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High-resolution bathymetry of the Alderney Race and its geological and sedimentological description (Raz Blanchard, northwest France)

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ABSTRACT
We present a high-resolution 1:15,000 bathymetric map (Main map) of Alderney Race located offshore of northwestern France, with the strongest currents in Europe. We use this map, underwater video transects and Shipek grabs to improve geological maps previously published. We distinguished Proterozoic crystalline rocks, Paleozoic and Cretaceous sedimentary rocks on the present-day sea floor. Some structures as faults and folds are also mapped. We identified a Quaternary cover made of pebbles, boulders and blocks interpreted as corestones resulting in differential erosion and alteration of the substratum. This cover is commonly encrusted by fixed fauna, such as bryozoans and barnacles. Finally, we describe the present-day mobile sediment cover characterized by sand patches and pebble dune fields (up to 10 m in height). Our videos show the presence of mobile fine-grained sediment patches under the resolution of our map lying between the cobble and pebble cover. We summarize our interpretations on a non-exhaustive geological-sedimentary map.

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High-resolution bathymetry; Morpho-sedimentological cartography; Alderney Race; Shipek grab; submarine camera

1. Introduction

The English Channel is characterized by strong tidal currents, reaching up to 5 m.s^{-1} in the Alderney Race and thus is a suitable area for tidal turbines installation for Marine Renewable Energy creation. Several studies on tidal stream resource estimation and turbine impact on the flow have been carried out in the Alderney Race (Bailly du Bois, Dumas, Solier, & Voiseux, 2012; Coles, Blunden, & Bahaj, 2017; Thiébot, Bailly du Bois, & Guillou, 2015), however only a few studies about sediment transport (Thiébot et al., 2015) and bathymetry have been done. Although deposition of fine particles is expected to be difficult with strong currents, Foveau and Dauvin (2017) described mobile sediment patches, mainly composed of sand and pebbles. Coarser sediments dominated by pebbles and cobbles have been described by Larsonneur, Bouysse, and Auffret (1982) around the exposed bedrock. Foveau and Dauvin (2017) also described poorly sorted and rounded coarse sediments lacking of fixed fauna, reflecting the important bedload transport in these high-energy environments.

In the Alderney Race, the morphology of the bedrock and the presence of sediments available for transport are poorly constrained. However, this knowledge essential for tidal turbine installation: (i) for improvement of tidal stream resource estimation with numerical modeling considering the turbulence generated by bed roughness and depth variations, (ii) for the impact of the turbines on sediment, and conversely (iii) for possible sediment abrasive impact on the turbines.

This paper aims to (1) describe and identify different morphologies from the bathymetric map (Main map) in the Alderney Race area, (2) provide an interpretation for these different bathymetric morphologies using previously published geological and sedimentological information, new underwater video observations and sediment samples, and (3) show the presence of fine sediments potentially mobile with the strong current of the study area.

2. Regional setting

The study area displays Paleo and Neoproterozoic crystalline rocks and Paleozoic and Cretaceous sedimentary rocks (Figure 1(B)). It includes the Icartian gneiss (Paleoproterozoic Pentevrian basement, 2.1 Ga) exposed in the Anse du Culeron (located on Figure 2). The Neoproterozoic crystalline rocks consist of two generations of quartz diorite plutons, emplaced from 620 to 608 Ma in a back-arc setting and from 570 to 540 Ma during the Cadomian orogeny (e.g.

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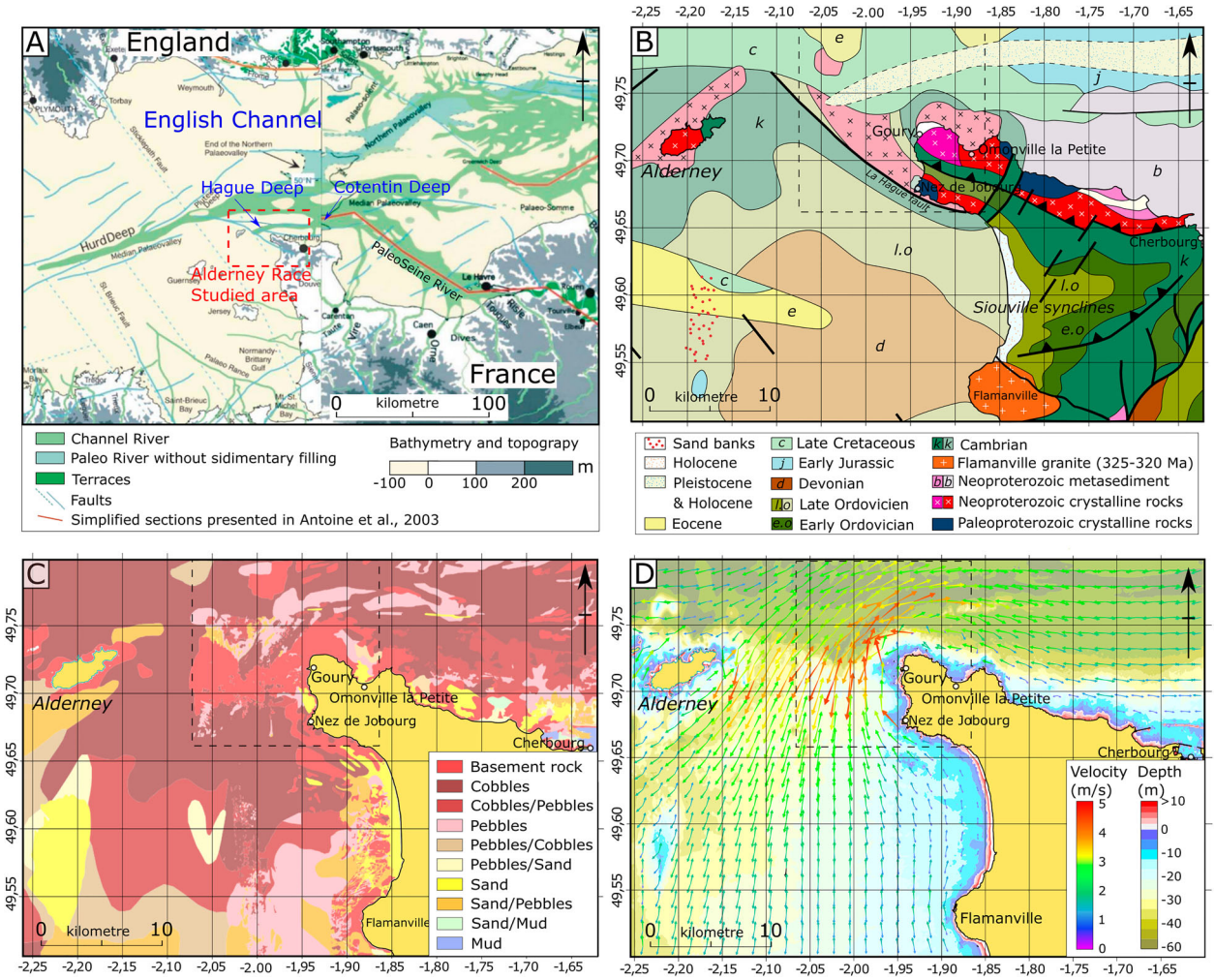

