P2 and P3), corresponding to large depressions (3–8 m deep with regards to local mean channel depth), have been evidenced within the narrowest section of the channel between the Belon harbour and Gorgen Cove (Main Map, Hydro-morphological map; P2 and P3 on Figure 2).

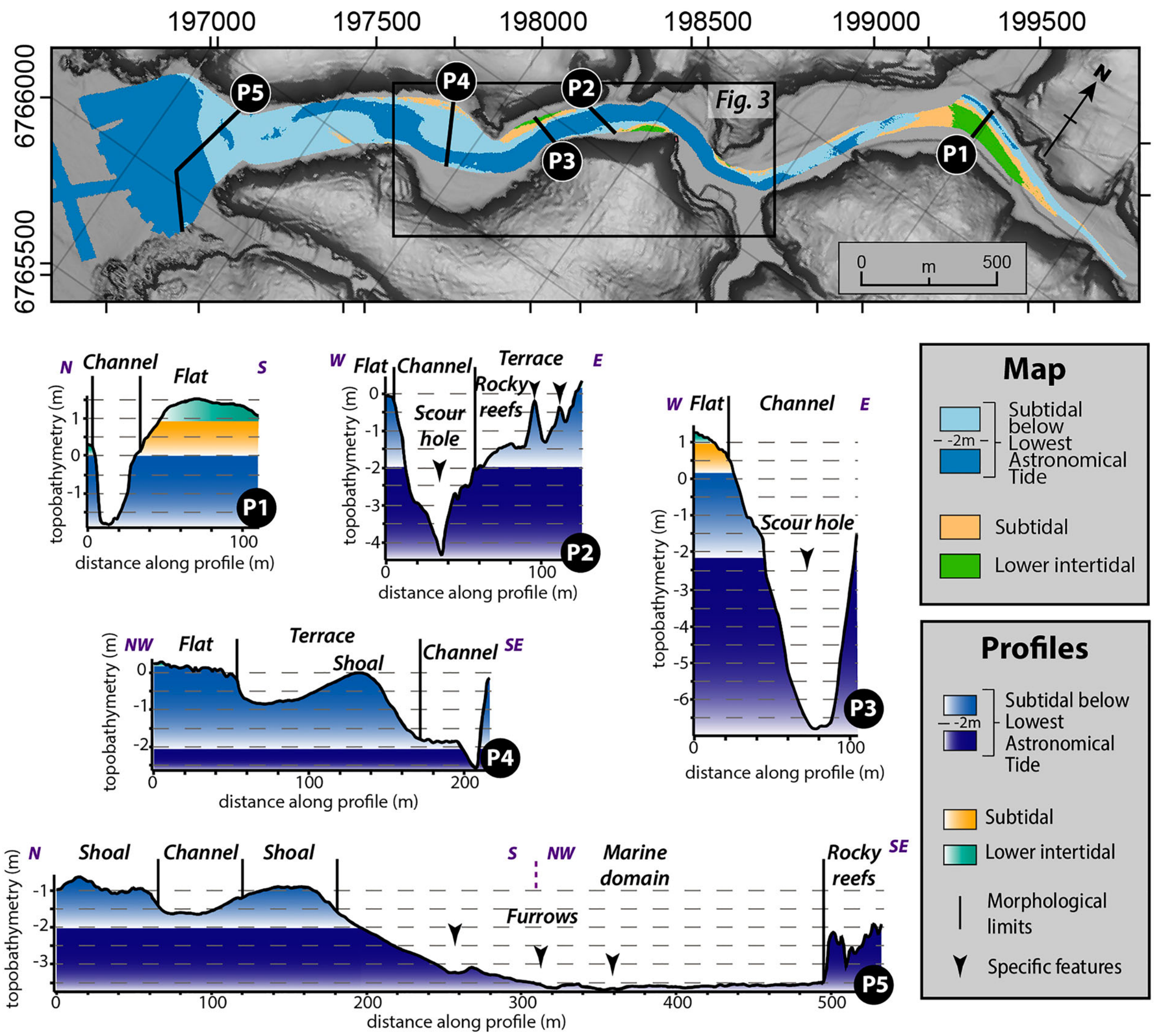


Figure 2. Map of the classified bathymetry based on the French hydrographic datum (SHOM) with interpretation of the substratum morphology and location of the morphological profiles, P1 to P5. All profiles exhibit a morphological description and the detailed vertical segmentation of the bathymetry into 'subtidal below lowest astronomical tide', 'subtidal' and 'intertidal' domains. Spatially limited morphological features such as furrows, rocky reefs and scour holes are located by a black arrow.

