



Mapping benthic marine habitats featuring coralligenous bioconstructions: a new approach to support geobiological research

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Abstract. Seabed mapping represents a very useful tool for seascape characterization and benthic habitat study and requires advanced technologies for acquiring, processing, and interpreting remote data. Particularly, acoustic instruments, such as high-resolution swath bathymetry sounders (i.e., multibeam echosounder: MBES), allow us to recognize, identify, and map the extension of benthic habitats without applying invasive mechanical procedures. Bathymetry and backscatter (BS) data are crucial to perform modern habitat mapping. Although the acquisition and processing of bathymetric data follow standardized procedure (e.g., Hydrographic Organization guidelines), and recent studies have proposed recommendations for backscatter acquisition and processing, a broadly validated methodological approach, integrating geomorphometric analysis for benthic habitat mapping, is still lacking. In this work, a new approach for benthic habitat mapping, with a focus on coralligenous bioconstructions, was developed using the open-source software QGIS. This methodology, tested within the Isola Capo Rizzuto Marine Protected Area (Calabria, Italy), is designed to be freely reproducible by researchers working in the field of marine ecosystem monitoring and conservation. Through the proposed mapping procedure, it is possible to (i) identify benthic habitats in selected study areas by combining bathymetry and BS data with geomorphological indices performed in QGIS and (ii) quantitatively define the 2D and 3D distribution of coralligenous bioconstructions in terms of surface cov-

ered, thickness, and volume. Moreover, the statistical analysis of quantitative morphometric data allowed for comparison of geometric characteristics of different coralligenous morphotypes. The obtained results, combined with improvement of minimally invasive sampling and geobiological–geochemical characterization, can contribute to the development of protocols aimed at monitoring marine bioconstructed ecosystems, many of which are protected by national and international regulations due to their importance for Mediterranean biodiversity preservation, and plan actions for their protection and persistence.

1 Introduction

Bioconstructions are geobiological bodies formed in situ by growth of skeletonized organisms and represent habitats that host a great variety of benthic species. They experience a wide array of dynamic phenomena, resulting from the balance between the action of habitat builders, dwelling organisms, and bio-eroders over decadal to millennial timescales. Along the Mediterranean continental shelf, the most conspicuous bioconstructed habitats are represented by coralligenous build-ups (Bracchi et al., 2015, 2017, 2022, 2025; Basso et al., 2022; Cipriani et al., 2023, 2024; Bazzicalupo et al., 2024, 2025; Sanfilippo et al., 2025), vermetid reefs (Picone and Chemello, 2023), sabellariid build-

ups (Sanfilippo et al., 2019, 2022; Deias et al., 2023), and polychaete–bryozoan bioconstructions (Guido et al., 2013, 2016, 2017a, b, 2019a, b, 2022), whereas cold-water corals occur in deeper settings (Lo Iacono et al., 2018; Rueda et al., 2019; Foglini et al., 2019). Coralligenous is known as a biocenosis complex consisting of a hard biogenic substrate primarily generated by the superimposition of calcareous red algae able to form 3D structures, supporting a high biodiversity (e.g., Ballesteros, 2006; Bracchi et al., 2022; Rosso et al., 2023; Sciuto et al., 2023; Donato et al., 2024). Although recent studies have highlighted some terminological uncertainty in the definition of coralligenous habitat (e.g., Jardim et al., 2025, and references therein), within the geobiological literature the term coralligenous bioconstructions is widely and consistently adopted to indicate these biodiversity-rich, three-dimensional biogenic structures characterized by several layers of encrusting coralline algae (e.g., Ingrosso et al., 2018; Bracchi et al., 2017, 2022; Basso et al., 2022; Cipriani et al., 2023, 2024; Ferrigno et al., 2024).

Pérès and Picard (1964) and Pérès (1982) identified coralligenous as the ecological climax stage for the Mediterranean circalittoral zone, with some bioconstructions also occurring in dim-light very shallow settings (Ballesteros, 2006; Bracchi et al., 2016; Basso et al., 2022). Coralligenous produces various morphotypes on the seafloor and plays a key role in the formation and transformation of seascape over geological time (Bracchi et al., 2017; Marchese et al., 2020). Architecture and morphology are mainly influenced by biological carbonate production, which responds to different factors, like physiography, oceanography, terrigenous supply, and climate (Schlager, 1991, 1993; Betzler et al., 1977; Bracchi et al., 2017). Based upon the nature of the substrates, coralligenous morphotypes have been categorized in two main groups: (i) banks, flat frameworks mainly built on horizontal substrata and, and (ii) rims, structures on submarine vertical cliffs or close to the entrance of submarine caves (Pérès and Picard, 1964; Laborel, 1987; Ballesteros, 2006; Bracchi et al., 2017; Marchese et al., 2020; Gerovasileiou and Bianchi, 2021). Moreover, Bracchi et al. (2017) introduced a new classification for coralligenous morphotypes on sub-horizontal substrate using a shape geometry descriptor in order to obtain a more objective description of these morphologies, classified into the following: (i) tabular banks, i.e., large tabular structures with a significant lateral continuity that completely cover the seafloor, forming an extensive habitat; (ii) discrete reliefs, i.e., smaller, distinct structures often arranged in clusters that do not fully cover the seafloor, leaving patches of sediment between them; and (iii) hybrid banks, a category grouping intermediate morphologies between tabular banks and discrete reliefs. These structures can coalesce into a larger formation, resembling tabular banks, while still maintaining individual characteristics. Hybrid banks often occur alongside other habitats, and their distribution is influenced by local sediment and hydrodynamic conditions (Bracchi et al., 2017).

Although coralligenous bioconstructions occur along almost the entire Mediterranean continental shelf, they have been mapped only in a few areas and their distribution is still underestimated (De Falco et al., 2010, 2022; Innangi et al., 2024). In addition, as known hot spot of biodiversity, along with its low accretion rate of $0.06\text{--}0.27\text{ mm yr}^{-1}$ and its sensitivity to natural and anthropogenic impacts (Di Geronimo et al., 2001; Bertolino et al., 2014; Basso et al., 2022; Cipriani et al., 2023, 2024), coralligenous is acknowledged as a priority habitat for protection under the EU Habitats Directive, is part of the Natura 2000 network (92/43/CE), and is subject to specific conservation plans within the framework of the Barcelona Convention (UNEP-MAP-RAC/SPA, 2008; UNEP-MAP-RAC/SPA, 2017). Moreover, together with other vulnerable settings (e.g., cold-water corals), coralligenous is monitored under the Marine Strategy Framework Directive (MSFD, EC, 2008; SNPA, 2024). As a result, non-destructive methods have been developed to assess the health status and ecological quality of this habitat (Bracchi et al., 2022). For all these reasons, seabed mapping can provide a very useful tool for seascape characterization and mapping of coralligenous and other vulnerable habitats (Chiocci et al., 2021). In particular, acoustic instruments, such as high-resolution swath bathymetry sounders, side scan sonars, and acoustic profiling instruments, enable the quick detection and identification of benthic habitats and thus the mapping of their extension without any direct contact that might represent a threat for these vulnerable ecosystems (Bracchi et al., 2017; Chiocci et al., 2021).

Several studies have demonstrated that such technologies, especially when combined with backscatter (BS) data and geometric descriptors, significantly enhance the study of seafloor properties and the discrimination of benthic habitats, such as coral reefs, improving the understanding of their spatial distribution and ecological significance (Fonseca and Mayer, 2007; Lecours et al., 2015, 2016; Brown et al., 2012; Lamarche and Lurton, 2018; Abdullah et al., 2024).

In this work, a semiautomated GIS-based approach for benthic habitat mapping was proposed and tested in shallow coastal waters, off Capo Bianco, within the Isola Capo Rizzuto Marine Protected Area (Crotone, southern Italy). The method combines high-resolution bathymetric and BS data obtained through multibeam echosounder (MBES) surveys and geomorphological and geomorphometric indices in order to develop innovative approaches for eco-geomorphological and geobiological characterization of the seafloor. The benthic habitat mapping proposed here has proven to be capable not only of identifying marine bioconstructions, but also of quantitatively defining their spatial and three-dimensional distribution in terms of area, volume, and height relative to the substrate from which they arise. For these reasons, the procedure represents a powerful tool for accurately delineating the extension of the bioconstructions and evaluating their evolution over time in response to natural and/or anthropogenic changes. Furthermore, the combination of this

mapping approach with minimally invasive sampling systems and geobiological–geochemical characterization of marine bioconstructions may represent a potent tool for monitoring these delicate habitats.

2 Methodological approach

High-resolution acoustic data of the study area offshore of Capo Bianco were collected during several MBES surveys (Fig. 1) performed between February and July 2024 as part of the project “Tech4You PP2.3.1: Development of tools and applications for integrated marine communities and substrates monitoring; Action 1: Development of hardware and software systems for three-dimensional detection, sampling and mapping of underwater environments”, an implementation of the previous bathymetric and backscatter data acquisition and elaboration of CRSM-ARPACAL.

