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Ecogeomorphology and vulnerability in a Mediterranean ria-type coast (La Maddalena Archipelago, NE Sardinia, western Mediterranean)

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ABSTRACT

This paper presents a map describing the main geomorphological and sedimentological features, hydrodynamics, benthic habitat distributions and human impact on the coastal and marine areas of the Archipelago of La Maddalena (NE Sardinia, western Mediterranean). This cartography is based on an interdisciplinary sea-land approach, with the aim being to support sustainable and successful beach management in the face of a changing climate and environment, thereby contributing to the achievement of the Agenda 2030 Sustainable Development Goals (13, 14 and 15). In the Main Map (1:14,000 scale), the static and dynamic features of the beach systems and adjacent inner shelf are divided into thematic sections that include the geomorphological elements, hydrodynamics, sedimentological distributions, benthic habitat (mainly *Posidonia oceanica* meadow) and anthropogenic impacts. The map establishes a fundamental, multidisciplinary benchmark that is able to provide substantial scientific support to policymakers in relation to future vulnerability-assessment activities and the definition of land-management strategies.

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Geomorphology; coastal management; *Posidonia oceanica*; human impact; sustainability; Mediterranean Sea

1. Introduction

Coastal zones worldwide are exposed to significant pressure from urban development, tourism, industrial production, port activities and agriculture. These human functions are often in conflict with the need to preserve natural coastal systems, whose ecological processes are also essential for human well-being (Agardy & Alder, 2005). Infrastructure and urbanisation in high-density populated coastal areas can drastically limit, and even impede, natural adaptive processes such as the inland migration of dune systems or other morphodynamic adjustments. The impact of human activities is proportionally greater in the Mediterranean than in any other coastal zone globally (Coll et al., 2010). Furthermore, climate models predict that the Mediterranean basin will be one of the regions most sensitive to future climate and environmental changes (Galli et al., 2017; IPCC, 2013; Lejeune et al., 2010). The effects of climate change on Mediterranean coastal areas are expected to be significant, mainly due to interactions with anthropogenic disturbances at a local scale. Low-lying coasts and archipelagos (small islands) are particularly vulnerable, and are at risk of inundation, flooding and erosion due to rising sea levels and the growing frequency and intensity of storm events

(Calado et al., 2011; Kundzewicz et al., 2001; Wooldroffe, 2008). Moreover, in Mediterranean archipelagos, and particularly in Sardinia, the small size of islands, the orientation and exposure of the coasts, and the dearth of fluvial inputs (sediment supply) induce a more fragile and unstable coastal equilibrium. The small embayed beaches of archipelagos mainly receive siliciclastic sediment inputs from the erosion of banks and cliffs, while the authigenic bioclastic sediment component is mainly the product of *Posidonia oceanica* meadows. Such an ecogeomorphological configuration leads, on the one hand, to the formation of small beaches of good environmental quality (sands with unique morpho-sedimentological, compositional and colorimetric characteristics, and high coastal water transparency, which induces better bathing quality). However, on the other, it produces beach systems characterised by a delicate equilibrium that requires appropriate planning and management based on our understanding of the interactions between physical processes, ecogeomorphological settings and urbanisation (Tintoré et al., 2009).

In this context of Sardinia's diversity, the mapping of small coastal systems requires significant effort to synthesise the outputs of studies into a format that is useful to coastal managers. Currently, there are only a limited number of cartographic products that use an

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integrated sea-land approach to identify, understand and describe static and dynamic processes in Mediterranean coastal areas, including in relation to sea-level rise and increasingly common extreme events linked to global warming (Buosi et al., 2019; De Muro, Ibba, et al., 2017; De Muro, Porta, et al., 2017; De Muro, Pusceddu, et al., 2017; De Muro et al., 2018; Porta et al., 2020). This type of multidisciplinary cartographic approach can also help to improve our understanding of the association between humans and their environment. In so doing, it contributes to the implementation of the United Nations Sustainable Development Goals (SDGs) 2030 (UN, 2015), in particular SDG13, SDG14 and SDG15, which are the sustainable use of ocean, marine and terrestrial ecosystems.

In this paper, the focus is on geomorphological processes and anthropogenic pressures on the coastal sectors and inner-shelf zone in the Archipelago of La Maddalena (NE Sardinia, Italy, western Mediterranean; Figure 1). In this context, our study is a key tool for the development of a sustainable and successful beach-management plan (Buosi et al., 2017). This paper aims to: (1) describe ecogeomorphological features, sedimentary facies, benthic habitat, hydrodynamics and human interventions; (2) provide a multidisciplinary benchmark for the medium- and long-term planning of Mediterranean beach management; and (3) identify emerging ecogeomorphological issues that make the analysed coastal stretches more vulnerable to future climate and environmental changes.

2. Study area

2.1. Geographical and geological setting

The study area is in NE Sardinia (Italy, western Mediterranean; Figure 1), on the SE side of the Strait of Bonifacio, and includes the southern section of the La Maddalena Archipelago. The Archipelago covers an area of about 50 km² and consists of seven main islands (Figure 1) separated from the coasts of Gallura by a 20 km-long, roughly WNW-ESE-oriented strait, the Bucinara Channel. This strait has steep flanks (up to 21%) and an almost flat bottom, with water depths ranging from -35 m to -60 m (Bartole & De Muro, 2012). The coastal area is characterised by an alternation of deep bays and headlands, which are controlled structurally by tectonic lineaments.

Geologically, the study area is characterised by Palaeozoic intrusive granitoid rocks belonging to the Sardinia-Corsica Hercynian batholith (Upper Carboniferous-Permian; Carmignani et al., 2001). Also present are porphyritic-microgranite dikes, pegmatites and aplites, as well as calkalkaline, transitional, alkaline-basaltic and quartz-rich dikes, which are mainly oriented NW-SE and NNW-SSE (Carmignani et al., 2016). This dyke complex is arranged along late

Hercynian fracture lines and defines the morphostructural arrangement of the area (Figure A1 in Appendix). Marine deposits from the second Miocene sedimentary cycle outcrop at Capo Testa (Santa Teresa di Gallura). Ancient marine deposits (Pleistocene) and marine-to-continental deposits (Holocene) also outcrop locally (De Muro & Orrù, 1998; Vacchi et al., 2020).

The prevalent winds recorded in the study area come from the NW and are responsible for 68% of the storm events that occur (Bartole & De Muro, 2009, 2012). Winds from the NE are less frequent (19%) and typically blow during the winter (December to March).

2.2. Human occupation

The Archipelago of La Maddalena has always played an important role in the occupation history of the northern Sardinia due to its geographic strategic position. The maritime traffic has been intense since ancient times as this area was a key crossing point for the Phoenician, Punic and Roman trades. Napoleon (as a young navy officer) with a small French Fleet (1793), and Admiral Nelson with his British Fleet (1803) also resided for long time in the area. In the 1900s, the maritime traffic was mainly linked to the presence of the Italian Navy, to commercial and fishing activities and to a USA Navy Base that for 36 years (1972–2008) served as home port for nuclear submarine tenders. Impacts from anchoring in the La Maddalena Archipelago have, therefore, ancient origins. Presently, the maritime activities are mainly driven by the growth of tourism and promoted by the proliferation of ports and touristic resorts (Figure 2, Table 1).