Anthropic features are mostly located close to the Belon harbour (Figure 3), with mooring lines within the channel, riprap on the channel flank, buildings and slipways (Figure 3(B)). Upstream the Belon harbour, channel flanks are characterised by ripraps upslope and oyster farms are observed on the tidal flats (Main map, Specific features). Downstream the Belon harbour, only few oyster farms are evidenced on the tidal flats near the Porscouric Inlet and Gorgen Cove.

3.2. Sediment classes description and spatial distribution

The granulometric information derived from GRADISTAT (Blott & Pye, 2001) is detailed in a published database (Michel et al., 2020). Three samples, representative of each sediment class displayed on the sediment map (Main Map), are presented in Table 2.

Globally, sediments within the subtidal zone of the Belon estuary are mostly sandy (sand content higher than 85% for 92% of the samples). Only three samples, within the subtidal zone, exhibits lower sand content of 17.2%, 25% and 62%, respectively upstream the Gorgen Cove, within the Belon Harbour and downstream the Pennmor Inlet, in the narrowest part of the estuary. Coarse sediment content over the whole estuary notably varies (from 0% to 83%) between the different sections of the estuary and the carbonate content as well (34% to 85%) (Table 3). The overall mud content of the estuary does not exceed 3.9% within the area covered by the acoustic data but reaches 53.7% (Main Map, sediment map) for the samples outside the acoustic cover, located in sheltered zones (i.e. embayment on intertidal flats).

In terms of spatial distribution, sediment classes located upstream the Belon Harbour are mixed with a slight overall dominance of 'sandy sediments' (Main Map, sediment map and Table 3). A local

Table 1. Detailed description of the estuarine morphologies, channel, channel flanks, and tidal flats for each of the described sections. Depths referred to the French Hydrographic Datum. Rock formation occurrence is displayed in the last column with relative occurrence (major and minor formations). Only the Marine domain is described as the West and East coast.

	Morphologies				
Zones	Channel	Channel flank	Tidal flats[a]	Others	Rock formations occurrence
Upstream the Belon Harbour	– Width: 5 to 40m – Depth: −0.5 to −2.1m	– Mean slope: 22° – Slope angles up to 33° with ripraps	– Width up to 111m – Slope: 1-2°		Majors: Nerly and Kerfany groups, Moëlan orthogneiss Minor: Lanmeur orthogneiss
Belon Harbour	– Width: 40 to 70m – Depth: −0.7 to −6.3m – Two scour holes of 4.7 and 6.3 m depth	– Slope angle up to 45° with ripraps at the base of the buildings	– Width up to 17m – Slope: 1-2°		Major: Nerly and Kerfany groups
Downstream the Belon Harbour	– Width: 70 to 125m – Depth: −1.3 to −14.2m – Two scour holes of 14.2 and 7.6m depth	Contact/Slope angle: – Rocky banks/16° – Shoals/4°	– Width up to 52m – Slope: 1-2°	– Shoal and terrace at the transition between the channel and tidal flats/ banks on both riverside – Depth: up to 0m – Width: 20 to 128m	Major: Moëlan orthogneiss Minor: Nerly and Kerfany groups
Marine domain	– Depth: −1.5 m to −5m – Slope: <1°			One mouth bar (shoal), 50 cm high, at the transition with the downstream section. Four furrows, incised 20 cm below the seafloor.	West coast: Porz-Manech and Moëlan othogneiss East coast: Nerly and Kerfany groups

[a]Tidal flat width corresponds to their extension form the channel flank towards the acoustic cover limit.

