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Geomorphology of four wave-dominated microtidal Mediterranean beach systems with *Posidonia oceanica* meadow: a case study of the Northern Sardinia coast

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ABSTRACT

The results of this geomorphological study, which focuses on four Mediterranean embayed microtidal wave-dominated beach systems and the related inner shelf, are reported on a detailed geomorphological map (1:12,000 scale). The study area is located between Punta di Li Francesi and Lu Poltiddolu in NW Sardinia, W of the Strait of Bonifacio. The **Main Map** presents geomorphological, sedimentological, hydrodynamical and ecological (underwater vegetation) features indicated in nine sections of the map legend. Integrative maps (1:40,000 scale) of side-scan sonar surveys, sedimentary facies, survey routes and sampling point locations are also represented on the **Main Map**. This work summarizes 25 years of historical geomorphological datasets and can be considered as a reference for future comparisons of the study area as indicated by current European legislation. In addition to the scientific value of this study, the proposed map can be an important tool for coastal, beach and inner shelf management.

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Morphosedimentology; ecogeomorphology; embayed microtidal wave-dominated beach; *Posidonia oceanica*; coastal management; Strait of Bonifacio

1. Introduction

This work describes the geomorphological features of four microtidal embayed Mediterranean wave-dominated beach systems and related inner shelf. The study covers the area between Punta di Li Francesi and Lu Poltiddolu, which is divided into two sectors (Figure 1), with particular attention paid to the morphosedimentological processes, forms and deposits. The main purpose of this work is to describe geomorphological, sedimentological, morphodynamical processes through coastal integrated mapping that also supports the understanding of ecological issues, as previously demonstrated for key Mediterranean, Australian and Strait of Magellan sites (De Muro, Di Grande, Brambati, & Ibba, 2015; Pennetta et al., 2016; Tecchiato, Buosi, Ibba, Ryan, & De Muro, 2016).

The study area is located in the Strait of Bonifacio (W Mediterranean Sea), in N Sardinia (Figure 1), and has been studied by the Coastal and Marine Geomorphology Group (CMGG) of the University of Cagliari since the 1980s. This work aims to contribute towards planning strategies for improved environmental conditions in the marine environment by providing historical geomorphological datasets for identifying type-specific reference conditions to be used for further comparisons. This information is required by the Marine Strategy Framework Directive (EC, 2008) and

environmental conditions in the area are expected to show improvement by 2020.

Brambati and DeMuro (1992a, 1992b) established the first geomorphologic and morphodynamic research on the beach systems of the study area, with successive studies focused on the mapping of Pleistocene-Holocene palaeo-shorelines (Brambati & DeMuro, 1992c) and recent marine sediments (De Muro, Ferrara, Follesa, & Ibba, 2004). At a later stage, the studies (De Muro, Batzella, Kalb, & Pusceddu, 2008) were continued thanks to new research projects financed by the RAS (Regione Autonoma della Sardegna). In particular, in-depth research (De Falco et al., 2014) was conducted on the *Posidonia oceanica* (L) Delile meadow (De Falco, De Muro, Batzella, & Cucco, 2011; Simeone, De Muro, & De Falco, 2013) and its 'factory' role for the production of carbonate sediment in the Mediterranean area (Batzella et al., 2011; Pusceddu et al., 2011). *P. oceanica* meadow is protected by EU legislation including the Habitat Directive (Habitat Type 1120; EC, 1992), the Water Framework Directive (2000/60/EC) and the EC (2008). The importance of seagrass in protecting the coastline from erosion is well-recognized (Ondiviela et al., 2014). In particular, *P. oceanica* meadow has been found to reduce littoral erosion thanks to attenuation of hydrodynamic forces, increased sediment retention and reduced sediment



Figure 1. The study area is located in Western Mediterranean Sea, and can be divided into two sectors, A and B, including four beach systems.

resuspension (Gacia & Duarte, 2001; Vacchi et al., 2016). These factors contribute to beach stability, further enhanced by biogenic sediment supply from the meadow (De Muro & De Falco, 2015; De Muro, Ibba, & Kalb, 2016).

The present map summarizes data acquired and processed from 1990 to 2015 and contains topographic-bathymetric, echographic, sedimentary, ecological and hydrodynamic information.

The [Main Map](#) shows coastal processes and dynamics of the studied area and describes morphological features, hydrodynamics and sedimentological

features (distribution of siliciclastic and bioclastic sediment, and sediment facies).

The legend is made up of 51 descriptors, divided into 9 sections.

- Geological basement and structural elements: structural and geological features.
- Forms, processes and deposits of backbeach: Aeolian deposits and forms of the four principal beach systems.
- Form, processes and deposits of the backshore: different features of the backshore. This information

includes areas affected by the deposition of ‘seagrass berm’ (Banquette) according to Simeone, De Falco, Como, Olita, and De Muro (2008) and De Falco et al. (2008).

- Forms and processes of shoreface and inner shelf: small-scale geomorphological features and hydrodynamic processes observed on shoreface and inner shelf.
- Sediment features of beach system and inner shelf: sedimentary features according to their environmental origin (siliciclastic or bioclastic) and texture, as well as the sedimentological characteristics of intermattes (coarse and very coarse bioclastic sediment).
- Other sea bottom features: benthic characteristics of the sea bottom, such as distribution of underwater vegetation, beachrock and other undifferentiated rocky outcrops.
- 7–9. Hydrographic features, topographic and bathymetric features and man-made forms: these support an understanding of hydrographic, topographic and bathymetric features as well as other forms linked to human activity.

