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ORIGINAL ARTICLE

Presence of Biogenic Reef at Sabellaria Spinulosa (Leuckart, 1849) Detected in the North-Est Adriatic Sea (Ravenna Coastal Area, Italy): Preliminary Studies for their Geoconservation and Protection

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Abstract
Coastal zone management necessitates a comprehensive and shared interdisciplinary understanding of the various processes involved in the anthropogenically accelerated rapid spatiotemporal evolution, including the climatic perspective, that defines the littoral system. This study aims to present an initial assessment of the atypical occurrence and distribution of biogenic reefs belonging to the Sabellariidae family on the sandy coastal beds of the northern Adriatic Sea. Although sporadic mentions of their potential presence have been made, their specific locations and distribution have never been accurately identified and mapped. These fragile biogenic reefs have the potential to serve a functional role in coastal ecosystems, as recognized by the conservation strategies of the Mediterranean and the objectives of the EU Habitats Directive. In addition to describing the primary physiographic, physical-dynamic, and environmental characteristics of the study area, this article outlines the key findings from preliminary geomorphological-sedimentological investigations and compares them with similar Sabellaria structures studied in diverse environmental conditions along the Italian coasts. The research conducted thus far, utilizing side-scan sonar and direct observations by scuba divers, has confirmed their coherence and functionality as valuable habitats and hotspots.

Keywords Sandy beach system · Geophysical survey · Marine protected areas · Coastal management

Introduction

Along the sandy coasts of Italy, the Sabellariidae family forms biogenic reefs in shallow coastal ecosystems. These reefs exhibit the ability to interact with both biotic and abiotic factors, such as sediment granulometry, hydrodynamics, weather-climatic patterns, temperature, salinity, and nutrients (Harrison et al. 2011). By cementing loose infralittoral clastic sediments, these organisms create hotspots with significantly higher biodiversity compared to the surrounding sandy areas. Furthermore, they aid in mitigating coastal erosion by stabilizing the substrate and trapping sediments. These reefs have the potential to develop into new habitats that offer valuable ecosystem services, emphasizing the importance of their conservation and protection (Sandulli 2012; Commission Directive (EU) 2017/845; WoRMS 2022).

Among the Sabellariidae species, Sabellaria alveolata and Sabellaria spinulosa (Leuckart, 1849) are the most prevalent along the Mediterranean coasts. Sabellaria alveolata predominantly constructs intertidal and subtidal reefs, capable of attaining substantial sizes (EUNIS habitat type code A2.711). Conversely, S. spinulosa (Leuckart, 1849) (EUNIS habitat type A5.611) generally develops in subtidal environments, forming isolated tubes, short-lived crusts, and occasionally discontinuous and fragmented biogenic rocks

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of limited height (Delbono et al. 2003; La Porta and Nicoletti 2009; Sandulli 2012; Politecnico delle Marche 2015; Lisco et al. 2017; Gravina et al. 2018; Bonifazi et al. 2019; EUNIS 2019; Sanfilippo et al. 2021; Borghese et al. 2022; Franzitta et al. 2022).

In this context, the accidental discovery of S. spinulosa's biogenic structures by free divers and scuba diver volunteers on the seabed of Lido di Dante represents the first instance of widespread structures identified and mapped along the sandy northern Adriatic Sea coastline. Previously, there had only been sporadic and general reports regarding the possible presence of this genus in the area (Reef check Mediterranean Sea 2002; Fava et al. 2010; Mikac et al. 2013; Ingrosso et al. 2018).

Within the context of the Emilia-Romagna coastline in the Regione Emilia-Romagna, there exists a notable conflict arising from the coexistence of extensive settlements primarily focused on tourism and beach destinations (Farnè 2007). In this regard, the village of Lido di Dante, situated in the southeastern area of Ravenna, holds significant environmental importance due to the near-continuous presence of numerous sites included in international and national protection systems, such as the Natura 2000 network, BirdLife International, and the Po Delta Regional Park. Remarkably, this area has managed to escape the widespread construction boom observed in recent decades along the Ravenna coast, thereby preserving its remarkable geomorphological and bioecological value.

Within the approximately 6 km stretch of coastline between the Fiumi Uniti and Savio river mouths (Fig. 1), there exists only a confined and small urban settlement in the northernmost sector, protected by a breakwater and hosting three limited bathing establishments and two campsites. The remaining territory, mostly free from intrusive human structures, showcases distinct geomorphological features, as well as unique flora and fauna. This region is characterized by a dynamic interface between land and sea, encompassing"emerged-submerged beaches, dune belts, pine forests (Pinus pinaster), and wetlands"(Nobili 2010; RER 2011; Sekovski et al. 2015; Ministero Difesa 2022).

Of particular significance within this area is the mouth and its surrounding environs of the Torrente Bevano, the final meandering estuary in the entire upper Adriatic Sea that retains its ability to naturally evolve. It also serves as a Geosite of regional importance (Ciavola and Armaroli 2010; Balouin et al. 2006; Montanari and Marasmi 2013; RER Ambiente 2013).

Methods and Datasets

In general, the primary physical-dynamic and geomorphological characteristics of the area align with the concept of'Beach Systems', which represents a well-established model. These systems are characterized by dissipative beaches where wave and swash processes play a dominant role. Geometrically, these beaches exhibit a classic concave upward slope, which can be represented schematically with a profile that views the coastline as a continuum extending from the beach to the inner continental shelf (Fig. 2).

The profile of the beach system is characterized by distinct zones that exhibit different behaviors in response to hydrodynamic processes and external forces, delineating depth intervals that facilitate a gradual transition between them. These zones, which possess variable depths and widths that change over space and time, maintain their unique characteristics within dissipative beaches governed by wave and swash processes. Geometrically, these beaches conform to a classic concave upward slope (Wright and Short 1984; Short and Jackson Dashtgard et al. 2012; Short A. 2012; Dronkers 2005; Mangor et al. 2017; Flanders Marine Institute 2022).

It is worth noting that the profile has been updated based on the work of Hamon-Kerivel et al. (2020) to reflect the fact that the morphodynamics of the coastal seabed, particularly in the immediate coastal zone, have not been extensively studied from a temporal scale ranging from annual to decadal and secular. As a result, there is still ambiguity surrounding the delineation of its development. These uncertainties primarily gather from the simplification of wave processes (especially long-period waves) during the transition from the continental shelf to the foreshore, where waves begin to strongly interact with the seabed. The seabed influences the behavior of waves, modifying their original parameters that are relevant to their propagation in deep water, as they approach the zone where significant interactions with the seabed occur. These interactions involve processes such as wave attenuation, breaking, and the generation of secondary wave motions (Woodroffe 2003; Short 2012; Dronkers 2016; Powell et al. 2019).

Hamon-Kerivel et al. (2020) highlight the need to address certain ambiguities regarding the definition of the seaward depth limit, which varies across different disciplines such as coastal engineering, oceanography, and ecology. These ambiguities call for a comprehensive and diachronic assessment of land-sea interactions. To achieve this, interdisciplinary integration between abiotic and biotic models is crucial, especially for practical applications and coastal management. This integration should be carried out at various spatial and temporal scales to facilitate the understanding of correlations and exchanges between environmental compartments within the gradual transition zone between land and sea. This concept is often referred to as the"land-sea transition zone"(Middelburg and Soetaert 2004; Hopkins et al. 2011; Ramesh et al. 2015; Stal 2016; Unesco 2017; Jurasinski et al. 2018; Halvorsen et al. 2019; Rudolph et al. 2020; Malone et al. 2020; Lester et al. 2020; Franke et al. 2022; Keith et al. 2022; Zielinski et al. 2022).