The Archipelago is recognised as a National Park (established in 1994) and as a ‘Site of Community Importance’ (pSIC) under the Habitats Directive (92/43/CEE Habitat) on the conservation of natural habitats and of wild fauna and flora. The area of La Maddalena Archipelago National Park (about 200 km²) and its surroundings host a population of around 95,000 permanent residents (http://osservatorio.sardegnaturismo.it/sites/default/files/2021-04/OsservatorioTurismo_Report2020_20210415_1.pdf) distributed among the historical coastal villages of Santa Teresa di Gallura, La Maddalena, Palau, Arzachena, Golfo Aranci, and Olbia, with a number of boat moorings of about 8,200 (Figure 2, Table 1; <https://tuttobarche.it/porti-sardegna>; <https://m.marinanow.it>). During the summer months, the area experiences a significant increase in population caused by the many tourists visiting the numerous touristic villages in the area. In the last two years (2019 and 2020), the study area, besides the number of permanent residents, registered approximately 3.7 and 1.5 million of total annual overnight stays, respectively (<http://osservatorio.sardegnaturismo.it/>

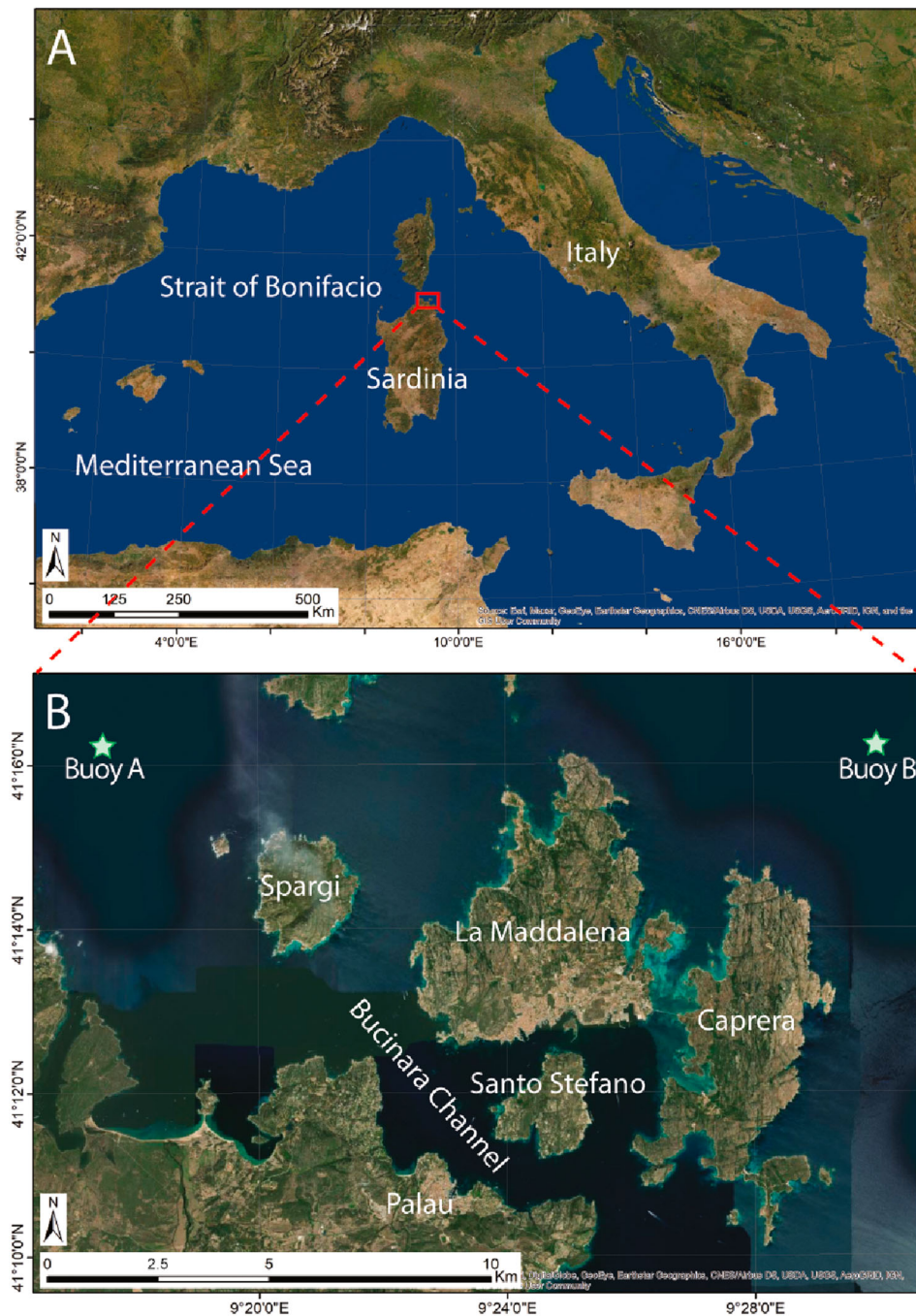


Figure 1. Geographical setting of the study area located in the Western Mediterranean Sea (A). Location of the study area in the North-eastern Sardinia (B). Green stars in panel B indicate the position of the two virtual buoys A and B used for wave climate reconstruction.

[sites/default/files/2021-04/OsservatorioTurismo_Report2020_20210415_1.pdf](https://www.researchgate.net/publication/351111111/sites/default/files/2021-04/OsservatorioTurismo_Report2020_20210415_1.pdf)). The number of visiting boats is up to 16,000 yearly (La Maddalena Park, 2015–2017). During the last 20 years, the growth of tourism and increased human disturbance have negatively influenced the local natural processes and equilibria (De Muro & De Falco, 2015), into an ever-increasing pressure on the environment.

3. Methods

Integrated geomorphological, sedimentological, benthic habitat and hydrodynamic studies were

carried out by the Coastal and Marine Geomorphology Group (CMGG) at the University of Cagliari. This type of integrated studies based on a multidisciplinary approach has been already applied to several Mediterranean microtidal wave-dominated systems and adjacent inner shelf (Batzella et al., 2011; De Muro, Batzella, et al., 2010; De Muro, Pusceddu, et al., 2010; Pusceddu et al., 2011). The results of these studies were processed to produce the map of the La Maddalena Archipelago (Main Map), which includes one detailed and two inset maps: (Map 1) morpho-sedimentological (1:14,000 scale, central map); (Map 2) sedimentary facies (1:40,000 scale,

