Mapping benthic marine habitats featuring coralligenous bioconstructions: a new ~~protocol~~ approach ~~functional~~ to support geobiological ~~researches~~ 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 sounder (*i.e.*, Multibeam Echosounder: MBES), allows 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.~~, however they require careful end–product development and, to date, no standardized procedure exists.~~ Although the acquisition and processing of bathymetric data follows standardized procedure (*e.g.*, Hydrographic Organization guidelines), and recent studies proposed recommendation for backscatter acquisition and processing, a broadly validated methodological approach, integrating geomorphometric analysis for benthic habitat mapping, is still lacking. In this work, a ~~protocol~~ new approach for benthic habitat mapping, with focus on coralligenous bioconstructions, was developed using the open–source software QGIS. This ~~protocol~~ 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 on selected study areas by combining bathymetry and BS data with geomorphological indices performed in QGIS; ii) quantitatively define the 2D and 3D distribution of coralligenous bioconstructions in terms of surface covered, 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 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 skeletonised 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 bioeroders ~~on a relatively large temporal scale~~ over decadal to millennial timescale. Along the Mediterranean continental shelf, the most conspicuous bioconstructed habitats are represented by coralligenous build–ups (Bracchi et al., 2015, 2017, 2022; Basso et al., 2022; Cipriani et al., 2023, 2024), vermetid reefs (Picone and Chemello, 2023), sabellariid build–ups (Sanfilippo et al., 2019, 2022; Deias et al., 2023) and polychaetes–bryozoan bioconstructions (Guido et al., 2013, 2016, 2017a, b, 2019a, b, 2022), whereas cold–water corals occur in deeper settings (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). 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, that responds to different factors, like physiography, oceanography, terrigenous supply and climate (Schlager, 1991, 1993; Betzler et al., 1997; 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 & Picard, 1964; Laborel, 1987; Ballesteros, 2006; Bracchi et al., 2017; Marchese et al., 2020; Gerovasileiou & 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 ~~improve its knowledge by ensuring an objective description~~ obtain a more objective description of these morphologies, classified in: 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 morphologies intermediate between tabular banks and discrete reliefs. These structures can coalesce into a larger formation, resembling tabular banks, while still maintain 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 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 0.06–0.27 mm/yr 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 sounder, side scan sonar and acoustic profiling, enable the quick detection and identification of benthic habitats and thus mapping 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; Brown et al., 2012; Lamarche and Lurton, 2018; Abdullah et al., 2024).
In this work, a semi–automated GIS–based ~~protocol~~ 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 ~~backscatter (BS)~~ data obtained through MBES surveys and geomorphological and geomorphometric indices in order to develop innovative approaches for eco–geomorphological and geobiological characterisation of the seafloor. The benthic habitat mapping ~~protocol~~ here proposed has proven 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 delineate the extension of the bioconstructions and evaluate their evolution over time in response to natural and/or anthropogenic changes. Furthermore, the combination of this mapping ~~protocol~~ 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 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", in implementation to the previous bathymetric and backscatter data acquisition and elaboration of CRSM–ARPACAL.
The ~~protocol~~ approach proposed for benthic habitat mapping and defining of spatial and three–dimensional distribution of coralligenous bioconstruction is ~~briefly~~ shown in Figure 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 SQL language.

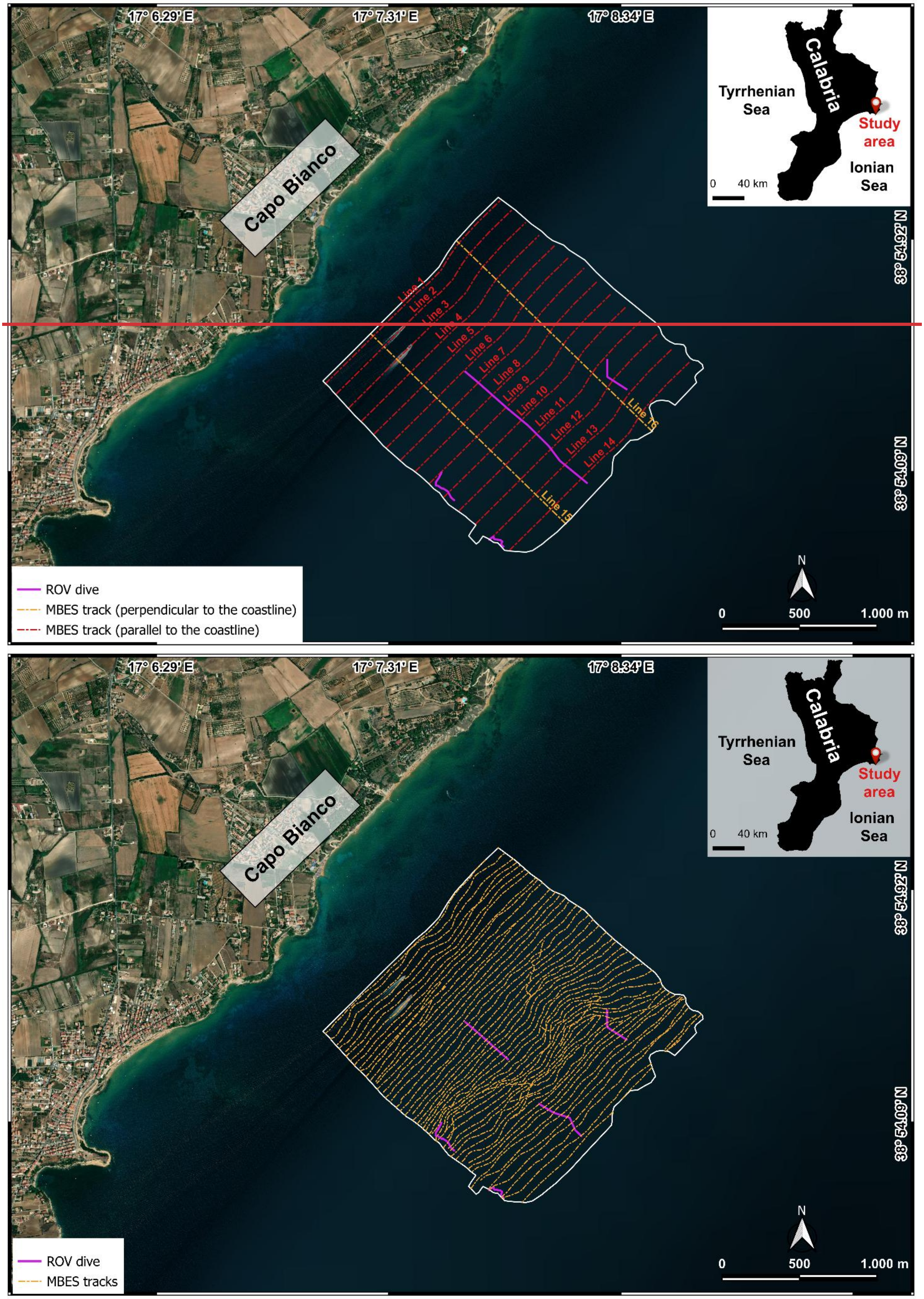
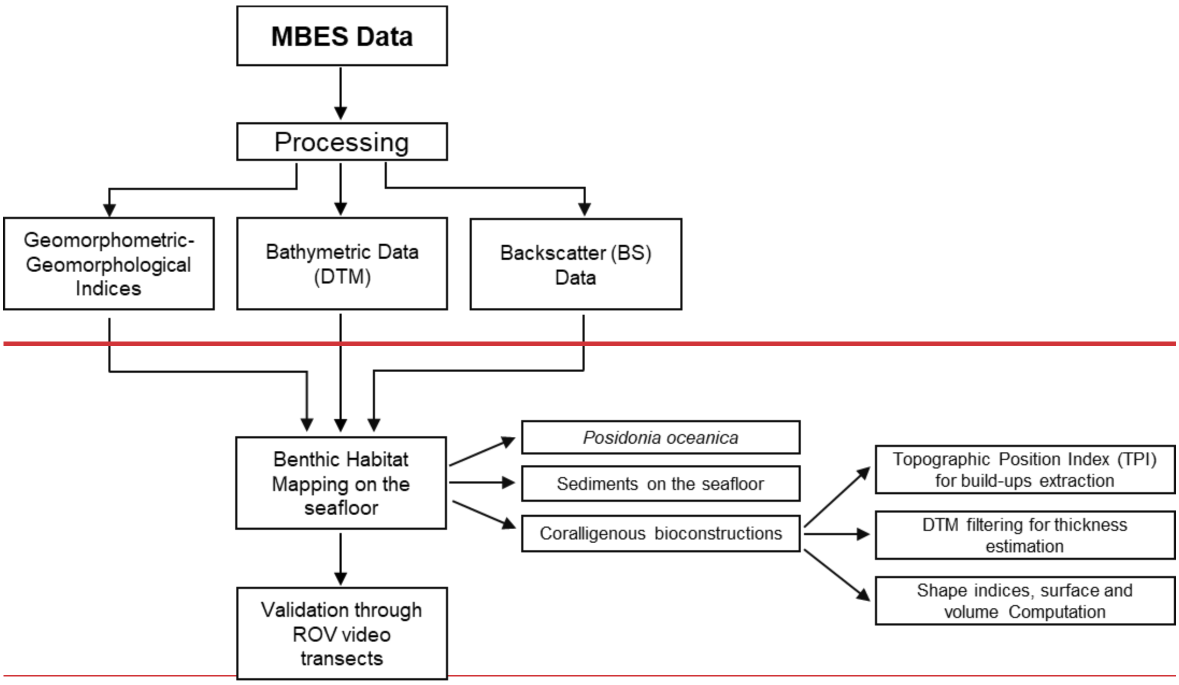


Figure 1: Study area off Capo Bianco (Calabria, Italy) and location of the MBES tracks and ROV–video transect (~~modified~~ basemap from Esri World Imagery).



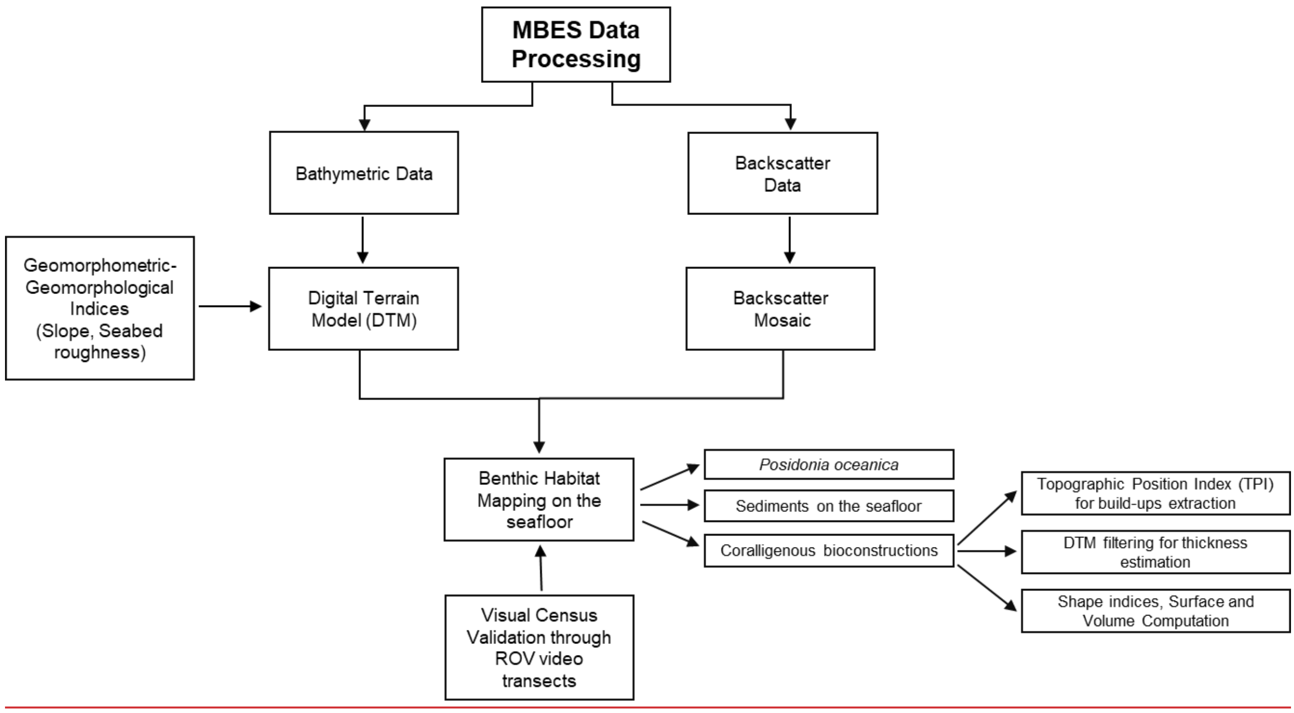


Figure 2: Conceptual model of the workflow for the development of the proposed benthic habitat mapping ~~model~~ approach.