The approach proposed for benthic habitat mapping and defining of spatial and three-dimensional distribution of coralligenous bioconstruction is shown in Fig. 2. In particular, mapping operations were conducted using QGIS 3.34.9 “Prizren”. The most representative morphological indices, represented by slope and seafloor roughness, were extracted from the digital terrain model (DTM). Due to the large amount of data resulting from the need to obtain a high-resolution mapping of benthic habitats, backscatter and bathymetry values, together with geomorphological–geomorphometric indices, were imported and queried into PostgreSQL, an open-source and free relational database management system (RDBMS) capable of executing queries in Structured Query Language (SQL).

Once the spatial extension and distribution of the benthic habitat had been defined by a combination of bathymetric, backscatter, slope, and seafloor roughness data, the extraction of coralligenous build-ups was performed using the topographic position index (TPI), according to Marchese et al. (2020). Moreover, area, shape index (SI), maximum diameter (Dmax) thickness, and volume were calculated for each extracted polygon. Finally, the benthic habitat mapping model was ground-truthed by visual analysis of remotely operated vehicle (ROV) video transects performed along specific paths within the study area. The underwater video surveys were obtained using a VideoRay Defender equipped with a functional prototype of the optical module dedicated to mapping, comprising a stereo camera, a high-resolution camera, and a lightning system (Severino et al., 2023). Both cameras have been meticulously calibrated to correct for optical distortions, ensuring accurate and reliable data acquisition. The selected cameras were the GoPro Hero 9 Black, serving as the high-resolution camera, and the Stereolabs ZED2i, serving as the stereo camera. The GoPro Hero 9 Black is a small-sized action camera with a 26.3 MP CMOS sensor capable of acquiring videos at a resolution of 5120×2880 at 30 fps, digital stabilization, and a horizon-

tal field of view up to 128° . The ZED2i is a stereo camera with dual 4 MP sensors of $2 \mu\text{m}$ pixel size, a depth range between 0.3 to 20 m, a video resolution of 2208×1242 at 15 fps, and a horizontal field of view of 110° . The stereo camera communicates with the surface control unit by means of a single-board microcomputer, a NVIDIA Jetson Nano, which supports the CUDA architecture for parallel elaboration. The GoPro Hero 9 Black features Bluetooth low-energy (BLE) and Wi-Fi communication capabilities. The acquisition parameters for both cameras can be configured via the enclosure using a custom user interface accessible on the surface computer.

2.1 Bathymetric and backscatter data

MBES surveys have been carried out using a pole-mounted, Norbit iWBMS Long-Range Turnkey Multibeam Sonar System integrated with GNSS/INS (Applanix OceanMaster), operating with real-time kinematic (RTK) corrections, ensuring high positioning accuracy during the surveys. Data were collected in 59 tracks with a swath overlap of 20%–40% performed at an average speed of 2.315 m s^{-1} . A total of three sound velocity profiles per day were collected before starting the acquisition using a sound velocity profiler: Valeport miniSVP. Considering the absence of freshwater inputs and the relative stability of the water column across the depth range, this was deemed sufficient to ensure reliable sound speed correction.

The MBES survey provided both bathymetry and BS data. The processing of MBES bathymetric data was performed using QPS Qimera and included corrections for tide, heading, heave, pitch, and roll. The correction of sound velocity was carried out using profiles obtained with the Valeport miniSVP. Subsequently, the soundings underwent manual cleaning to remove spikes. The bathymetric dataset was exported as a 32-bit raster file with a cell size of 0.05 m, obtained through interpolation of soundings using a CUBE surface model.

Backscatter data were processed using QPS Fledermaus, based on time series data and applying standard corrections for sonar configuration (e.g., source level, beam pattern, receiver gain) and environmental factors (e.g., absorption, slant range, footprint geometry). The processing was performed according to the general principles outlined in the Backscatter Working Group guidelines (Lurton et al., 2015), which provide detailed recommendations for the acquisition, correction, calibration, and processing of MBES backscatter data. The final output, exported as an 8-bit raster file with a 0.05 m cell size, was used to extract morphological and acoustic patterns of the seafloor.

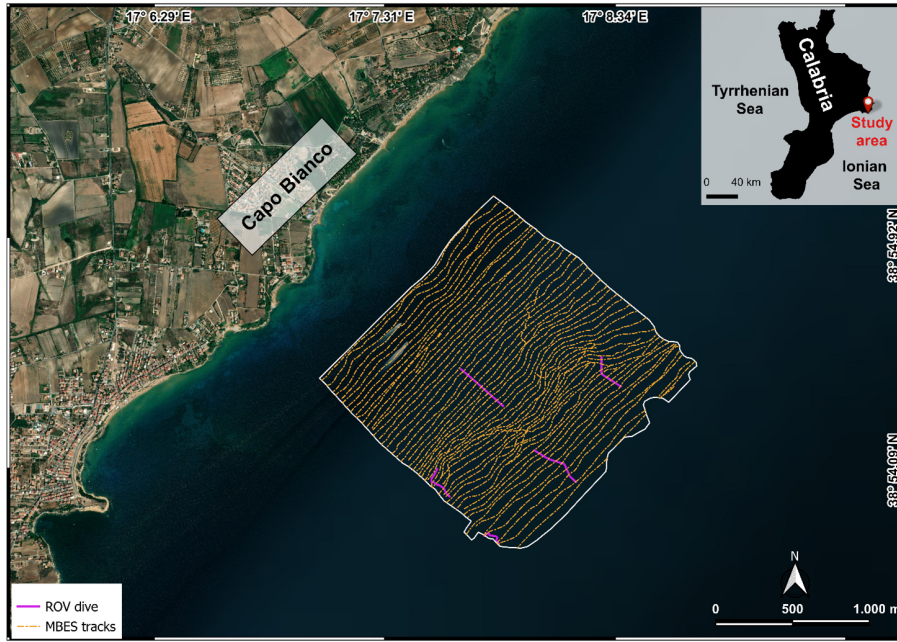


Figure 1. Study area off Capo Bianco (Calabria, Italy) and location of the MBES tracks and ROV video transect (basemap from Esri World Imagery).

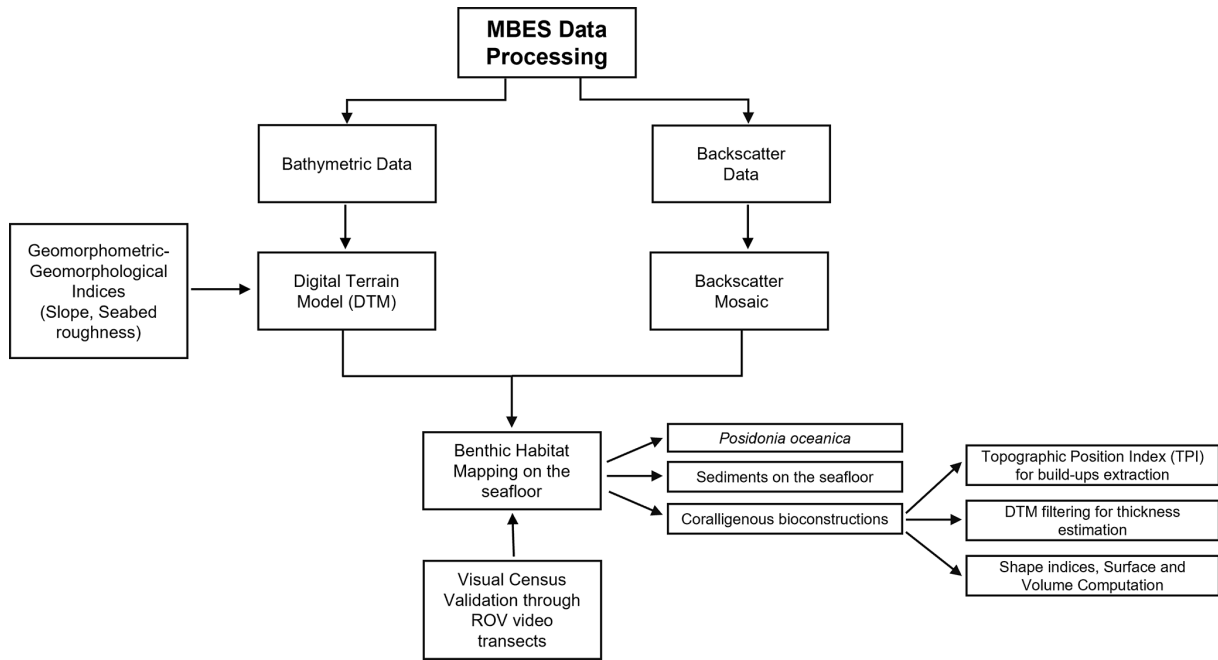


Figure 2. Conceptual model of the workflow for the development of the proposed benthic habitat mapping approach.