2. Geographical and geological setting

The coastal area shown on the map extends for a total of 17 km and includes four main beach systems: Vignola, Lu Tuvunatu, Naracu Nieddu-Lu Litarroni-La Piana and Rena Matteu-Bureddaggia-Rena Majori-La Licia (Figure 1). These beach systems were defined based on the mapping scale and selecting beaches of dimensions that allow mapping of shoreface features. These systems extend for 1263, 1610, 313 and 1039 m, respectively, showing a prevalent SW–NE orientation.

The coastal stretch analyzed in this work is mainly exposed to wind and waves between 000° and 270° (Figure 2(B) and 2(C)), given the prevalent storm events are Mistral and westerly winds (Bertotti & Cavaleri, 2008). The resulting dominant swell waves (more than 500 km of the maximum geographical fetch) come from the NW (Figure 2(A)), with the maximum significant wave height reaching 7.5 m. This generates a high-energy wave climate, with the mean wave power reaching 6.3 kW/m for the wave crest (ECMWF 1979–2012 data) and shown in Liberti, Carillo, and Sannino (2013). The study area is protected from E, SE, S and SW storms, but winds blowing from these directions should not be overlooked in relation to deflation processes. These winds are less persistent, but intense (Figure 2(C)), and, by blowing from the land, contribute to sand transport seawards.

The study area is divided into two main sectors (Figure 1): Sector A, between Punta di Li Francesi and Monti Russu, and Sector B, between Monti

Russu and Monti Biancu. The resulting main wave exposure angles and geographical fetches are measured with the QGIS software for Sector A between 277° and 304° (500 km fetch), and for Sector B between 266.5° and 303° (500 km fetch), as shown in Figure 2(A).

The first beach system mainly receives potential sedimentary input from the hydrographic basins of Riu Vignola (57 km²) and Riu la Foci (6.3 km²); the second from Riu li Saldi (11 km²); the third from Riu lu Litarroni (5.1 km²) and Riu Sperandeu (16 km²); and the fourth from Riu sa Faa (4.4 km²), Riu lu Cantaru (5.6 km²) and Riu Giuchessa (10.7 km²).

The geological basement of this area is characterized by Paleozoic rocks of the Hercynian granitoid complex (Sardinian-Corsican Hercynian batholith – Upper Carboniferous-Permian), as explained by Carmignani et al. (2008) and VV.AA. (2008). The outcropping rocks have a typical sequence of intrusive events with variable compositions represented by tonalities to leukogranitic, monzogranitic and granodiorites plutons (290–300 M.y. ago).

Five intrusive units were recognized in the examined area (Figure 3). All the outcrops are covered by either colluvial detritus and scarce alluvial deposits or soil with gravelly and sandy horizons, which are produced by the in-situ erosion of granite. These soils are drained and transported seawards by the rivers noted above.

A basalt sill-type complex, together with veins of granitic porphyries, masses of microgranites, and aplitic and pegmatitic veins (Carmignani et al., 2001), are also present and are mainly oriented NW–SE and NNW–SSE. This dyke swarm, which is typical of NE Sardinia, is arranged along late Hercynian fracture lines and defines the morphostructural arrangement of the entire region and the hydrodynamics of the four beach systems. The Quaternary lithologies are mainly characterized by Pleistocene and Holocene deposits. The former are made up of terraced alluvial gravel, with subordinate Aeolian sandstone (upper Pleistocene-Holocene).

Holocene beach deposits are present, with thicknesses ranging from 1 to 3 m, and are made up of sand, sandstone, calcirudites, bivalve gravel, gastropods with subordinate sandy-silty deposits, and calcilutites. The Holocene deposits belong to both littoral and alluvial environments. In the shoreface zone of the first and third beach systems (see Figure 1), sandstone and conglomerates have been found in facies of beachrock. According to previous studies (De Muro & Orrù, 1998), their presence at 0 ÷ –35 m (1791 cal. BP radiometric age) is linked to the Middle Holocene high stand phase. On the backshore, beach deposits consisting of sand and gravel were also found contiguous to well-classed dune sand Aeolian deposits.