Figure 1. (A). Map of the English Channel showing the deeps that coincide with the paleo-Seine and its tributaries (Antoine et al., 2003) and the location of our study area (red rectangle); (B). Geological map (modified from geological map of France 1/50 000); (C). Sedimentary map (modified from data.shom); (D). Simplified bathymetric map showing the maximal tidal current intensities at high and low tides from numerical model MARS2D, resolution of 100 m (method from Bailly du Bois et al., 2012).

Dallmeyer, D'Lemos, Strachan, & Mueller, 1991; Inglis, Samson, D'Lemos, & Miller, 2005). Cadomian structures in the area consist of SE-directed thrusts striking N45, with a left-lateral component (e.g. Ballèvre, Le Goff, & Hébert, 2001; Chantraine et al., 2001).

The Paleozoic succession consists of Cambrian to Devonian sedimentary rocks, exposed in the Siouville and Jobourg Synclines (Figure 1(B)), striking N110. These synclines are a result of the Variscan Orogeny (Dissler & Gresselin, 1988), that occurred around 320 Ma in the area (Ballèvre, Bosse, Ducassou, & Pitra, 2009).

The Mesozoic succession is composed of Triassic conglomerates, exposed near the La Pernelle Plateau and Upper Cretaceous flint-bearing chalk mapped in the offshore in the northwest part of our study area (Larsonneur & Walker, 1982). During the Mesozoic, several regression and transgression cycles occurred above the Variscan basement. Early to Middle Jurassic sedimentary rocks deposited and have been subsequently eroded in the Cotentin Peninsula (e.g. Dugué, 2007). During the Early Cretaceous a major regressive event occurred, evidenced by a weathering and peneplation surface found in Brittany and Normandy (Bessin, Guillocheau, Robin, Schroëtter, & Bauer, 2015). During the Late Cretaceous, previously emerged surfaces were drowned by transgression, as BRGM maps (Bureau des Ressources Géologiques et Minières) show remnants of Upper Cretaceous flint-bearing chalk above Proterozoic and Paleozoic rock in Brittany (e.g. Doré, Dupret, Le Gall, & Chalot-Prat, 1977; see Bessin et al., 2015 for more details).

During Cenozoic, the Cotentin Peninsula underwent uplift, as shown by four marine terraces and four Rasas (Pedoja et al., 2018). This regional uplift is related to the far-field effects of the Alpine orogeny that induced the reactivation of some faults, such as the La Hague fault (e.g. Lagarde et al., 2000, 2003). Quaternary eustatic sea level falls (up to −110 m below present-day sea level) linked with major climatic changes induced strong incision, as the Cotentin and the La Hague deeps (up to 90 m bsl) are interpreted as a fluvial paleo-drainage related to tributary rivers of the Seine (Antoine et al., 2003) (Figure 1(A)).