2.2 Geomorphological–geomorphometric indices

Geomorphologic and geomorphometric indices were obtained using SAGA (System for Automated Geoscientific Analysis; Conrad et al., 2015) Next Gen Provider and GDAL plugins. In particular, the slope, expressed in degrees, was

calculated using the dedicated function implemented in the GDAL plugin using a ratio of vertical units to horizontal of 1.0 and applying the Zevenbergen–Thorne formula instead of the Horn formula. Indeed, the Zevenbergen–Thorne method (Zevenbergen and Thorne, 1987), which considers a second-order finite difference, is more dedicated to geo-

morphological applications as it uses a particular weighting scheme that emphasizes changes in curvature and terrain shape. Seabed roughness was assessed using the terrain roughness index (TRI), which provides a quantitative measure of terrain heterogeneity (Riley et al., 1999). In particular, TRI values close to 0 indicate fairly regular and uniform surfaces, moderate TRI values correspond to more pronounced irregularities, and high TRI values identify rugged morphologies and/or complex structures on the seafloor. TRI was calculated using the SAGA module “Terrain Roughness Index” with the following settings: a circle as a search mode, a search radius of 0.5 m, a Gaussian weighting function, a value of 3.00 for the power, and a bandwidth of 75.00. The values of these parameters were selected through a trial-and-error method in order to best highlight the heterogeneity of the seabed.

2.3 Topographic position index

The topographic position index (TPI) was calculated at the finest possible scale (minimum radius: 1.00 m; maximum radius: 5.00 m) according to the DTM resolution and using a power of 3.00 and a bandwidth of 150.00. TPI is a morphometric parameter based on neighboring areas useful in DTM analysis (Wilson and Gallant, 2000). Specifically, positive TPI values indicate areas that are higher than the average of their surroundings, TPI values near zero correspond to flat areas or regions with a constant slope, and negative TPI values represent areas lower than their surroundings. In order to facilitate the extraction of coralligenous build-ups from surrounding seafloor and reduce the occurrence of artifacts, a TPI threshold of 0.2 was used and all the grid cells below this value were not considered to be coralligenous bioconstructions. The TPI scale (1.00–5.00 m) and value (0.2) were chosen through a trial-and-error approach in order to preserve the high resolution of the extraction, which is crucial for accurate volume computation.

2.4 DTM filtering

TPI parameters extracted the distribution of the coralligenous build-ups with high resolution in terms of perimeter boundaries. The thickness calculation for each coralligenous build-up was developed by the creation of a “reference surface” (without build-ups) using the SAGA DTM Filter (slope-based) tool implemented in QGIS 3.34.9. This tool uses concepts as described by Vosselman (2000) and can be used to filter a DTM, categorizing its cells into ground and non-ground (object) cells. A cell is considered ground if there is no other cell within the kernel radius where the height difference exceeds the allowed maximum terrain slope at the distance between the two cells. The thickness estimation of each coralligenous build-up was obtained by subtracting the average depth of each polygon extracted using TPI from the

average depth value of the reference surface at that specific zone.

After estimating the height of each build-up relative to the seabed on which it developed, the shape index (SI – McGarigal and Marks, 1995) was calculated using the module “Polygon Shape Indices” in SAGA in order to describe a seafloor landscape characterized by distinct coralligenous morphotypes. Finally, the covered surface and volume of each polygon were calculated using a vector field operation implemented into QGIS.

3 Geological setting

The study area, located offshore of Capo Bianco (Isola Capo Rizzuto, Calabria, Italy), belongs to the Crotona Basin (CB) (Fig. 3), the widest Neogene basin of the Calabria region, partly exposed along the Ionian coast and partly documented offshore. It represents a segment of the Ionian forearc basin on the inner portion of the Calabrian accretionary wedge (Cosentino et al., 1989; Cavazza et al., 1997; Bonardi et al., 2001; Minelli and Faccenna, 2010). The basin infill is structured into several distinct tectono-stratigraphic sequences, which reflect an extensional to transtensional tectonic regime, occasionally interrupted by transpressional to compressional events (Malinverno and Ryan, 1986; Faccenna et al., 2001; Reitz and Seeber, 2012; Zecchin et al., 2012; Massari and Prosser, 2013; Milia and Torrente, 2014).

Since the mid-Pleistocene, a significant uplift (0.70–1.25 m kyr⁻¹; Zecchin et al., 2004), combined with glacio-eustatic sea level fluctuations, has led to the formation in the Crotona Peninsula of five orders of marine terraces (Palmentola et al., 1990; Westaway, 1993; Westaway and Bridgland, 2007; Santoro et al., 2009; Faccenna et al., 2011; Bracchi et al., 2014; Santagati et al., 2024), which unconformably overlie the Piacenzian–Calabrian marly clays of the Cutro Formation (Zecchin et al., 2004).

The Cutro terrace (first-order terrace), ascribed to MIS 7 (Marine Isotope Stage 7) by Zecchin and Caffau (2011), is a mixed marine to continental terrace, consisting of the products of carbonate (algal build-ups and biocalcarene passing into shoreface and foreshore deposits) to siliciclastic (shoreface, fluvial channel fill, lagoon–estuarine, and lacustrine deposits) sequences (Zecchin and Caffau, 2011).

The second order (MIS 5e), represented by the Campolongo–La Mazzotta terrace, is characterized by bioclastic and siliciclastic sandstones, with local bioclastic deposits and algal patch reefs (Mauz and Hassler, 2000; Zecchin and Caffau, 2011).

The Le Castella–Capo Cimiti terrace (third-order terrace), probably associated with MIS 5c (Mauz and Hassler, 2000), shows extensive algal reefs and shoreface deposits, with elevation variations due to normal fault displacement (Zecchin et al., 2004; Nalin et al., 2012).

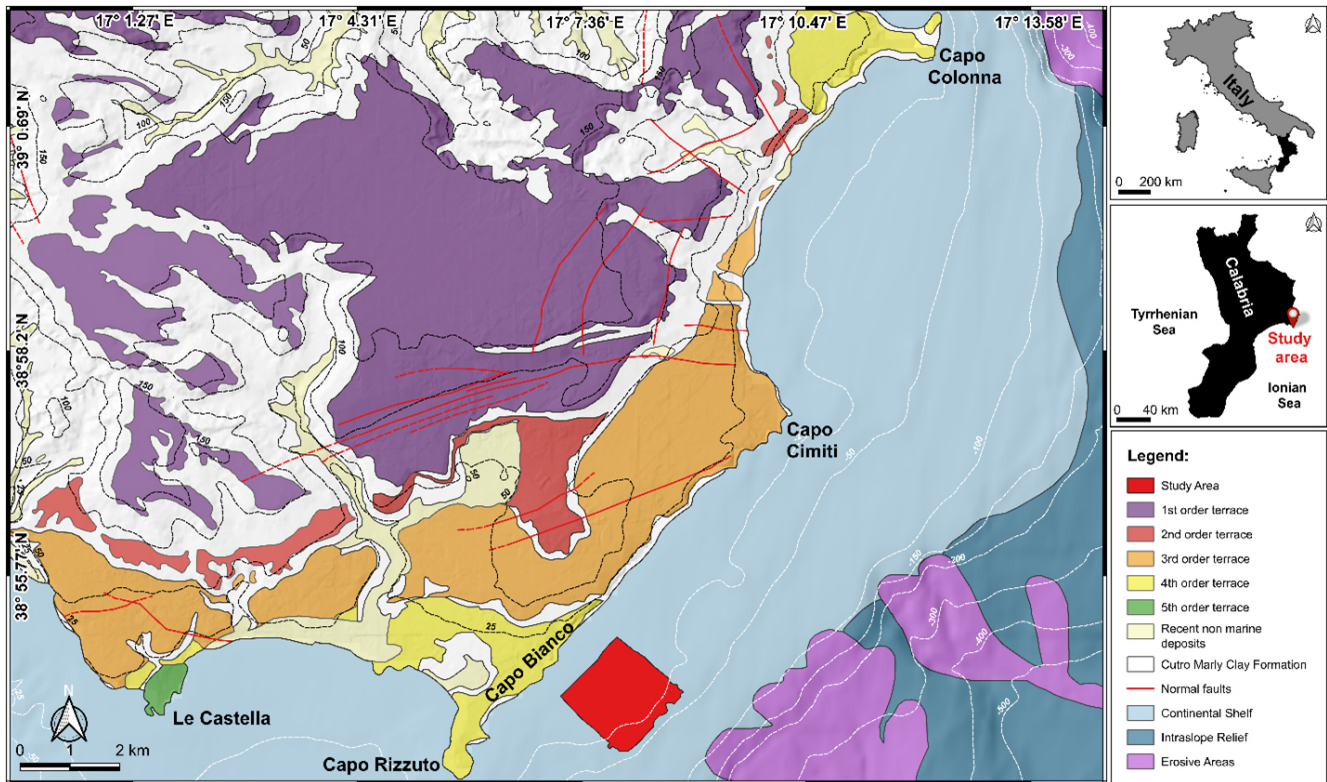


Figure 3. Conflated geological map of the Crotona peninsula, with the indication of the five orders of terraces (modified from Bracchi et al., 2014), and physiographic domains identified offshore of the area in the framework of the MaGIC project (modified from Chiocci et al., 2021).

The Capo Colonna marine terrace (fourth-order terrace), correlated with MIS 5.3 (Palmentola et al., 1990; Zecchin et al., 2004, 2009) or MIS 5.1 (ca. 80 ka; Gliozzi, 1987; Belluomini et al., 1988; Nalin et al., 2006; Nalin and Massari, 2009), consists of a planar surface with a sedimentary cover overlaid by a wedge of colluvium tapering (Bracchi et al., 2014).