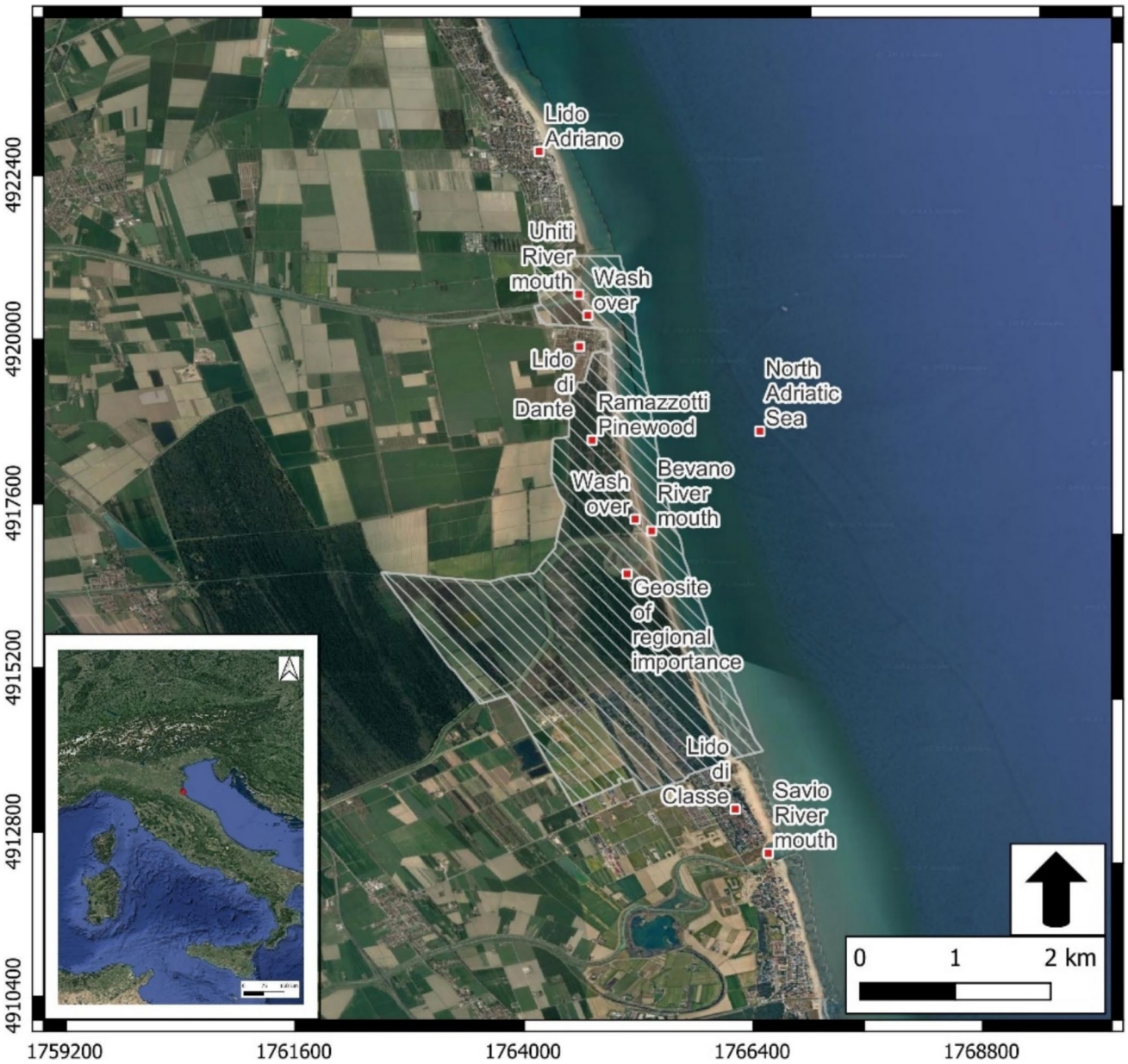

Fig. 1 Area of interest, with site of community interest IT4070009 (Map created with GIS, base WMS Regione Emilia Romagna Orthophoto 2020, EPGS:3003)

These considerations and orientations are in line with current European legislation, particularly in the field of Maritime Spatial Planning/MSP (EU 2014). It is essential to implement planning measures that ensure the sustainable use of marine resources while prioritizing environmental protection at both regional and broader scales (RER ICZM-MSP 2022; Interreg Adrion Programme 2022).

The Northern Adriatic Sea and Emilia-Romagna Coastal Hydrology

The northern Adriatic Sea has been extensively studied in various scientific disciplines, including geostrophic currents, bathymetry, physical, geological, chemical, and bioecological aspects. Numerous studies have been conducted on the surficial circulation of the Adriatic Sea, which exhibits a

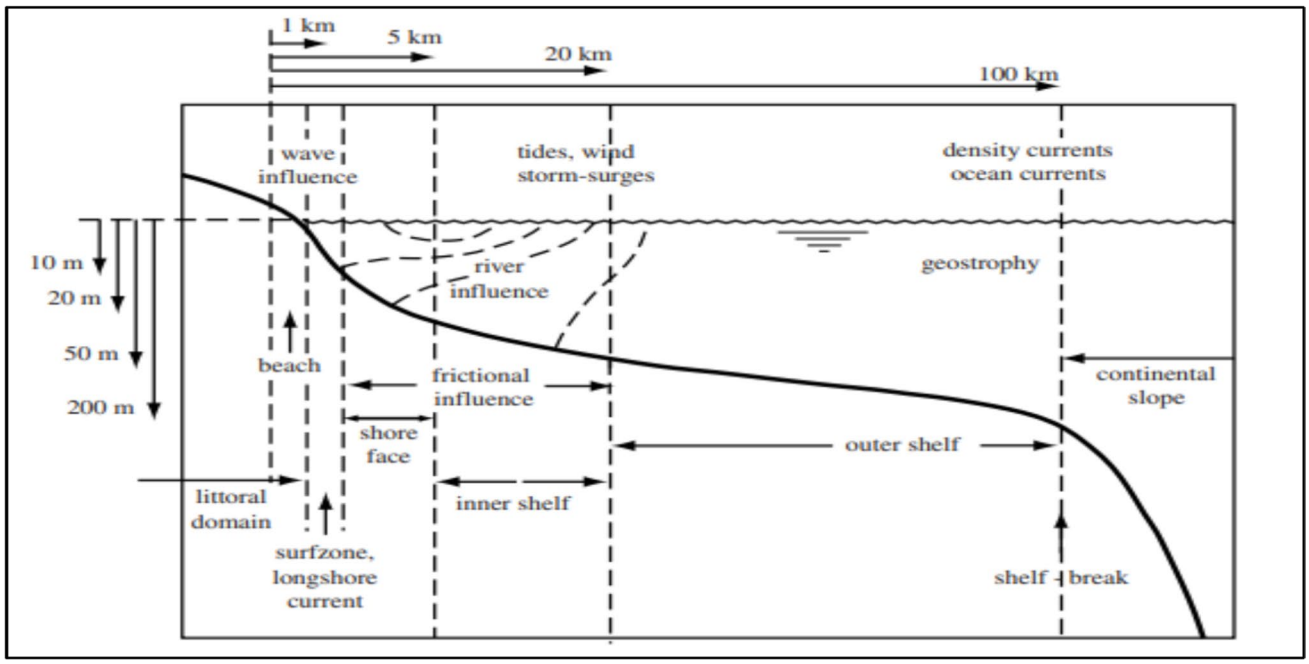

Fig. 2 Conceptual cross-section adopted for Lido di Dante beach systems (Dronkers 2016)

persistent cyclonic movement with seasonal and interannual variations. This circulation is characterized by different branches (Pinardi et al. 2004; Kuzmić et al. 2006; Coll et al. 2007; Marini et al. 2008; Solidoro et al. 2009; Bolanos et al. 2014; Pasquini et al. 2016).