Once the spatial extension and distribution of the benthic habitat have been defined by 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 ROV–video transect performed along specific paths ~~identified in the~~ 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). ~~The primary objective of this hardware is to generate high–resolution, scaled 3D models through the use of a stereo camera system.~~ 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 horizontal field of view up to 128°. The ZED2i is a stereo camera with dual 4 MP sensors of 2 mμ pixel size, a depth range between 0.3 m to 20 m, capable of acquiring video with a 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 WBMS Basic multibeam sonar system~~ 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 ~~16~~ 59 tracks with a swath overlap of 20–40 % performed at an average speed of 4.5 knots. ~~Several sound velocity profiles~~ 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. BS data were processed using QPS Fledermaus, and the final output was exported as an 8–bit raster file with 0.05 m cell size.

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's one. Indeed, the Zevenbergen–Thorne method (1987), that considers a second–order finite difference, is more dedicated to geomorphological 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, while high TRI values identify rugged morphologies and/or complex structures on the seafloor. TRI was calculated using SAGA module "Terrain Roughness Index" with the following settings: circle as search mode; a search radius of 0.5 map units (m.u.); gaussian weighting function: a value of 3.00 for the power; a bandwidth of 75.00. The values of these parameters were selected though 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 (min radius: 1.00 m.u.; max radius: 5.00 m.u.) 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 neighbouring 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 region with a constant slope, while 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 artifact, a TPI threshold of 0.2 was used and all the grid cells below this value were not considered as coralligenous bioconstructions. TPI scale (1.00–5.00 m.u.) 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 boundary. 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 concept as described by Vosselman (2000) and can be used to filter a DTM, categorizing its cell into ground and non–ground (object) cell. 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 et al., 1995) was calculated using the module "Polygon Shape Indices" of SAGA in order to describe a seafloor landscape characterized by distinct Coralligenous morphotypes. Finally, covered surface and volume of each polygon were calculated using vector field operation implemented into QGIS.

3 Geological setting

The study area, located offshore Capo Bianco (Isola Capo Rizzuto, Calabria, Italy), belongs to the Crotone Basin (CB) (Fig. 3)~~, The CB is~~ the widest Neogene basin of the Calabria region, ~~in part~~ partly exposed along the Ionian coast and in part documented offshore. It represents a segment of the Ionian fore arc basin ~~located on the internal part~~ on the inner portion of the Calabrian accretionary wedge (Cavazza et al., 1997; Bonardi et al., 2001; Minelli and Faccenna, 2010). ~~The basin infill, developed within the context of rollback subduction, was controlled by south–eastward migration of the Calabrian arc and the opening of the Tyrrhenian Sea (Serravallian–Tortonian onward) (Malinverno and Ryan, 1986; Faccenna et al., 2001; Milia and Torrente, 2014).~~ 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, ~~this region experienced~~ a significant uplift (~~Westaway, 1993; Westaway and Bridgland, 2007; Faccenna et al., 2011~~ 0.70-1.25 m/ky; Zecchin et al., 2004), ~~which~~, combined with glacio–eustatic sea level fluctuations, led to the formation in the Crotone Peninsula of five orders of marine terraces ~~in the Crotone Peninsula along the Ionian coast of Calabria~~ (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), ~~Zecchin et al. (2004) recognized five orders of terraces in the Crotone peninsula, considering a regional uplift of 0.70–1.25 m/ky. The terraces are spread out along the southern Crotone area and are unconformably transgressive on~~ which unconformably overlie the Piacenzian–Calabrian marly clays of the Cutro Formation (Zecchin et al., 2004).

The Cutro Terrace (1st order terrace), ~~represents the oldest and most elevated terrace in the Crotone area, and has been ascribed to MIS 7 (ca 200 kyr) (Zecchin et al., 2011). It is a mixed marine to continental terrace, consisting of the products resulting from the succession of two different sedimentary cycles: i) carbonate sedimentation, transitioning into algal build-ups and biocalcarenite passing into shoreface and foreshore sandstones and calcarenite; ii) predominantly siliciclastic sediments, comprising shoreface, fluvial channel fill, lagoon–estuarine and lacustrine deposits (Zecchin et al., 2011).~~ ascribed to MIS 7 by Zecchin et al. (2011), is a mixed marine to continental terrace, consisting of the products of carbonate (algal build-ups and biocalcarenite passing into shoreface and foreshore deposits) to siliciclastic (shoreface, fluvial channel fill, lagoon-estuarine and lacustrine deposits) sequences (Zecchin et al., 2011).

The 2nd order ~~is represented by the Campolongo–La Mazzotta terrace, ascribed to MIS 5e by Maunz and Hassler (2000). These deposits are mainly composed of bioclastic and hybrid sandstones westward and by mostly siliciclastic sandstones eastwards. Bioclastic deposits and local algal patch reefs, which also contain small colonial corals, are found on La Mazzotta Hill (Zecchin et al., 2011).~~ (MIS 5e), represented by the Campolongo-La Mazzotta terrace, is characterized by bioclastic and siliciclastic sandstones, with local bioclastic deposits and algal patch reefs (Maunz and Hassler, 2000, Zecchin et al., 2011).

The Le Castella–Capo Cimiti terrace (3rd order terrace), ~~was probably associated to the MIS 5c (Maunz and Hassler, 2000; Zecchin et al., 2004; Nalin et al., 2012). The upper Pleistocene cover thins down northward of Capo Cimiti, along the present coastline, and is located between 10 m and 65 m of elevation due to normal fault displacement. Carbonate sediments, represented primarily by algal reefs and secondarily by bioclastic to hybrid sandstones, extensively occur in the eastern and central parts of the terrace. To the west, bioclastic deposits of lower to upper shoreface environments dominate (Zecchin et al., 2004; Nalin et al., 2012).~~ probably associated to the MIS 5c (Maunz and Hassler, 2000), shows extensive algal reefs and shoreface deposits, with elevations variation due to normal fault displacement (Zecchin et al., 2004; Nalin et al., 2012).

The Capo Colonna marine terrace (4th order terrace), ~~consists of a planar surface gently inclined eastward, with a sedimentary cover quite continuously exposed along the northern coast of the promontory and covered, in its proximal segment, by a wedge of colluvium tapering eastward (Bracchi et al., 2014). The terrace deposits correlate either with MIS 5.3 (ca 100 ka; 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 & Massari, 2009).~~ correlated to 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 & Massari, 2009), consists of a planar surface with a sedimentary cover overlied by a wedge of colluvium tapering (Bracchi et al., 2014).

The Le Castella marine terrace (5th order terrace) ~~is the youngest. Its deposits, exceptionally well exposed along present-day coastline, form an unconformity-bounded, transgressive-regressive cycle, similar to those observed in other terraces of the Crotone area (Nalin et al., 2007; Nalin & Massari, 2009; Zecchin et al., 2010; Bracchi et al., 2014; Bracchi et al., 2016). Zecchin et al. (2004, 2010) identified two different facies for coralline algal build-ups and associated bioclastic deposits in the lower portion of the cycle. The age of the Le Castella marine terrace deposits remains debated: indeed, these deposits have been correlated with MIS 5.3 (Gliozzi, 1987), MIS 5.1 (Palmentola et al., 1990) and MIS 3 (Zecchin et al., 2004; Mauz & Hassler, 2000; Santagati et al., 2024).~~ records an unconformity-bounded transgressive-regressive cycle (Nalin et al., 2007; Nalin & Massari, 2009; Zecchin et al., 2010; Bracchi et al., 2014; Bracchi et al., 2016), with two

different facies for coralline algal build-ups and associated bioclastic deposits in the lower portion (Zecchin et al., 2004, 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 & Hassler, 2000; Santagati et al., 2024).
The marine terraces exposed in 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 "Crotone" 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 characterised by an undulating morphology including the Luna and the Capo Rizzuto Swell. The southern section of the sheet covers the offshore extension of the Crotone forearc basin (Chiocci et al., 2021). This work aims to enhance the understanding of the Crotone Basin offshore features, with focus on underwater bioconstructed habitats.

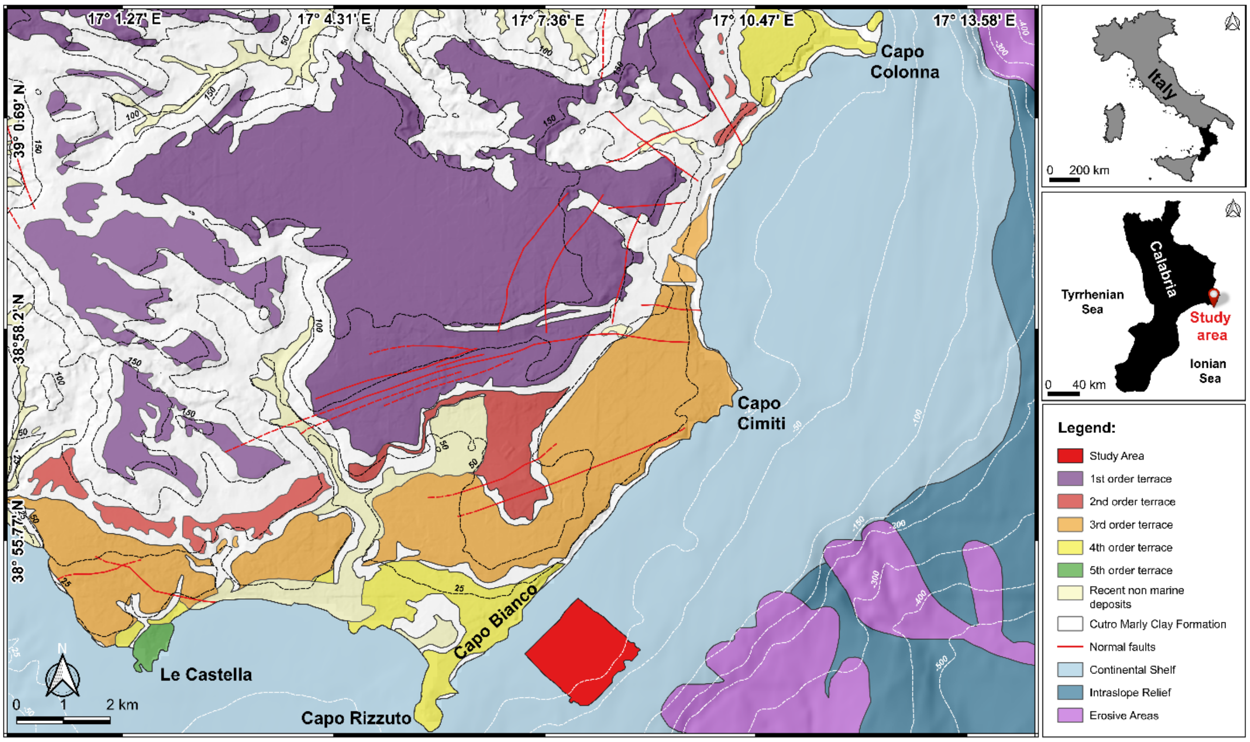


Figure 3: Conflated geological map of the Crotone peninsula, with the indication of the five order terraces (modified from Bracchi et al., 2014), and physiographic domains identified offshore the area in the frame of the MaGIC Project (modified from Chiocci et al., 2021).

4 Results

4.1 ~~Morphological and m~~ 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 identification of the benthic habitats. In particular, bathymetric data revealed a seafloor with depths ranging from -7.3 m 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 -15m 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; ii) the presence of scattered roughness associated with irregularities on the seafloor (Fig. 4D).