The Le Castella marine terrace (fifth-order terrace) records an unconformity-bounded transgressive–regressive cycle (Nalin et al., 2007; Nalin and Massari, 2009; Zecchin et al., 2010; Bracchi et al., 2014, 2016), with two different facies for coralline algal build-ups and associated bioclastic deposits in the lower portion (Zecchin et al., 2004; Zecchin and Caffau, 2011). The age of these deposits remains debated, as they have been correlated with MIS 5.3 (Gliozzi, 1987), MIS 5.1 (Palmentola et al., 1990) and MIS 3 (Zecchin et al., 2004; Mauz and Hassler, 2000; Santagati et al., 2024).

The marine terraces exposed in the emerged portion near the study area demonstrated extensive carbonate production due to the development of algal bioconstruction throughout the Late Pleistocene. This production also appears to currently affect the seafloor. However, although the onshore portion of the CB has been well studied, its offshore extension is still less known (Pepe et al., 2010). Nevertheless, data

from the MaGIC project related to Sheet 39 “Crotona” covered a vast area extending from the Neto Submarine Canyon to the Capo Rizzuto Swell. In this section, the continental shelf reaches up to 7 km wide, with the shelf break located at depths of 80–120 m. The slope encompasses the southern portion of the Neto Canyon headwall and the Esaro Canyon along with its tributaries. The average continental slope gradient is less than 5° and is characterized by an undulating morphology including the Luna and the Capo Rizzuto Swell. The southern section of the sheet covers the offshore extension of the Crotona forearc basin (Chiocci et al., 2021). This work aims to enhance the understanding of the Crotona Basin offshore features, with a focus on underwater bioconstructed habitats.

4 Results

4.1 Morpho-acoustic characteristics of the seafloor

The comparison between bathymetric (Fig. 4a) and backscatter (Fig. 4b) data with those related to slope (Fig. 4c) and seafloor roughness (Fig. 4d) allowed for the definition of the morphological and morpho-acoustic characteristics of the study area off Capo Bianco (Calabria, Italy) and the iden-

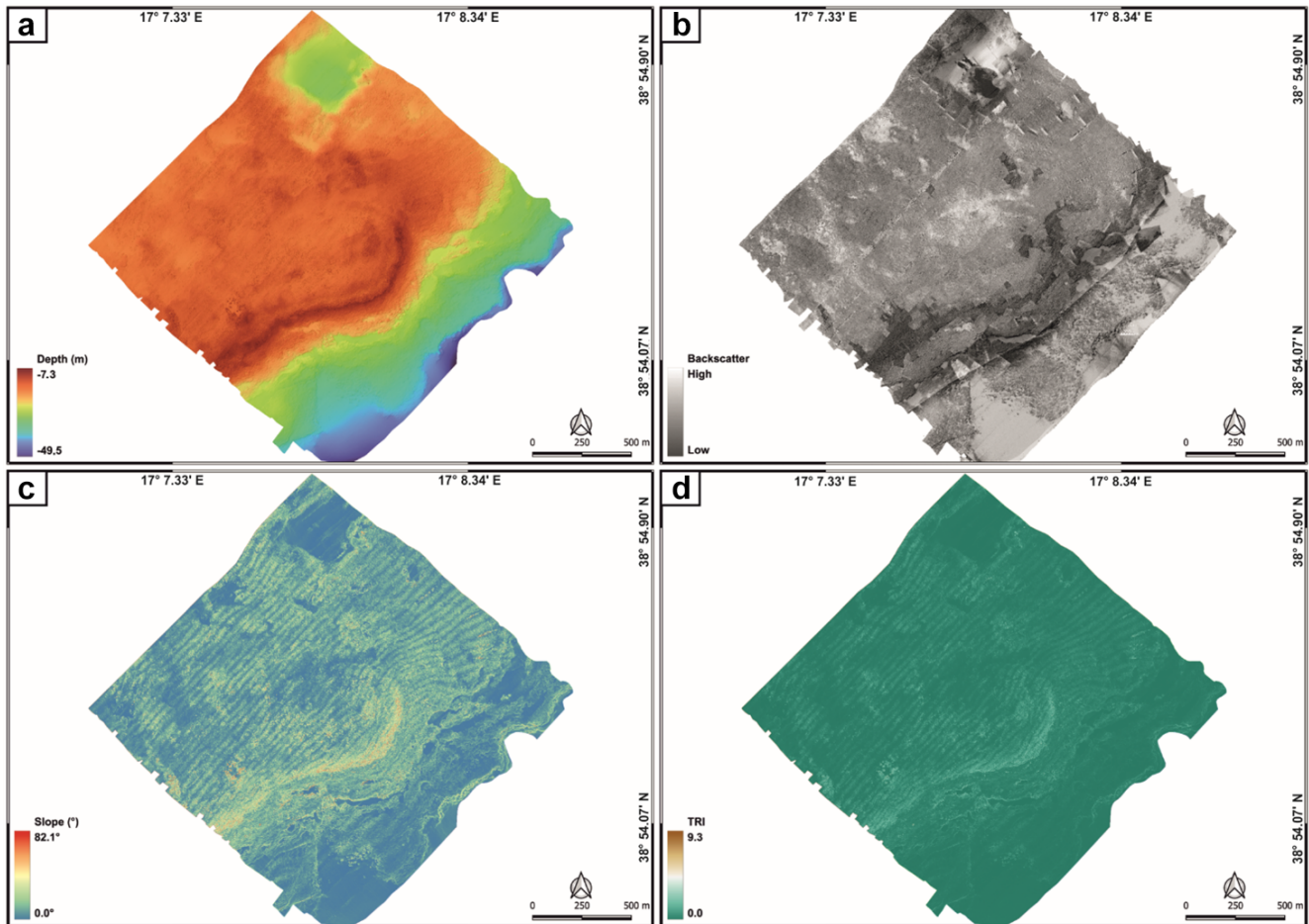


Figure 4. Geomorphological characteristics of the study area expressed through processed bathymetric data (a), backscatter data (b), and geomorphometric indices, like slope (c) and terrain roughness index (d).

tification of the benthic habitats. In particular, bathymetric data revealed a seafloor with depths ranging from -7.3 to -49.5 m (Fig. 4a). The transition towards the deeper areas is not gradual but shows an evident break in slope (starting from about -15 m depth), especially in the central zone of the study area. The shallower portion is characterized by widespread irregularities, while the deeper areas appear generally more regular, with less pronounced variations. Slope analysis (Fig. 4c) reveals maximum values (up to about 80°) along the break in slope, highlighting a steep and well-defined margin. The surrounding areas show lower slopes, with scattered peaks associated with seafloor irregularities. The terrain ruggedness index showed (i) a higher roughness along the break in slope (where the highest TRI values were recorded) and in its immediate vicinity and (ii) the presence of scattered roughness associated with irregularities on the seafloor (Fig. 4d).

Combining bathymetric and backscatter (Fig. 4b) data with slope and seafloor roughness values, different morphoacoustic features were identified (Fig. 5).

- *Posidonia oceanica* meadows, characterized by an intermittent speckled fabric of moderate backscatter. *Posidonia* covers seabed areas characterized by low slopes and slight roughness, spanning a depth range from about -6 to -25 m. In the depth range from -1 to -25 m, analysis of ROV video transects showed that the *Posidonia* meadow forms a mosaic with the coralligenous habitat.
- Banks of coralligenous, characterized by a complex fabric of moderate to low backscatter. They covered areas characterized by moderate to high slopes and medium to high roughness, spanning a depth range from about -15 to -25 m,
- Discrete coralligenous build-ups surrounded by medium to coarse sediment and maerl are characterized by a dotted pattern of moderate backscatter. They covered areas characterized by low slopes and medium roughness and occupy the area between the end of

the banks and the final depth of the MBES survey, at approximately -40 m depth.

- Fine to medium sediment, characterized by homogeneous patterns of medium to high backscatter. It covers scattered portions throughout the study area at various depths and is characterized by very low TRI values.

The combination of the various morpho-acoustic features enabled the identification of four main benthic habitats (Fig. 6): (i) *Posidonia oceanica* meadows, (ii) mosaic of coralligenous and *Posidonia*, (iii) coralligenous sensu stricto (i.e., bioconstructions that are not spatially intermixed with *Posidonia oceanica*), and (iv) fine to medium sediment.

The *Posidonia* habitat, testified by its typical BS signal (intermittent speckled fabric of moderate backscatter), dominates in shallow areas (down to about -15 m depth), where it primarily colonizes rocky substrate. In this area, ROV imagery and bathymetric data also highlight the occurrence of sub-spherical rocky blocks on the seabed, often surrounded by *Posidonia oceanica* (Fig. 5).

Between -15 and -25 m, the *Posidonia* backscatter signal gradually attenuates and coralligenous bioconstructions start to be discernible. This transitional belt, which occupies about 0.37 km², was classified as a mosaic of coralligenous and *Posidonia oceanica*. Visual analysis of ROV video transects, used as ground truth, indicates that in this zone, bioconstructions, mainly belonging to the bank morphotype, develop on a hard substrate that marks the widespread break in slope throughout the study area.

Below -25 m, *Posidonia* is no longer detected and the predominant benthic habitat is represented by coralligenous sensu stricto. These bioconstructions, often associated with fine to medium sediment and maerl, predominantly belong to the discrete relief morphotype and tend to align subparallel to the shoreline.