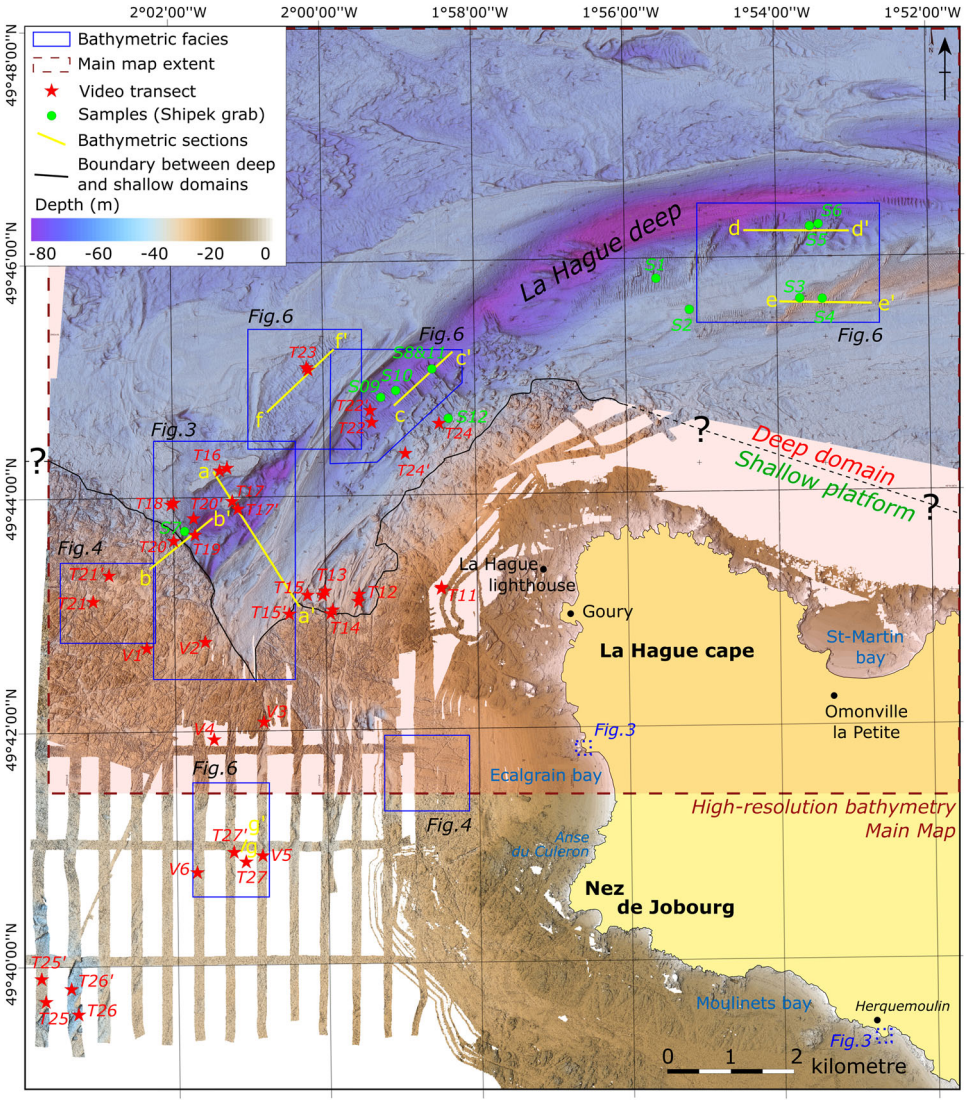

Figure 2. Bathymetric map of the Alderney Race with the location of video transects (red stars, named Tn or Vn with indicating the end of transect). Specific bathymetric morphologies (blue rectangles) are described in detail on the next figures. The yellow transects indicate the bathymetric sections. The dashed brown rectangle represents the high bathymetric map extent.

At present, strong tidal currents prevent significant deposition in the deeps, preserving the Quaternary fluvial paleo-drainage (Lericolais, 1997). The regional two-dimensional currents model (MARS2D) of Bailly du Bois et al. (2012) shows high northward/southward tidal currents west of La Hague Cape (red arrows in Figure 1(D)). North of the Peninsula, the eastward/westward currents align with the La Hague deep. This model has been validated by numerous physical oceanographic data acquired with conventional techniques: bathymetric survey, measurement of variations in water levels, current measurements, tracking of drifters and dispersion of soluble tracers (details in Bailly du Bois et al., 2012). Since, other models and new field campaigns have been used to improve knowledge of the hydrodynamics (Thiébot et al., 2015). Currents generally exceed 2 m s^{-1} and reach up to 5 m s^{-1} during the peak of spring tide and thus are able to move particles of several cm in diameter according to Hjulström (1935). The sedimentary map from the Shom (Service Hydrographique et Océanographique de la Marine) database (Figure 1(C)) shows diverse types of sediments ranging from sand in the bays to cobbles near the exposed bedrock. Despite the strong currents in this area, patches of mixed sand and pebbles are described in the Alderney Race area on this map and in Foveau and Dauvin (2017) (Figure 1(C)).

3. Methods

3.1. Bathymetry

Various bathymetric sources were data used to build the bathymetric map come from:

(1) the HOMONIM project for the main dataset, acquired using multibeam echosounders (resolution up to 1 m) or with a single beam sounder (resolution up to 100 m) (Shom, 2015);
(2) the NHDF (Normandie Hauts de France) lidar project 2016–2017 focused on the coastal fringe with a horizontal resolution of 1 m (Shom-

ROLNP, 2018) up to 10 m of depth (at least) and sometimes 20 m (depends on the transparency of the water);

(3) and the BATHAGUE project 2008–2010, for the shallow depths (from 2 or 3 m up to 60 m) and acquired by IRSN (Institut de Radioprotection et de Sûreté Nucléaire) using an interferometric sonar (resolution up to 1 m) (Bailly du Bois, 2008).

The final bathymetric map was created using Universal Transverse Mercator (UTM 30N) conformal projection and WGS84 reference ellipsoid. The height reference (0 m elevation) was fixed on the low spring tide mean level in Goury (located on bathymetric map). The difference between the local Hydrographic zero and the terrestrial zero (IGN69) is 4.827 m (reference: Référénce Altimétriques Maritimes du Shom).

This map identified by a brown rectangle in Figure 2 covers the NW of Cotentin Peninsula. However, our study area extends southward, as the southern areas are essential to connect the onshore geology with offshore areas (Figure 1(B)). This southern area is not integrated into the bathymetric map because of the lack of high-resolution bathymetric data (blanks in Figure 2 and bathymetric map).

We used the high-resolution bathymetric map to identify different morphologies, such as tilted Paleozoic beds, Paleozoic and Proterozoic crystalline rocks, Cretaceous flatbed surfaces and present-day subaqueous dunes. The interpretation of these substrate types confirmed using onshore-offshore correlations from the available geological maps and compared with aerial photographs of the emerged rocky platform. We also used the bathymetric map to build bathymetric sections allowing the observation of large structures, such as dunes and the measurement of bedding dips, only for the low-dipping Cretaceous strata.

3.2. Nature of the seabed

We used an underwater camera and a Shipek grab to confirm our interpretations of the described morphologies from bathymetric map and provide additional and more accurate information on sedimentary cover (location of points in Figure 2).

The underwater video allows the characterization of the sediment cover at the scale of several square meters. However, the camera can only be deployed for 15 min when currents decrease during the short slack current water and only in good weather conditions. The deployment depth is limited by cable length for the high definition transmission to the boat (70 m). A scale of 10 cm fixed between the three weighted feet of the camera allows the estimation of the size of sediments when it reaches the bottom. Therefore, the videos provide information about the size of sediment on the bottom and their location for the lowest current velocity stage. Twenty-three video (covering in total about 3 km^2) transects were conducted for a qualitative description of the sedimentary cover.

As the Shipek grab is working only for pebbles or finer sediments that relatively rare in the area, only 8 samples among the 12 collected yielded a sufficient volume of sediment for analyses. These samples provide direct information on seabed composition.