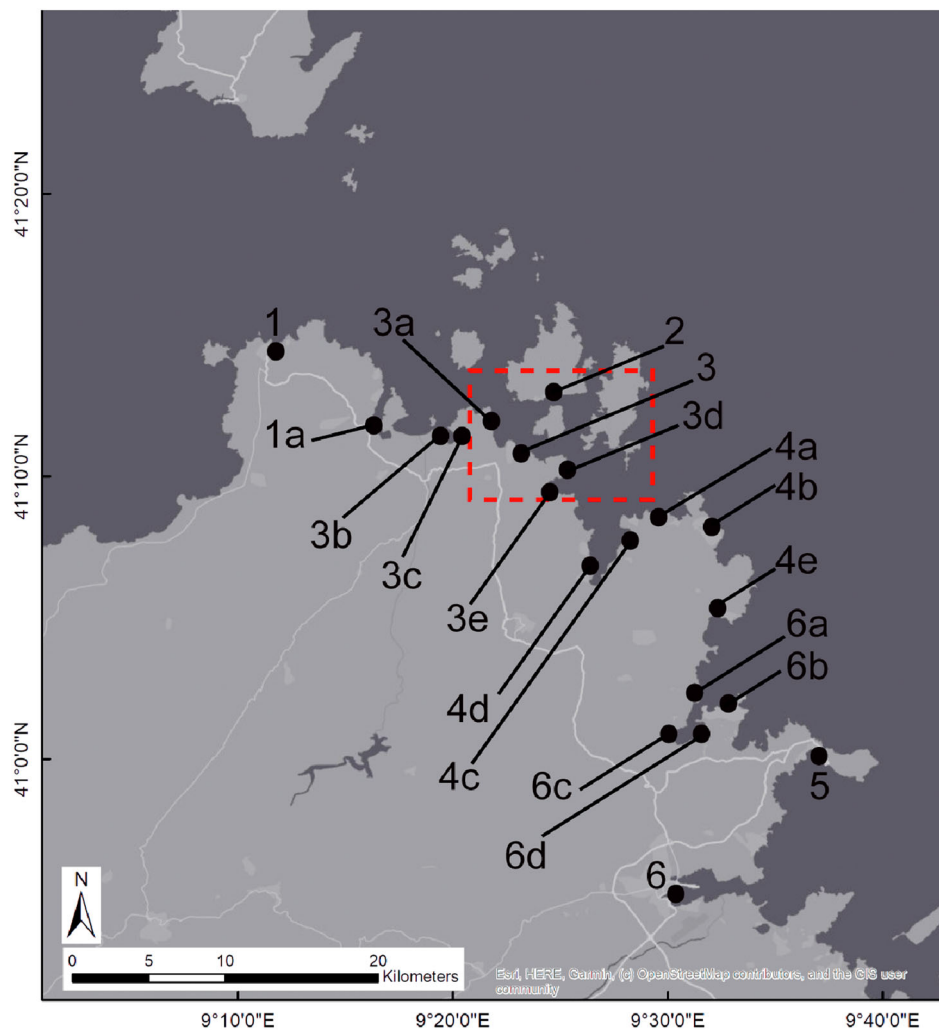


Figure 2. Location of the main coastal villages and harbours (hard structures) of the study area and its surroundings.

Table 1. Schematic summary of permanent residents, annual tourism occupancy (2019 and 2020) and boat moorings for each site shown in Figure 2.

Site (Villages and Touristic Centres)	Residents ⁽¹⁾	Annual Tourism Occupancy 2019 ⁽²⁾	Annual Tourism Occupancy 2020 ⁽²⁾	Boat Mooring Sites ^(3,4)
1 – S. Teresa di Gallura	5107	529,098	193,814	700
1a – Porto Pozzo	–	–	–	500
2 – La Maddalena	10,825	239,053	122,562	1310
3 – Palau	4187	566,480	268,307	475
3a – Porto Rafael	–	–	–	80
3b – Porto Pollo	–	–	–	46
3c – Costa Serena	–	–	–	211
3d – Capo d’Orso (Cala Capra)	–	–	–	50
3e – Le Saline + Porto Mannu	–	–	–	132
4 – Arzachena	13,452	1,221,813	412,680	–
4a – Poltu Quatu	–	–	–	311
4b – Porto Cervo	–	–	–	700
4c – Baja Sardinia (Cala Bitta)	–	–	–	183
4d – Cannigione	–	–	–	400
4e – Cala di Volpe	–	–	–	20
5 – Golfo Aranci	2475	286,286	104,989	436
6 – Olbia	59,035	890,582	394,820	1237
6a – Portisco	–	–	–	605
6b – Porto Rotondo	–	–	–	655
6c – Cugnana (Cala dei Sardi)	–	–	–	140
6d – Sa Jaga Brujada	–	–	–	50
Total	95,081	3,733,312	1,497,172	8241

Sources: (1) http://osservatorio.sardegnaturismo.it/sites/default/files/2021-04/OsservatorioTurismo_Report2020_20210415_1.pdf; (2) <http://italia.indettaglio.it/>; (3) <https://www.tuttobarche.it/porti-sardegna/>; (4) <https://m.marinanow.it>.

bottom left); and (Map 3) multibeam echosounder surveys (1:40,000 scale, bottom right).

3.1. Seabed morphology

Bathymetric surveys were carried out to reconstruct the seafloor's morphological conformation. The bathymetry was performed using single-beam and multibeam echosounder. Single-beam data from the shallow water areas (shoreface/upper limit of the meadow) were acquired using an Echosounder/DGPS (Differential Global Positioning System) system interfaced with navigation software (sampling frequency of 5 Hz). Multibeam bathymetry data were collected by the Istituto Idrografico della Marina Militare (IIMM; Map 3).

3.2. Sediment features and sedimentary facies

To determine sediment features (Map 1) and sedimentary facies distribution (Map 2), a total of 424 sediment samples (Figure A2(A) in Appendix), about 200 g in weight, were collected using a Van Veen grab from the shoreface and inner shelf of the examined area; 71 samples were collected using a bailer along the shoreline.

The grain-size analyses of these sediments were performed on the $>63\ \mu\text{m}$ fractions, while the pipette sedimentation method (Folk, 1974) was used to examine the fractions $<63\ \mu\text{m}$. Each sediment sample was dry sieved through a battery of sieves spaced at $\frac{1}{4}\ \phi$ per unit (Wentworth, 1922). The limits and names of the size grades were calculated following the Nota textural classification (Nota, 1958).

The mineralogical composition of sediments was determined under an optical microscope by the identification of the percentage of quartz, feldspars, lithoclasts and skeletal grains in each sample (Lewis & McConchie, 1994).

Sedimentary facies were identified in the study area (Map 2, Table 2) based on their grain size and their mineralogical/petrographical composition (De Falco et al., 2011; De Muro et al., 2016; Lecca et al., 2005). Classification of sedimentary facies and seabed features was achieved by performing a segmentation of the backscatter mosaic into discrete classes and carrying out a ground-truthing of the identified acoustic classes using sediment samples information. Acoustic classes were associated with the most occurring textural type, derived from sediment samples analyses, observed within the spatial boundaries of each acoustic class.

3.3. Benthic habitat and seagrass mapping

The mapping of the *Posidonia oceanica* meadows and benthic habitat is based on: (1) side-scan sonar images

acquired by the universities of Cagliari and Trieste as part of the PALEOCLIGE project (1:10,000 scale, Edgetech DF 1000 side-scan sonar; Figure A2(C) in Appendix) and by the Italian Ministry of the Environment, Land and Sea (Ministero dell'Ambiente, del Territorio e del Mare, 1:50,000 scale, Edgetech 260 TD side-scan sonar; Figure A2(B) in Appendix); (2) orthophotos and IKONOS 2005 satellite images acquired through the Web Map System (WMS) service of the Sistema Informativo Territoriale Regionale (SITR) 'Sardegna Geoportale' (www.sardegnageoportale.it), and (3) several scuba diving surveys performed by Osservatorio Coste E Ambiente Naturale Sottomarino (O.C.E.A.N.S., Faro di Punta Sardegna, Palau).

3.4. Wave climate assessment and hydrodynamics

The hydrodynamic processes occurring in the archipelago and reported in Map 1 (nearshore currents, due to 25° and 286° wave direction) were determined after the analysis of major storms and the reconstruction of wave patterns.

The wave climate was reconstructed from the Copernicus Marine Environmental Monitoring System (CMEMS) database and using the two virtual buoys A and B (Figure 1(B)). The CMEMS database covers the period between 2006–2018 and provides wave parameters obtained through numerical simulations with a time step of one hour.

By mean of the Delft3D software package (Deltares, <http://oss.deltares.nl/web/delft3d>), the major storms identified at the virtual buoys were propagated from the buoy locations to obtain the wave patterns and the hydrodynamic processes occurring in the archipelago (Map 1).

3.5. Anthropogenic impact

The main anthropogenic impact was identified in terms of the long-term scale by analysing historical cartography, satellite, aerial and side-scan sonar images; scuba diving and field surveys were used for the short-term scale.

4. Results

4.1. Coastal zone and inner-shelf geomorphology

The coastal area encompasses about 100 beaches confined in length by rocky promontories and controlled towards the offshore by the *P. oceanica* meadow's upper limit, which contains and traps terrigenous and bioclastic sediments.