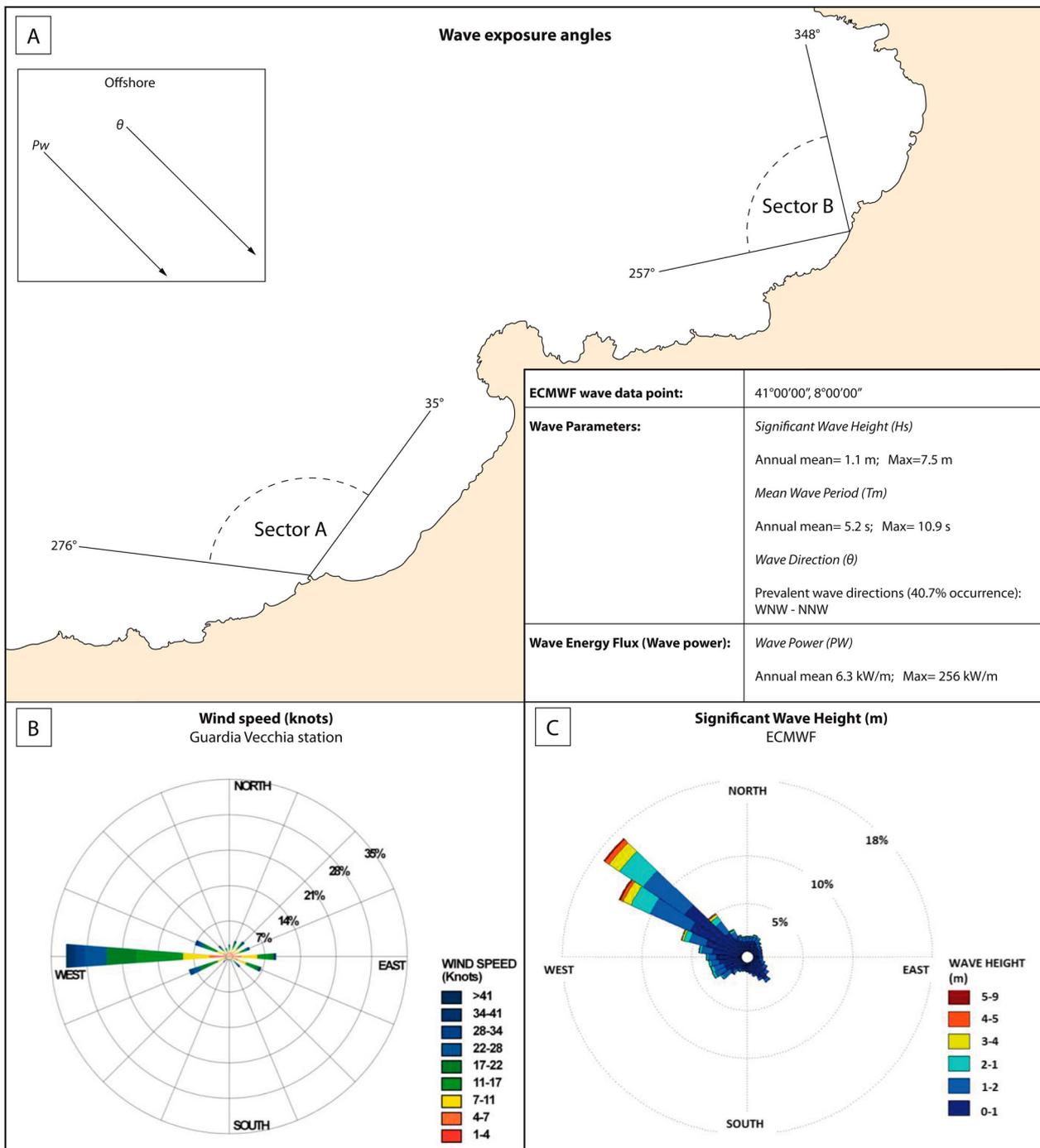


Figure 2. (A) Wave exposure angles of the sectors A and B of the study area. (B) Wind data (Marina Militare–Guardia Vecchia Station–La Maddalena). (C) Wave data (ECMWF located at 41°00'00", 8°00'00" period 1979–2012).

3. Methods

The geomorphological map presented herein integrates the findings of historical studies carried out since the 1980s with newly acquired datasets from the ‘PALEO-CLI.GE 2000’ and VV.AA. (2002) campaigns. The map uses the ‘Carta Tecnica Regionale’ (VV.AA., 1998) 1:10,000 scale as topographic basemap particularly sections 427020, 427030, 427050, 427060 and 427070.

The key is based upon the Guidelines for Italian Geomorphological Maps at a scale of 1:50,000 (VV.AA., 1994), and the Italian Geological Map at 1:50,000 Scale (VV.AA., 2009). The key was integrated

and adapted to suit the aims of this work and, considering available data, the variety of morphological features observed in the area.

The research for drafting the *Main Map* was carried out following the methodology set up by the CMGG at the University of Cagliari (De Muro, Batzella, De Falco, & Porta, 2010; De Muro, Pusceddu, Buosi, & Ibba, 2016). This methodology was established to:

- study the sedimentological and morphodynamic processes of Mediterranean microtidal wave-dominated beaches;