4. Results and discussion

4.1. Geology of the deep domain

The La Hague deep consists of a deep submarine trough that coincides with a Quaternary channel of a paleo-tributary of the Seine River incised into the Upper Cretaceous chalk (e.g. Antoine et al., 2003). The Shipek grab samples and videos, mainly showing Cretaceous flint rocks pebbles in the area (Figure 3(B, C)) together with the relatively flat bedding dips on the bathymetric map support the Cretaceous age for the substratum, as proposed by Larsonneur and Walker (1982). This deep is striking NE–SW west of the La Hague Cape and then E–W north of the La Hague Cape (bathymetric map). At its southern termination, the deep progressively connects with the shallow platform, as the depth gently decreases southwestward.

West of the La Hague deep, an isolated small deep is developed in Cretaceous chalk (Figure 3(D)). This deep is separated from the La Hague deep by three main steps slightly dipping eastward (from 2° up to 5°, profile a-a′, Figure 3(F)) and interpreted as slightly dipping Cretaceous strata. This is supported by the presence of similar cuesta morphologies located west of the small deep.

Across the small deep, the correlation between the flat strata (see the red star Figure 3(A,D and F)) and the slightly dipping strata suggests a gentle anticlinal striking N45°, developed in the Cretaceous rocks. This interpretation is supported by the work of Benabdelhouahed (2011), who showed several folds with similar orientations related with the far-field effect of the Alpine orogeny in the English Channel. The small deep is opened at the crest of the anticline and includes different depressions, reaching up to 90 m bsl (Figure 3(D)). Similar structures in the English Channel have been attributed to thermokarst developed in the Cretaceous chalk (Lericolais, 1997). Therefore, the small deep may be interpreted as resulting of karstic processes affecting the Cretaceous chalk and occurring during Pliocene-Pleistocene lowstands. According to our video, the cuesta morphologies west of the small deep are covered by relatively angular cobbles and blocks with fixed fauna (Figure 3(E)). These may correspond either to Pliocene-Pleistocene periglacial deposits, similar to those of the Herquemoulin locality

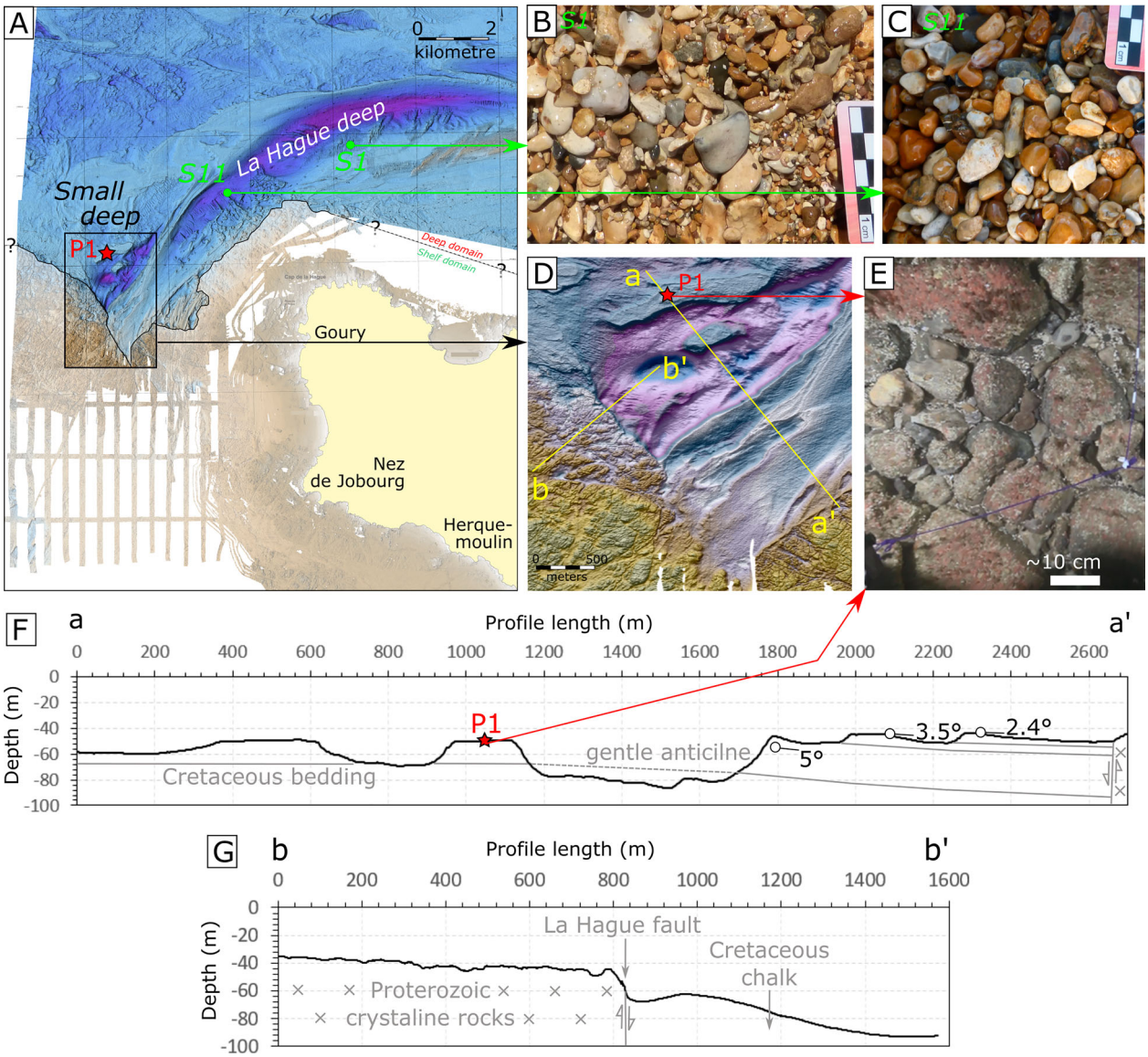

Figure 3. Bathymetry, samples and geologic interpretations of the La Hague deep and the small deep. (A). Bathymetric map of the Alderney Race showing the location of the La Hague deep and of the small deep; (B and C). Photographs of Shipek grab samples with cretaceous flint rocks pebbles collected in the La Hague deep. (D). Detailed bathymetric view of the small deep. (E). Photographs extracted with the underwater camera showing relatively angular cobbles and blocks with fixed fauna. (F and G). aa′ and bb′ transects with simple geologic interpretations.