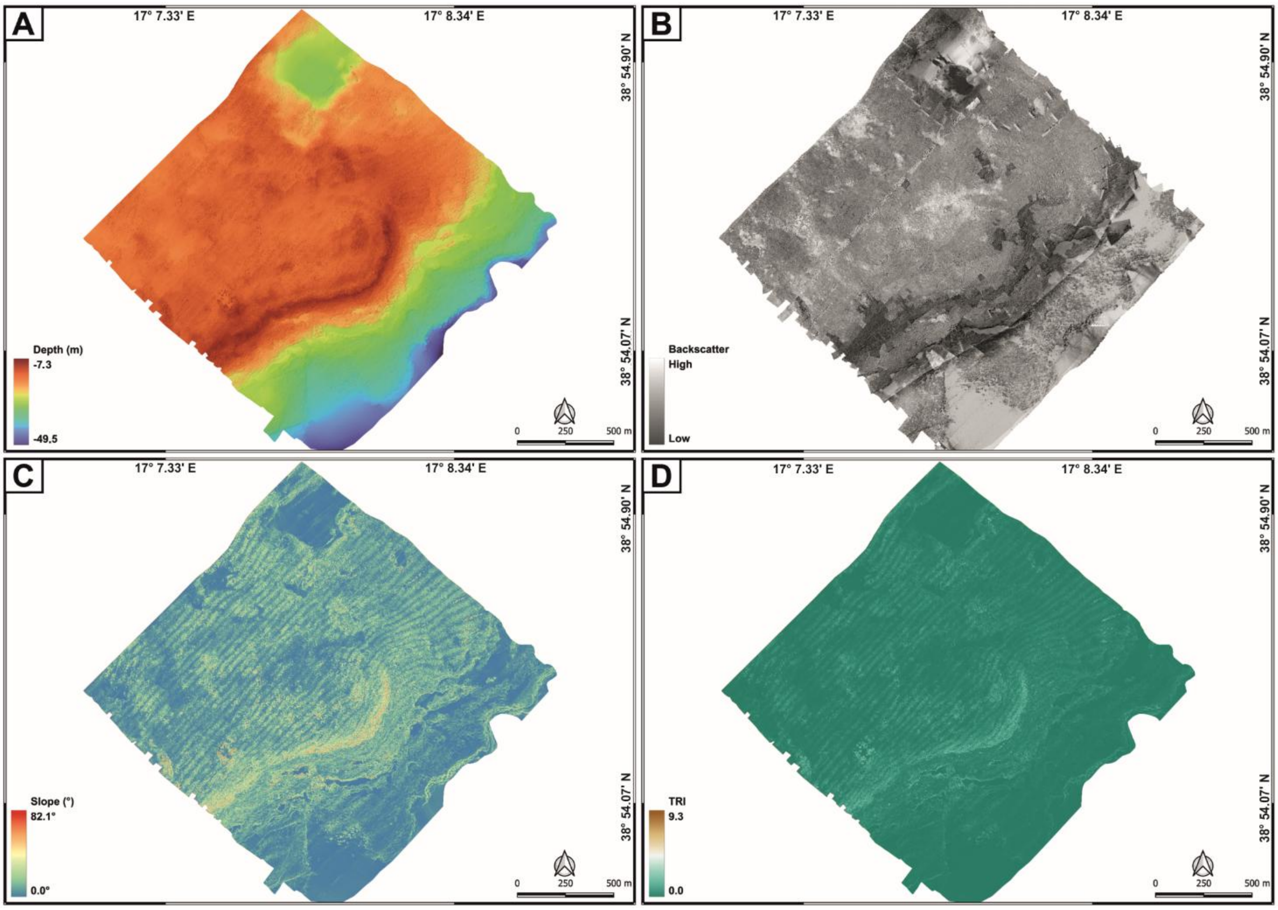


Figure 4: Geomorphological characters of the study area expressed through processed bathymetric **(A)**, backscatter **(B)** data and geomorphometric indices, like slope **(C)** and Terrain Roughness Index **(D)**.

Combining bathymetric and backscatter (Fig. 4B) data with slope and seafloor roughness values, different morpho–acoustic 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 m to -25 m. In the depth range from -15 m to -25 m, analysis of ROV–video transects showed that *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 m 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 pattern of medium to high backscatter. It covers scattered portions throughout the study area at various depths and is characterized by very low TRI values.

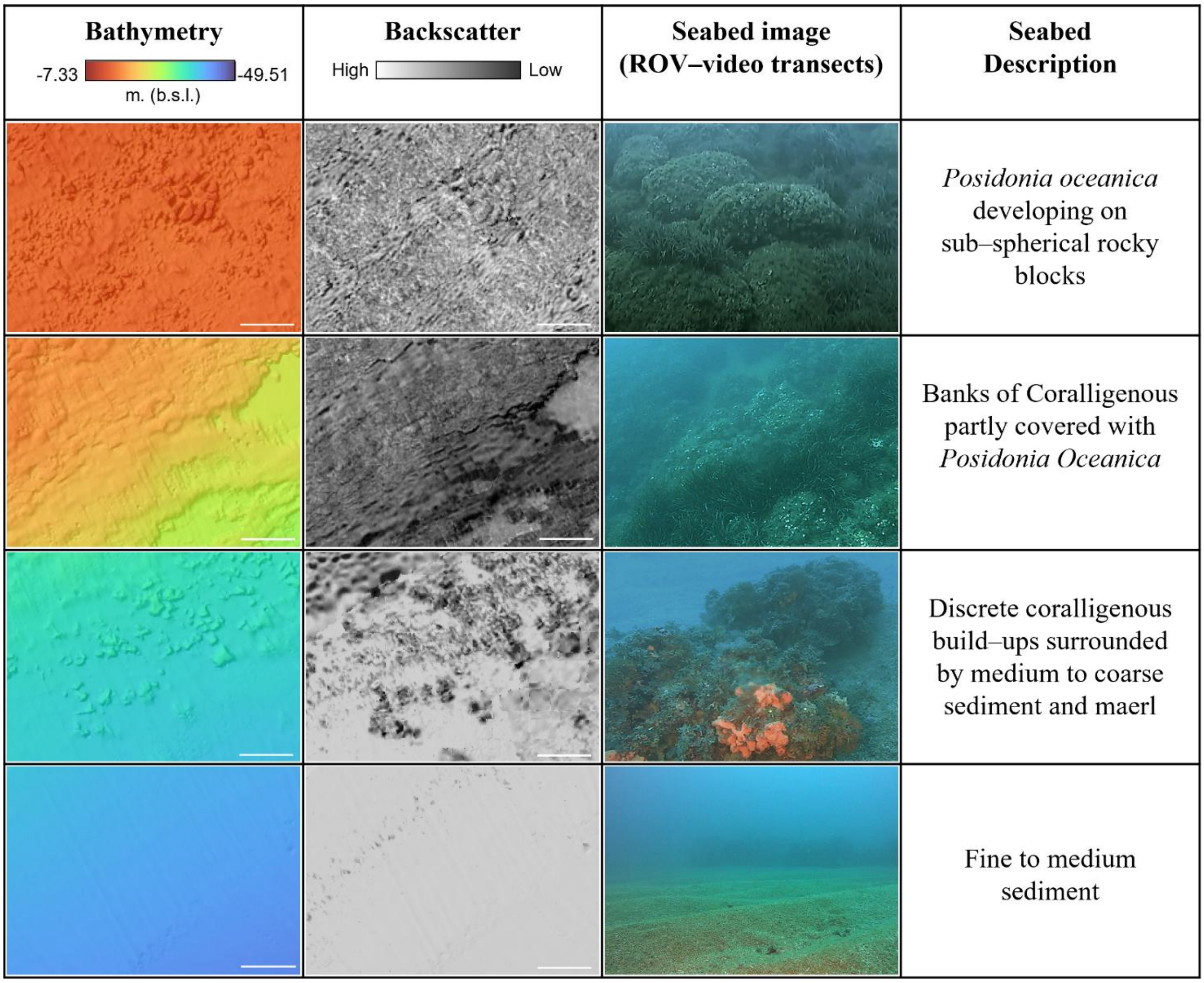


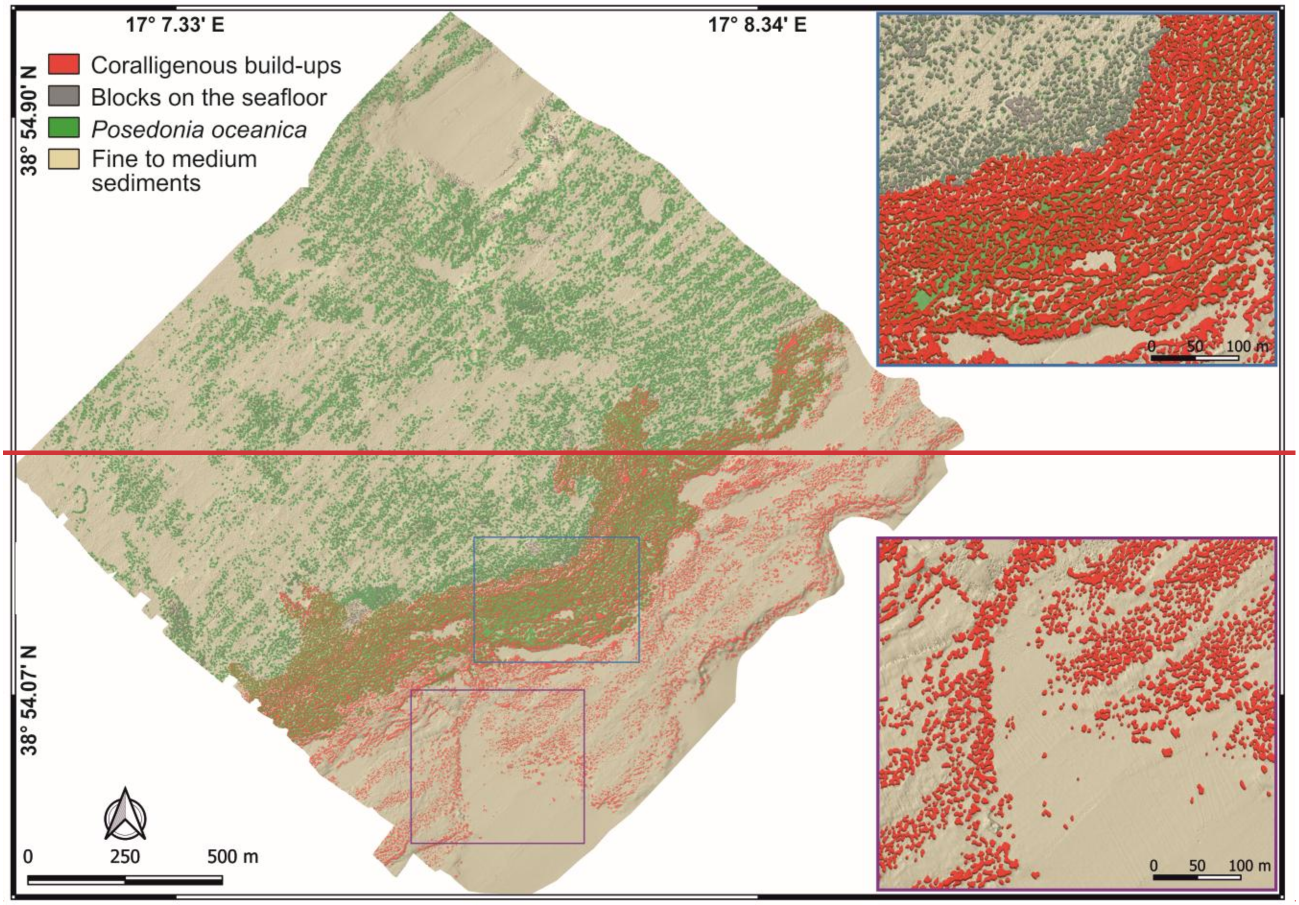
Figure 5: Morpho–acoustic features identified by bathymetric and BS data, together with ROV videos interpretation. White scale bar is 20 m.

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*); iv) fine to medium sediment.

The *Posidonia* habitat, testified by its typical BS signal (intermittent speckled fabric of moderate backscatter), dominate 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 m and -25 m, the *Posidonia* backscatter signal gradually attenuates and coralligenous bioconstructions start to be discernible. This transitional belt, that occupies about 0.37 km^2, 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 banks 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 reliefs morphotype and tend to align sub-parallel to the shoreline.



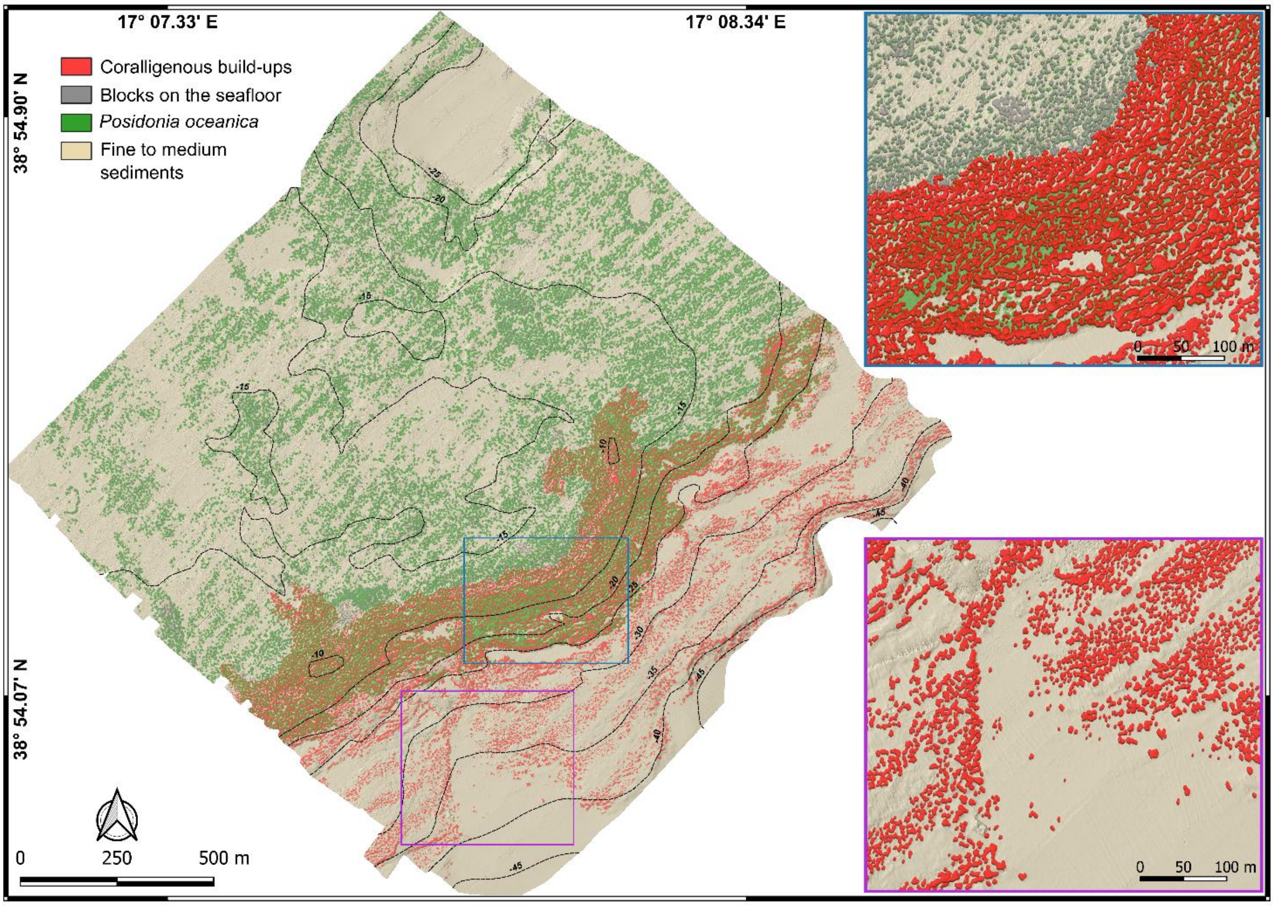


Figure 6: Mapping model of the underwater benthic habitats in the study area off Capo Bianco (Calabria, Italy). Note, in the blue and purple boxes, two magnifications of representative areas of the model where coralligenous bioconstructions and rocky blocks on the seabed are depicted in 2.5D.