4.2 Extraction of coralligenous build-ups

The model extracted 12 384 polygons, but only 9211 positive morphologies were finally related to coralligenous build-ups considering the hillshade values and validation from ROV video transects collected within the study area (Fig. 7a). This means that about 25 % of the polygons extracted using the TPI were found to be artifacts after the reclassification and the polygonization of resulting raster. According to Marchese et al. (2020), the artifacts may be due to (i) occurrence of *Posidonia oceanica* (Innangi et al., 2015) (Fig. 8a), (ii) bad roll correction (Fig. 8c), and/or (iii) artifact concentrations on DTM boundaries (Fig. 8e). While artifacts of types (ii) and (iii) can be reduced by performing more accurate MBES surveys (i.e., larger coverage, greater overlapping, and narrower swath width), those related to *Posidonia oceanica* represent real morphological features that cannot be removed by improving survey quality.

Table 1. Classification of coralligenous polygons, based on SI values, and results in terms of area and volume.

| Morphotype | Shape index values | Average thickness (m) | Area (m ²) | Volume (m ³) |
|------------------|--------------------|-----------------------|------------------------|--------------------------|
| Banks | ≤ 2 | 0.65 | 155 677 | 116 094 |
| Discrete reliefs | > 2 | 0.49 | 69 830 | 40 806 |

The identification of artifacts was based on specific patterns inconsistent with expected coralligenous morphologies, and their removal was carried out manually as part of the data cleaning process (Fig. 8b, d, and f). The time required for the cleaning phase strongly depends on the quality of the survey execution, the geomorphological and ecological complexity of the study area, and the experience of the operator performing the cleaning. These factors can significantly influence the extent and efficiency of manual artifact removal.

Regarding the distinction between coralligenous bioconstructions and *Posidonia oceanica* in the mosaic area, the separation was primarily based on the characteristics of the backscatter signal. Specifically, as discussed previously, *Posidonia* is associated with a moderate, speckled acoustic texture, while coralligenous bioconstructions exhibit a more complex and spatially structured acoustic signature. These interpretations were supported by ROV video transects, which help to validate the differentiation.

4.3 Shape index, thickness, surface, and volume of coralligenous build-ups

Shape index (SI) values allowed distinguishing between banks (tabular bank sensu Bracchi et al., 2016; $SI \leq 2$) and discrete reliefs (discrete reliefs and hybrid banks sensu Bracchi et al., 2016; $SI > 2$) (Fig. 7b). Following this approach, it was possible to identify 7001 polygons belonging to the morphotype of the banks and 2210 classified as discrete reliefs. As shown in Table 1, banks have a greater average thickness (Fig. 7c) compared to discrete reliefs (0.65 m vs. 0.49 m, respectively) and cover an area of $155\,677$ m², which represents about 5.2 % of the seabed in the study area. In contrast, discrete reliefs cover only 2.6 % of the seafloor, with a surface area of $69\,830$ m². The volume (Fig. 7d) occupied by discrete reliefs ($40\,806$ m³) is also significantly lower than that of the banks ($116\,094$ m³). These data are consistent with the fact that discrete reliefs are characterized by smaller extent and thickness compared to the banks.

5 Discussion

Acoustic techniques, such as high-resolution swath bathymetry sounding (including backscatter), side scan sonar detection, and acoustic profiling, are optimal tools

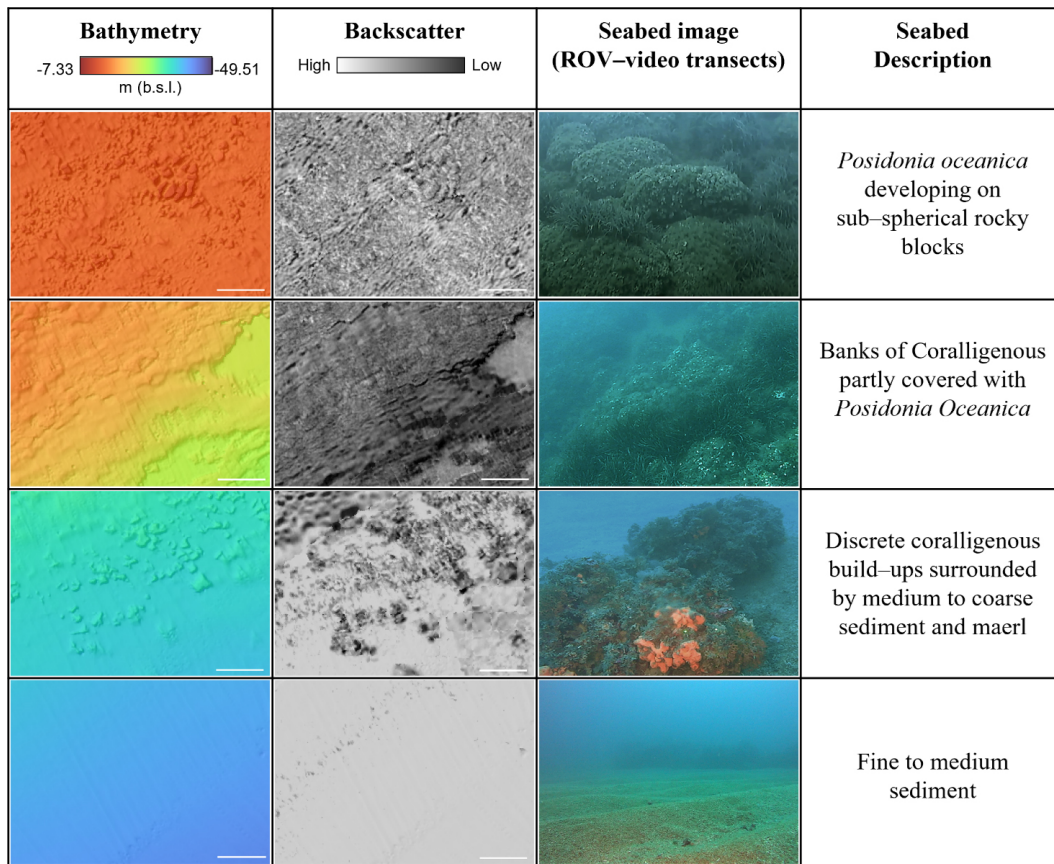


Figure 5. Morpho-acoustic features identified by bathymetric and BS data, together with ROV video interpretation. The white scale bar is 20 m.

for quickly recognizing and identifying the extension of benthic habitats on the seabed and mapping their distribution without mechanical collection of samples, which would damage this delicate ecosystem (Bracchi et al., 2017).

Traditionally, the segmentation of MBES datasets has been performed manually, despite the fact that the process might be inaccurate and subjective (Cutter et al., 2003; Bishop et al., 2012). Initial attempts at automation employed object-oriented methods using object-based image analysis (OBIA) or considered a comprehensive set of remote data to accurately characterize seabed landforms for documenting the extension of benthic habitat (e.g., Lucieer and Lamarche, 2011; Ismail et al., 2015; Janowski et al., 2018; Fakiris and Papatheodorou, 2012). More recently, the growing availability of high-resolution MBES data has encouraged the application of deep learning approaches, particularly convolutional neural networks (CNNs) and fully convolutional neural networks (FCNNs), which produce pixel-wise classifications in order to create semantically segmented maps. These methods have proven effective in identifying geomorphological features such as bedrock outcrops, pockmarks, and submarine dune and ridges, offering high accuracy and repeatability (Arosio et al., 2023; Garone et al., 2023). Addition-

ally, 3D CNNs have been applied to automated denoising of MBES data, enhancing the efficiency of bathymetric data workflows (e.g., Stephens et al., 2020).

Nonetheless, a universally accepted and standardized methodology for geomorphological classification of the seafloor is still lacking. Indeed, existing approaches remain highly case-specific, depending on the study area, data quality, and research objective. Moreover, relatively limited attention has been devoted to the morphological characterization of coralligenous bioconstructions, despite their ecological relevance. Indeed, only a few studies have attempted to map these complex biogenic structures in detail. Bracchi et al. (2017) proposed a categorization of coralligenous morphotypes on subhorizontal substrate based on integrated acoustic data and ground truthing, defining new morphological classes such as tabular banks, hybrid banks, and discrete reliefs across the Apulian shelf. Subsequently, Marchese et al. (2020) proposed a protocol that combines acoustic datasets and geomorphometric analysis, performed using ArcGIS™, in order to define the 2D and 3D complexity of coralligenous build-ups and to quantify how much carbonate is deposited. More recently, Varzi et al. (2023) produced a morpho-bathymetric map for the continental shelf offshore