(Font, Lagarde, Amorese, Coutard, & Ozouf, 2002) or to cobbles remaining there after chalk erosion.

4.2. Geology of the shallow platform

The deep domain is separated from the shallow platform by two different morphologic features. In front of Goury, the shallow platform boundary coincides with the eastern river bank of the paleo-fluvial channel of the La Hague deep. Southwest of our study area, the shallow platform is bounded by a steep scarp that is 15–50 m high, with an average slope angle of 25° (profile b-b′, Figure 3(G)). This scarp belongs to the Alderney – La Hague fault zone, described as an active fault during the Quaternary (Lagarde, Amorese, Font, Laville, & Dugué, 2003). The presence of Cretaceous chalk in the northern block at the same height than the Proterozoic crystalline rocks supports the previous interpretation of an uplifting southern block (Lagarde et al., 2003) suggesting a post-Cretaceous uplift, possibly related to the Alpine deformation. The rectilinear shape of the contact in map view discards the possibility of a simple onlap of the Cretaceous chalk on a steep surface developed in the crystalline rocks.

On the shallow platform, we identified two clear different morphologies on our bathymetric map that correspond to (i) Proterozoic crystalline rocks (Figure 4(B)), and (ii) Paleozoic sedimentary rocks (Figure 4(E)). On our bathymetric map, the crystalline rocks are characterized by a dense network of fractures that are similar to those on the aerial photograph from the Goury rocky platform (Figure 4(D)). The fracture set striking N45 may correspond to Cadomian fractures and the fracture set striking

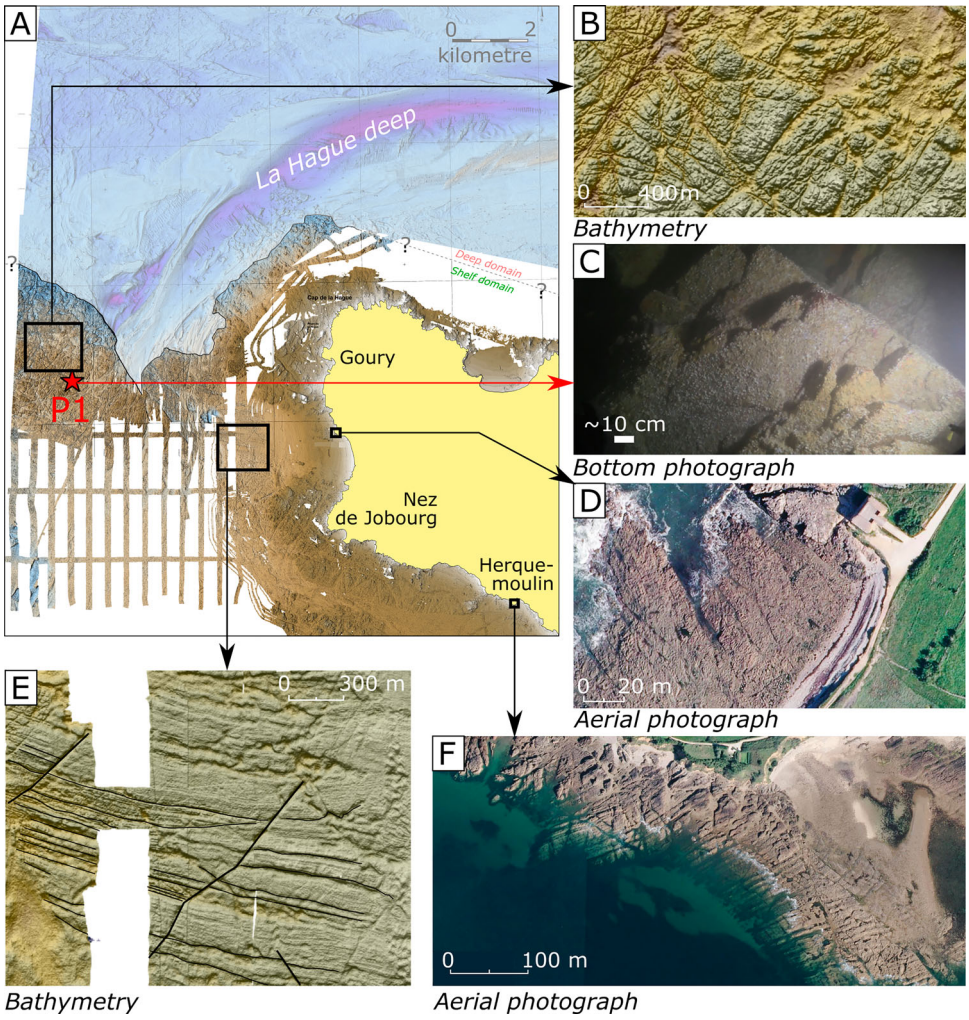

Figure 4. Examples of the bedrock morphologies in the shallow platform. (A). Bathymetric map of the Alderney Race showing the location of the detailed views of the bedrock (B and E), aerial photographs (D and F) and submarine photograph (C). Crystalline Proterozoic (B) and sedimentary Paleozoic (E) bathymetric morphologies compared to their coastal equivalents from aerial photographs from the Baie d'Ecalgrain (D) and Herquemoulin rocky platform (F).