4.2 Extraction of coralligenous build–ups

The model extracted 12384 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 ~~and manually deleted after the re-classification and the polygonization of resulting raster.~~ after the re–classification 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)~~, creating false elongated structures;~~ iii) artifacts concentration 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.

The identification of artifacts was based on specifical pattern inconsistent with expected Coralligenous morphologies, and their removal was carried out manually as part of the data cleaning process (Fig. 8B, D, 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.

~~Naturally, the time consuming operation of filtering and manually detecting erroneous polygons could be avoided performing more accurate MBES surveys (*i.e.*, larger coverage, greater overlapping and narrower swath width) free of artifacts.~~

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

Shape Index (SI) values allowed to distinguish between banks (tabular bank *sensu* Bracchi et al., 2016; SI ≤ 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 155677 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 69830 m². The volume (Fig. 7D) occupied by discrete reliefs (40806 m³) is also significantly lower than that of the banks (116094 m³). This data is consistent with the fact that discrete reliefs are characterized by smaller extent and thickness compared to the banks.

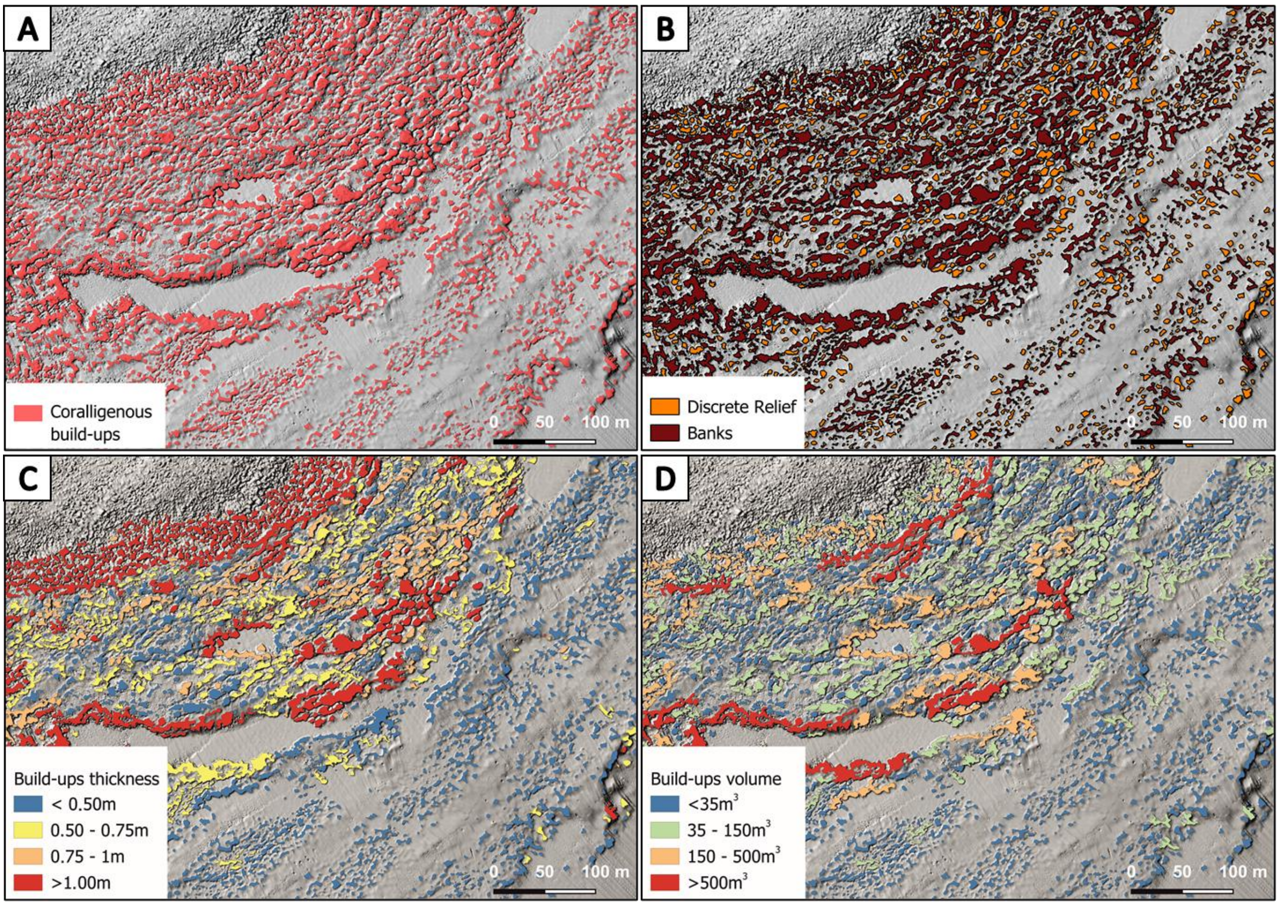


Figure 7: (A) Result of build–ups extraction using TPI. **(B)** Differentiation of coralligenous build–ups into discrete relief and banks based on the SI value. **(C)** Estimation of build–ups thickness. **(D)** Calculation of the volume for each coralligenous polygon.

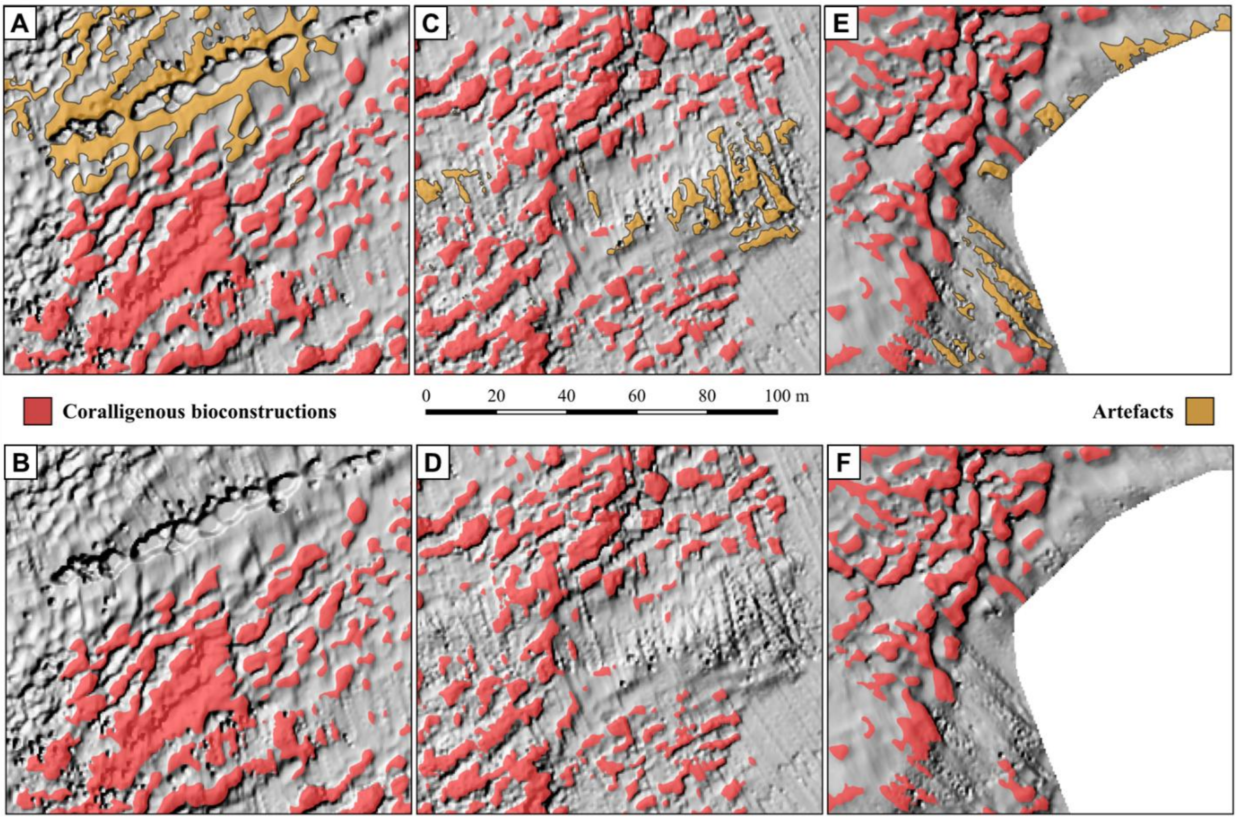


Figure 8: Examples of artifacts identified during polygon extraction and their manual removal. (**A**) False positive caused by the presence of Posidonia oceanica and (**B**) the same area after removal; (**C**) artifact due to bad roll correction and (**D**) corrected version; (**E**) artifacts at the boundary of the DTM and (**F**) cleaned result.

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	155677	116094
Discrete Reliefs	> 2	0.49	69830	40806

5 DISCUSSION

Acoustic techniques, such as high–resolution swath bathymetry sounder (including backscatter), side scan sonar and acoustic profiling are optimal tools for quickly recognize and identify the extension of benthic habitats on the seabed and map their distribution without mechanical collection of samples, which would damage this delicate ecosystem (Bracchi et al., 2017).

~~Conventionally, the segmentation of MBES data sets is carried out manually, despite the process might be inaccurate and subjective (Cutter et al., 2003; Bishop et al., 2012). Only few studies have successfully developed object oriented methods that use object based image analysis (OBIA) or consider a comprehensive set of remote data to accurately characterize seabed landforms to document the extension of benthic habitat (Lucieer and Lamarche, 2011; Ismail et al., 2015; Janowski et al., 2018; Fakiris et al., 2019). However, geomorphometric techniques can objectively characterize submarine habitat and features from the shallow to deep environments (Lecours et al., 2016; Janowski et al., 2018), but a standardized technique for seafloor classification has never been developed (Micallef et al., 2012). Recently, 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 on a sector of the Apulian continental shelf and to quantify how much carbonate is deposited.~~

Traditionally, the segmentation of MBES data sets have been performed manually, despite 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 et al., 2019). 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, submarine dune and ridges, offering high accuracy and repeatability (Arosio et al., 2023; Garone et al., 2023). Additionally, 3D CNNs have been applied to automated denoising of MBES data, enhancing the efficiency of bathymetric data workflow (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 attempt to map these complex biogenic structures in detail. Bracchi et al. (2017) proposed a categorization of coralligenous morphotypes on sub-horizontal 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. (2022) produced a morpho-bathymetric map for the continental shelf offshore Marzamemi (Sicily, Italy) that contained quantitative description for the distribution and extent of coralligenous reefs.