Downstream of the shoreface zone, a 20 km-long channel (Bucinara Channel) divides the northern

Table 2. Sedimentological characteristics of sedimentary facies.

Sediment facies	Gravel/ pebble %	Sand %	Mud %	Quartz + Feldspar %	Other minerals %	Lithoclasts %	Bioclasts %	Depositional environments
(A) Siliciclastic sands and gravels	32 ±31.3	66.2 ±31.5	1.8 ±0.8	36.8 ±20.6	3.2 ±2.7	49.0 ±27.2	11.0 ±7.4	Shoreface (0–16 m)
(B) Mixed bioclastic- siliciclastic sediments	15.8 ±13.8	73.00 ±20.1	11.2 ±19.7	28.5 ±13.8	2.9 ±3.2	25.2 ±21.6	43.4 ±27.3	Transition from shoreface to the upper limit of meadow (2–25 m)
(C) Mixed bioclastic and siliciclastic gravelly muddy sands	6.4 ±3.3	56.3 ±27.4	37.3 ±29.3	24.5 ±15.0	0.9 ±1.5	3.3 ±3.2	71.3 ±17.5	Intermattes (3–35 m)
(D) Bioclastic detritic bottoms	13.8 ±17.0	68.4 ±25.2	17.8 ±23.8	20.9 ±11.7	0.8 ±1.8	4.8 ±5.4	73.5 ±16.5	Lower limit of meadow/middle shelf (20–55 m)
(E) Mixed detritic bottoms	16.1 ±11.9	69.3 ±21.7	15.6 ±23.3	28.4 ±5.1	4.0 ±4.1	12.8 ±8.8	54.6 ±8.4	Middle shelf (30–45 m)
(F) Siliciclastic detritic bottoms	19.2 ±9.8	79.2 ±10.6	1.6 ±1.6	29.8 ±19.5	4.5 ±5.3	40.0 ±13.5	25.7 ±11.7	Middle shelf (35–42 m)

Sardinia coast from the main islands of the Archipelago (La Maddalena, Caprera, S. Stefano and Spargi). The Bucinara Channel has a variable depth ranging from –35 m in the western-most portion to –50 m in the E. Another NS-oriented channel occurs in the northern part of the Archipelago between La Maddalena and S. Stefano in the W and Caprera to the E. Several sand-dune fields occur in the central zone of the Bucinara Channel in 30–40 m water depth (Map 1). The subaqueous dunes have a linear form and a NW-SE orientation. Subaqueous barchan-type dunes (around 17 km²) are present in the southern inner shelf of S. Stefano. The dune is mainly sand with variable percentages of mud.

Other sedimentological features, megaripples, ripple marks and comet marks occur in the central zone of the Channel, where one current direction predominates.

Several closed depressions extend in the study area: (1) a sandy sediment zone (about 988 m²) in the northwestern-most part of the area at a depth of 45 m (Map 1); (2) a second muddy sand depression between the S. Stefano and Caprera, which covers an area of about 906 m² at depth of 35 m; and (3) another smaller closed depression (63 m²) in the inner shelf E of Punta Rossa (depth of about 35 m), which is covered by a continuous meadow of *P. oceanica*. Knick points and isolated sea-bottom reliefs are ubiquitous features of the shoreface and inner shelf of the Bucinara Channel (Map 1).

4.2. Sedimentary facies and benthic habitats

Six sedimentary facies were identified (Map 2, Table 2): (1) Facies A is located between the shoreline and the upper limit of the *P. oceanica* meadow and is characterised by siliciclastic sand and gravel; (2) Facies B, at the transition from the shoreface to the seagrass meadow's upper limit, has mixed bioclastic-siliciclastic sediments; (3) Facies C (mixed bioclastic and siliciclastic gravelly muddy sand) was sampled in the uncolonised substrate occurring within the meadow

(‘intermattes’); (4) Facies D consists of bioclastic detritic bottoms (mixed gravelly sand and muddy sand; Map 2) linked to the seagrass meadow's lower limit. The central area of the channel, which experiences the most energetic hydrodynamic processes, includes (5) Facies E, mixed bioclastic and siliciclastic gravelly sands; and (6) Facies F, siliciclastic detritic bottoms (mainly quartz and lithoclast sands; Map 2).

The following benthic habitats and substrate types were identified in the study area (Map 1): (1) uncolonised sandy substrates dominating the seafloor between the shoreline and the upper limit of the seagrass meadow (0–5/10 m depth); (2) a seagrass meadow, mainly *P. oceanica*, occurring in the depth range 5–35/40 m; (3) *P. oceanica* atolls, showing a preferential distribution in (a) sheltered bays with sandy sediment N of Punta Tegge (La Maddalena), (b) in the Golfo di Stagnali and Porto Palma (Caprera), and (c) in several bays along the N, W and S coasts of S. Stefano Island (Map 1); (4) maerl beds composed of biogenic gravelly sand with free calcareous algae (Melobesiae) at a depth of 35–40 m in the central area of the channel; (5) rocky outcrops covered by *P. oceanica*; and (6) rocky substrates (Maps 1 and 2).

4.3. Hydrodynamics

Two main nearshore currents (Map 1) were simulated in the study area and computed considering by the identified major storms and the reconstructed wave patterns at the two Virtual Buoys.

The wave climate at the virtual Buoy A is mainly dominated by W and WNW swells. These wave conditions originate from strong Mistral storms and reach the Archipelago via the Bonifacio Strait. The harshest sea condition taken from the CMEMS time-series at Virtual Buoy A has a significant wave height of 6.8 m and a mean wave direction of 286°. The more heterogeneous wave climate observed at the virtual Buoy B is driven by W and WNW, however, waves from the first and second quadrants are also not rare. In particular, although the most frequent sea