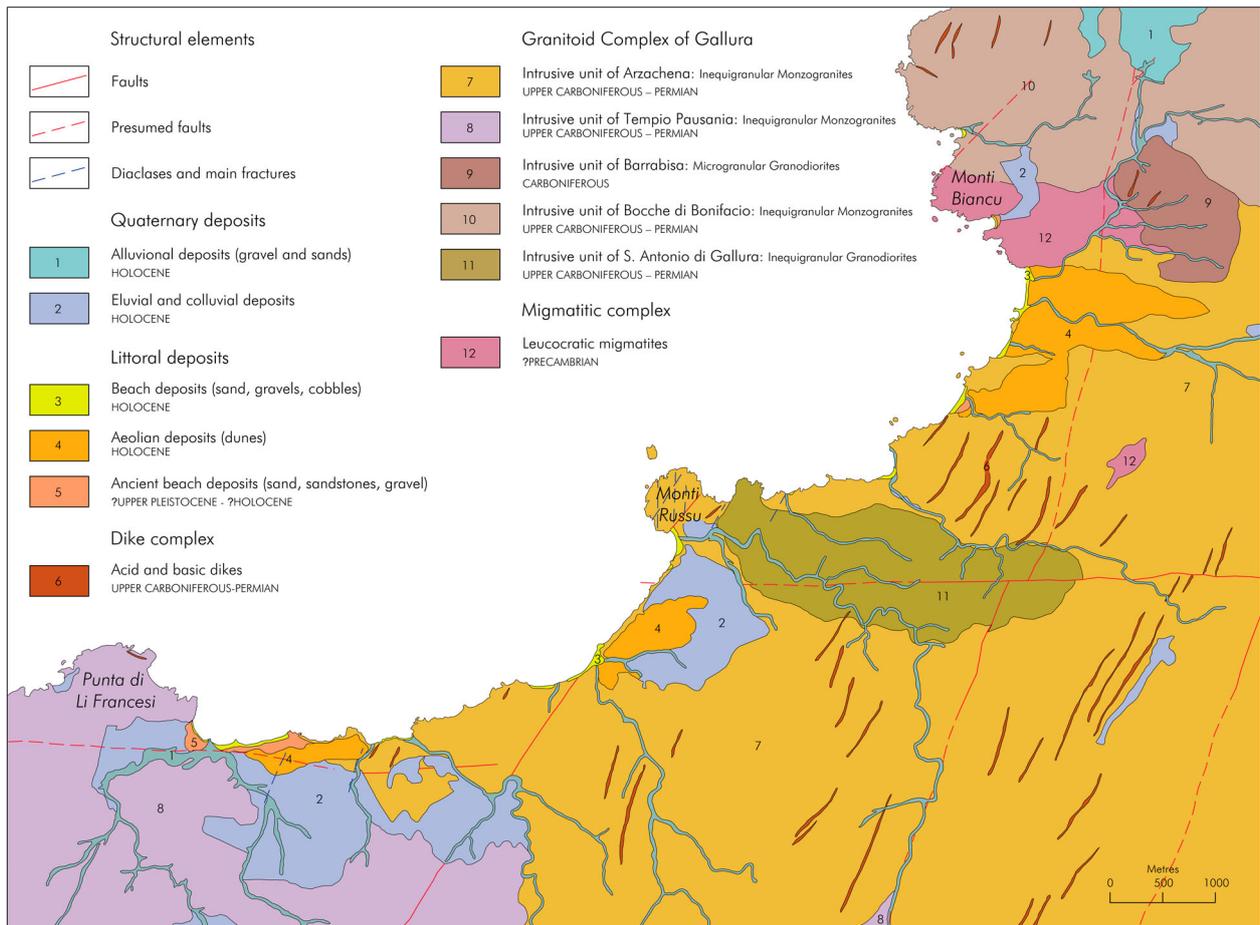


Figure 3. Geological overview of the study area (VV.AA, 2008, modified).

- evaluate the anthropic effects, criticalities and evolution trends; and
- provide guidelines for coastal management.

The reconstruction of the historical evolution of the area is based on the interpretation of aerial photographs which allowed the identification of ‘macro indicators’ such as: dune areal extent; shoreline position; distribution of underwater vegetation (principally *P. oceanica*); rocky outcrops; anthropological elements; and hydrography.

The coastal dunes are classified into two types following Masselink, Hughes, and Knight (2011).

- Primary sand dunes (including fore dunes and embryo dunes), which are located immediately inland of the beach and are significantly affected by wave processes.
- Secondary sand dunes (including mature fore-dune ridges and transgressive dunes), which are located adjacent to and inland of a primary sand dune and are dissociated from wave processes through coastal progradation.

Dune system features are based on the interpretation of orthophotos and a Digital Elevation Model of 2008. The bar axis is the result of the interpretation

of a satellite image (source Google Earth) and RAS orthophotos.

The sea bottom morphology and the bathymetry were derived from research expeditions covering an area extending from Punta di Li Francesi to the promontory of Capo Testa. The instruments used for data collection were a sub-bottom profiler at 3.5, 30 and 33 kHz; side-scan sonar at 100 kHz; and uniboom at 300 J.

All coordinates are based on the UTM – WGS84 datum coordinate system. A total of 216 nm echosounder profiles and 12.5 nm side-scan sonar profiles were obtained (for identification and sea bottom mapping). Based on these surveys, 80 geomorphological scuba dives were undertaken with the aim of defining sandy areas; identifying and sampling palaeo-shorelines in facies of beachrock; and locating the underwater vegetation (principally identified as *P. oceanica*) upper limit.

A total of 136 sediment samples were taken along transects perpendicular to the shoreline using a grab with a 5 dm³ capacity for the shoreface (following the method of Carobene & Brambati, 1975). The location of these surveys is displayed on the integrative maps (‘survey routes and sampling point map’, ‘sedimentary facies map’ and ‘side-scan sonar survey map’) of the Main Map.

The sediment samples were analyzed following standard sedimentological methods (texture, composition and facies analysis). The grain size distribution was determined following the American Society for Testing Materials (ASTM) international standard methodology, with sieves spaced at $\frac{1}{4}\Phi$ between 2000 and 63 μm (Wentworth, 1922). The mineralogical composition of each sample was determined using binocular microscope analysis. The volume percentage of each mineralogical and compositional class was determined using the areal comparison method (Lewis & McConchie, 1994). The samples were grouped in compositional facies following the general classification already used in the Sardinia area (Lecca, De Muro, Cossellu, & Pau, 2005) and implemented for the Strait of Bonifacio by De Falco et al. (2011).

The bathymetric and sedimentological data obtained in this study were used as the input parameters for wave and hydrodynamic models. In order to understand the main factors regulating local morphodynamics, numerical simulations of wave and coastal currents were performed using the Deltares DELFT3D software (<http://oss.deltares.nl/web/delft3d>). Significant case studies of stormy events were selected for the simulations from wave climate data of the European Centre for Medium-Range Weather Forecasts (ECMWF), covering the period 1979–2012 and located at 41°00′00″, 8°00′00″.

4. Sedimentological and hydrodynamic features

The geomorphology of the main shoreface sedimentary features (e.g. bar and trough) is the result of local hydrodynamic processes (e.g. longshore and rip current), which influence the distribution of superficial sediments. An in-depth analysis of sediment samples was carried out to confirm this.

The exchange and mixing of sediment between backshore and shoreface was identified, and this is due to the strong and storm-induced hydrodynamic currents. Consequently, bimodal and polymodal sediment formed, mainly berms, shoreline and the beach step. In Sector A, relict sediment was found at a depth of 20 m. This sediment is only slightly related to the present dispersion phenomena and characterizes the transitional zone between the beach step and berms. This feature likely represents a Holocene palaeo-shoreline. Lithogenic sediment was found to derive from intrusive, volcanic and metamorphic rocks.