The ~~mapping protocol~~ approach proposed in this work, based on the workflow shown in Figure 2 ~~3~~, 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 ~~Detected habitats~~ Spatial distribution of benthic habitats and seafloor morphology

~~The comparison between the bathymetric and backscatter data with the indices derived in QGIS and the model validation through ROV video transects allowed to identify several habitats: *Posidonia* oceanica meadows, mosaic of coralligenous and *Posidonia*, Coralligenous sensu stricto, and fine to medium sediment.~~

~~The *Posidonia* habitat, testified by its typical BS signal (intermittent speckled fabric of moderate backscatter), was recognised down to -25 m water depth. *Posidonia* oceanica habitat dominate in shallow areas, down to about -15 m depth, developing primarily on rocky substrate. The seafloor is characterized by the presence of sub–spherical rocky blocks (Fig. 6), which possibly result from gravitational processes affecting the 4^{th} order terrace emerging landwards, and pockets of fine to medium sediments.~~

~~From -15 m to -25 m, *Posidonia* BS signal gradually attenuates and Coralligenous bioconstructions start to be discernible. This transitional belt, that occupies about 0.37 km^2, was classified as mosaic of Coralligenous and *Posidonia*. The visual analysis of the ROV video transects, used as ground truth, suggests that in this zone bioconstructions, which predominantly belong to the banks morphotype develop on a hard substrate that marks a widespread break in slope all throughout the study area. This break marks the end of the transition zone, characterized by the simultaneous presence of Coralligenous and *Posidonia*.~~

~~By comparing the morphological characteristics of the seabed with the alignment of the emerged marine terraces, the presence of an additional submerged terraced surface becomes evident. It could represent a submerged portion of the 5th order terrace, currently exposed only in the Le Castella area. The submersion of this portion of the terrace in the study area would be justified by the presence of a tectonic feature with extensional kinematics, located approximately along the coastline, which, in this area, shows a distinctly straight alignment with a N-S orientation. Further studies, focusing on the geological characterization of the substrate on which coralligenous banks developed and the correlation of these lithotypes with those outcropping on land, could confirm this hypothesis.~~

~~Deeper than -25 m, upon close MBES data and ROV inspection, *Posidonia* disappears and the predominant benthic habitat is represented by Coralligenous sensu stricto. Bioconstructions, often associated with fine to medium sediment and maerl, predominantly belong to the morphotype of discrete reliefs. Bioconstructions tend to align sub-parallel to the shoreline. This distribution is associated with the presence of relatively pronounced seafloor structures, as revealed by ROV-video transects. This observation might suggest: i) a significant control of hydrodynamic conditions on the formation, development and distribution of coralligenous build-ups, or ii) an overprint of the bioconstructions on a seafloor already sculpted by the evolution of the bottom during glacial/interglacial cycles. However, further investigation is needed, including bottom current monitoring using appropriate instruments (*e.g.*, current meter), in order to better define these bedforms.~~

The benthic habitat distribution identified in the study area exhibits a clear spatial zonation, which appear to be influenced by both substrate characteristics and geomorphological features. In the shallowest sector (above -15m depth), *Posidonia oceanica* represent the prevalent benthic habitat. In the intermediate depth range (down to approximately -25m 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 sub-horizontal 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 these evidences, the submerged surface can be correlated with the 5th order terrace exposed near Le Castella, characterized by a gently seaward-inclined surface and a morphological step interpreted as paleocliff (Bracchi et al., 2016). The different orientation of the submerged scarp in the study area (NE-SW), compared to the emerged paleocliff associated with 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 5th 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 distinctly 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 4th 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 -25m) hosts several coralligenous build-ups, predominantly belonging to banks morphotype. Similar spatial arrangements have been observed in submerged terraces of southeastern Sicily (Varzi et al., 2022) 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 5th order terrace of Le Castella (Bracchi et al., 2016).

In the deeper sector of the study area (below -25m depth), *Posidonia* is no longer present and the benthic assemblages are composed by Coralligenous *sensu stricto* associated with fine to medium sediments and maerl. These bioconstructions mainly belong to discrete reliefs morphotype and tend to follow a sub-parallel orientation relative to the shoreline, a distribution pattern that appears 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); 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. (2022). However, further investigations, including in situ hydrodynamic and sediment transport measurements, are necessary to validate these hypotheses.

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 a geomorphometric parameters for their extraction from the seafloor. Variability of coralligenous morphotypes (Bracchi et al., 2017) poses several challenges to their automated extraction from DTM. Since build–ups raise 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) 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 neighbourhood. 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 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-thrut validation. Once the appropriate input parameter for TPI calculation (e.g., Power, Bandwidth, minimum and maximum radius) ad 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

~~Computation of maximum diameter, surface and volume for each build–up were performed using vector field operation in QGIS. Quantitative morphometric data extracted from the proposed benthic habitat model were plotted in the scatterplots of Figure 8.~~ 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, were plotted in the scatterplots of Figure 8, providing new insights into 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. 8A). 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. 8B). However, discrete reliefs show a more irregular distribution, with a greater dispersion of data (R^2= ~~0.36~~ 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 area and shape indices (SI) of coralligenous build–ups (Fig. 8C), 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 (Dmax), as suggested by an R^2 value of 0.78 (Fig. 8D). 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. 8F) and discrete reliefs (Fig. 8E), 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 scale and associated with different environmental conditions. The same spatial mixing of these morphotypes, which may be due to small-scale variations in substrate type, hydrodynamic regime, or inherited seabed features, which locally favour distinct growth mode despite spatial proximity (Bracchi et al., 2017; Marchese et al., 2020; Varzi et al., 2022), was also observed in our study area.

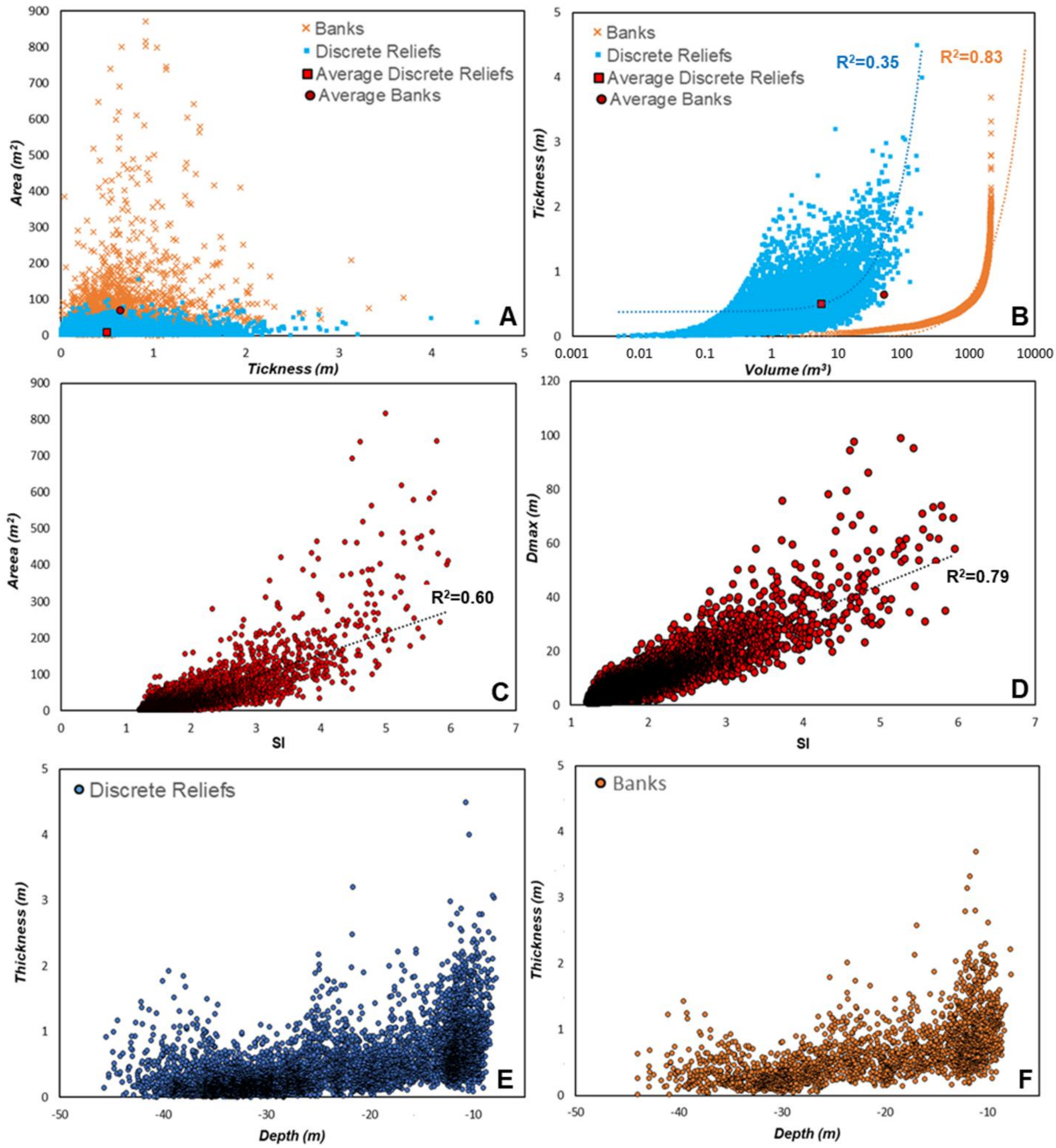


Figure 8: Scatterplot representing relationships between: area and thickness **(A)**; thickness and volume **(B)**; area and shape index **(C)**; maximum diameter and shape index **(D)**; thickness and depth for banks **(E)** and discrete relief **(F)**. These quantitative geometric data were extracted by the benthic habitat mapping model proposed in this work. SI: shape index; Dmax: maximum diameter.

CONCLUSIONS

A new mapping ~~protocol~~ approach starting from high–resolution acoustic data acquired through MBES surveys performed offshore Capo Bianco (Isola Capo Rizzuto Marine Protected Area) was developed and presented here. The method ~~protocol~~ represents a step forward, as it builds on an integrated two 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 ~~protocol~~, 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.

The resulting model proved capable not only in identifying and differentiating the benthic habitats but also in 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 reliefs morphotype exhibit a much more pronounced lateral growth component compared to the banks. If confirmed through an accurate geobiological characterization, these finding 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.

Author contributions

Conceptualization: G.M., A.G.; Methodology: G.M, A.G., G.I., F.M.; Formal analysis and investigation: G.M., M.C., G.I.; U.S.; F.M.; Writing – original draft preparation: G.M., M.C., G.V., F.P., A.L., E.C., R.S.; Writing – review and editing: R.D., C.A., F.B., V.A.B., D.B., A.R., A.G.; Funding acquisition: A.G., F.B.; Resources: R.D., F.B., A.L., E.C., A.G.; Supervision: A.G.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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Open Research

The data sets needed to evaluate results and conclusion 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 survey 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 (https://qps.nl/qimera/). Backscatter data processing was performed using QPS Fledermaus (https://qps.nl/fledermaus/). Figures 1, 3, 4, 6, 7 were made with QGIS 3.34.9 “Prizren” software (https://qgis.org/project/overview/). Figures 8 were generated using Microsoft Excel (https://www.microsoft.com/it-it/microsoft-365). Data used to generate the figures are available upon request to the corresponding author.

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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 sounder (*i.e.*, Multibeam Echosounder: MBES), allows 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 follows standardized procedure (*e.g.*, Hydrographic Organization guidelines), and recent studies proposed recommendation 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 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 on selected study areas by combining bathymetry and BS data with geomorphological indices performed in QGIS; ii) quantitatively define the 2D and 3D distribution of coralligenous bioconstructions in terms of surface covered, 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 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 skeletonised 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 bioeroders over decadal to millennial timescale. Along the Mediterranean continental shelf, the most conspicuous bioconstructed habitats are represented by coralligenous build–ups (Bracchi et al., 2015, 2017, 2022; Basso et al., 2022; Cipriani et al., 2023, 2024), vermetid reefs (Picone and Chemello, 2023), sabellariid build–ups (Sanfilippo et al., 2019, 2022; Deias et al., 2023) and polychaetes–bryozoan bioconstructions (Guido et al., 2013, 2016, 2017a, b, 2019a, b, 2022), whereas cold–water corals occur in deeper settings (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). 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, that responds to different factors, like physiography, oceanography, terrigenous supply and climate (Schlager, 1991, 1993; Betzler et al., 1997; 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 & Picard, 1964; Laborel, 1987; Ballesteros, 2006; Bracchi et al., 2017; Marchese et al., 2020; Gerovasileiou & 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 in: 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 morphologies intermediate between tabular banks and discrete reliefs. These structures can coalesce into a larger formation, resembling tabular banks, while still maintain 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 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 0.06–0.27 mm/yr 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 sounder, side scan sonar and acoustic profiling, enable the quick detection and identification of benthic habitats and thus mapping 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; Brown et al., 2012; Lamarche and Lurton, 2018; Abdullah et al., 2024).

In this work, a semi–automated 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 MBES surveys and geomorphological and geomorphometric indices in order to develop innovative approaches for eco–geomorphological and geobiological characterisation of the seafloor. The benthic habitat mapping here proposed has proven 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 delineate the extension of the bioconstructions and evaluate 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 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", in implementation to 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 Figure 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 SQL language.