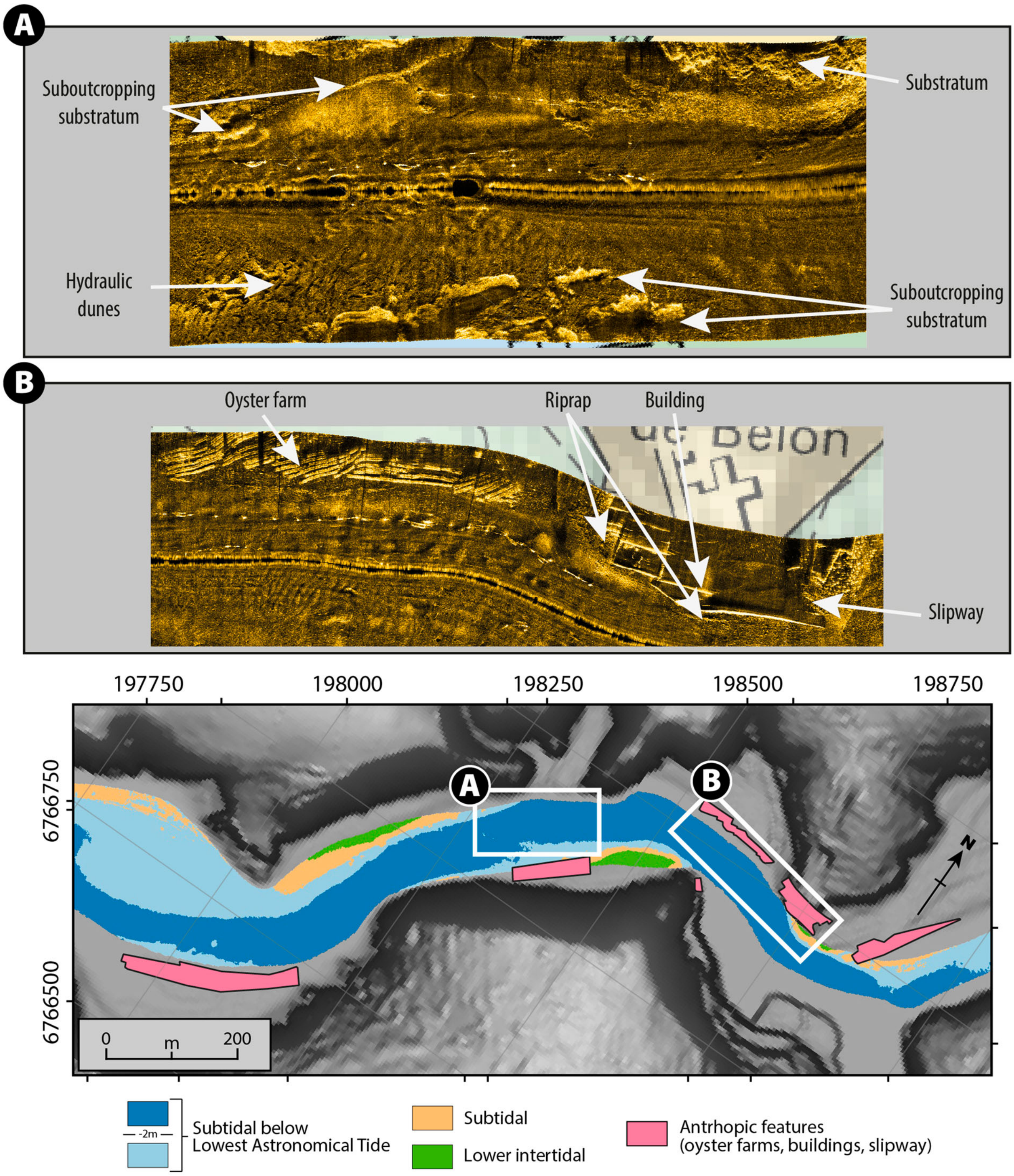


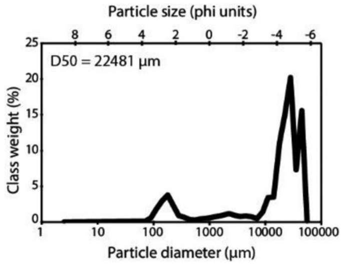
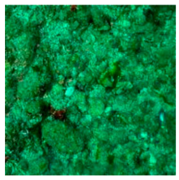
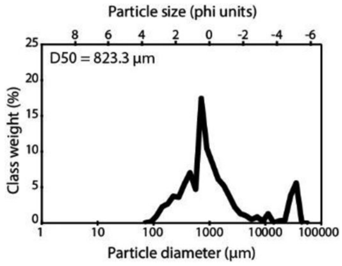
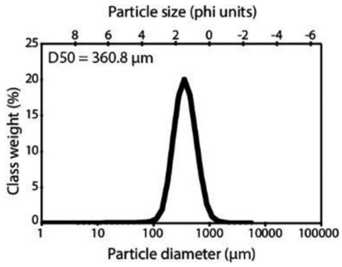
Figure 3. Sampled side-scan sonar mosaic exhibiting: (A) natural features, such as outcropping and sub-outcropping substratum, hydraulic dunes, and (B) anthropic features such as mooring lines, slipways, buildings and oyster farms. Both sampled mosaics are located on the classified bathymetric map based on the French hydrographic datum with the location of the interpreted substratum (in red) and location of the main anthropic features (in pink).