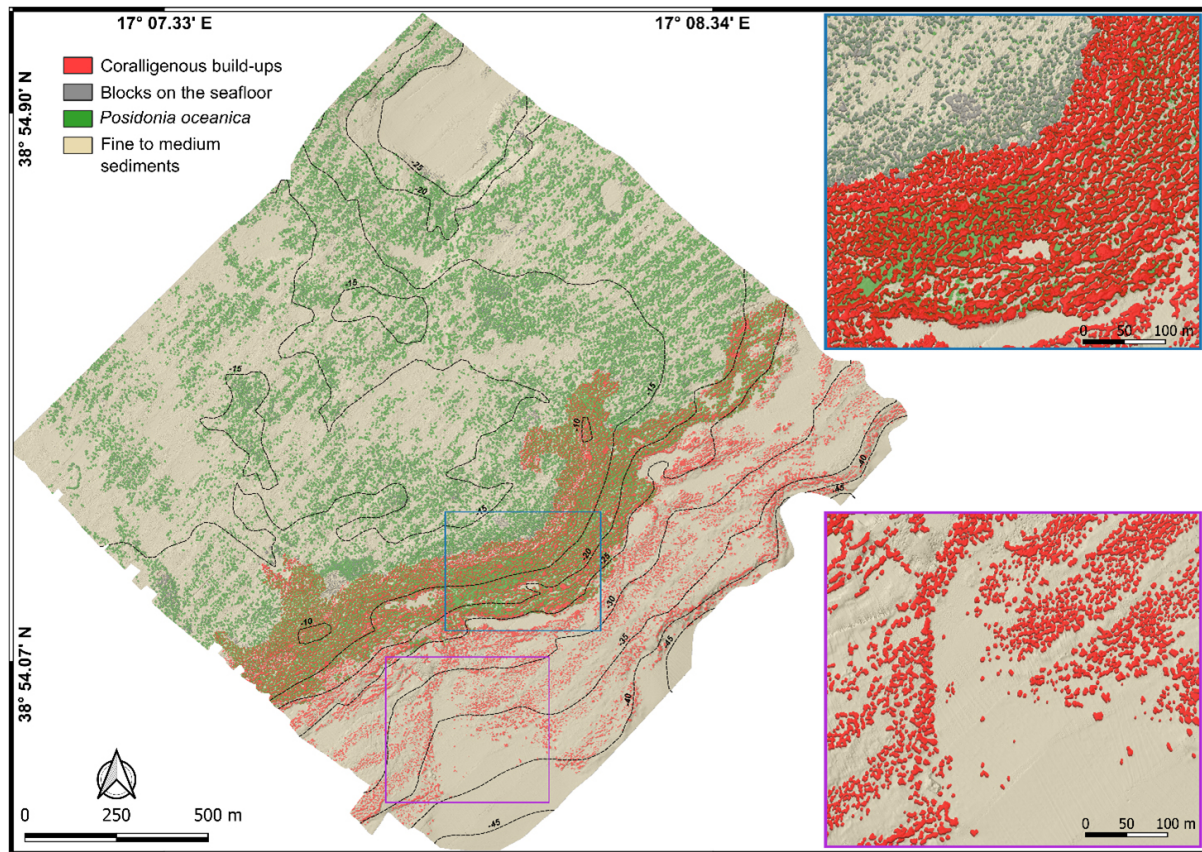


Figure 6. Mapping model of the underwater benthic habitats in the study area off Capo Bianco (Calabria, Italy). Note, in the blue and purple boxes, two magnifications of representative areas of the model where coralligenous bioconstructions and rocky blocks on the seabed are depicted in 2.5D.

of Marzamemi (Sicily, Italy) that contained a quantitative description for the distribution and extent of coralligenous reefs.

The approach proposed in this work, based on the workflow shown in Fig. 2, represents the first attempt to define the benthic habitat in the Isola Capo Rizzuto Marine Protected Area and to quantify the extent and morphometric characteristics of coralligenous bioconstructions present therein using exclusively open-source software during post-processing phases.

5.1 Spatial distribution of benthic habitats and seafloor morphology

The benthic habitat distribution identified in the study area exhibits a clear spatial zonation, which appears to be influenced by both substrate characteristics and geomorphological features. In the shallowest sector (above -15 m depth), *Posidonia oceanica* represents the prevalent benthic habitat. In the intermediate depth range (down to approximately -25 m depth), a mosaic of *Posidonia* and coralligenous bioconstructions develops, indicating a transitional zone where

environmental conditions allow the coexistence of seagrass and algal reefs.

Comparison between the morphological characteristics of the seabed with the alignment and elevation of the emerged marine terraces highlights the presence of a flat, laterally continuous submerged surface, as typically observed in relict marine terraces (e.g., Savini et al., 2021; Lebrec et al., 2022). This subhorizontal platform is bounded seaward by a break in slope, located at approximately -15 m depth, interpreted as the outer margin of the terrace. Based on this evidence, the submerged surface can be correlated with the fifth-order terrace exposed near Le Castella, characterized by a gently seaward-inclined surface and a morphological step interpreted as a paleoclipf (Bracchi et al., 2016). The different orientation of the submerged scarp in the study area (NE–SW), compared to the emerged paleoclipf associated with the Le Castella marine terrace (NW–SE to E–W), may be reasonably attributed to local coastal curvature and/or tectonic influences. The submersion of this portion of the fifth-order terrace in the study area would be justified by the possible presence of a tectonic feature with extensional kinematics located approximately along the coastline, which shows a dis-

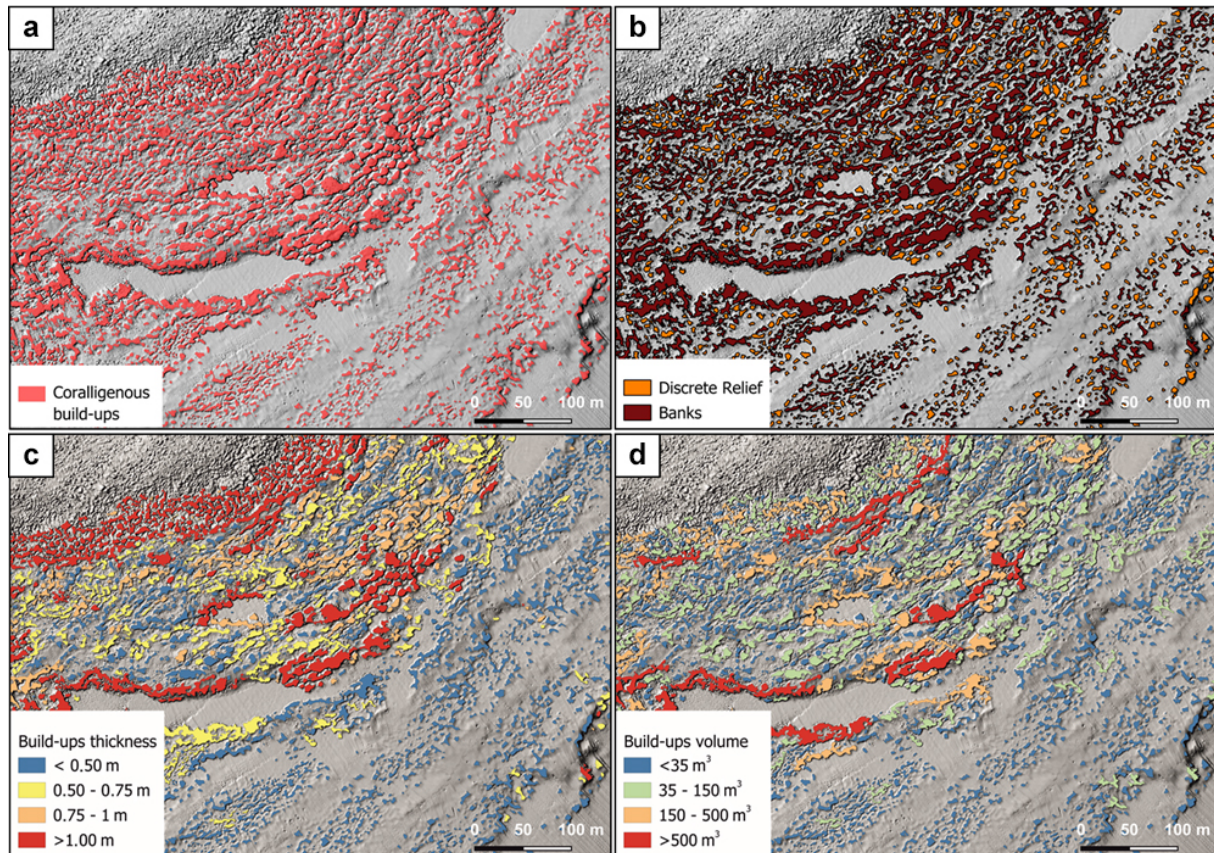


Figure 7. (a) Result of build-up extraction using TPI. (b) Differentiation of coralligenous build-ups into discrete relief and banks based on the SI value. (c) Estimation of build-up thickness. (d) Calculation of the volume for each coralligenous polygon.

tinctly straight alignment with a N–S orientation. However, further investigations are needed to confirm this hypothesis.

The inner portion of the submerged surface is characterized by the presence of sub-spherical blocks, often colonized by *Posidonia oceanica*, which possibly result from gravitational processes affecting the adjacent fourth-order marine terrace located upslope. This interpretation is supported by their rounded morphology, typically associated with detachment and downslope transport, and by the presence of scarps in the emerged portion of the study area, which could indicate past gravitational instability.

The outer portion and the edge of the submerged platform (down to approximately -25 m) host several coralligenous build-ups, predominantly belonging to the bank morphotype. Similar spatial arrangements have been observed in submerged terraces of southeastern Sicily (Varzi et al., 2023) and on wave-cut ravinement surfaces associated with fossil marine terraces, such as the mid-Pleistocene Cutro terrace (Nalin et al., 2006) and the emerged fifth-order terrace of Le Castella (Bracchi et al., 2016).