Currently, there are online and real-time resources available based on a numerical model that provides oceanographic data, including daily and forecast information, for the entire Adriatic basin. This model has a horizontal resolution of 2 km and 20 vertical levels and is coupled with a biogeochemical NPDZ domain, allowing for predictions related to the marine ecosystem, such as algal blooms or the status of hypoxia/anoxia in the water column (Arpae-Informare 2022).

At the regional and local levels, datasets are available that consider the influence of river inputs and the resulting local stratifications in temperature, salinity, and density. These factors lead to significant variations in current speeds, particularly along the coast. The circulation patterns in the northern and southern areas of the port of Ravenna exhibit distinct characteristics. The circulation to the north is highly variable between winter and summer due to the direct influence of the Po River, while to the south (starting approximately from Lido Adriano and Dante), the current direction remains relatively constant throughout the year, predominantly southerly (Arpae-Struttura Oceanografica Daphne 2022).

Furthermore, periodic assessments of the chemical and bioecological status of the water column and sediments are

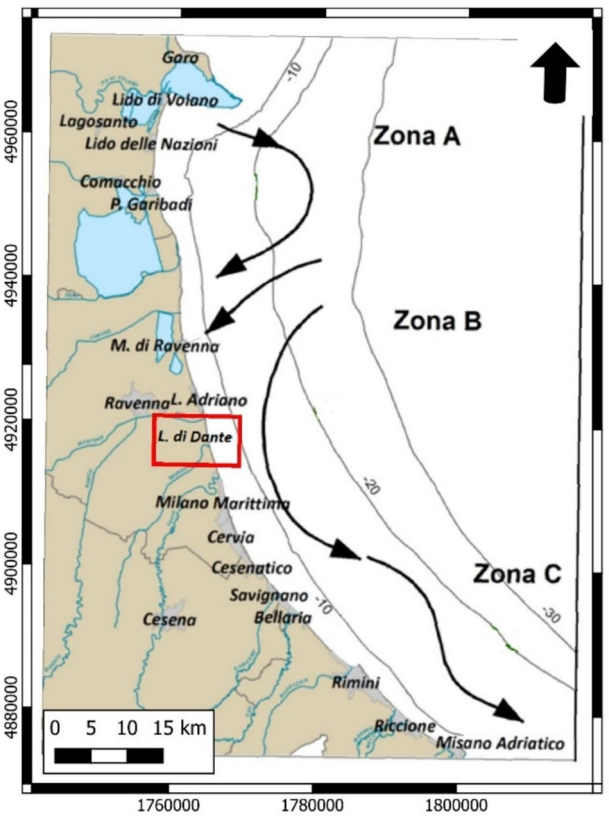

Fig. 3 Map of the climatological circulation of Emilia Romagna on the surface; black arrows indicate'downwelling'dynamics along the coast, typical of the wind regime in this area. (modified from Arpae Report 2020), (Map created with GIS, EPGS:3003)

conducted in accordance with European and national legislation (Arpae-Struttura Oceanografica Daphne 2022) Fig. 3.

The local meteo-marine climates in the Emilia-Romagna coastal region are well-defined, considering factors such as tides, the direction and magnitude of prevailing wave motion, littoral drifts, storm surges, wave set-up, and run-up events. Datasets derived from sea storm analyses over the past 50 years provide information on these aspects (RERambiente 2011; SGSS-RER 2017; Arpae 2021a, b).

In terms of wave regime, approximately 60% of cases are characterized by low-energy waves with significant heights generally less than a meter, associated with SE winds (Sirocco). The most energetic waves are typically associated with winds from the E-NE quadrant (Bora). Specifically for the Lido di Dante area, data recorded since 2007 by the Nausicaa wave buoy located off Cesenatico (8 km south of Lido, in 10 m depth) show that the predominant wave direction is from the E or Levante sector, followed by the ESE and ENE sectors. The most frequent wave class is the low category ($0.20 \leq Hs \leq 1.25$ m), with the ENE quadrant of Bora contributing significantly. Average maximum wave heights are around 1.6 m, but peaks exceeding 4.0 m have been recorded in recent years (Scarelli et al. 2017a, b).

Storm surge events in the Adriatic are influenced by seiche (SESSE), which are free oscillations that can persist for several days after the triggering factors end, due to the semi-enclosed nature of the Adriatic basin. These events can lead to anomalous rises in sea level, known internationally as the"Acqua alta phenomenon". The high-water events caused by persistent Sirocco winds, particularly affecting Venice, result in the highest tidal elevations along the northern Adriatic coastline (Comune di Venezia 2022).

Regarding fluvial inputs, updated information and datasets are available for the Lido di Dante area, considering the Fiumi Uniti and Savio rivers. The consistency and type of fluvial inputs have diminished over time (Cilli et al. 2021). Additionally, the area has experienced subsidence due to natural processes and anthropogenic activities. The natural subsidence rate is estimated to be around 2–3 mm/year, but in the Lido di Dante area, topographical subsidence rates of approximately 35–55 cm have been observed over the past 50 years. Initially, these subsidence rates were associated with the exploitation of water tables, and later with the depletion of important gas deposits in the marine area (Angela-Angelina Platform, Fig. 4; Perini 2019; MISE 2020; Polcari et al. 2022).

Geomorphological and Sedimentological Outline of the Lido di Dante Beach System

The bathymetric map represented in Fig. 4 illustrates the detailed configuration of the seabed in front of the Lido di Dante coastline, specifically in the transition zone from the beach system to the inner continental shelf. The map is based on narrow beam data, which allows for a high-resolution representation of the seabed topography.

In this region, the seabed exhibits a very gentle slope, with an inclination of approximately 4 m over a span of 10 kms (equivalent to a gradient of 0.02°). However, the natural continuity of the seabed is partially disrupted by various anthropogenic structures, including emerged and submerged breakwaters, sealines, and the Angela-Angelina gas field platform located approximately 3 kms offshore. These structures can alter the natural morphology of the seabed and may contribute to the accentuation of certain erosive features. Notably, the channelled depressions that originate at the heads of the artificial breakwaters are particularly susceptible to erosion and exhibit distinctive characteristics that can be observed in the bathymetric map.