dominance of 'mixed sediments' and 'coarse sediment' is observed at the St-Léger Inlet, within the channel and on the tidal flats respectively. Within the Belon harbour, seabed nature is dominated by 'coarse sediment' within the channel and 'mixed sediments' on the flats (Table 3). Downstream the Belon harbour, the 'mixed sediments' are dominant until the Gorgen Cove, with local 'sandy sediments' patches. Downstream the Gorgen Cove, 'sandy sediments' are predominant, while 'mixed sediments' are restricted to the channel centre and 'coarse sediment' to local patches. Some 'mixed coarse and sandy sediment' are covering the bottom of the furrows evidenced in the marine domain.

3.3. Hydrodynamic structures

Hydraulic dune orientation and asymmetry are a useful information to interpret the seabed sediment dynamics (Ferret et al., 2010; Le Bot & Trentesaux, 2004) within the estuary. All mapped hydraulic dunes are located within the channel. Some structures

Table 2. Description of three sediment samples (AUP3-008, AUP3-027, AUP3-014) representative of the three sediment classes (coarse sediment, mixed coarse and sandy sediment and sandy sediment) interpreted in the Belon estuary and based on the modified Folk classification (Long, 2006).

Sample ID/Sediment class	Granulometric distribution	Sample picture	Seabed video capture
AUP3-008 **Coarse sediment**			
AUP3-027 **Mixed Coarse and Sandy sediment**			
AUP3-014 **Sandy sediment**			

Sample location is exhibited on the Main map. Sample description includes the granulometric distribution and the D50 value calculated from GRADISTAT, a picture of the sample taken aboard the R/V 'Monod' and a capture of the associated video profile.

are also located on the flank of the shoals but only within the downstream section (Main Map, Specific features). None have been evidenced on the tidal flats or within the marine domain. We distinguished several types of hydraulic dunes with crests orthogonal to the main currents, wavelength ranging from 2 to 14.6 m and heights ranging from 5 to 93 cm (Main Map and Table 4). Some have symmetrical shapes; others display an asymmetry in the direction of flood or ebb currents (Table 4). Some hydraulic structures exhibit complex morphologies and have been classified into two groups: the first one corresponds to a group characterised by a complex pattern of irregular dunes and the second group corresponds to hydraulic dunes associated with anthropic features (particularly to mooring posts).

The overall distribution of the hydrodynamic structures varies sensibly along the estuary. Upstream the Belon Harbour, the spatial distribution of ebb and flood-oriented feature is balanced with an occurrence of complex mixed dunes. Within the Belon Harbour, hydraulic structures are mostly related to the occurrence of anthropic features. Downstream the Belon Harbour, all 4 types of hydraulic structures are represented. The occurrence of ebb and flood-oriented features becomes more prominent downstream the Gorgen Coven and symmetrical dunes have been highlighted within the centre of the channel at the Belon estuarine mouth.

4. Discussion

4.1. The influence of the geological context

The geology and tectonic contexts are considered as the main key factors controlling the morphology of a ria-type estuary (Castaing & Guilcher, 1995). Considering the morphology of the channel, the location of the Gorgen Cove and the connection of three main inlets, the general morphology of the Belon estuary is strongly controlled by the geological formations and tectonic features. Indeed, the three orthogneiss formations of the Belon estuary corresponds to strong rock formations, while Nerly and Kerfany groups correspond to less competent formations which are most subject to erosion (Bucher & Grapes, 2011). Therefore, the incision of the Belon estuary since Pliocene (Béchennec et al., 1996) was driven by the distribution of rock formations and their tectonic contact. Its

Table 3. Detailed description of the estuarine sediment cover and seabed nature within the channel, on the tidal flats and the shoals for both sediment samples and sediment classes (in italic). Sediments outside the acoustic cover are not included within this synthesis. Rock formations acronyms displayed within the "Zones" column are: NKG, Nerly and Kerfany groups; LO, Lanmeur orthogneiss; MO, Moelan orthogneiss; PMO, Porz-Manech orthogneiss. The main rock formation is underlined.