Three main types of benthic cover were identified using a combination of side-scan sonar sonograms, aerial photographs and scuba diving surveys: uncolonized sediment, rocky outcrops and underwater vegetation (Bartole & De Muro, 2012; Fish & Carr, 1990).

(1) The uncolonized sandy substrate was found in Sector A, mainly in Vignola (to about 40 m depth, due

to sediment supply from the delta of Riu Vignola and Riu di La Foci) and Lu Littarroni zones (to about 15 m depth). In Sector B, this substrate was identified mainly in the fourth beach system, extending from the shore to –40 m depth.

- (2) The rocky outcrop extends almost continuously, from the shoreline to a maximum 10 m depth along both sectors of the study area, with an interruption in the vicinity of the first and fourth beach systems.
- (3) The underwater vegetation covers an almost continuous region extending from a depth of about –5 m and, in some cases –10 m, to about –35 m, reaching a maximum at –45 m in front of Monti Russu. Three main interruptions in the meadow (showing sandy substrate dominance) were recorded off the first and fourth beach systems, the latter showing a larger extent.

Generally, there are two main complex systems of submerged bars and troughs off the third and fourth beach systems.

The surf zone is, on average, between 400 and 550 m wide. The morphodynamic beach state (according to the classification of Short, 1979) is principally rhythmic bar and beach (RBB) and longshore bar and trough (LBT). In the third and fourth beach systems, a multi-bar setting has been observed, which consist of two bars in the third system and up to three bars in the fourth system.

The beaches examined are wave-dominated (the main phenomena affecting the coastal morphodynamics are waves), and have a microtidal regime.

Three main storm directions were chosen to simulate three primary possible scenarios driving coastal morphodynamics: W, NW and N. Waves, tides and sedimentological and bathymetric data were the inputs for these hydrodynamic models.

Storm Waves from the W generate eastward and northeastward longshore currents along both sectors, and these increase in velocity E of Monti Russu. The longshore currents break into two main rip currents, one of those is more intense in proximity to Monti Russu, and the second occurs offshore of the fourth beach system (Figure 4). At both locations, it seems that the coastline configuration acts as an obstacle to the longshore flow, resulting in an offshore deviation which creates two rip currents. The two areas which were affected by longshore drift first, and by rip currents later, have a similar bottom configuration:

- an opening in the *P. oceanica* meadow;
- a deposition of fine sand longshore (generally at –5 m); and,
- medium sand moving offshore;

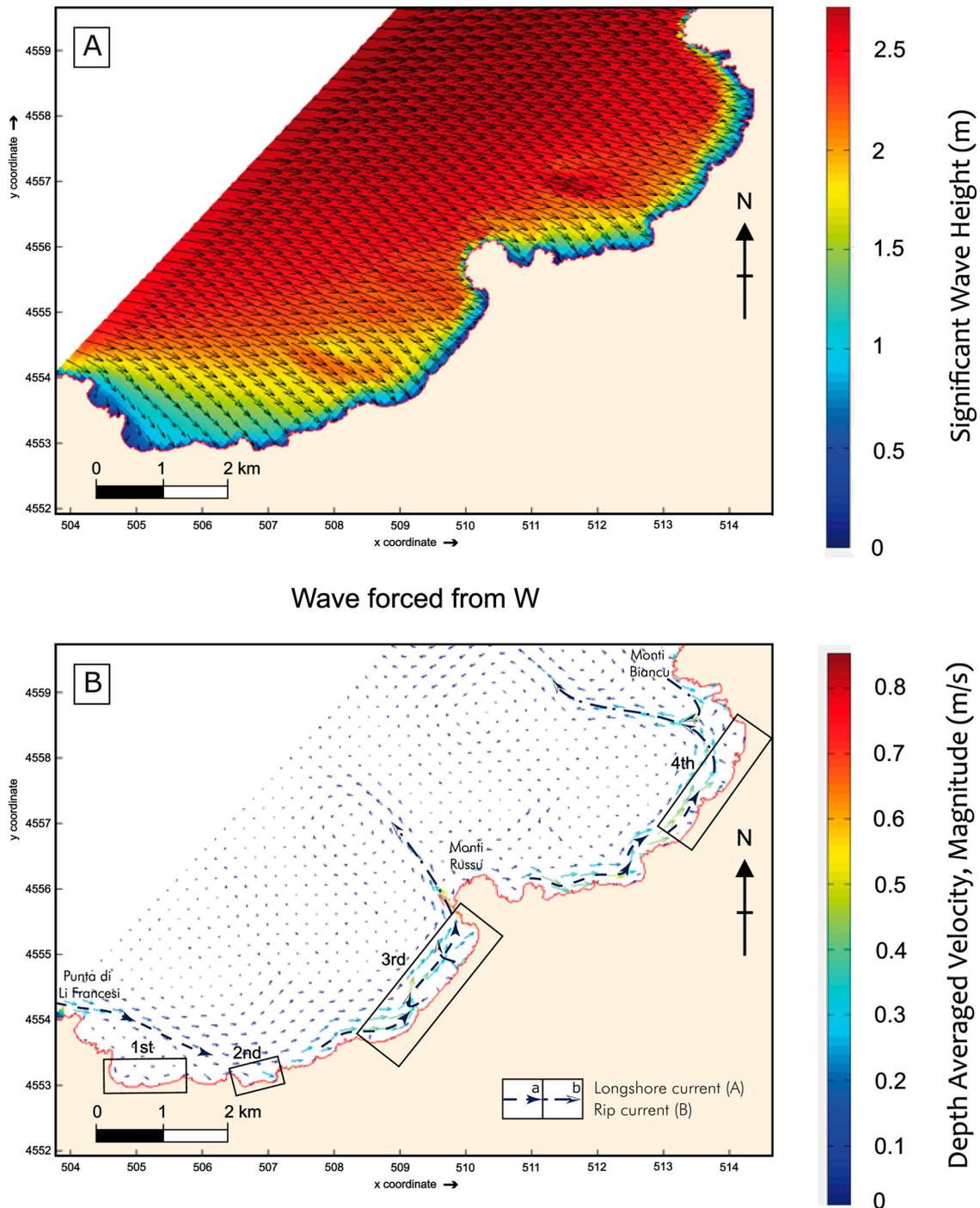


Figure 4. Wave and hydrodynamic models forced by waves from the W, 24 h storm duration. (A) Wave model; (B) Hydrodynamic model.