In the deeper sector of the study area (below -25 m depth), *Posidonia* is no longer present and the benthic assemblages are composed of coralligenous *sensu stricto* associated with

fine to medium sediments and maerl. These bioconstructions mainly belong to the discrete relief morphotype and tend to follow a subparallel orientation relative to the shoreline, a distribution pattern that appears to be associated with relatively pronounced seafloor structures (as revealed by ROV video transects). This spatial configuration suggests that environmental or geomorphological factors may influence the development and positioning of build-ups. Particularly, two hypotheses are proposed to explain this pattern: (i) the influence of bottom currents and internal waves, which may promote the alignment of coralligenous bioconstructions, as observed in mesophotic carbonate systems of the Maltese shelf by Bialik et al. (2024), and (ii) an overprint of the build-ups onto inherited seabed morphologies, shaped by sea level fluctuation and regional uplift during the Quaternary glacial–interglacial cycles, as documented on submerged terraces offshore Marzamemi (SE Sicily) by Varzi et al. (2023). However, further investigations, including in situ hydrodynamic and sediment transport measurements, are necessary to validate these hypotheses.

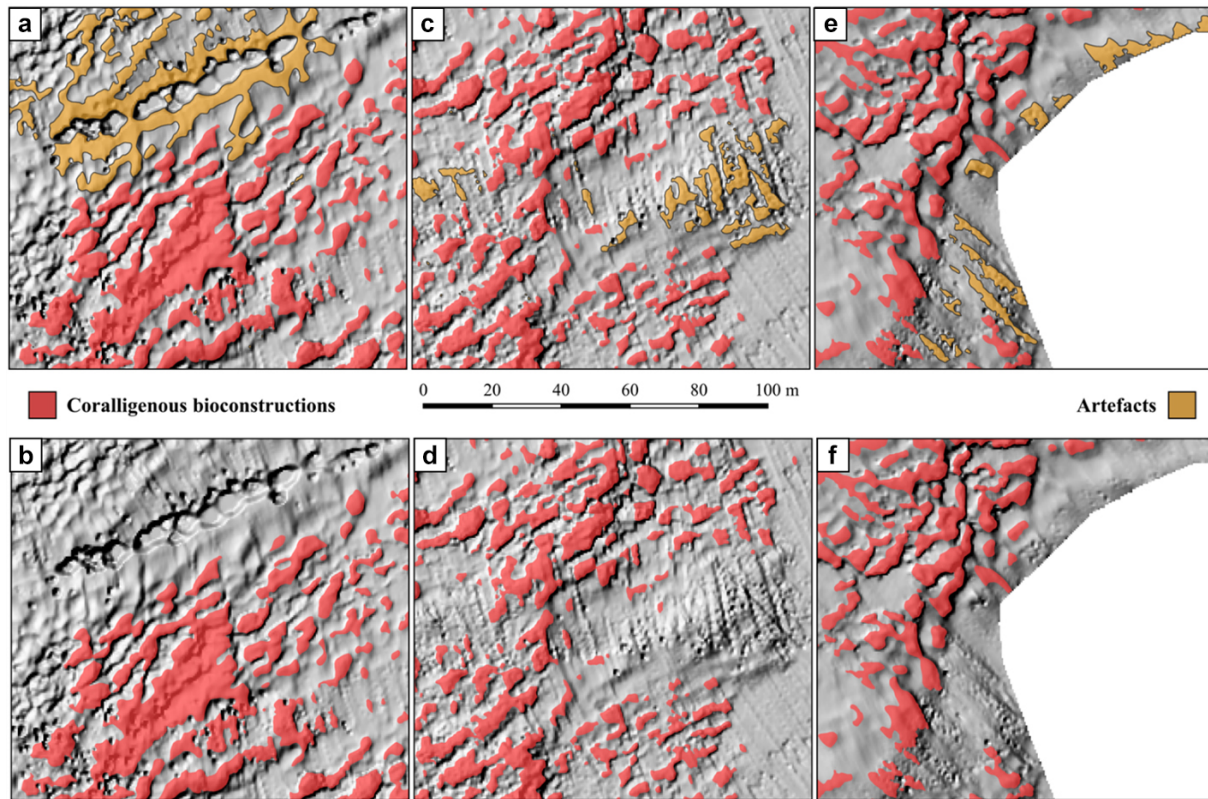


Figure 8. Examples of artifacts identified during polygon extraction and their manual removal. (a) False positive caused by the presence of *Posidonia oceanica* and (b) the same area after removal, (c) artifact due to bad roll correction and (d) the corrected version, and (e) artifacts at the boundary of the DTM and (f) the cleaned result.

5.2 TPI-based feature extraction

Coralligenous build-ups were treated as distinct features in both two- and three-dimensional spaces, with the aim of using geomorphometric parameters for their extraction from the seafloor. Variability of coralligenous morphotypes (Bracchi et al., 2017) poses several challenges for their automated extraction from the DTM. Since build-ups rise from the surrounding seafloor, their detection could be performed by slope analysis. However, while slope proves effective for accurately segmenting isolated small-scale features (Savini et al., 2014; Bargain et al., 2017), it struggles to incorporate the inner areas of banks into the segmentation process. The high 3D complexity in these areas makes it challenging to create a continuous polygon. On the other hand, geomorphometric parameters like the rugosity index (i.e., TRI; Riley et al., 1999; Micallef et al., 2012) are more successful in defining the overall distribution of bank morphotypes, but they fail to provide an accurate estimation of the size of discrete reliefs. Therefore, as noted by Marchese et al. (2020), TPI offers a good compromise for detecting coralligenous morphotypes. Indeed, it assesses the relative topographic position of a central point by calculating the difference between its elevation and the average elevation within a predefined neighbor-

hood. In this work, the input parameters for the calculation of the TPI have been refined in order to minimize the artifacts during the extraction process. Specifically, the choice of a threshold value of 0.2 (lower than 0.3 used by Marchese et al., 2020), combined with higher values of power and bandwidth compared to the default ones, has allowed for a 15 % reduction in the artifact percentage compared to Marchese et al. (2020). These adjustments have therefore significantly reduced the manual review time, improving the automatization of the extraction process.

The threshold value adopted for the TPI analysis was defined through a trial-and-error procedure, as described in the methodological section. In particular, threshold values lower than 0.2 increased the morphological adherence of the extracted features to seabed forms, but at the cost of a higher number of false positives (especially in areas covered by *Posidonia oceanica*, where slight topographic variations were incorrectly interpreted as relevant morphotypes). Conversely, threshold values higher than 0.2 reduced the occurrence of artifacts but led to the omission of low-relief structures, thus compromising the completeness of mapping. In this work, a threshold value of 0.2 proved to be an effective compromise, ensuring a satisfactory balance between the accuracy of morphotype extraction and the minimization

of false positive. This configuration allowed for the preservation of relevant coralligenous bioconstructions, including low-relief build-ups, while significantly limiting the occurrence of artifacts.

The proposed approach, although developed only for a specific coastal area, can be transferred to other regions, provided that adequate calibration is performed. The effectiveness of TPI-based extraction depends on several factors, and no universally applicable threshold value exists, as it must be adapted to the resolution and quality of bathymetric data, as well as to the site-specific geomorphological and geobiological variability. To date, no standardized procedure is available for determining the optimal threshold; however, its selection can be refined through iterative testing supported by ground-truth validation. Once the appropriate input parameter for TPI calculation (e.g., power, bandwidth, minimum and maximum radius) and a suitable threshold value are identified, the method allows for the extraction of morphologically distinct features, provided these are sufficiently expressed relative to the surrounding seafloor.

5.3 Morphological development of coralligenous build-ups

The quantitative morphometric data (i.e., surface, thickness, volume, maximum diameter, and shape indices), extracted from the benthic habitat mapping model proposed in this work, are plotted in the scatterplots of Fig. 9, providing new insights into the spatial distribution, morphotype variability, and growth pattern of the coralligenous build-ups across the study area.

Most polygons, representing aggregates of different coralligenous build-ups, are characterized by areas smaller than 200 m² and less than 1 m thick (Fig. 9a). However, discrete reliefs and banks display some differences in their distribution: discrete reliefs tend to cluster in the lower part of the graph (smaller areas and lower thickness), whereas banks with similar thickness generally exhibit larger areas on average.

The volume of the build-ups is strongly dependent on thickness, suggesting that vertical growth plays a key role in the formation of these structures (Fig. 9b). However, discrete reliefs show a more irregular distribution, with a greater dispersion of data ($R^2 = 0.35$). This trend suggests that volume increase depends not only on thickness but also on a significant lateral growth component. Conversely, banks exhibit a more regular trend, with volume increasing proportionally with thickness. The strong correlation between thickness and volume ($R^2 = 0.83$) aligns with a growth pattern that is almost exclusively vertical for this morphotype.

The relationships between the area and shape index (SI) of coralligenous build-ups (Fig. 9c), despite a moderate data dispersion, revealed a positive correlation ($R^2 = 0.61$), suggesting that more irregularly shaped bioconstructions (typically associated with the morphotypes of banks) tend to cover

larger areas. Moreover, banks also tend to have larger maximum diameter (D_{max}), as suggested by an R^2 value of 0.78 (Fig. 9d). However, the greater variability in area might reflect higher spatial complexity in the distribution of these structures.