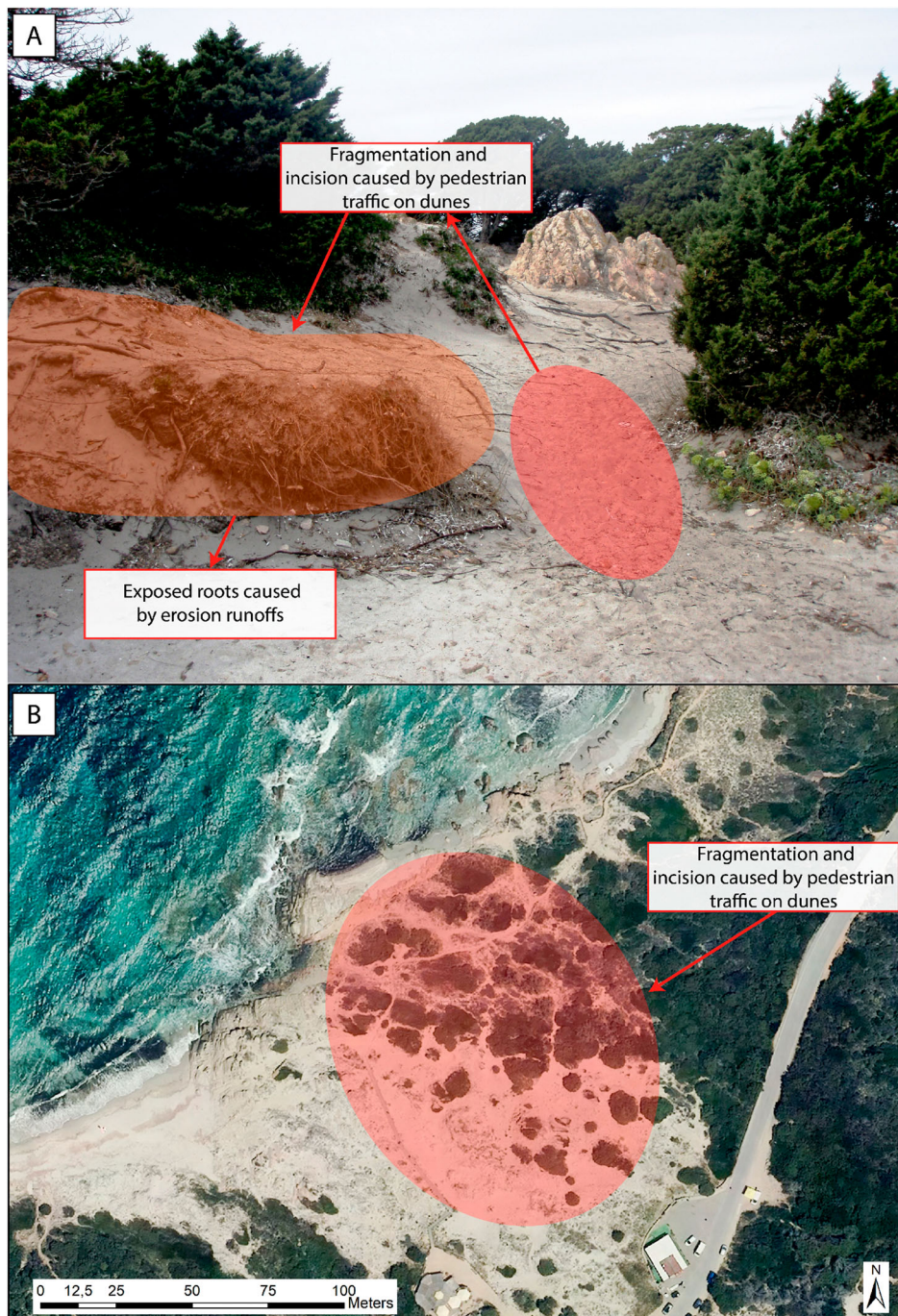


Figure 3. Human impacts on dunes. Reduction of vegetation cover caused by pedestrian traffic on the dune systems of (A) the Cavaliere (Budelli Island) and (B) Bassa Trinita beaches (La Maddalena Island, air photo view), in the Archipelago of La Maddalena.

state is from the WNW, the most severe wave storms are from the NNE. These wave storms originate in the Tyrrhenian Sea and hit the northern shorelines of the Archipelago. The strongest wave storm from the CMEMS hindcast time-series at the virtual Buoy B has a significant wave height of 6.3 m and a mean direction of 25°.

4.4. Anthropogenic impact

Several effects of human activities have been recognised in the backshore, shoreface and inner-shelf zones of the Archipelago of La Maddalena. In general,

the main anthropogenic pressures on the backshore can be summarised as follows:

- Human trampling on dunes that damages the local vegetation. Trampling over dunes can lead to the destruction of dune vegetation and fragmentation of plant coverage, through the formation of paths and incisions that lead to the reduction of vegetation to smaller isolated patch and increase of bare soil area. This process enhances deflation processes, weathering and erosion runoffs resulting in a loss of sediment volumes (Map 1; Figure 3).

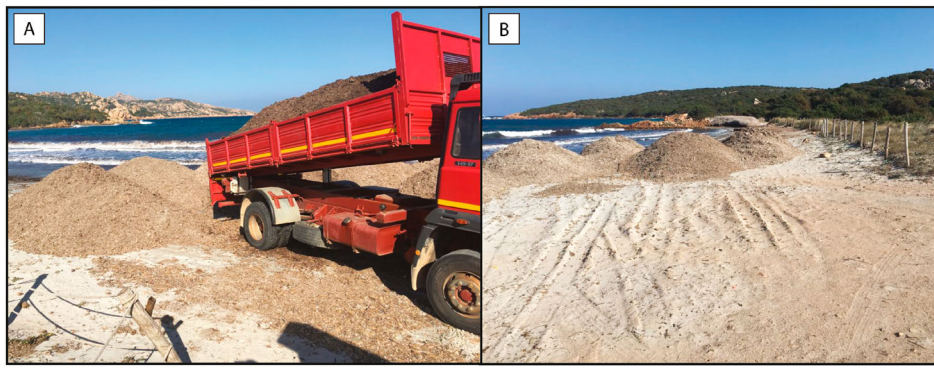


Figure 4. Mechanical removal of *Posidonia oceanica* beach-cast litter from the beach face, berm and backshore of Cala Portese beach (Caprera Island) in the Archipelago of La Maddalena (A and B). Removal operations affect the beach morphology, flattening and lowering the backshore and dune level, thereby compacting the sediment and making the beach more vulnerable to overwash.

- The accidental removal of sediments by beach users.
- The removal of sediment for building purposes.
- Vehicles transit for the removal of *P. oceanica* beach-cast litter (Figure 4), and placement/displacement of café and restaurant kiosks that flatten and lower the backshore and dune level, thereby compacting the sediment and making the beach more vulnerable to overwash.
- The presence of infrastructure on the foredunes.
- The artificial nourishment of embayed beaches (Map 1).

The shoreface and inner-shelf zones are mainly affected by:

- Anchoring, resulting in the fragmentation of the seagrass meadows, with a consequential retreat of the upper limit and the potential loss of sedimentary volumes outside the beach system (Map 1; Figure 5).
- Dumping, dredging, the movement of ships, fishing and other port activities (Map 1; Figure 6).
- Wakes generated by recreational boats, causing a substantial source of erosive energy directed at the shoreline and fine-sediment resuspension.

5. Discussion

This work contributed to highlight the interactions between the ecogeomorphological setting, sedimentary facies, benthic habitat, hydrodynamics and human pressures in the coastal zones of the La Maddalena Archipelago. Maps 1 and 2 show that *P. oceanica* meadows play a key ecogeomorphological role in the sedimentary budget and physical equilibrium of these wave-dominated, microtidal coastal systems. The well-known sediment-retention capacity of the seagrass meadow (De Falco, Simeone, et al., 2008; De Muro, Kalb, et al., 2010; Tecchiato et al., 2016)

produces an accumulation of sediment between its upper limit and the shoreline. In the shoreface, a zoning of sediment is visible in Map 1: from the shoreline to the seagrass upper limit, the sediments range from sand (sand >95%) to sandy mud (30% > sand > 5%). This sediment zonation is influenced by the energy of the environment; close to the shoreline zone, where the energy is higher, the deposition of coarser sediments prevails; whereas towards the meadow's upper limit, in a less energetic environment, the deposition of finer sediments is favoured. In contrast, the deeper portions of the continental shelf show a depositional environment characterised by finer sediment close to the lower limit of the meadow and coarser materials (sand) towards the offshore (Map 1). These coarse-grained sediments show a longitudinal accumulation as a consequence of depositional processes induced by seabottom currents that are stronger in the narrower sections of the Bucinara Channel. Subaqueous dunes, megaripples, ripples and comet marks indicating sediment mobility were found in these areas. These forms suggest that sediment transport and stronger NW-SE-oriented currents occur on the seabed in the central area of the Channel, where mixed bioclastic and siliciclastic gravelly sands from facies E and F were also mapped (Map 2). *Posidonia oceanica* meadows are the main source of biogenic carbonate sediment in the small embayed beaches along the island coasts of the Archipelago; along the mainland coasts, the beach systems are mainly fed by fluvial terrigenous material originating from the alteration of the Palaeozoic basement. The mainland's sandy beaches are wider when associated with river outlets and the supply of terrestrial sediment (Map 1). In general, Mediterranean beaches, and especially those with limited fluvial inputs, are sustained by *Posidonia* meadows that provide biogenic sediment and biomass and confine siliciclastic materials. It has been estimated that *Posidonia* beds can produce 390–1147 g m⁻² year⁻¹ of calcium carbonate (De Falco, Baroli, et al., 2008). Indeed, some