In the case of Sector B, a deposition of fine sand further offshore is found (from -15 m to -40 m).

In the NW scenario, an intense eastward shore-parallel longshore current enters the studied embayment from the W and accelerates after the Monti Russu promontory (the acceleration corresponds to abrasion platforms in all the simulated scenarios). The longshore current recirculates in two small vortices with negative vorticity (Figure 5). The bathymetry drives wave transformation toward the coast, creating wave power hot-spots (areas where the wave energy

concentrates). The wave action controls the seabed morphology, shaping it (openings in the *P. oceanica* meadow have been found in both sectors, corresponding with hot-spots where the rocky outcrops are located). Rocky outcrops and abrasion platforms therefore influence the current flow, which accelerates on those morphologies. The morphology and hydrodynamics are interconnected, influencing each other reciprocally. The process of acceleration on the abrasion platforms is an example of the links between the hydrodynamic simulations and the coastal geomorphology

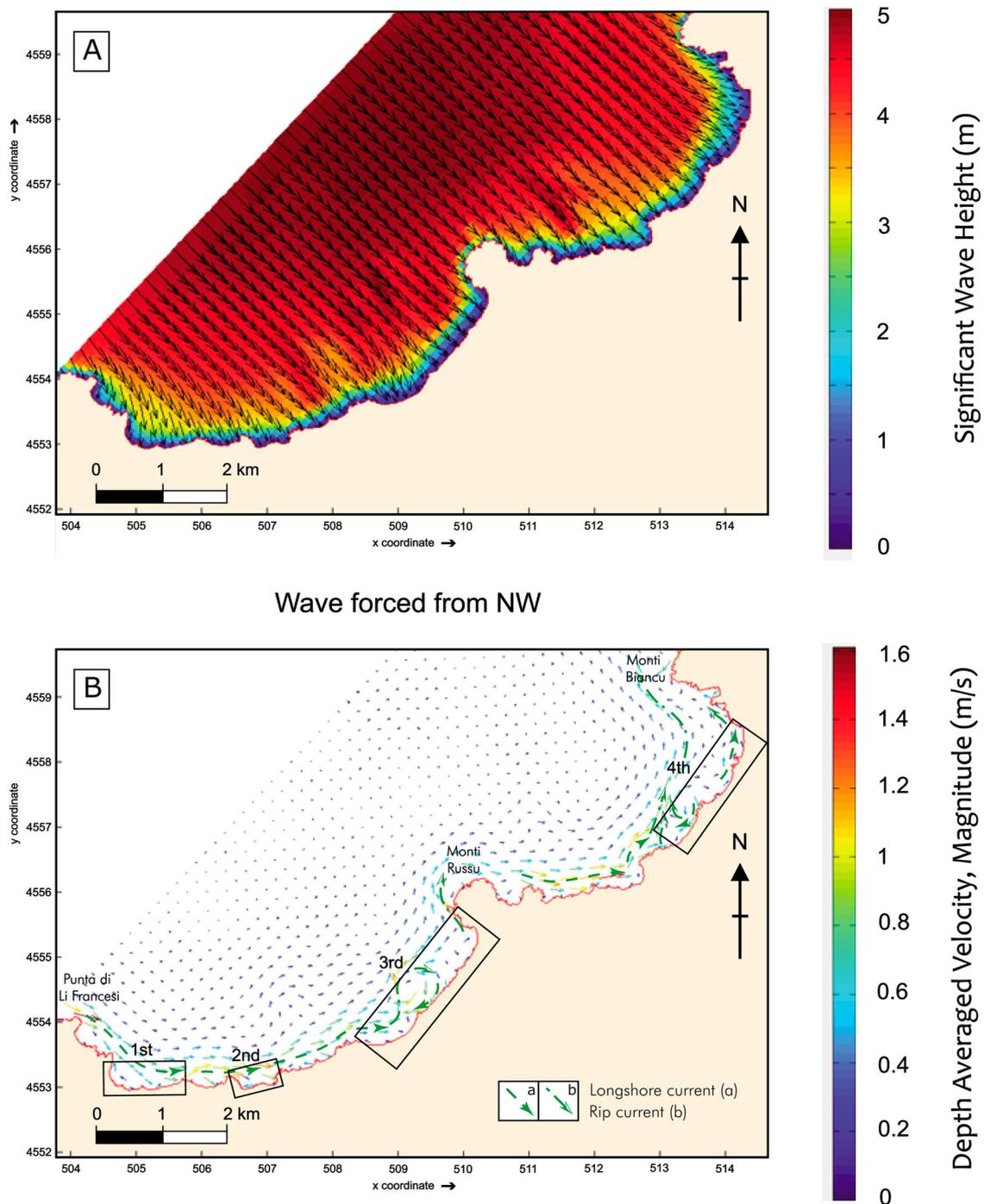


Figure 5. Wave and hydrodynamic models forced by waves from the NW, 24 h storm duration. (A) Wave model; (B) Hydrodynamic model.

observed in the field; as well as the opening in the *P. oceanica* meadow corresponding with the rip currents in the two sectors.