Zones (associated main rock formations)	Sediment cover/*Seabed nature*			
	Channel	Tidal flats[a]	Shoals	Other
Upstream the Belon Harbour (<u>NKG, MO</u>, LO)	Sandy and Mixed sediments – D50:260–823 – Sorting: 1.52–3.775 – %$CaCO_3$: 45–63 – %Mud: 0–2.1	Sandy, mixed and coarse sediments – D50: 212–324 – Sorting: 1.42–4.31 – %$CaCO_3$: 34–64.4 – %Mud: 0–2.1		– Cockle's facies at location of sample AUP3-23
Belon Harbour (<u>NKG</u>)	Coarse sediments – D50: 20193 – Sorting: 10.37 – %$CaCO_3$: 85.6 – %Mud: 1.1			
Downstream the Belon Harbour (<u>MO</u> and NKG)	Sandy and mixed sediments – D50: 234–22481 – Sorting: 1.58–5.769 – %$CaCO_3$: 46.72–75.15 – %Mud: 0–3.9	Sub-outcropping substratum	*Sandy, mixed and coarse sediments* – D50: 235–497 – Sorting: 1.41–2.83 – %$CaCO_3$: 66 -83 – %Mud: 0–0.9	– Outcropping substratum at the banks – Rocky reefs between the Belon Harbour and the Gorgen Cove
Marine domain (PMO, MO, NKG)	Sandy sediments with localised mixed and coarse sediments – D50: 144–584 – Sorting: 1.4–1.48 – %$CaCO_3$: 41.8–65.6 – %Mud: 0.1			– Rocky banks

D50 and sorting values are given in µm. [a]Tidal flat width corresponds to their extension form the channel flank towards the acoustic cover limit.

Table 4. Detailed description of the hydraulic structures ebb or flood-oriented dunes, complex and irregular dunes and symmetrical dunes.

Sections	Hydraulic structures			
	Ebb oriented dunes	Flood-oriented dunes	Complex and irregular dunes	Anthropic features related structures / *Symmetrical dunes*
Upstream the Belon Harbour	– *S*: 3109 m^2 – *H*: 10–40 cm – λ: 6.7–10 m	– *S*: 5938 m^2 – *H*: 16–45 cm – λ: 2.8–5.1 m	– *S*: 856 m^2 – *H*: 10–14 cm – λ: 5.4–7.6 m	
Belon Harbour	– *S*: 1695 m^2 – *H*: 10 cm – λ: 2–3.5 m	– *S*: 4853 m^2 – *H*: 25–67 cm – λ: 4.3–7.6 m	– *S*: 11305 m^2 – *H*: 34–93 cm – λ: 9.5–14.5 m	– *S*: 8984 m^2 – *H*: 43–82 cm – λ: 10–13 m
Downstream the Belon Harbour	– *S*: 5753 m^2 – *H*: 5–35 cm – λ: 2–10 m	– *S*: 26953 m^2 – *H*: 7–50 cm – λ: 1.7–14.6 m	– *S*: 5098 m^2 – *H*: 16–37 cm – λ: 2.8–9 m	– *S: 8282 m^2* – *H: 5–10 cm* – *λ: <2 m*

Hydraulic features associated with anthropic features are also described. S: Surface covered by the dune fields, H: height and, λ: wavelength of the dunes.

sediment filling since Pliocene shaped the present-day morphology of the channel and the tidal flats distribution.

4.2. A multi-sources sedimentary system

Castaing and Guilcher (1995) described systems of 'Sandy Rias' as mostly sandy with an overall low mud content. This description corresponds to the overall Belon estuary sedimentary system with a dominance of sandy sediments downstream and a balanced distribution of coarse and sandy sediment upstream. In the Belon estuary, muddy sediments are exclusively located in sheltered areas, within inlets, or in the Gorgen cove downstream and on the upper intertidal tidal flats upstream. This distribution of the muddy sediments, mostly upstream, also corresponds to the 'Sandy ria' systems and has been described in other South Brittany rias such as the Laita or the Goayen (Castaing & Guilcher, 1995), or in the United-Kingdom in the Avon estuary (Masselink et al., 2009).