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

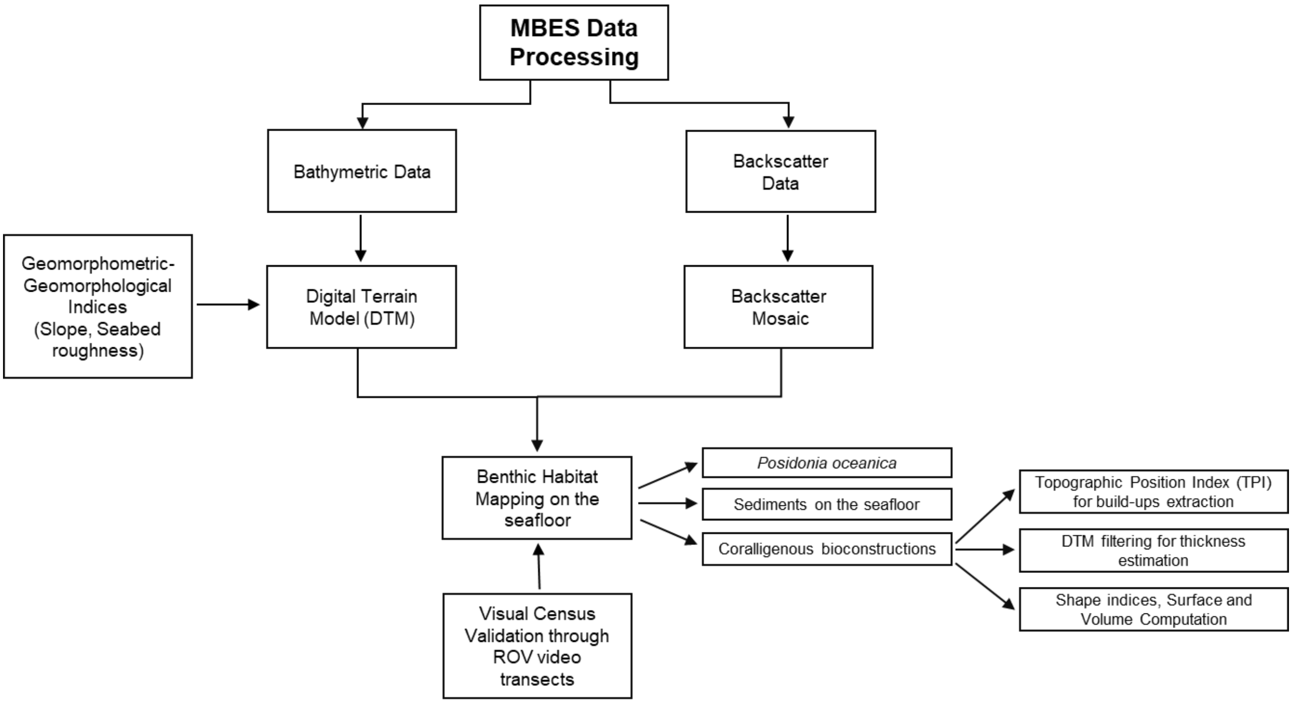

Figure 2: Conceptual model of the workflow for the development of the proposed benthic habitat mapping approach.

Once the spatial extension and distribution of the benthic habitat have been defined by 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 ROV–video transect 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 horizontal field of view up to 128°. The ZED2i is a stereo camera with dual 4 MP sensors of 2 mμ pixel size, a depth range between 0.3 m to 20 m, capable of acquiring video with a 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 4.5 knots. 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. BS data were processed using QPS Fledermaus, and the final output was exported as an 8–bit raster file with 0.05 m cell size.

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's one. Indeed, the Zevenbergen–Thorne method (1987), that considers a second–order finite difference, is more dedicated to geomorphological 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, while high TRI values identify rugged morphologies and/or complex structures on the seafloor. TRI was calculated using SAGA module "Terrain Roughness Index" with the following settings: circle as search mode; a search radius of 0.5 map units (m.u.); gaussian weighting function: a value of 3.00 for the power; a bandwidth of 75.00. The values of these parameters were selected though 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 (min radius: 1.00 m.u.; max radius: 5.00 m.u.) 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 neighbouring 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 region with a constant slope, while 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 artifact, a TPI threshold of 0.2 was used and all the grid cells below this value were not considered as coralligenous bioconstructions. TPI scale (1.00–5.00 m.u.) 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 boundary. 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 concept as described by Vosselman (2000) and can be used to filter a DTM, categorizing its cell into ground and non–ground (object) cell. 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 et al., 1995) was calculated using the module "Polygon Shape Indices" of SAGA in order to describe a seafloor landscape characterized by distinct Coralligenous morphotypes. Finally, covered surface and volume of each polygon were calculated using vector field operation implemented into QGIS.

3 Geological setting

The study area, located offshore Capo Bianco (Isola Capo Rizzuto, Calabria, Italy), belongs to the Crotone Basin (CB) (Fig. 3), ~~The CB is~~ the widest Neogene basin of the Calabria region, partly exposed along the Ionian coast and in part documented offshore. It represents a segment of the Ionian fore arc basin on the inner portion of the Calabrian accretionary wedge (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/ky; Zecchin et al., 2004), combined with glacio–eustatic sea level fluctuations, led to the formation in the Crotone 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 (1st order terrace), ascribed to MIS 7 by Zecchin et al. (2011), is a mixed marine to continental terrace, consisting of the products of carbonate (algal build-ups and biocalcarenite passing into shoreface and foreshore deposits) to siliciclastic (shoreface, fluvial channel fill, lagoon-estuarine and lacustrine deposits) sequences (Zecchin et al., 2011).

The 2nd 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 (Maunz and Hassler, 2000, Zecchin et al., 2011).

The Le Castella–Capo Cimiti terrace (3rd order terrace), probably associated to the MIS 5c (Maunz and Hassler, 2000), shows extensive algal reefs and shoreface deposits, with elevations variation due to normal fault displacement (Zecchin et al., 2004; Nalin et al., 2012).

The Capo Colonna marine terrace (4th order terrace), correlated to 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 & Massari, 2009), consists of a planar surface with a sedimentary cover overlied by a wedge of colluvium tapering (Bracchi et al., 2014).

The Le Castella marine terrace (5th order terrace) records an unconformity-bounded transgressive-regressive cycle (Nalin et al., 2007; Nalin & Massari, 2009; Zecchin et al., 2010; Bracchi et al., 2014; Bracchi et al., 2016), with two different facies for coralline algal build-ups and associated bioclastic deposits in the lower portion (Zecchin et al., 2004, 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 & Hassler, 2000; Santagati et al., 2024).

The marine terraces exposed in 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 "Crotone" 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 characterised by an undulating morphology including the Luna and the Capo Rizzuto Swell. The southern section of the sheet covers the offshore extension of the Crotone forearc basin (Chiocci et al., 2021). This work aims to enhance the understanding of the Crotone Basin offshore features, with focus on underwater bioconstructed habitats.

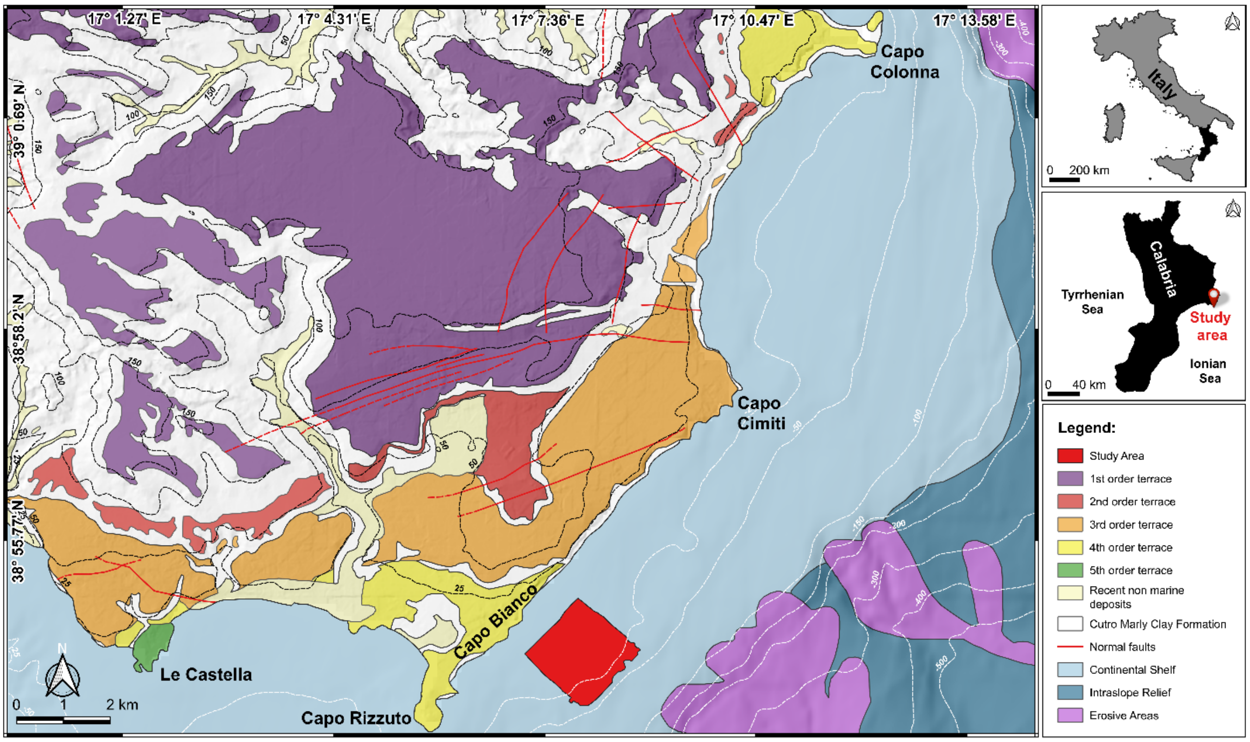

Figure 3: Conflated geological map of the Crotone peninsula, with the indication of the five order terraces (modified from Bracchi et al., 2014), and physiographic domains identified offshore the area in the frame of the MaGIC Project (modified from Chiocci et al., 2021).

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 identification of the benthic habitats. In particular, bathymetric data revealed a seafloor with depths ranging from -7.3 m 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 -15m 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; ii) the presence of scattered roughness associated with irregularities on the seafloor (Fig. 4D).

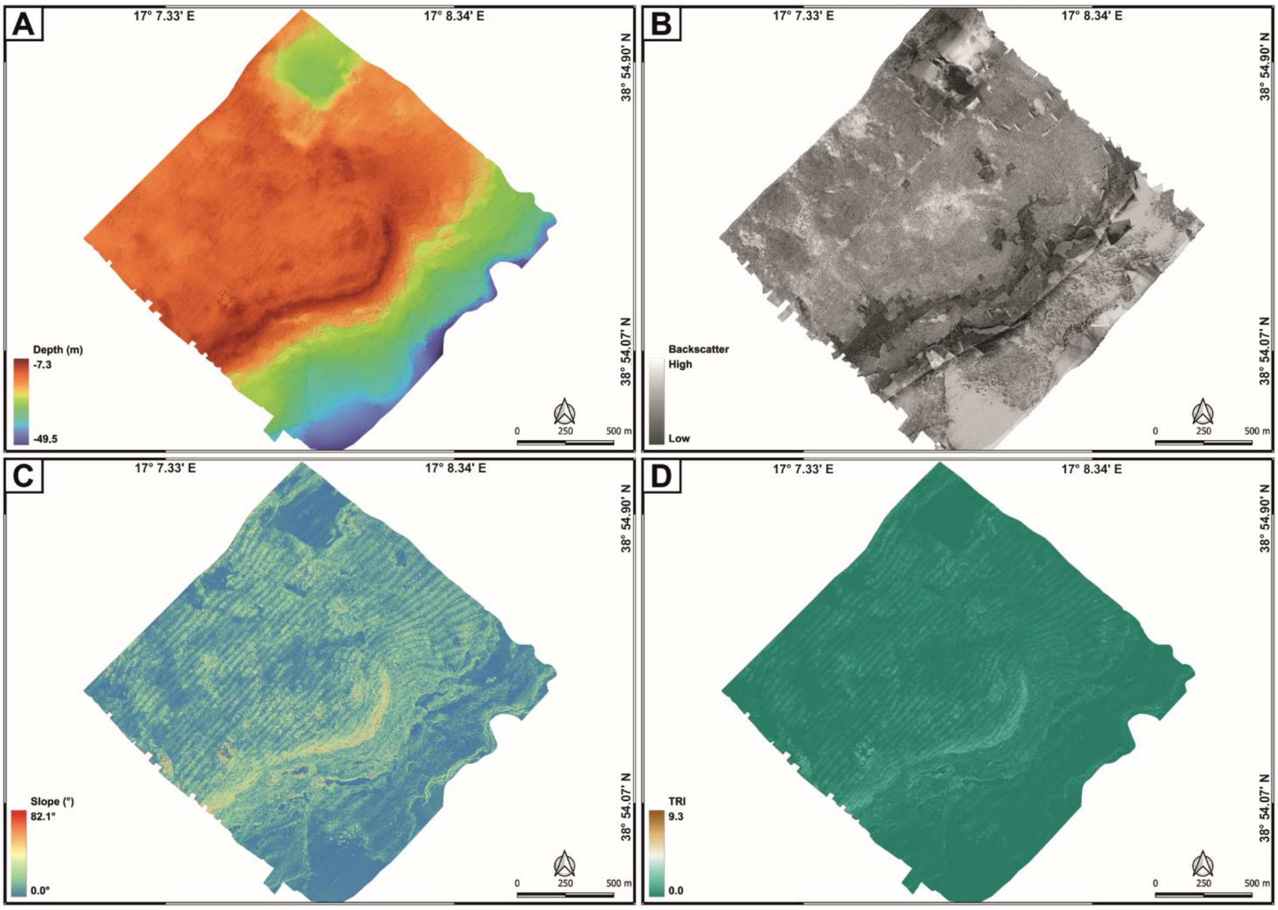

Figure 4: Geomorphological characters of the study area expressed through processed bathymetric **(A)**, backscatter **(B)** data and geomorphometric indices, like slope **(C)** and Terrain Roughness Index **(D)**.