With waves coming from the N (Figure 6), two rip currents, a cyclonic vortex and two longshore currents characterize Sector A. The first is an eastward longshore current in the first beach system, while the second is westward. The two longshore currents meet at the boundary between the first and second beach systems, where a northeastward rip current begins. In Sector B, an eastward longshore current recirculates in a topographic vortex with negative vorticity

(clockwise circulation), where a northwestward rip current originates.

With storms from the NW (Figure 5) and N (Figure 6), a coastal vortex with negative vorticity takes place W of the fourth beach system. In all scenarios, a rip current corresponding with the fourth beach system is simulated by the hydrodynamic model. The *P. oceanica* meadow is interrupted in exactly the same zone, probably due to the intense coastal hydrodynamics in the area, leaving room for further investigations and *in-situ* measurements to allow validation of these preliminary observations.

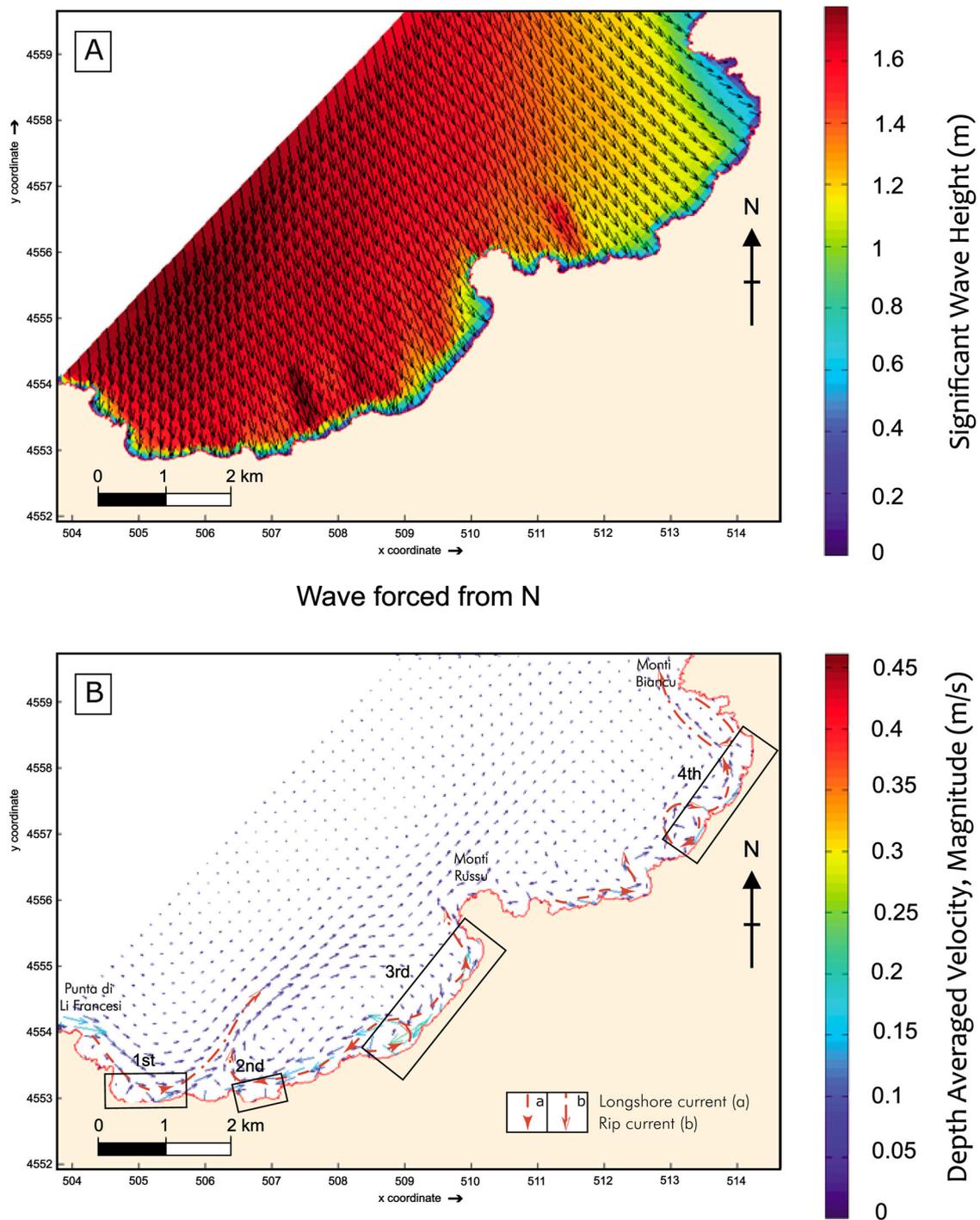


Figure 6. Wave and hydrodynamic models forced by waves from the N, 24 h storm duration. (A) Wave model; (B) Hydrodynamic model.

5. Conclusions

Largely recognized *P. oceanica* functions (e.g. production of biogenic/bioclastic material, reduction of wave energy) and substrate type control the retention of sediment in the upper shoreface zone, allowing beach systems to survive very high-energy storms in the studied area (the mean wave power calculated is 6.3 kW/m, in general accordance with Sannino et al., 2011).

From the wave and the coastal current simulations (forced from the three prevalent storm directions),

some general indications regarding the link between shoreface morphology and large-scale coastal hydrodynamics were recognized; however, more detailed simulations and *in-situ* measurements are needed to confirm the initial findings. Firstly, an acceleration of longshore currents on the abrasion platforms occurs in all the simulated scenarios. Secondly, the flow seems to be restricted between the beach face and the *P. oceanica* meadow upper limit. Thirdly, it seems clear that the general behavior of the upper limit of the *P. oceanica* meadow is, in some cases, driven by

the hydrodynamic regime as already observed in the existing literature in other study areas in the Mediterranean Sea (Brambilla, van Rooijen, Simeone, Ibba, & De Muro, 2016; Vacchi et al., 2014).