The sub-bottom profiler profiles with Chirp technology conducted in the area near Lido Dante have provided valuable insights into the geometric-stratigraphic structure of the late Holocene coastal depositional wedge. These profiles were part of a project conducted by Regione Emilia Romagna and CNR-Ismar to investigate the subsurface structure of coastal deposits in submerged areas.

Figure 5, which is a recently published example from CNR-Ismar (2017), illustrates one of these profiles recorded near Lido Dante. These profiles offer a better understanding of the local characteristics of the silicoclastic coastal sedimentary succession within the first ten meters of the water column. The interpretation of these profiles aligns with the concepts of Sequence Stratigraphy, as proposed by Patruno and Helland-Hansen (2018).

In particular, Fig. 5 outlines the current low axial gradient seabed structure and highlights the presence of the most recent Holocene depositional unit. This unit is characterized by a progradational geometry, indicating the deposition of sediment in a seaward direction. Within this depositional unit, there are regressive deposits of high stationing in prodelta facies (fs1), which transition upwards to beach deposits (fs2). These facies associations and their vertical succession are defined in the Geological Maps of the Adriatic Sea by Ispra (2001).

These findings contribute to the understanding of the sedimentary processes and the evolutionary history of the coastal zone near Lido Dante during the late Holocene.

The granulometric texture of the most recent and superficial beach deposits near Lido Dante can be attributed to the sedimentary contribution of local rivers such as the Savio, Bevano, and Fiumi Uniti. These rivers primarily transport sediment in a north–south direction along the coast, resulting in a distribution of grain sizes parallel to the shoreline in distinct barometric bands at varying energy levels. Samples collected near the shore and at a depth of − 2m exhibit a significant proportion of medium sand (15–30%), indicating

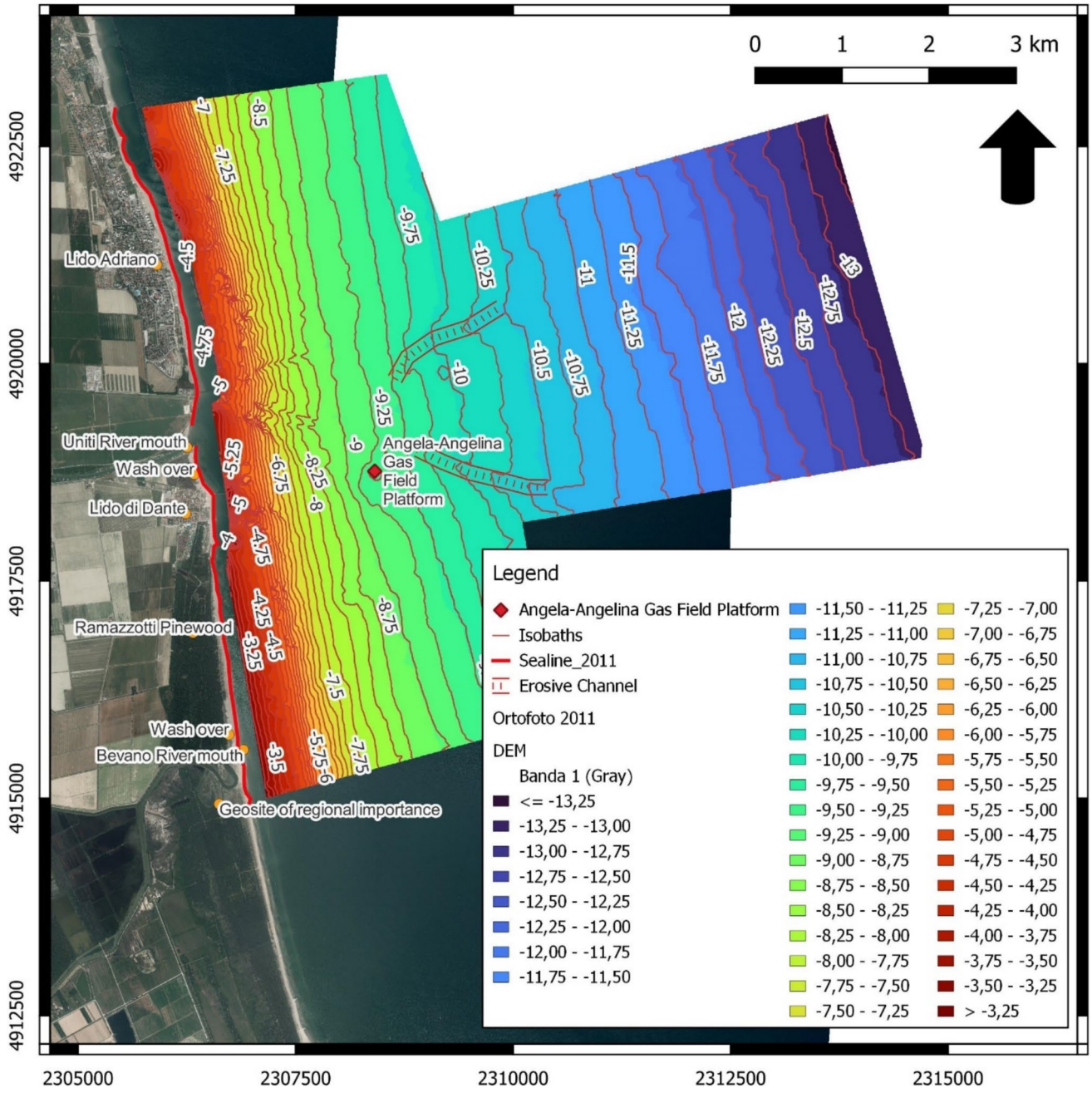

Fig. 4 Bathymetric map, derived from recent narrow beam data (courtesy of Eni S.p.A) (Map created with GIS, base WMS Regione Emilia Romagna Orthophoto 2020, EPGS:3004)

the influence of energetic littoral drifts. These samples also show good sorting and positive skewness, reflecting the energy characteristics associated with frequent littoral transport induced by waves and currents.

As the depth increases, samples collected at approximately − 4m depth reveal a dominance of fine sand (65–80% represented by an average diameter of fine sand). With further depth, the sediment composition transitions to very fine, poorly sorted sands, silt, and eventually clayey sediments beyond approximately − 8/− 10m depth. This vertical variation in sediment grain sizes corresponds to the progressive reduction in energy levels with increasing water depth.