According to Castaing and Guilcher (1995), the carbonate content of 'Sandy Rias' decreases upstream because of the increased distance with the marine sediment source. The carbonate content of sandy sediments within the Belon estuary decreases slightly upstream the Belon Harbour (loss of nearly 10%) but remains higher (~64%) than the carbonate content, described in other rias, such as the Laita and the Goayen in South Brittany (Castaing & Guilcher, 1995). It can be explained by: (1) the shell remobilisation and fragmentation (Wiedemann, 1972) and (2) the transfer of marine sediment upstream (Naughton et al., 2007). There is also a slight increase in the carbonate content between the marine domain (~65%) and the sandy sediments within the downstream section (~75%). This difference is most likely related to the transfer of the marine sediment towards the downstream section of the Belon estuary, because of the influence of the tide and possibly wind currents (Friend et al., 2006). The coarsest sediments with low carbonate content (~40%) are interpreted as lithoclastic ones and are most likely sourced from the erosion of the rocky banks or from the fluvial input. Lithoclastic sediments are observed in the most upstream section of the estuary and within the scour hole downstream the Belon harbour. This distribution corresponds to sections scoured within the Nerly and Kerfany groups, formed of micaschists, and foliated and altered gneiss, more subject to erosion (compared to the orthogneiss formations) (Bucher & Grapes, 2011). Indeed, after Perillo (1995b), erosion of inner estuary rocks, within rias, is an important input to the sedimentary budget. However, one coarse sample in the Belon harbour is characterised by a high carbonate content (85.6%). It is then interpreted to be the result of the accumulation of shells from the surrounding oyster farms. Therefore, the dominance of sandy sediments downstream is most likely related to the input of marine sands with tides and wind currents (Friend et al., 2006) associated with the transport of lithoclastic sands from upstream, while the lithoclastic coarse sediments are locally trapped within the scour holes (Shaw et al., 2012). The upstream section is differentiated from the downstream one due to the input of coarse carbonated sediments, sourced from oysters farms, and coarse lithoclastic sediment derived from the erosion of the Nerly and Kerfany groups. Then, the sandy sediments upstream are most likely sourced from a mixing of substratum erosion and shell fragmentation. The lower relative abundance of sandy sediments upstream can be explained by their evacuation towards the channel and then downstream with the channel flow (Castaing & Guilcher, 1995).

4.3. Estuarine dynamics

Considering all the morphological, sedimentological and hydrodynamic observations (Main Map), we proposed a general scheme of flow circulation for the Belon estuary (Main Map, Hydro-morphological map). This flow scheme highlights a spatial distribution of ebb dominated bedforms on the inside bend and flood-dominated bedforms on the outside bend of the meanders (Brown & Davies, 2010; Leuven et al., 2016). Downstream the Gorgen Cove, flood-oriented bedforms are also located on top of the shoals. The symmetrical dunes observed downstream illustrate the potential influence of wind-induced currents and waves, especially coming from the marine environment (Charru et al., 2013; Dalrymple & Rhodes, 1995). The influence of the tidal and wind induced currents on the marine sediment transport towards the inner part of the estuary has already been evidenced in other systems (e.g. Fowey Ria, Friend et al., 2006; Avon estuary, Masselink et al., 2009; and the Goayen in South Brittany, Castaing & Guilcher, 1995). Complex hydraulic dunes within the estuaries are most likely associated with successive influence of both ebb and flood currents (Lopes et al., 2006; Lopes & Dias, 2007), and multiple reflections on the channel flanks upstream because of the channel convergence (Park et al., 2017) giving raise to turbulent conditions. Such dunes are observed in the Belon harbour down to the Penmor inlet where the narrowing and the sinuosity of the channel may explain such processes. Downstream the Belon Harbour, the occurrence of scours may also be explained by these complex current interactions (Cheng & Valle-Levinson, 2009), either at the location of confluence between inlet and main channel (Pierini et al., 2005) or due to complex channel morphologies (Brown & Davies, 2010). These complex and strong currents participate in the sediment winnowing and in the scour holes formation (Shaw et al., 2012), as evidenced in the Dyfi Estuary (Brown & Davies, 2010). Some hydraulic structures also formed in relation to the flow perturbation induced by the moorings posts (Koopmans et al., 2017) are observed in the Belon harbour.