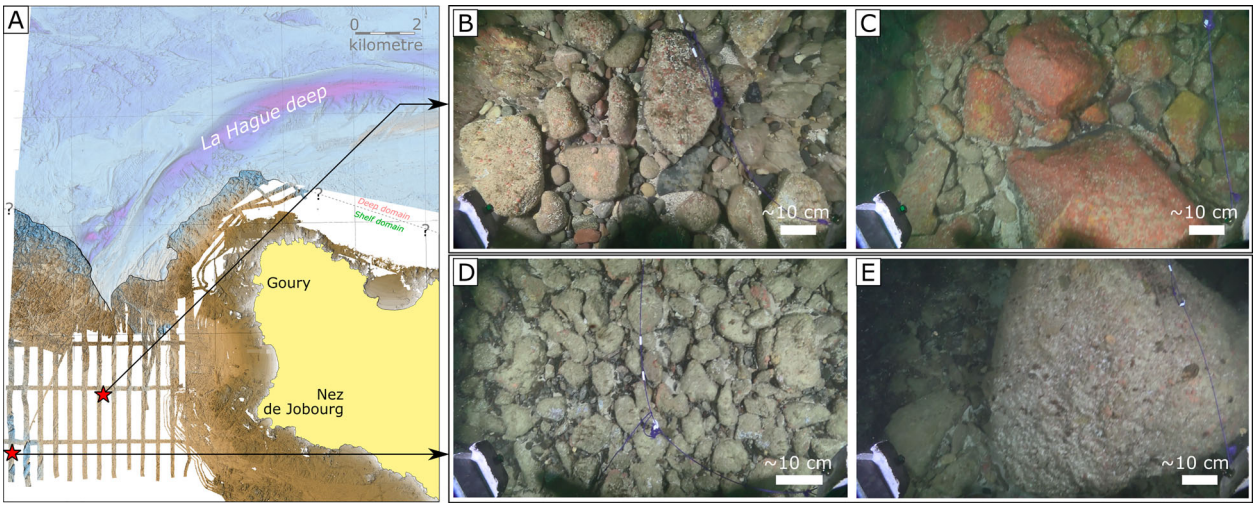

Figure 5. Examples of cobbles and blocks with fixed fauna and possible corestones in the shallow platfrom. (A). Bathymetric map of the Alderney Race showing the location of the submarine photographs. (B and D). submarine photographs showing cobbles with fixed fauna. (C and E). submarine photographs showing possible corestones.

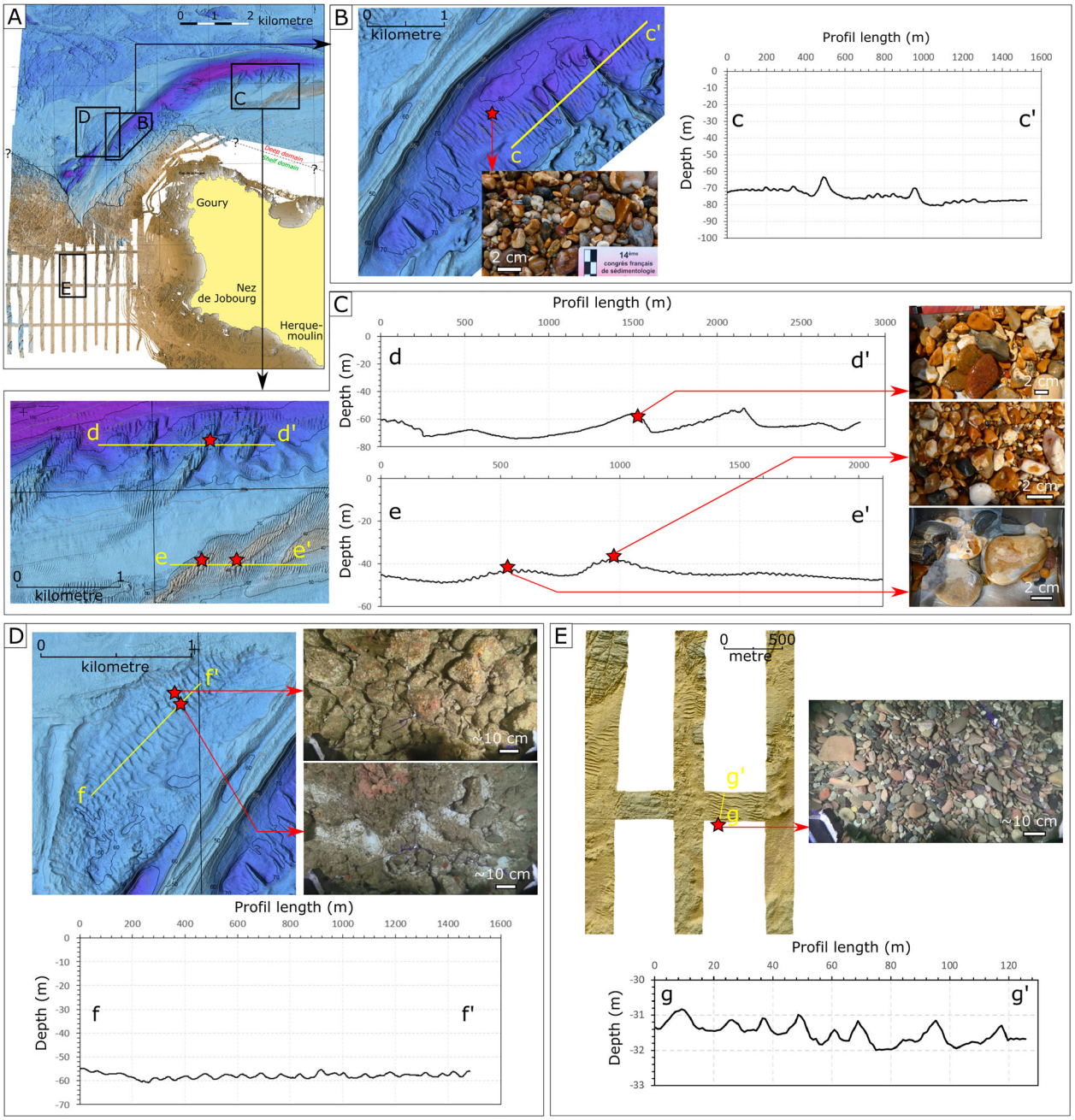

Figure 6. Examples of giant to very large dunes field in the Aldernay Race. (A). Bathymetric map of the Alderney Race showing the location of the dune fields presented in this figure. (B and C). Detailed bathymetric map, longitudinal transects and Shipek grab samples of active dunes fields in the La Hague deep. (D). Detailed bathymetric map, longitudinal transect and submarine photographs of inactive dunes fields west of the La Hague deep. (E). Detailed bathymetric map, longitudinal transect and submarine photographs of active dunes fields in the shallow platform.

N110 may correspond to Variscan fractures. The Paleozoic sedimentary rocks are recognizable by tilted beds visible on the high-resolution bathymetry map and are similar to those on the aerial photograph from the Herquemoulin rocky platform (Figure 4(F)). Our mapping of crystalline and Paleozoic sedimentary rocks facies is supported by offshore-onshore correlations, as we identified the offshore continuation of the Jobourg and Siouville Synclines (Figure 1(B)).