This geometric-depositional framework aligns with the interpretations presented by Einsele (2000) and is schematically represented in Fig. 6. The profile depicted in Fig. 6 is consistent with the physiographic zoning and littoral cell (SICELL) classification adopted by the Emilia-Romagna Region for regional littoral management, as discussed by

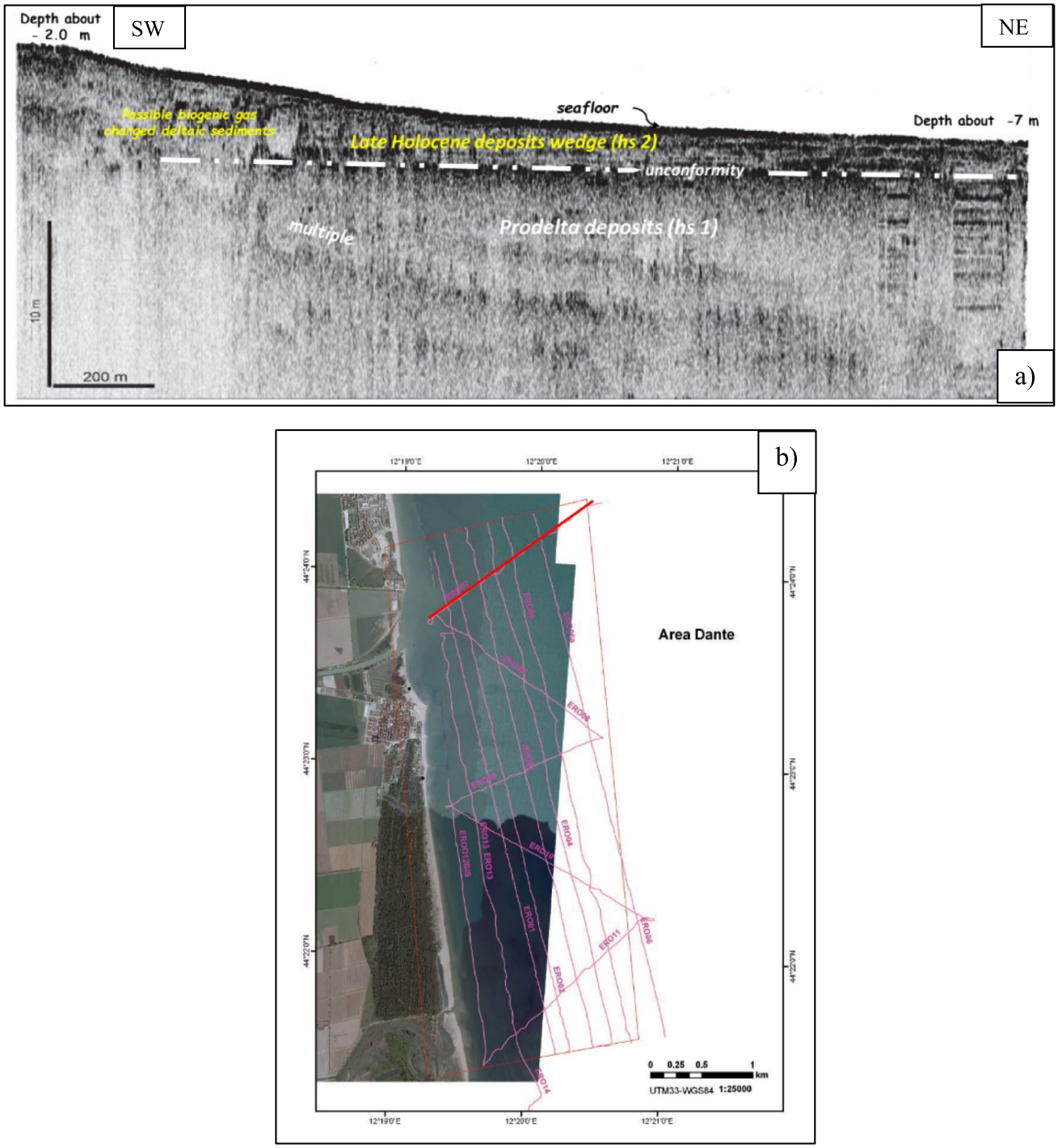

Fig. 5 **a**) Schematic interpretation of the main seismo-acoustic facies of the siliciclastic deposits recognizable from the subbottom profile detected in the Lido di Dante's area by Ismar-CNR survey and correlated with units in progradational geometries connected to the last Adriatic holocenic high sea level (Versilian HST); the profile has the orientation SW-NE. Key: hs1 = Pelitic complex of prodelta internal shelf of clayey clay and silt with variable degree of bioturbation; hs2 = deposits in beach facies with well sorted fine to medium sands and development of possible biogenic gas impregnations correlated with organic matter deposition driven by rapid and thick flood deposition (from NL 33–10 Ravenna superficiale); **b**) the red trace indicates the position of the profile above (a)

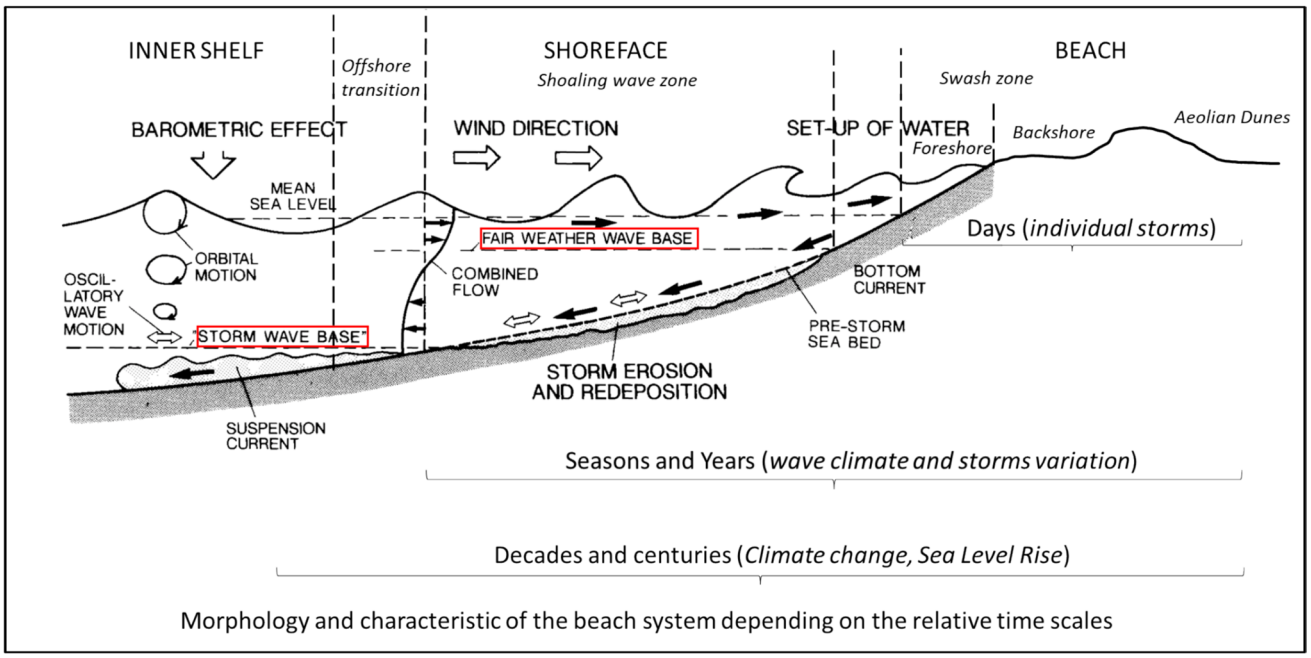

Fig. 6 Main morphological assessment of beach system adopted in this study (modified from Einsele 2000)

Montanari et al. (2015). This framework provides a coherent understanding of the physical dynamics and spatial–temporal variations in sediment distribution along the coast near Lido Dante.

In the Lido di Dante area, the beach system is characterized by a depth of closure to wave-induced sediment transport of approximately − 4/− 5m, known as the fair-weather wave base (FWWB). This depth represents a morphodynamic boundary indicating the point where ordinary seasonal or annual waves are capable of transporting sediment shoreward. Additionally, there is a deeper depth of approximately − 8/− 9m, associated with waves generated by storm surges and major storms, known as the storm wave base (SWB).