The hypothesis in this work of openings in *P. oceanica* meadow upper limit being driven by coastal currents has been confirmed in two locations: in front of the fourth beach system, and W of Monti Russu. In both locations, the meadow interruptions were found exactly where intense (rip and longshore) currents occur as a result of all simulated storm directions; and the *P. oceanica* meadow leaves space for sand-dominated substrate.

In the third and fourth beach systems, the surf zone extends for about 500 m (Brambati & DeMuro, 1992a), and two main systems of submerged bars and troughs were found, and are classified following Short (1979) as principally RBB and LBT.

Further investigation (e.g. hydrodynamic, sediment transport, in field measurements) is suggested for a better understanding of the coastal morphodynamic processes in the studied area, as those processes can be representative of general phenomena. In particular, greater attention is paid in the literature to the connection between the growth of *P. oceanica* and coastal hydrodynamics (Infantes, Terrados, Orfila, Canellas, & Alvarez-Ellacuria, 2009; Vacchi et al., 2014), and the influence that underwater vegetation has on the hydrodynamics (Sánchez-González, Sánchez-Rojas, & Memos, 2011). The present study can be a starting point for investigations of phenomena such as the prediction of the position of the upper limit of the *P. oceanica* meadow, taking into account previously unconsidered parameters (such as the longshore, rip and bottom currents, the effect of abrasion platforms on the flow and generally the influence of different types of sea bottom).

Finally, the **Main Map** presented in this work (integrating geomorphological, sedimentological, hydrodynamical and ecological features) can be used for both coastal management and for future reference of the coastal environment conditions in the studied area for upcoming investigations and comparisons.

Software

The data were processed using Autodesk-Map-3D software to create a georeferenced topographic-bathymetric basemap. This software was also used for the sediment map. The textural sediment classification and grain size parameters were obtained for each sample using the Gradistat software (Blott & Pye, 2001). The WAVE and FLOW modules of the Deltares Delft-3D software were used for simulating wave and coastal currents. QGIS was used to obtain a complete characterization of geomorphological features and map completion. Adobe Illustrator-CS5 was used to

produce the digital cartography, and PDF files for future printing.

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Disclosure statement

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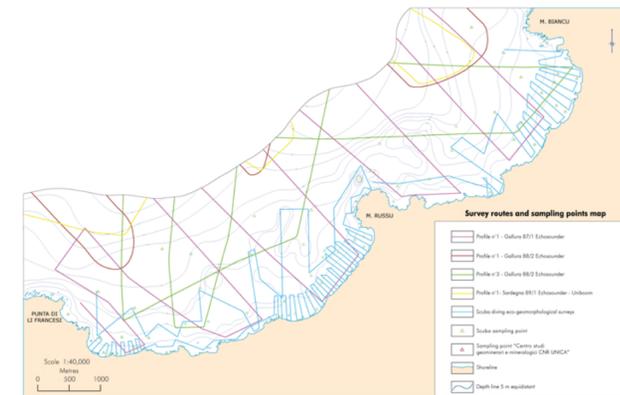
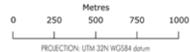


Geomorphology of four wave-dominated microtidal Mediterranean beach systems with *Posidonia oceanica* meadow: a case study of Northern Sardinia coast

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Scale 1:12,000



GEOLOGICAL BASEMENT AND STRUCTURAL ELEMENTS

- Hercynian basement lithologies (palaeozoic), alluvial, eluvial and colluvial deposits (quaternary)
- Faults (A); presumed faults (B)
- Diaclases and main fractures

FORMS, PROCESSES AND DEPOSITS OF BACKBEACH

- Natural: Primary dune, Secondary Dune, Man-made stabilized dune, Urbanized dune
- Human impact: Primary Dune ridge

FORM, PROCESSES AND DEPOSITS OF THE BACKSHORE

- Sand, gravel and cobble of the backshore
- Shoreline: cliff-rock (A); sandy beach (B)
- Shoreline: sandy/gravelly beach (C); gravelly/cobble beach (D)
- Area interested by the deposition of the "seagrass berm" (Banquette)

FORMS AND PROCESSES OF SHOREFACE AND INNER SHELF

- Bar axis, Trough axis, Concave knick point, Ripples marks, Mega ripples, Relief lodges, Abrasion platform, Point of maximum Wave energy transfer

- Longshore current (A); Rip current (B) due to 360° wave direction
- Longshore current (A); Rip current (B) due to 315° wave direction
- Longshore current (A); Rip current (B) due to 270° wave direction

SEDIMENT FEATURES OF BEACH SYSTEM AND INNER SHELF

- Gravel, Very coarse sand, Coarse sand, Medium sand, Fine sand
- Mixed siliclastic-bioclastic/bioclastic gravel and sand
- Biogenic gravel and sand (intermatte)
- Biogenic sand and gravel

OTHER SEABOTTOM FEATURES

- Underwater vegetation, mainly *Posidonia oceanica* (L) Delle
- Beachrocks, Rocky outcrops

HYDROGRAPHIC FEATURES

- Stream (A); River (B)
- Concentrated drainage ditch

TOPOGRAPHIC AND BATHYMETRIC FEATURES

- Contour line (50 m interval), Contour line (10 m interval), Depth line 5 m equidistants

MAN-MADE FORMS

- Motorway and asphalt road, Non-asphalt road, Buildings, Tower (A); Bridge (B)