The relationship between depth and thickness of coralligenous bioconstructions, divided into banks (Fig. 9f) and discrete reliefs (Fig. 9e), reveals that both morphotypes exhibit average decreasing thickness with increasing depth. However, discrete reliefs show greater thickness variability, with higher dispersion of data at depths shallower than -25 m, whereas for the banks, data distribution is more regular. The decrease in the thickness of bioconstructions with increasing depth could be attributed to various causes, including changes in hydrodynamic energy, the characteristics of the substrate on which the bioconstructions develop, or sedimentation conditions.

To date, no previous study has provided morphometric analysis of coralligenous build-ups based on quantitative extraction of 2D/3D parameters (e.g., area, thickness, volume, shape indices) from high-resolution MBES data. Therefore, a direct comparison of our results with other Mediterranean coralligenous fields is currently not possible. Nonetheless, several works have described the geomorphological variability of coralligenous morphotypes across the Mediterranean basin (e.g., Bracchi et al., 2015, 2017, 2022; Marchese et al., 2020). These studies recognize the coexistence of morphotypes such as banks and discrete reliefs, often occurring over short spatial scales and associated with different environmental conditions. The same spatial mixing of these morphotypes that may be due to small-scale variations in substrate type, hydrodynamic regime, or inherited seabed features, which locally favor distinct growth modes despite spatial proximity (Bracchi et al., 2017; Marchese et al., 2020; Varzi et al., 2023), was also observed in our study area.

6 Conclusions

A new mapping approach starting from high-resolution acoustic data acquired through MBES surveys performed offshore of Capo Bianco (Isola Capo Rizzuto Marine Protected Area) was developed and presented here. The method represents a step forward, as it builds on two integrated foundational approaches in coralligenous habitat studies: the morphotyping of coralligenous based on the shape index and their spatial and volumetric quantification.

The innovation of this work lies in the synthesis of these methodologies, which were applied and refined in a new study area. Moreover, the approach, which integrates bathymetric and backscatter data with geomorphological and geomorphometric indices, was performed using open-source software, providing a detailed workflow that can be freely reproduced and adopted by organizations involved in research, monitoring, and conservation of marine habitats.

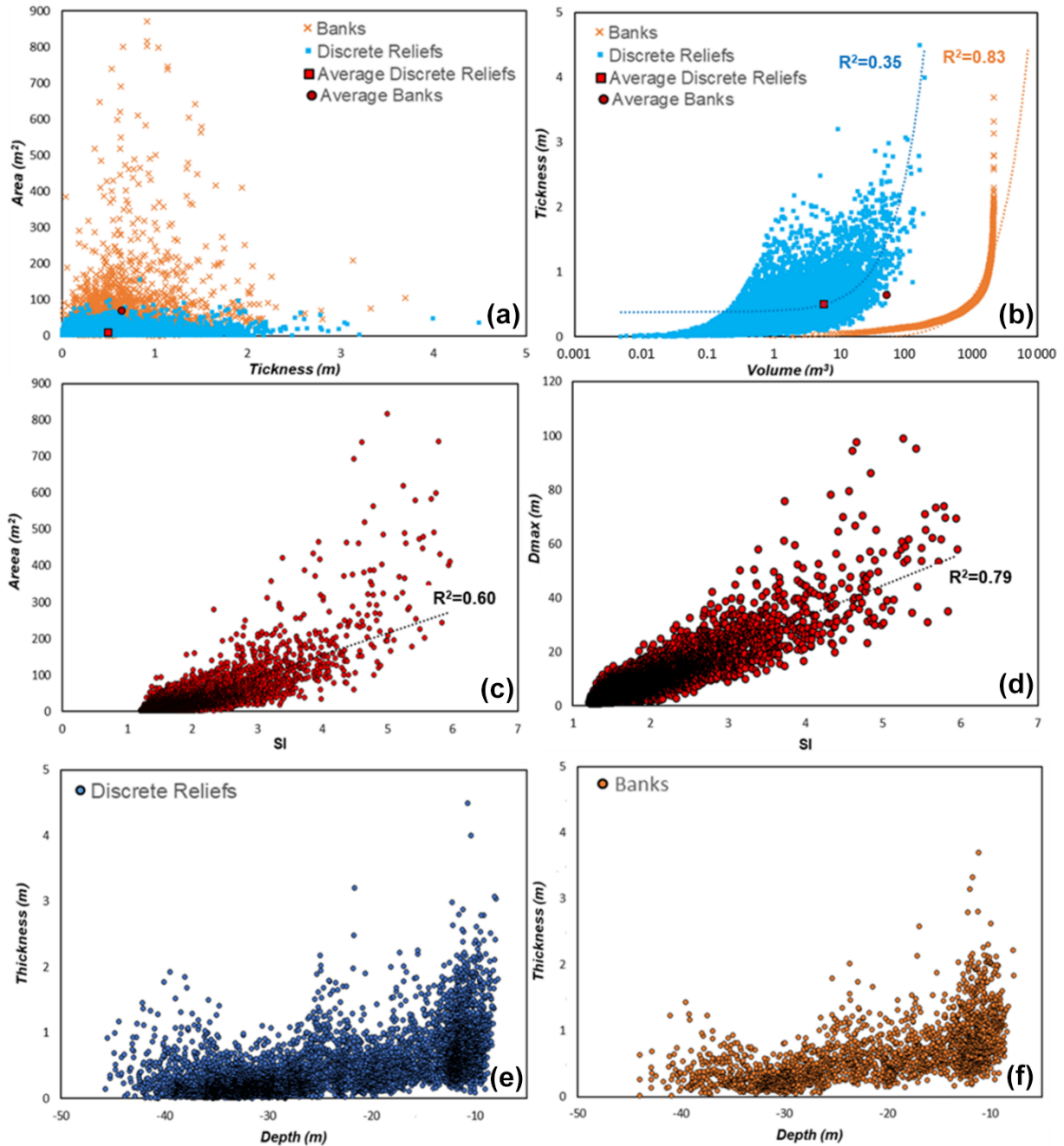


Figure 9. Scatterplot representing relationships between area and thickness (a), thickness and volume (b), area and shape index (c), maximum diameter and shape index (d), thickness and depth for banks (e), and discrete relief (f). These quantitative geometric data were extracted by the benthic habitat mapping model proposed in this work. SI: shape index; Dmax: maximum diameter.

The resulting model proved capable not only of identifying and differentiating the benthic habitats but also of providing new quantitative information regarding the spatial distribution and 2D/3D geometric characteristics of the extracted coralligenous build-ups. This innovative aspect, compared to the traditional mapping protocol, is crucial for the quantification of the structural complexity of these bioconstructions. Moreover, this approach enables monitoring of variations not

only in terms of the habitat's areal extent, but also in terms of vertical development of coralligenous relative to the substrate from which build-ups form. Indeed, the quantitative geomorphometric data obtained from the mapping model of Capo Bianco seafloor were analyzed, revealing significant insights into the covered surface, volume, and thickness of build-ups, as well as the relationships among these parameters. In particular, the results highlighted that the discrete relief morpho-

type exhibits a much more pronounced lateral growth component compared to the banks. If confirmed through accurate geobiological characterization, these findings could provide important new insights about the tempo and mode of the inception and development of these hard-biogenic substrates, crucial for the conservation of Mediterranean biodiversity.

Code and data availability. The datasets needed to evaluate the results and conclusions in this paper are available at http://geocube.unical.it/gmaruca/Dataset_Benthic_Habitat_Mapping.zip (Maruca et al., 2025). The raw data used in this study were acquired through MBES surveys using a pole-mounted, Norbit WBMS Basic multibeam sonar system integrated with GNSS/INS (Applanix OceanMaster). The processing of MBES bathymetric data was performed using QPS Qimera (http://geocube.unical.it/gmaruca/Dataset_Benthic_Habitat_Mapping.zip, last access: 4 September 2025; Maruca et al., 2025). Backscatter data processing was performed using QPS Fledermaus (http://geocube.unical.it/gmaruca/Dataset_Benthic_Habitat_Mapping.zip, last access: 4 September 2025; Maruca et al., 2025). Figures 1, 3, 4, 6, 7, and 8 were made with QGIS 3.34.9 Prizren software (http://geocube.unical.it/gmaruca/Dataset_Benthic_Habitat_Mapping.zip, last access: 4 September 2025; Maruca et al., 2025). Figure 9 was generated using Microsoft Excel (http://geocube.unical.it/gmaruca/Dataset_Benthic_Habitat_Mapping.zip, last access: 4 September 2025; Maruca et al., 2025). Data used to generate the figures are available upon request to the corresponding author.

Author contributions. Conceptualization: GM, AG. Methodology: GM, AG, GI, FM. Formal analysis and investigation: GM, MC, GI, US, FM. Writing – original draft preparation: GM, MC, GV, FP, AL, EC, RS. Writing – review and editing: RD, CA, FB, VAB, DB, AR, AG. Funding acquisition: AG, FB. Resources: RD, FB, AL, EC, AG. Supervision: AG.

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