Closure depth, while not a strict limit for sediment transport, serves as an empirical indicator of the increasing potential for coastal sediment transport within the limits defined by closure depths. In the Lido di Dante area, these depth conditions coincide with a transition in the composition of the sediments. Sandy sediments up to the upper shoreface and sandy-pelitic sediments in the lower one, then pass to silty-clayey muds in the inner shelf. Area where silt and clay particles are deposited mainly due to turbid plumes carried offshore by rivers and which are deposited there by flocculation.

This zonation allows for a better understanding of the influence of medium to long-term episodic events compared to local inter-annual dynamics, such as seasonal variations between summer and winter. Various studies, including those by Lisi et al. (2010), Patterson (2013), Short and Jackson (2013), Ortiz and Ashton (2016), Gomes de Silva et al. (2020), Anthony and Aagaard (2020), and Athina et al. (2022), contribute to the knowledge of these dynamics and the morphological changes in the coastal system.

Field Survey and Mapping

In spring 2021, local scuba divers reported the presence of unusual and compact organogenic structures on the seabed between the mouth of the Fiumi Uniti river and the artificial reef constructed to protect the settlement (as shown in Fig. 7). This area is part of the Po Delta Park's local protected area system and was subjected to detailed bathymetric surveys, Side Scan Sonar (SSS) scans, and direct inspections by scuba divers. The data collection methods adhered to the protocols suggested for similar cases by the Italian Ministry for the Environment and the Reef Check Mediterranean Protocol, which is developed within the activities of the Citizen Science European Association.

To ensure accurate georeferencing of the surveys, a Trimble R1 GNSS 2 differential (NRTK) system was used in conjunction with Topcon's centimetric differential positioning service. The system was calibrated based on the SAPC0300 vertex of Lido di Dante within the Coastal Geodetic Network of the Emilia-Romagna Region. Elevations were referenced to mean sea level and corrected for tidal excursions. All acquired data were organized and stored in a database using the Esri ArcGIS environment. Georeferencing was done in the global

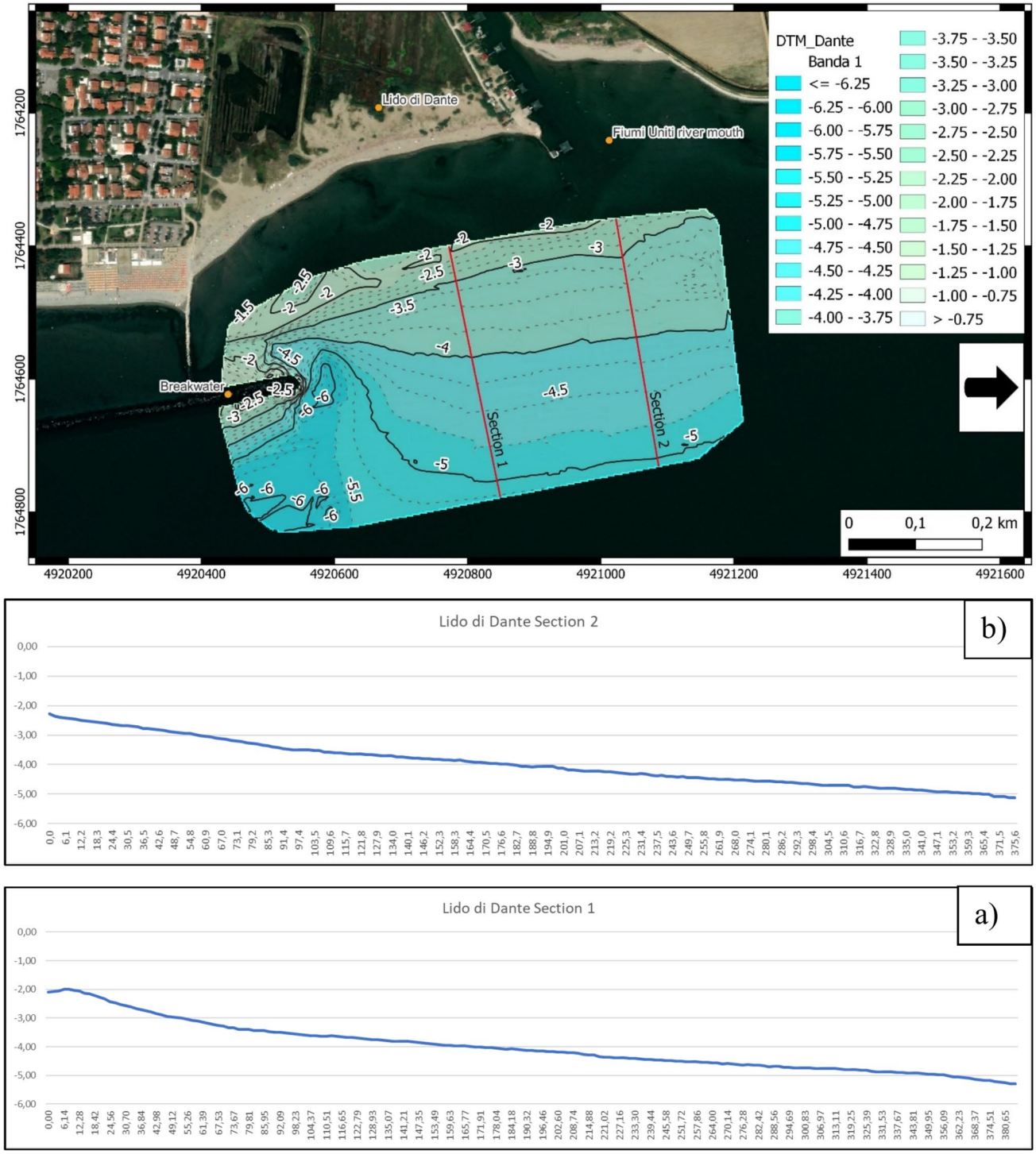

Fig. 7 DEM and 0.25 m isobath interval with 2 sections' profile a) and b) orientated W-E (Map created with GIS, base ESRI terrain, EPGS:3003)

ETRS89 system and connected to the Inspire 2022 Directive, which is based on spatial information infrastructures established and operated by the Member States of the European Union. In Italy, this is realized through the National Dynamic Network (RDN 2022), supporting GIS and cartographic applications for the regional territory of Emilia Romagna. The reference system was projected to the relative RDN2008 UTM Zone 32 N (EPSG:7791) conventionally included in spindle 33 (RER-Geoportale 2020).

Bathymetry

The survey activities utilized a portable high-resolution shallow water hydrographic single-beam echosounder called SyQwest—HydroBox. This echosounder is specifically designed for inshore and coastal hydrographic marine surveys. It operates at a frequency of 210 kHz and has an acoustic beam aperture of 8 degrees. The depth accuracy of the system is 1 cm, with a depth resolution of 0.01 m.

Prior to the survey, the echosounder was calibrated using a bar-check procedure, and the speed of sound in water was set to 1480 m/s, which is consistent with the freshwater inputs from the adjacent mouth of the Fiumi Uniti river. To calculate the tidal excursion, satellite positioning was used to measure the length of the transducer bar, and the water head measured by the echosounder at a given time was subtracted from the orthometric height of the antenna. This process is equivalent to directly measuring depths from the GNSS antenna.