This flow circulation scheme highlights the main controlling factors of morphologies and sediment distribution in such estuaries, which are: (i) the strong influence of the tide-related processes (Friend et al., 2006) that ascertains the tide-dominated character of the Belon estuary, and (ii) the influence of the width and sinuosity variations of the channel in response to the regional substratum structuration (Béchennec et al., 1996).

4.4. The Belon estuary: a typical ria-type

Regarding the sediment cover, the seabed nature and the geomorphology upstream and downstream the Belon Harbour, these characteristics correspond to the description of 'estuarine' sections proposed by Castaing and Guilcher (1995) and 'internal estuarine' sections from Evans and Prego (2003). Indeed, the morphology varies from a wide channel, associated with shoals, connected to rocky banks downstream towards a narrower channel associated with wide tidal flats upstream. This evolution of the 'estuarine' sections has been described in other rias, such as the Dee estuary (UK) (Moore et al., 2009) or the Orange estuary (South Africa) (Cooper, 2001). Downstream the Belon Harbour the occurrence of outcropping and sub-outcropping substratum, along with the narrowness of the channel, highlights the strong influence of the geological and tectonic framework. It ascertains the influence of the geological formation type and tectonic features into controlling the morphology of the ria (Castaing & Guilcher, 1995) and the location of the inlet connections (Béchennec et al., 1996) to the main channel. However, upstream the Belon Harbour, outcropping and sub-outcropping substratum is less observed, most likely because of the development of the flats such as in other rias such as the Avon estuary, UK (Masselink et al., 2009). This flat development can be explained by: (1) a low fluviatile discharge (Castaing & Guilcher, 1995) leading to a narrow channel, and (2) the influence of anthropogenic features such as ripraps (Figure 3) which constrain the channel (Reid & Church, 2015) and enable the tidal flat development. Variation in tidal flat extension has been described in the Ria De Aveiro (Lopes et al., 2006), with large tidal flat areas corresponding to the ebb dominated sections and localised tidal flats corresponding to flood dominated sections. This description is consistent with the observations made from hydraulic structures and ascertains the influence of the tide-related processes within the Belon estuary.

5. Conclusion

The recent high-resolution morpho-sedimentological mapping of the Belon estuary combining acoustic and sampling techniques allows us to ascertain its classification as a ria-type estuary, accordingly to Castaing and Guilcher (1995) and Evans and Prego (2003). It highlights the strong influence of the different geological formation competence and location, and tectonic features, as controlling factor onto the general morphology of the ria and estuarine morpho-sedimentological features. Regarding the estuarine segmentation proposed in the literature (Castaing & Guilcher, 1995; Perillo, 1995a; Reading, 1996), the detailed morphologies and sediment classes spatial distribution allow us to propose a segmentation of the Belon estuary with a marine section and an estuarine section (Evans & Prego, 2003), the latter differentiated downstream and upstream the Belon Harbour, respectively. Finally, the analysis of the bedform distribution and morphologies, as well as the sedimentological description, allows us to propose a general scheme for the estuarine hydrodynamic circulation. It highlights: (i) the strong influence of the tide onto the currents and the sediment distribution and mixing in the estuarine sections (Reading, 1996) as evidenced in other estuaries (Castaing & Guilcher, 1995; Lopes et al., 2006; Lopes & Dias, 2007), and (ii) the strong control of the geological and tectonic framework on the morphology of the channel and sediment distribution, which leads to the occurrence of zones with complex current interactions and turbulent conditions, forming scour holes and complex dunes. In further studies, this general hydrodynamic circulation scheme could be used as a reference for hydro-sedimentological modelling, allowing the quantification of hydrodynamic processes and possibly their contribution to the sediment dynamics within a typical ria-type estuary.

Software

Acoustic data from the Geoswath Plus interferometric sonar (©Kongsberg Geoacoustics) have been processed using Globe® (Poncellet et al., 2020) and SonarScope® (Augustin, 2016) softwares developed by IFREMER (https://www.flotteoceanographique.fr/en/Facilities/Shipboard-software/). CMAX-CM2 (C-MAX Ltd.©) side-scan sonar mosaics have been processed using HYPACK®2018 software. Manual digitalisation of morphologies and sediment classes has been performed using ArcMap 10.6 (©ESRI) Map layout and editing was performed using QGIS and Adobe Illustrator CC (©Adobe Systems Inc.).

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