Combining bathymetric and backscatter (Fig. 4B) data with slope and seafloor roughness values, different morpho–acoustic 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 m to -25 m. In the depth range from -15 m to -25 m, analysis of ROV–video transects showed that *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 m 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 pattern of medium to high backscatter. It covers scattered portions throughout the study area at various depths and is characterized by very low TRI values.

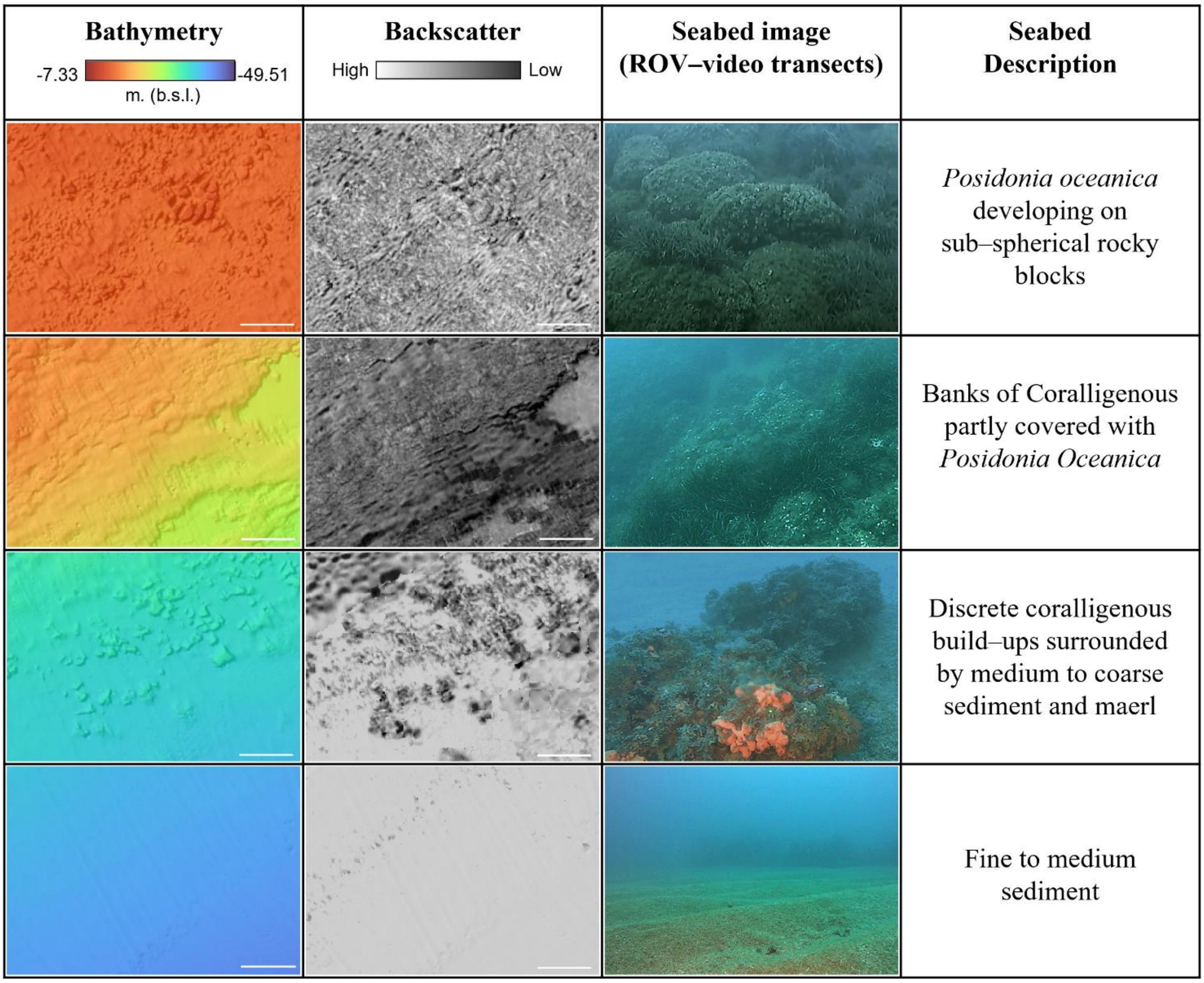

Figure 5: Morpho–acoustic features identified by bathymetric and BS data, together with ROV videos interpretation. White scale bar is 20 m.

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*); iv) fine to medium sediment.

The *Posidonia* habitat, testified by its typical BS signal (intermittent speckled fabric of moderate backscatter), dominate 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 m and -25 m, the *Posidonia* backscatter signal gradually attenuates and coralligenous bioconstructions start to be discernible. This transitional belt, that occupies about 0.37 km^2, 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 banks 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 reliefs morphotype and tend to align sub-parallel to the shoreline.

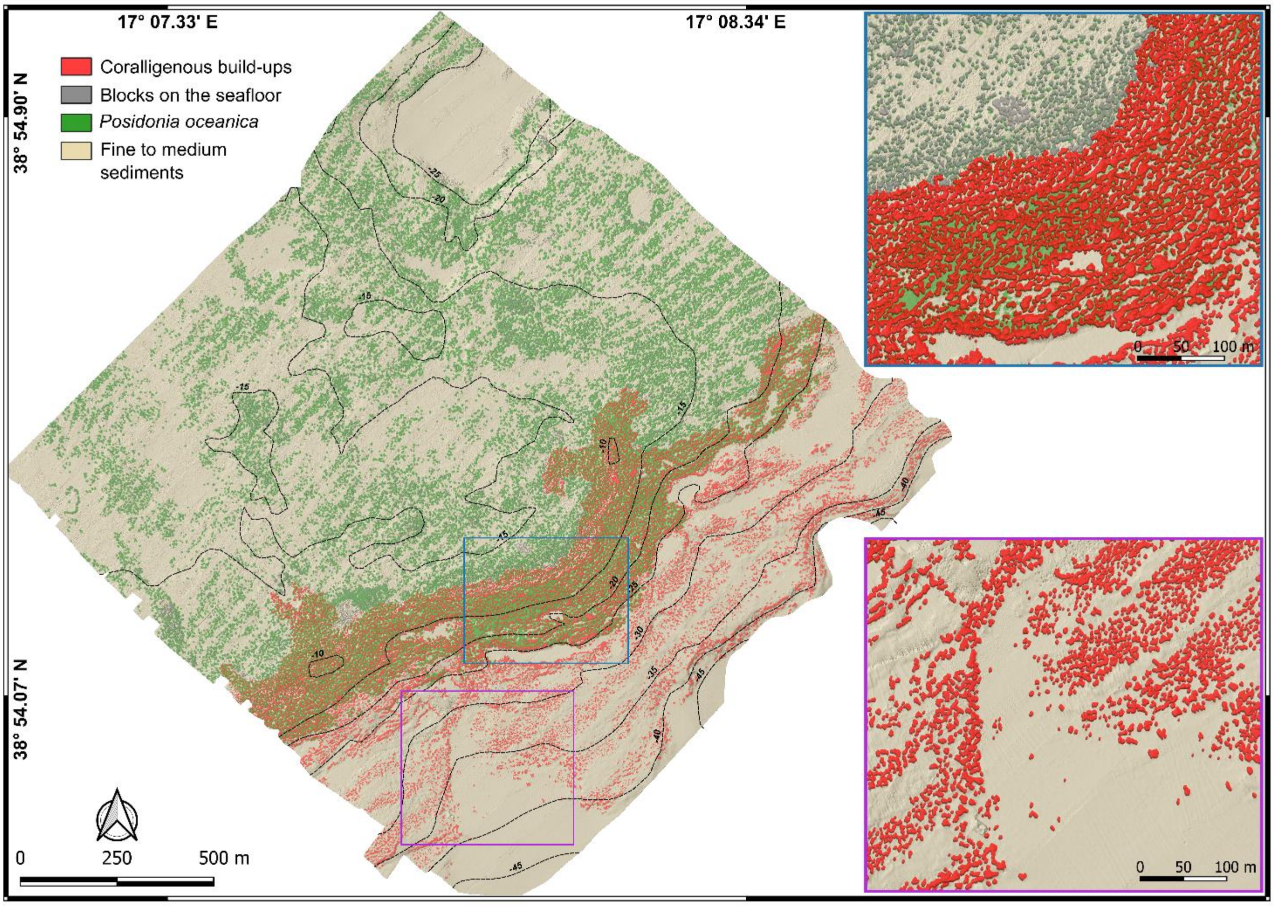

Figure 6: Mapping model of the underwater benthic habitats in the study area off Capo Bianco (Calabria, Italy). Note, in the blue and purple boxes, two magnifications of representative areas of the model where coralligenous bioconstructions and rocky blocks on the seabed are depicted in 2.5D.

4.2 Extraction of coralligenous build–ups

The model extracted 12384 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 re–classification 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); iii) artifacts concentration 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.

The identification of artifacts was based on specifical pattern inconsistent with expected Coralligenous morphologies, and their removal was carried out manually as part of the data cleaning process (Fig. 8B, D, 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 to distinguish between banks (tabular bank *sensu* Bracchi et al., 2016; SI ≤ 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 155677 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 69830 m². The volume (Fig. 7D) occupied by discrete reliefs (40806 m³) is also significantly lower than that of the banks (116094 m³). This data is consistent with the fact that discrete reliefs are characterized by smaller extent and thickness compared to the banks.

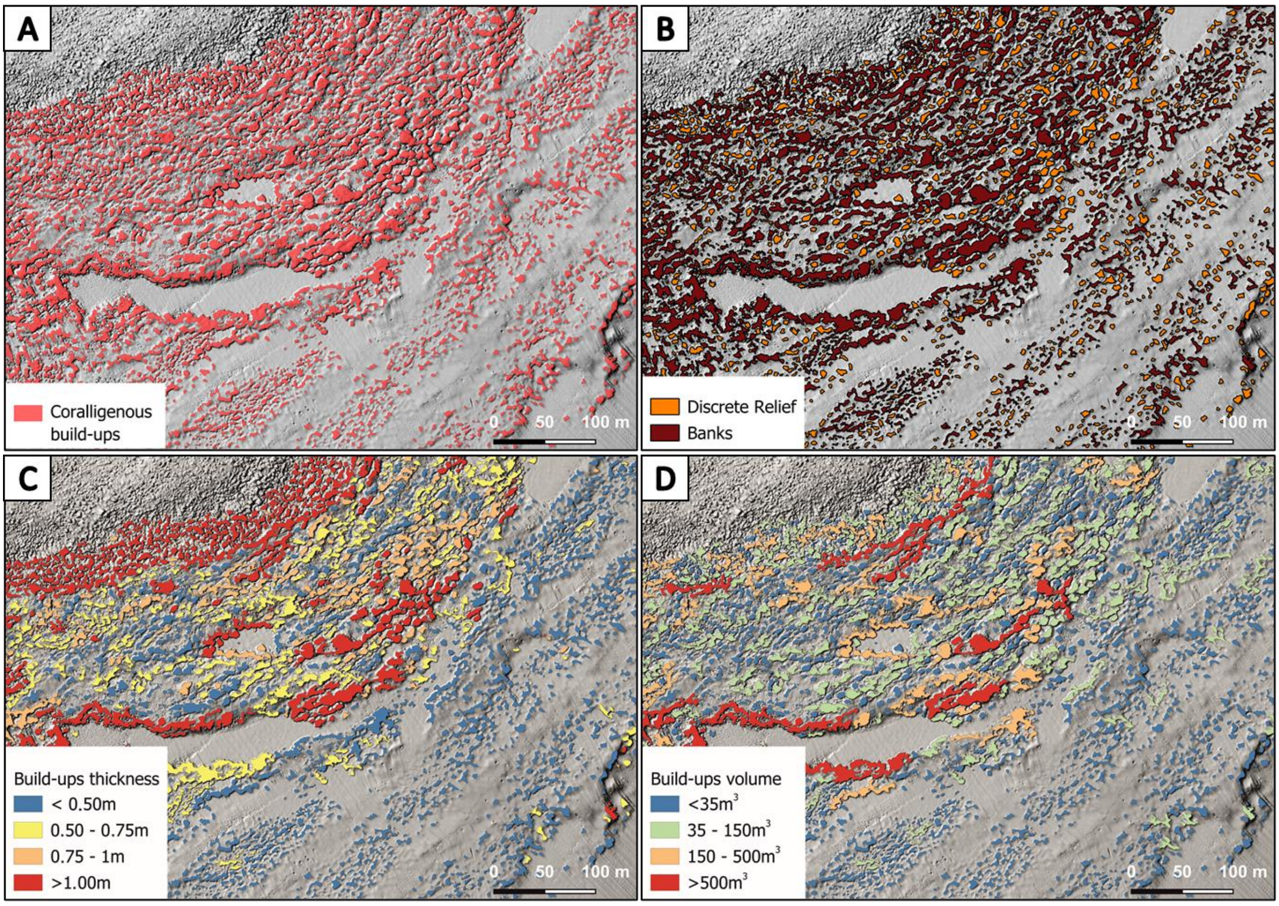

Figure 7: **(A)** Result of build–ups extraction using TPI. **(B)** Differentiation of coralligenous build–ups into discrete relief and banks based on the SI value. **(C)** Estimation of build–ups thickness. **(D)** Calculation of the volume for each coralligenous polygon.