The acquired data were processed using QGIS software. Initially, sporadic spikes caused by inconsistent GPS data quality were corrected. Then, the data were filtered and purified to remove false echoes, which are artifacts in the bathymetric data. The cleaned and corrected data were used to produce an elevation surface of the terrain through interpolation techniques in a GIS environment, specifically using the kriging algorithm, which is commonly used for such cases. The resulting elevation surface was used to derive isobaths with an inter-distance of 25 cm.

Figure 7 provides an outline of the investigated bathymetric range, which extends from − 2.0 to − 6.0 m. Under calm sea and no wind conditions, the seabed generally exhibits a consistent and regular deepening. However, there is a notable depression near the round head of the breakwater, where submerged structures induce marked vortices, as described by Zanuttigh et al. (2005).

Research conducted on the artificial structure in the Lido di Dante area, which was built around 1980 and subsequently partially modified, has indicated the absence of hard substrates in the area. The natural benthic aggregates found in the surf zone, which extends from a depth of approximately 0 to 4 m, were described as relatively species-poor. The dominant community in this zone was identified as *Lentidium mediterraneum*, which is characteristic of environments where hydrodynamics play a significant role as the main structuring factor. The studies conducted by Bachiocchi & Airoldi (2003), Zanuttigh et al. (2005), and Bertasio et al. (2007) support these findings.

Side Scan Sonar (SSS)

In order to determine the potential presence and extent of bioconstructions, the use of Side Scan Sonar (SSS) is commonly employed. Side Scan Sonar, especially when combined with direct visual checks, is considered the most suitable device for conducting rapid mappings to outline the actual spread of bioconstructions (Halvorsen et al. 2020). The investigations carried out in the area under examination utilized a SonarTech model S- 150P with Chirp technology, operating at a high frequency of 1250 kHz. The acquisition channels had an aperture of 50 m for the area further offshore and 40 m for the shallow water area near the shore.

To ensure good overlap and facilitate the generation of the final orthophoto mosaic, the sonar swipes were performed with an inter-distance of 15 m, even though the acoustic beam had an aperture of 20 m. The acquired digital data were processed and analysed using TRITON software, including the Perspective 7.6 module. The main processing operations involved navigation control, such as straightening the navigation route and applying towfish offsets, as well as slant range correction for column removal and precise bottom track value settings.

The sonograms were georeferenced on a pixel-by-pixel basis by integrating the recorded data with a'string'containing navigation data (x, y, z). This allowed the export of the corrected and georeferenced Side Scan Sonar transects in GeoTiff format. The acquired and georeferenced images were then individually processed and analysed by importing the photomosaic of the entire survey area into the QGIS environment. In QGIS, polygons representing the identified objects were digitized.

These methods, as described above, enable the visualization and analysis of the Side Scan Sonar data to identify and delineate the objects of interest, such as potential bioconstructions. The resulting polygons provide a spatial representation of the identified features, as shown in Fig. 8.

The mosaic images obtained from the Side Scan Sonar data reveal the presence of approximately 30 targets within the surveyed area. Further verifications conducted by divers confirm that around twenty of these targets can be attributed to structures associated with Sabellaria spinulosa (Leuckart, 1849). These structures are primarily characterized by large, irregularly shaped formations, with some solitary crusts observed to a lesser extent. The distribution of these structures covers an area of approximately 15,000 square meters (equivalent to about 1.5 hectares). The larger formations can reach heights exceeding 2–3 m and extend for tens of meters, while the thinner crusts are less than a meter in height (as pictured in Fig. 9).

The concentration and distribution of the Sabellaria spinulosa (Leuckart, 1849) structures within a small-scale gully perpendicular to the coast indicate the need for integrated considerations of hydrological and sedimentological interactions. The presence and characteristics of these bioconstructions are likely influenced by factors such as water flow patterns, sediment transport dynamics, and local

Fig. 8 Photomosaic Side Scan Sonar images (cartographic base from Google Earth 2020), the red circle indicates the area where there is the presence of *Sabellaria* (Leuckart, 1849) pictured in Fig. 9b

hydrodynamics. Understanding the interactions between these factors and the bioconstructions will provide valuable insights into the formation and maintenance of the Sabellaria spinulosa (Leuckart, 1849) structures in the area. Further investigation and analysis of the hydrological and sedimentological processes within the gully will contribute to a comprehensive understanding of the ecological and geomorphological dynamics in this region.

Discussion and Conclusion

The initial investigations conducted on a specific sector of the submerged beach of Lido di Dante have provided evidence and documentation of the presence of Sabellaria spinulosa (Leuckart, 1849) in the local coastal sandy bottoms, including those in the northern Adriatic Sea. Subsequent investigations will focus on verifying the potential presence of S. spinulosa (Leuckart, 1849) near other sections of the artificial breakwater, which spans approximately 1.3 kms and is divided into five sections with short stretches of sea separating them.

Side Scan Sonar surveys conducted in 2022 by CNR-Ismar in the internal and external portions of the southernmost artificial segment have indicated the existence of targets that were not clearly defined in their structure during the initial phase of the survey. These targets have the potential to be similar to the bioconstructions identified near the northernmost part of the artificial breakwater. The distribution of these targets is characterized by isolated bodies or small aggregates, which, under advantageous conditions, can expand and unite to form larger extensions. This spatial aggregation is facilitated by the intrinsic ability of S. spinulosa to originate from loose sands and undergo rapid modification and regeneration. However, these bioconstructions are also susceptible to fragmentation during energetic storm surges or as a result of various anthropic and natural impacts.

The presence of these conditions and their implications have been widely reported in the literature by researchers such as Bianchi (2001), Lisco et al. (2017, 2019, 2021), Gravina et al. (2018), Van Der Reijden et al. (2019), and MarineBiotech (2022). The upcoming investigations will further explore and analyse the potential presence and