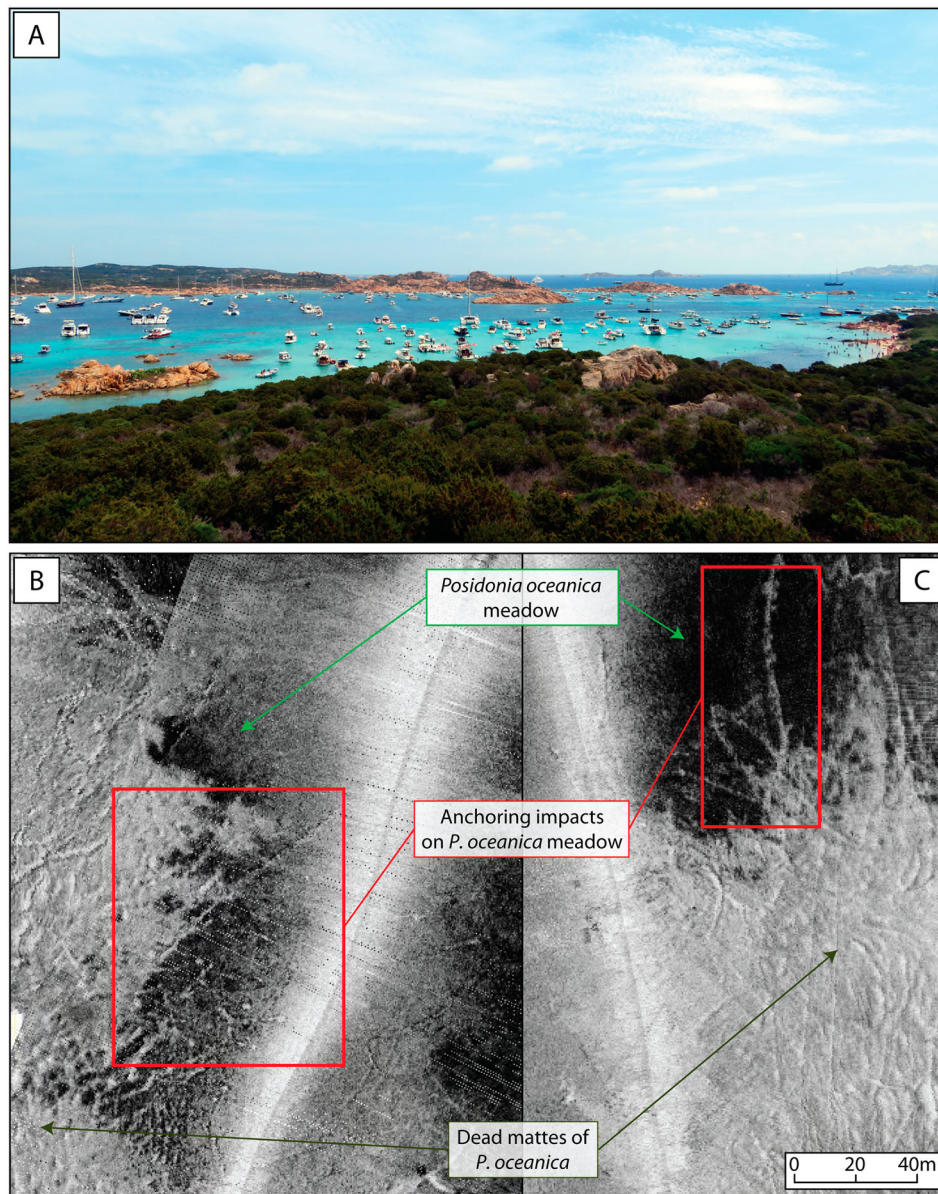


Figure 5. Effects of boat anchoring on *Posidonia oceanica* meadow. (A) Boat moorings off beach of Cavaliere (Budelli Island), in the Archipelago of La Maddalena. (B and C) Side Scan Sonar images showing the fragmentation of the seagrass meadow due to anchoring off Palau, with a consequential retreat of the upper limit and the formation of dead mattes.

Sardinian beaches would not exist without the meadows (e.g. Cala di Trana, Spiaggia Rosa, Piscinni; Simeone et al., 2013; Trogu et al., 2020).

Urbanisation, tourism and recreational activities have developed extensively over recent decades in the Archipelago of La Maddalena. Human impact makes these coastal zones more vulnerable to erosive processes. On dunes, degradation and patchiness of vegetation and development of blowouts are mainly triggered by pedestrian and vehicle traffic, and the presence of infrastructure. On the backshore, the removal of the seagrass necromass through the mechanical cleaning of some beaches flattens and lowers the backshore level, compacting the sediment and making this zone more vulnerable to overwash (De Falco, Simeone, et al., 2008; Passarella et al., 2020; Simeone et al., 2008; Trogu et al., 2020).

Boat anchors and chain scours are widespread in most of the sheltered bays (Map 1). Several studies have reported that anchoring on *P. oceanica* can have direct adverse effects on the meadow cover and shoot density (Francour et al., 1999; Milazzo et al., 2004), leading to the formation of intermattes. It is worth noting that the impact of boat anchoring on seagrass can be long-term, due to the slow rate at which *P. oceanica* grows. After sustaining damage, the seagrass takes several years to recover and only does so if all sources of disturbance are removed (Marbà & Duarte, 1997; Milazzo et al., 2004). The degradation and retreat of the upper limit of the meadow entails the minor attenuation of hydrodynamic forces and a reduced capacity for sediment retention by seagrasses. The loss of seagrass meadows is often followed by a considerable loss of sediment from the

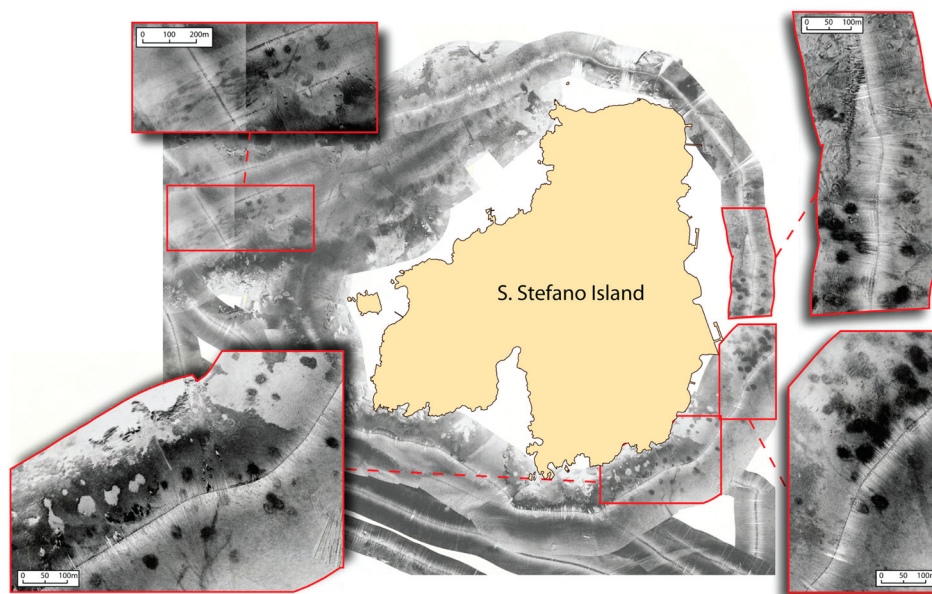


Figure 6. Side Scan Sonar images showing several dumping zones off the S. Stefano Island in the Archipelago of La Maddalena.

system and a negative sedimentary budget (e.g. De Falco, Baroli, et al., 2008; Gacia & Duarte, 2001). Increased boat traffic in the Archipelago of La Maddalena also has a significant impact on the *P. oceanica* coverage; wakes generated by recreational boats can trigger erosional processes in the meadow and may reduce water clarity through turbulence (Bilkovic et al., 2019; Houser, 2010). Each boat that travels through the narrow channels among the islands generates a complex series of anomalous waves characterised by greater heights, longer periods and different directions than those of wind-generated waves (Bilkovic et al., 2019). Wakes tend to be most harmful in shallow and narrow waterways of the Archipelago, because the wave energy does not have the opportunity to dissipate with distance from the boat, consequently triggering erosive processes.