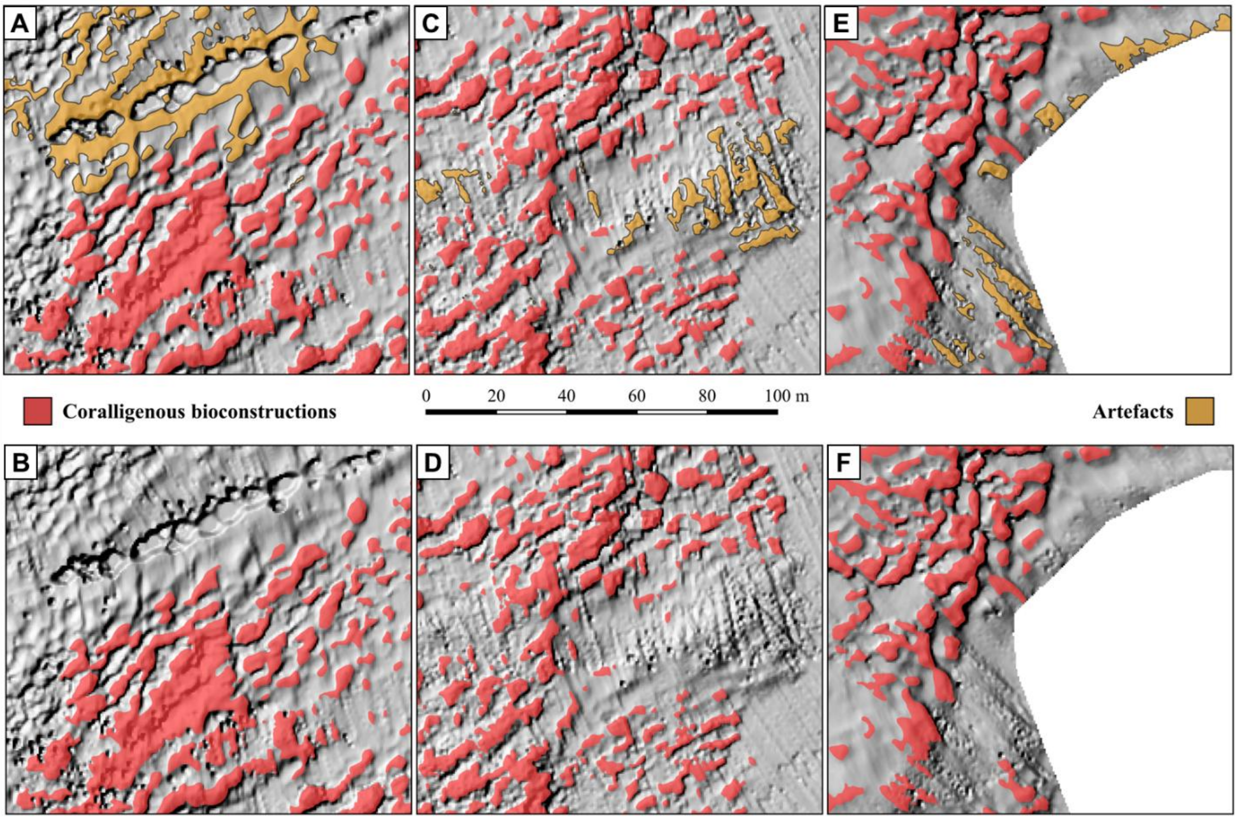

Figure 8: Examples of artifacts identified during polygon extraction and their manual removal. (**A**) False positive caused by the presence of Posidonia oceanica and (**B**) the same area after removal; (**C**) artifact due to bad roll correction and (**D**) corrected version; (**E**) artifacts at the boundary of the DTM and (**F**) cleaned result.

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	155677	116094
Discrete Reliefs	> 2	0.49	69830	40806

5 DISCUSSION

Acoustic techniques, such as high–resolution swath bathymetry sounder (including backscatter), side scan sonar and acoustic profiling are optimal tools for quickly recognize and identify the extension of benthic habitats on the seabed and map their distribution without mechanical collection of samples, which would damage this delicate ecosystem (Bracchi et al., 2017).

Traditionally, the segmentation of MBES data sets have been performed manually, despite 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 et al., 2019). 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, submarine dune and ridges, offering high accuracy and repeatability (Arosio et al., 2023; Garone et al., 2023). Additionally, 3D CNNs have been applied to automated denoising of MBES data, enhancing the efficiency of bathymetric data workflow (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 attempt to map these complex biogenic structures in detail. Bracchi et al. (2017) proposed a categorization of coralligenous morphotypes on sub-horizontal 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^{TM}, 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. (2022) produced a morpho-bathymetric map for the continental shelf offshore Marzamemi (Sicily, Italy) that contained quantitative description for the distribution and extent of coralligenous reefs.

The approach proposed in this work, based on the workflow shown in Figure 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 appear to be influenced by both substrate characteristics and geomorphological features. In the shallowest sector (above -15m depth), *Posidonia oceanica* represent the prevalent benthic habitat. In the intermediate depth range (down to approximately -25m 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 sub-horizontal 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 these evidences, the submerged surface can be correlated with the 5th order terrace exposed near Le Castella, characterized by a gently seaward-inclined surface and a morphological step interpreted as paleocliff (Bracchi et al., 2016). The different orientation of the submerged scarp in the study area (NE-SW), compared to the emerged paleocliff associated with 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 5th 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 distinctly 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 4th 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 -25m) hosts several coralligenous build-ups, predominantly belonging to banks morphotype. Similar spatial arrangements have been observed in submerged terraces of southeastern Sicily (Varzi et al., 2022) 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 5th order terrace of Le Castella (Bracchi et al., 2016).

In the deeper sector of the study area (below -25m depth), *Posidonia* is no longer present and the benthic assemblages are composed by Coralligenous *sensu stricto* associated with fine to medium sediments and maerl. These bioconstructions mainly belong to discrete reliefs morphotype and tend to follow a sub-parallel orientation relative to the shoreline, a distribution pattern that appears 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); 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. (2022). However, further investigations, including in situ hydrodynamic and sediment transport measurements, are necessary to validate these hypotheses.

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 a geomorphometric parameters for their extraction from the seafloor. Variability of coralligenous morphotypes (Bracchi et al., 2017) poses several challenges to their automated extraction from DTM. Since build–ups raise 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) 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 neighbourhood. 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 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-thrut validation. Once the appropriate input parameter for TPI calculation (e.g., Power, Bandwidth, minimum and maximum radius) ad 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, were plotted in the scatterplots of Figure 8, providing new insights into 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 m^2 and less than 1 m thick (Fig. 8A). 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. 8B). 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 area and shape indices (SI) of coralligenous build–ups (Fig. 8C), 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 (Dmax), as suggested by an R^2 value of 0.78 (Fig. 8D). 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. 8F) and discrete reliefs (Fig. 8E), 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 scale and associated with different environmental conditions. The same spatial mixing of these morphotypes, which may be due to small-scale variations in substrate type, hydrodynamic regime, or inherited seabed features, which locally favour distinct growth mode despite spatial proximity (Bracchi et al., 2017; Marchese et al., 2020; Varzi et al., 2022), was also observed in our study area.

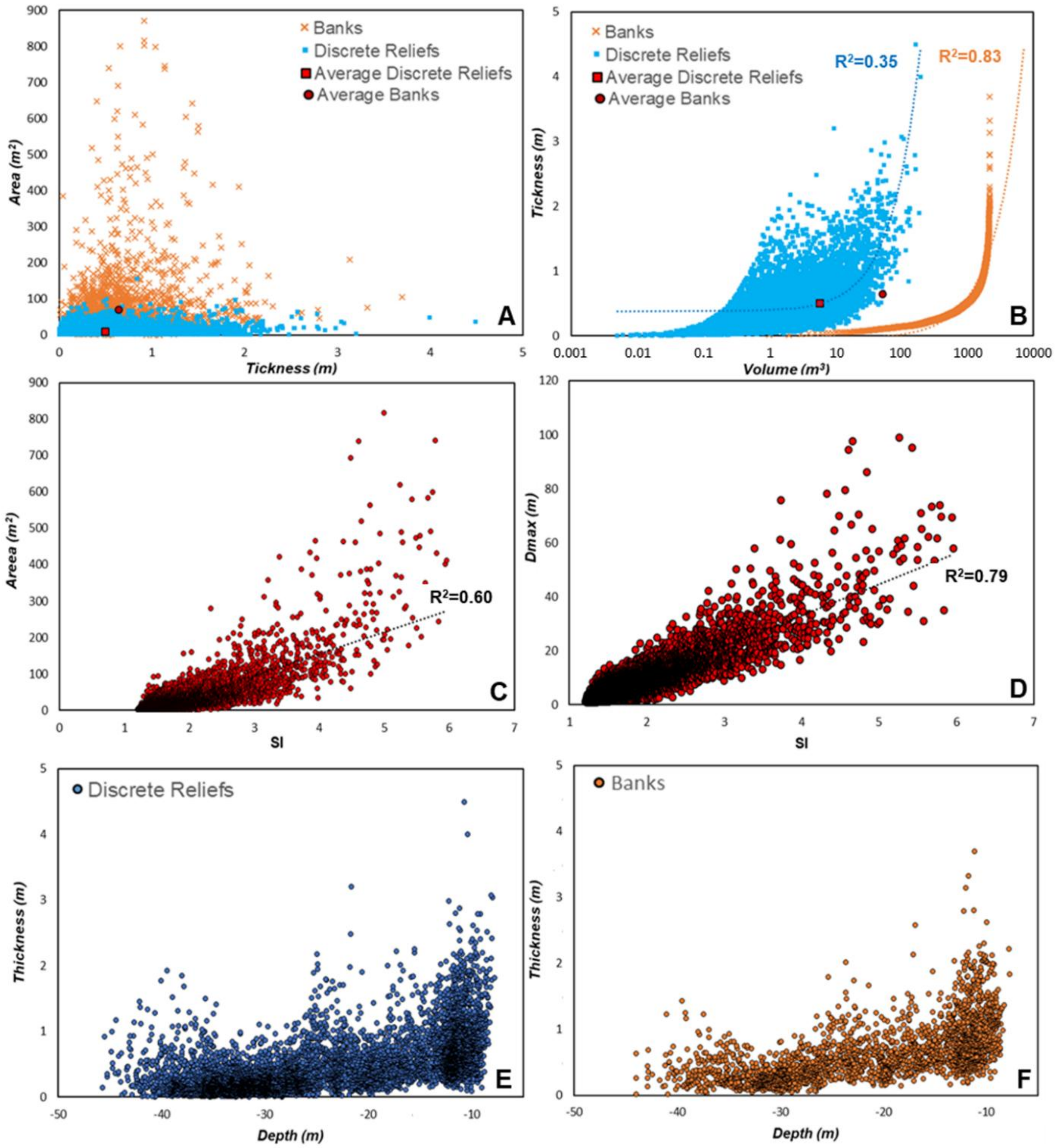

Figure 8: Scatterplot representing relationships between: area and thickness **(A)**; thickness and volume **(B)**; area and shape index **(C)**; maximum diameter and shape index **(D)**; thickness and depth for banks **(E)** and discrete relief **(F)**. These quantitative geometric data were extracted by the benthic habitat mapping model proposed in this work. SI: shape index; Dmax: maximum diameter.

CONCLUSIONS

A new mapping approach starting from high–resolution acoustic data acquired through MBES surveys performed offshore Capo Bianco (Isola Capo Rizzuto Marine Protected Area) was developed and presented here. The method represents a step forward, as it builds on an integrated two 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.

The resulting model proved capable not only in identifying and differentiating the benthic habitats but also in 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 reliefs morphotype exhibit a much more pronounced lateral growth component compared to the banks. If confirmed through an accurate geobiological characterization, these finding 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.

Author contributions

Conceptualization: G.M., A.G.; Methodology: G.M, A.G., G.I., F.M.; Formal analysis and investigation: G.M., M.C., G.I.; U.S.; F.M.; Writing – original draft preparation: G.M., M.C., G.V., F.P., A.L., E.C., R.S.; Writing – review and editing: R.D., C.A., F.B., V.A.B., D.B., A.R., A.G.; Funding acquisition: A.G., F.B.; Resources: R.D., F.B., A.L., E.C., A.G.; Supervision: A.G.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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authors' views and opinions, neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

Open Research

The data sets needed to evaluate results and conclusion 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 survey 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 (https://qps.nl/qimera/). Backscatter data processing was performed using QPS Fledermaus (https://qps.nl/fledermaus/). Figures 1, 3, 4, 6, 7 were made with QGIS 3.34.9 "Prizren" software (https://qgis.org/project/overview/). Figures 8 were generated using Microsoft Excel (https://www.microsoft.com/it-it/microsoft-365). Data used to generate the figures are available upon request to the corresponding author.

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