The Siouville Syncline is covered by blurry bathymetric morphology suggesting a Quaternary sedimentary cover confirmed by our videos. Our videos show that these sediments consist of angular and cobbles larger than 2 cm covered by fixed fauna (Figure 5(B,D)). Their angular shapes suggest limited transport and thus they may result from cryofracturing of the bedrock when the area was emerged during Quaternary cold periods, as proposed by Hommeril (1967) and Larsonneur and Walker (1982). Some very large blocks observed from our video (several decimeters, Figure 5(C,E)) may be interpreted as corestones resulting in differential erosion and alteration of the substratum.

4.3. Present-day sediment

Several subaqueous dune fields are observed across our study area (Figure 6), similarly to other areas of the English Channel (e.g. Ferret, Le Bot, Tessier, Garlan, & Lafite, 2010; Reynaud et al., 2003).

For the dune description, we use the classification defined by the SEPM Bedforms and Bedding Structures Research Symposium and details by Ashley (1990) and Berné et al. (1989). We provide the first-order parameters: wavelength (λ), height (h) and shape (2D or 3D). For some dune fields, we add second and third-order parameters like superposed bedforms, sediment size or water depth. These parameters are summarized in Table 1.

On the entire area, fields dunes are observed from 20 to 80 m bsl. In all cases, these dunes can be classified as large to giant dunes (Table 1). North of La Hague Cape (Figure 6(C)), large dunes are superposed on giant dunes with two different crest orientations. In this area, the orientation of the crests is systematically perpendicular to the tidal current. For the dune field e-e′ on Figure 6(C), dunes are N60° for the giant dunes and N35° for the large dunes corresponding to ebb and flood currents, respectively. In the transect d-d′ (Figure 6(C)), the crests of giant dunes are striking N45° and the crests of large dunes are striking N02° corresponding to the perpendicular direction of ebb and flood currents, respectively (Figure 1(D); validated by Bailly du Bois et al., 2012 and Thiébot et al., 2015). We noted that the profile d-d′ (Figure 6(C)) show an asymmetric shape indicating a flood dominance, confirmed by the current dynamic (Figure 1(D)).

In La Hague deep, the current field (Figure 1(D)) shows that the flow is driven by the deep geometry. Where the currents are fastest (red arrows Figure 1D), the longitudinal profile c-c′ (Figure 6(B)) shows an alternation of giant and large dunes (Table 1).

Southward, the shallow platform surface composed by the cobbles encrusted by the fixed fauna is covered by dune fields (Figure 6(E)). The videos show that these dunes consist of rounded pebbles without the development of fixed fauna suggesting a probable activity by bedload transport. These large dunes are striking from N90° to N115° orthogonal to the current and have a symmetrical profile (g-g′ Figure 6(E)) in cross section as the tidal current intensity (Figure 1(D)).

North of the small deep (Figure 6(D)), our bathymetric map shows a peculiar dune field. These dunes are symmetrical, with a wavelength of 620 m and a height of 1.9 m (transect f-f′ Figure 6(D)). Their height is low compared with their wavelength according to the classification of Ashley (1990) and Berné et al. (1989), and are composed of cobbles and blocks with fixed fauna (photographs Figure 6(D)) suggest that these dunes are currently inactive.

Table 1. Dunes parameters with the location in Figure 6.

	Main bedform					Secondary berform						
	Spacing (λ)	Height (h)	Orientatio n	Shape	Dune type	Alternation or Superposition	Spacing (λ)	Height (h)	Orientation	Second dune type	Estimation of particle size	Depth (d in m bsl)
Profile c-c′ Figure 6B	150 m	10,8 m	N145°	2d	Giant or very large dunes	Alternation	38 m	1,22 m		Large dunes	Rounded pebbles	70–80 m
Profile d-d′ Figure 6C	660 m	8,6 m	N45°	2d Asymetric	Giant or very large dunes	Superposition	20 m	2,1 m	NO2°	Large dunes	Rounded pebbles	60–70 m
Profile e-e′ Figure 6C	550 m	6,8 m	N60°	2d Symetric	Giant or very large dunes	Superposition	30 m	1,2 m	N35°	Large dunes	Rounded pebbles	40–50 m
Profile f-f′ Figure 6D	620 m	1,9 m	N140°	2d	–	–	–	–	–	–	Angular cobbles and blocks with fixed fauna	55–60 m
Profile g-g′ Figure 6E	12 m	1 m	N90° to N115°	2d	Large dunes	–	–	–	–	–	Rounded pebbles	30–31 m