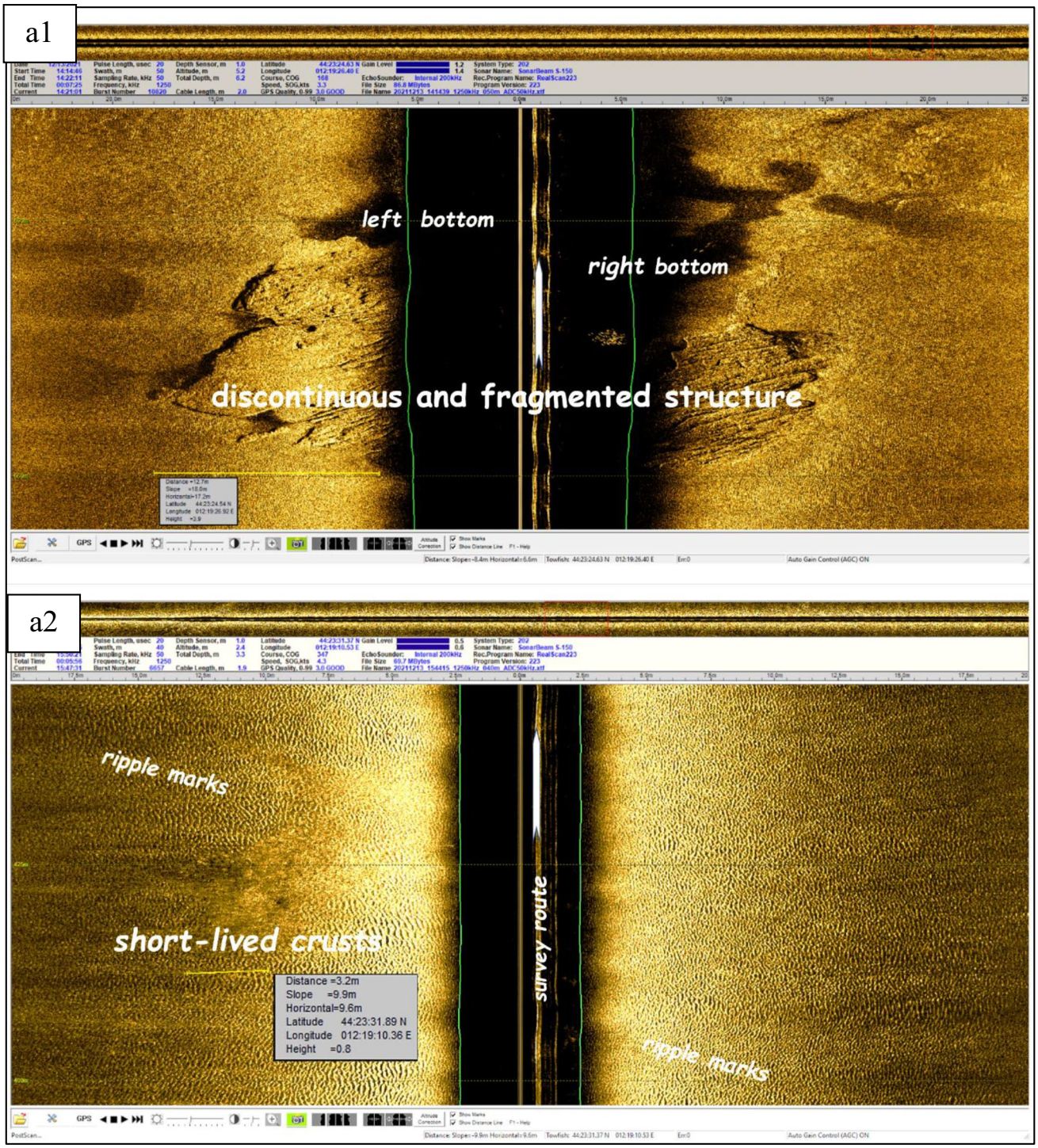

Fig. 9 a.1) and a.2) Representative examples of large structures (top) and thin crust (bottom) detected in the area; photos in b) are made in the area with a red circle in Fig. 8 and represent what they actually look and feel like under the sea

characteristics of S. spinulosa bioconstructions in the study area, contributing to the existing knowledge and understanding of these unique marine ecosystems.

The longevity of Sabellaria spinulosa (Leuckart, 1849) colonies is not well understood, but it is believed that bioconstructions formed by S. spinulosa can persist for several years. In the case of the structures identified in the Lido di Dante area, their probable origin is assumed to be relatively recent, considering the absence of previous reports by local fishermen or snorkelers. Recent sector literature

Fig. 9 (continued)

suggests that these bioconstructions exhibit considerable variability in their origin, modification, and rapid regeneration (Ospar 2008; Gravina et al. 2018; Lisco et al. 2021; Tillin et al. 2022; EUNIS 2022).

Further knowledge and assessments are necessary to determine the realistic potential of S. spinulosa (Leuckart, 1849) bioconstructions at the local and regional level for geoconservation and protection, aligning with current

guidelines aimed at strengthening strategies in the coastal and maritime domain. Relevant initiatives and frameworks include RER (Regional Economic Resilience), RITMARE (The Italian Research for the Sea), RER-ambiente, GIDAC-RER, Climate Group, and EMODnet (European Marine Observation and Data Network).

Future research will also focus on understanding the interconnections within the beach system, considering the physical-dynamic, geomorphological-sedimentological, and geochemical characteristics. This knowledge is crucial for the bio-ecological characterization of the bio-structures and their potential for providing ecosystem goods and services, including coastal protection from erosion and hazards. Studies by Faivre et al. (2017), Clark et al. (2017), Nelson et al. (2020), The Nature Conservancy (2021), and Franzitta et al. (2022) highlight the importance of such knowledge for effective coastal management.

In collaboration with the Municipality of Ravenna, specific attention will be given to projects exploring the transplantation of S. spinulosa (Leuckart, 1849) in selected sectors of the Lido di Dante seabed. These projects aim to enhance their presence as nursery areas, ecosystem services providers, agents of sediment stabilization, and contributors to the mitigation of coastal erosion. Furthermore, the combination of S. spinulosa (Leuckart, 1849) with low-impact artificial structures, incorporating flexible new modules, advanced production technologies, and cost-effective materials based on computational fluid dynamics simulations, is being studied to assess their potential hybrid contribution to ecosystemic functions and coastal erosion mitigation, as noted by Carr and Hixon (1997), Perkol-Finkel et al. (2006), Hunter and Sayer (2009), Davis and Smith (2017), USGS (2018), Gracia et al. (2018), Wiomsa (2021), and Zhang et al. (2022).

The presence of Sabellaria spinulosa (Leuckart, 1849) bioconstructions holds significant importance from a geoheritage perspective. These bioconstructions, often referred to as"biogenic reefs,"represent not only valuable biological formations but also key geological structures that contribute to the marine geoheritage of coastal areas. As dynamic natural entities, Sabellaria reefs play a crucial role in stabilizing sediments, influencing local geomorphology, and acting as living archives of environmental conditions. Their ability to form complex structures in response to both natural and anthropogenic factors makes them vital indicators of marine ecosystem health and resilience. Protecting these bioconstructions aligns with global efforts to conserve geodiversity, as they serve as unique examples of interactions between biological and geological processes. Recognizing the geoheritage value of Sabellaria spinulosa reefs promotes their inclusion in conservation and management policies, ensuring their preservation for scientific research, education, and the sustainable use of coastal environments.

Conclusion

The data acquired from the preliminary investigations conducted in the coastal area of Lido di Dante provide valuable information regarding the presence of Sabellaria spinulosa (Leuckart, 1849) biogenic structures. These findings not only describe the occurrence of these structures in the northernmost sector of the intertidal coast of the Adriatic Sea but also contribute to enhancing knowledge about these habitats, which are still considered"data deficient"in the Mediterranean region (EUNIS 2022).

The presence of S. spinulosa (Leuckart, 1849) in this specific sector of the Ravenna coast lays the foundation for future interdisciplinary campaigns aimed at furthering our understanding of these habitats. These campaigns can include various methodologies such as Side Scan Sonar surveys, high-precision underwater photogrammetry and geodetic surveys conducted by divers, utilization of remotely operated vehicles (ROVs) to create 3D models of submerged objects, and sampling for subsequent laboratory analyses.

By employing these interdisciplinary approaches, researchers can gather comprehensive data, including detailed spatial information, 3D models, and laboratory analyses, to better understand the characteristics and ecological significance of S. spinulosa bioconstructions in the study area. This data will contribute to the ongoing development and management of the coastal area, supporting local initiatives and decision-making processes.

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Data Availability The data that support the findings of this study are held by author Gabbianelli and are available upon request.

Declarations

Conflicts of Interest The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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