Most of these current stresses, as generated by anthropogenic activities, are expected to be exacerbated by climate change. Small islands and embayed and pocket beaches, where human impacts have diminished natural adaptive capacities and resilience, appear to be the most vulnerable, due to their small size, meteomarine characteristics, lack of fluvial sediment supply and their often negative sedimentary budgets (Velegrakis et al., 2008).

6. Conclusions

The morpho-sedimentological map of the Archipelago of La Maddalena outlines the connections between key geomorphological and sedimentological features, hydrodynamics, the distribution of the benthic habitat and human activities. These findings enabled us to recognise the crucial role played by *P. oceanica* meadows, not only in relation to the natural equilibrium

of these fragile and unstable ecosystems, but also in preventing beach erosion and supplying biogenic sediment.

This cartography is suitable for identifying emerging ecogeomorphological issues of concern in order to ensure that conservation efforts are directed towards mitigating impacts and increasing resilience, thereby contributing to the achievement of the Agenda 2030 SDGs (13, 14 and 15).

Software

The textural data were obtained with the Gradistat software (Blott & Pye, 2001).

The sample data and the SSS data were processed using Autodesk Map 3D and the QGIS 3.6 software to determine the grain-size distribution of the sediment and identify the main habitat.

The QGIS 3.6 software was also used to obtain the complete database, enabling us to identify the geomorphological features and construct the map.

The digital cartography was produced with Adobe Illustrator CS5 to create a PDF file and will be used for the future printing of the map.

Google Earth GIS was employed to calculate distances and angles of wave exposure and the fetch of the study area.

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Disclosure statement

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Data availability statement

The data that support the findings of this study are available from the corresponding author, SDM, upon reasonable request.

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Appendix

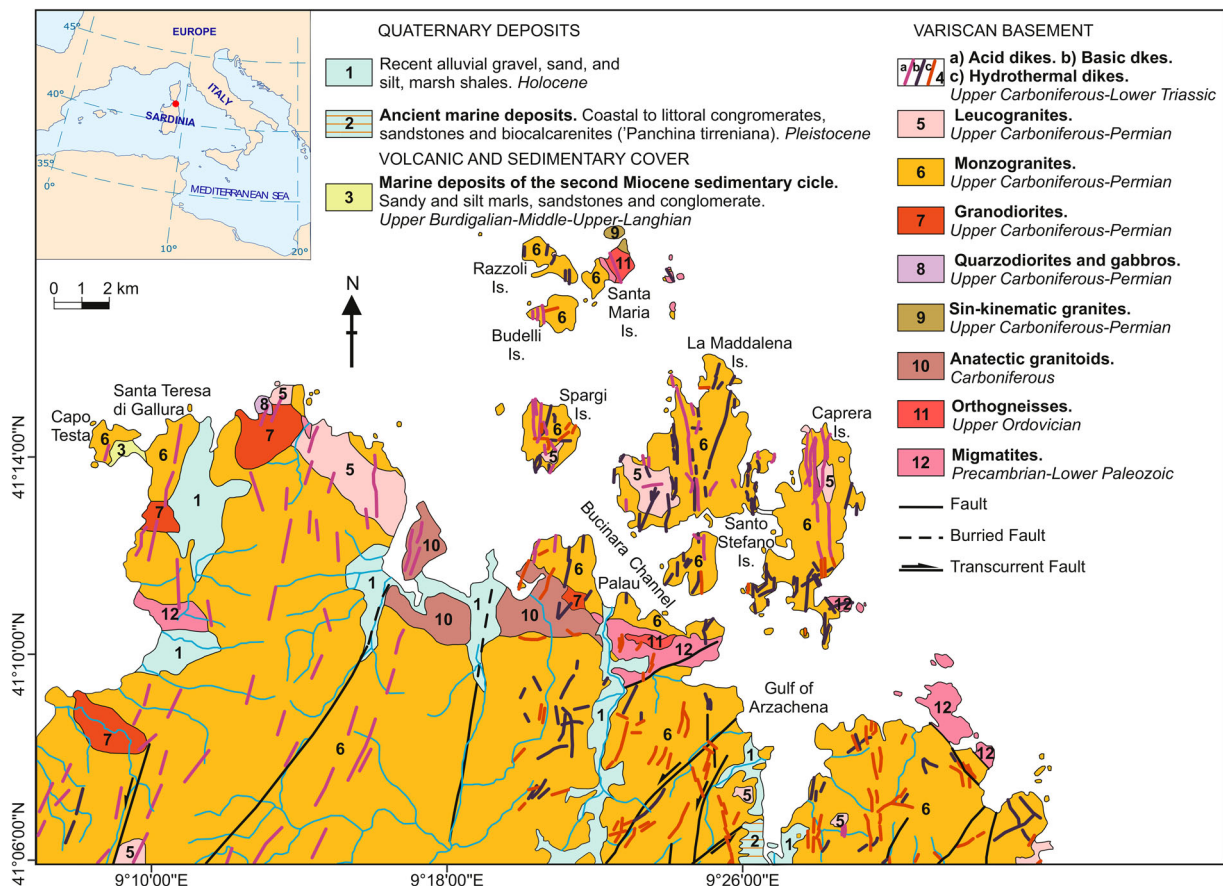
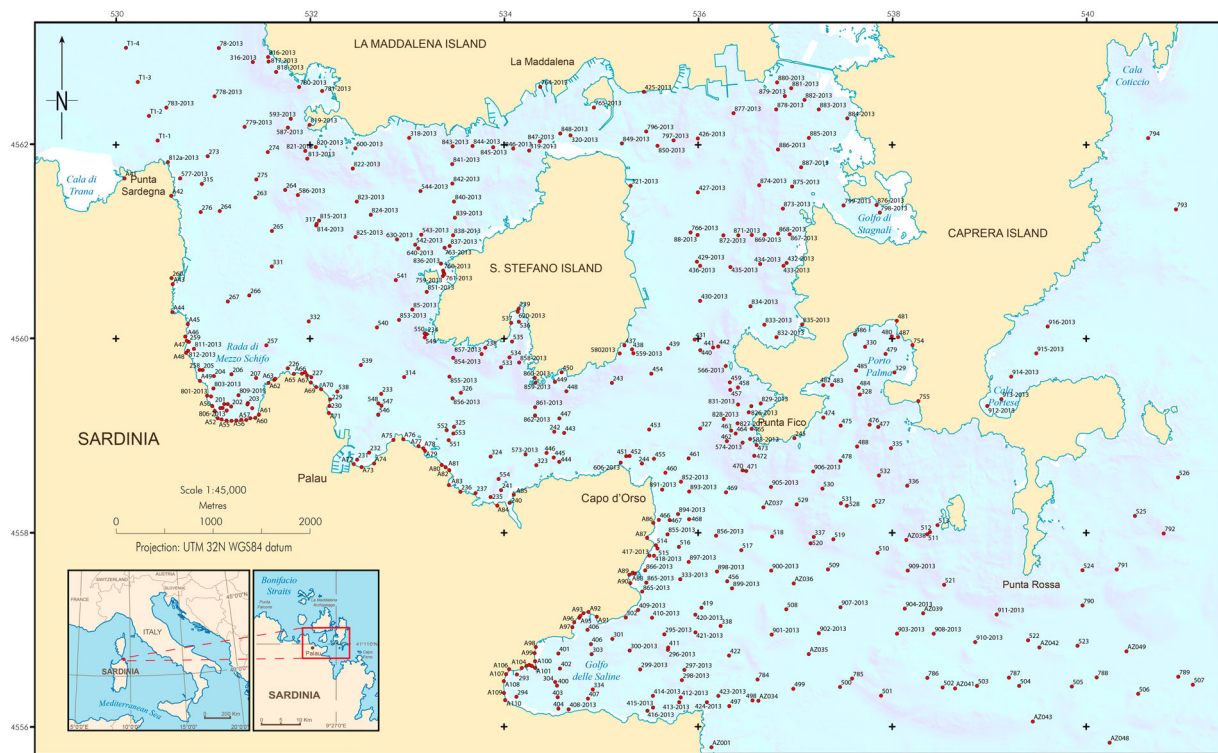
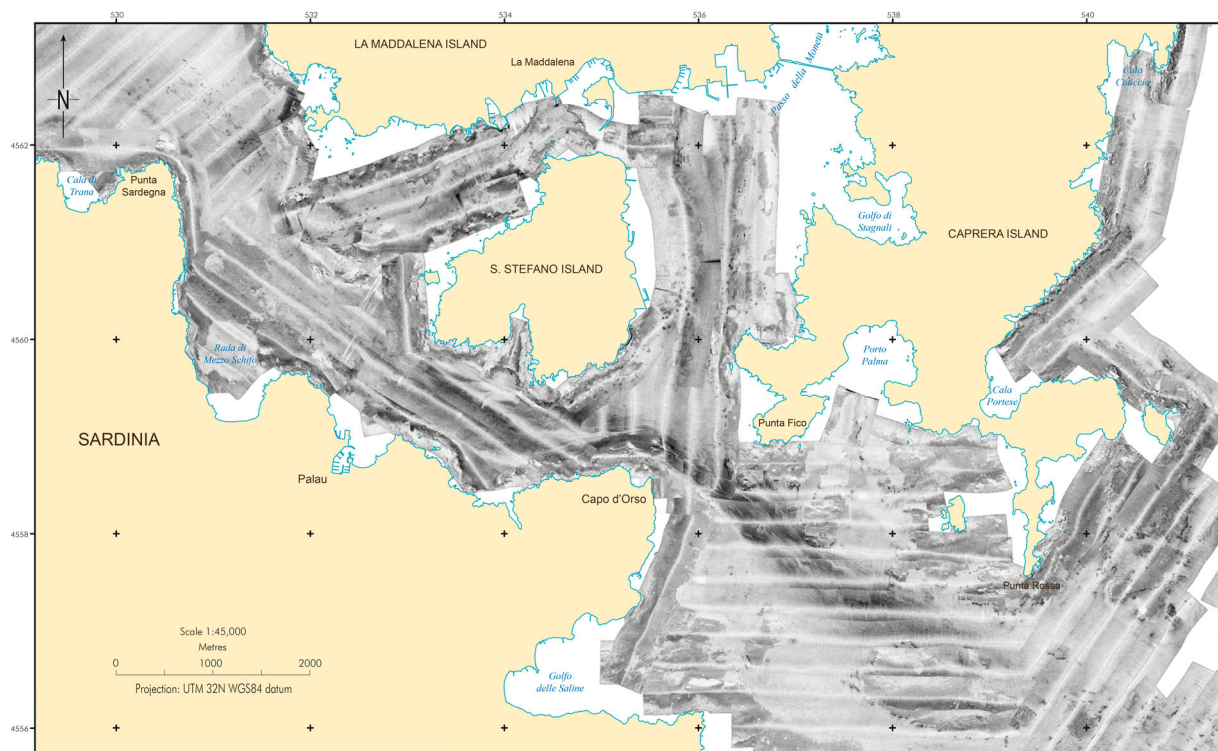