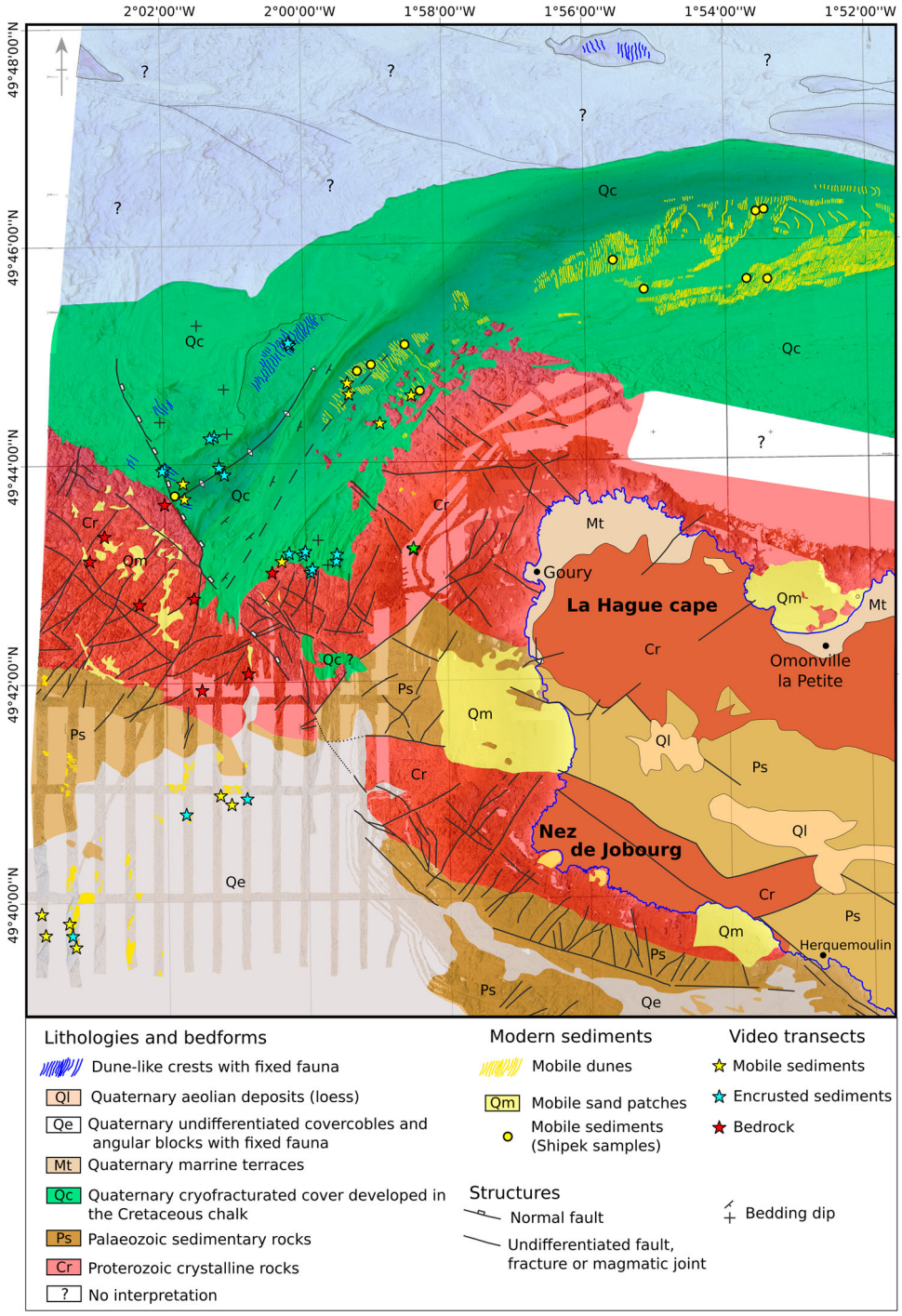

Figure 7. Non-exhaustive geological-sedimentary-dynamic map. The BRGM geological map is used for the onshore part and interpretations from our videos, Shipek samples and bathymetric map for the offshore part. The samples points are added and are colored according the dynamic dominance (mobile or sediments covered by fixed fauna).

As mapped on the Shom database, sediments are relatively rare in the area of maximum velocity. However, except for the last dune field, dunes are composed of rounded pebbles (photographs Figure 6(B,C and E)), mainly of flint rocks suggesting the presence of sediment available for transport (located on the final map by fine yellow and blue lines). In addition, we observe rounded pebbles in fractures in the crystalline rocks. These fractures creating large depressions (up to 200 m^2) are identified on the bathymetric map by blury zones (Figure 4(B)). And finally, we found large boulders, pebbles and sand at the foot of the scarp separating the shallow and the deep domain. The largest blocks are probably derived from the scarp and transported by gravitational processes. The finer sediments may move northward during the flood and southward during the ebb. However, the 15–50 m high scarp acts as a barrier for the coarse sediments.

5. Conclusions

Our new bathymetric map coupled with video acquisition at the sea floor, sediment samples, bathymetric morphology interpretations and onshore-offshore

correlations allows the building of a new geologic and sedimentologic map of Alderney Race (Figure 7). The main results highlighted by this map are summarized below.

- The shallow platform (from 0 to 35 m depth) is characterized by Proterozoic crystalline rocks and Paleozoic sedimentary rocks, partially outcropping. The Paleozoic sedimentary rocks are exposed in the Jobourg and Siouville Synclines that extend from offshore areas to the Cotentin Peninsula.
- The deep domain (from 50 m up to 90 m bsl) is characterized by Upper Cretaceous chalk exposures. In this domain, two distinct troughs are identified: the La Hague deep and a secondary small deep. The La Hague deep results of fluvial incision by a Quaternary paleo-tributary of the Seine River (Antoine et al., 2003). The small deep may be the result of karstic processes affecting the Cretaceous chalk, during the Pliocene-Pleistocene lowstands.
- The deep domain and the shallow platform are separated by a 15–50 m high scarp that belongs to the Alderney – La Hague fault zone, described as an active fault during the Quaternary (Lagarde et al., 2003).
- In several places, a coarse sedimentary cover is found dominated by angular cobbles and boulders covered by fixed fauna. These sediments are interpreted as Quaternary periglacial slope deposits and corestones resulting in cryofracturation of the bedrock.
- Up to four dune fields are identified on our map and the highest dunes are up to 10.8 m high in the La Hague deep. These dunes are commonly composed of pebbles and are orthogonal to the current directions calculated from the MARS2D regional model. The orientation of the dunes is partially driven by the La Hague deep that controls the orientation of strong tidal currents. Conversely, the strong currents prevent the filling of the La Hague deep, preserving the bathymetry.
- Small patches of fine-grained and possibly mobile sediments are mapped in protected areas as in the Vauville, Ecalgrain or Saint-Martin bays. Similar sediments are observed using the underwater videos in fractures in the substrate and between the cobbles and boulders.
- Our map shows a complex bathymetry with several features at the sea floor, such as corestones, thermokarstic depressions and large dunes. Although the MARS2D numerical model (resolution of 100 m) gives consistent results on average flow direction and intensity at the regional scale, future higher resolution models for turbulence estimation may take into account the complex bathymetry described in this paper. For example, the 15–50 m scarp related with the Alderney – La Hague fault zone may generate strong hydrodynamic effects in the water column, during the ebb, as it creates a steep barrier orthogonal to the ebb currents.

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Disclosure statement

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Software

The high-resolution bathymetry has been processed with QGIS. Final editing of other figures was performed using InkScape.

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