Figure A1. Geological map of the study area. Adapted from Carmignani et al. (2016).



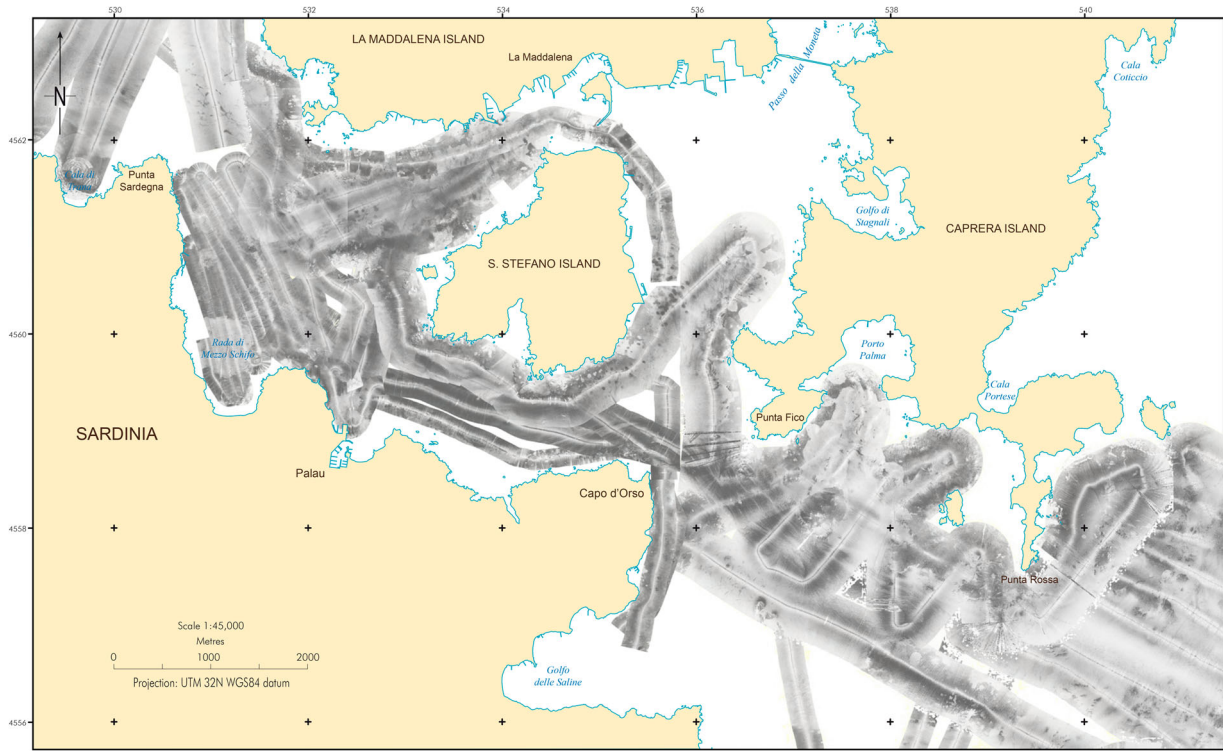
A - Sediment sampling points

Figure A2. Location maps of (A) sediment sampling points (1:45,000 scale); (B) side scan sonar survey Ministero dell’Ambiente e della Tutela del territorio (1:45,000 scale), and (C) side scan sonar survey PALEOCLIGE 2000 Project (Università di Cagliari e Trieste; 1:45,000 scale).



B - Side scan sonar survey (Ministero dell’Ambiente e della Tutela del territorio)

Figure 8 Continued



C - Side scan sonar survey (PALEOCLI.GE 2000 Project - Università di Cagliari)

Figure 8 Continued