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Geomorphology of the continental shelf of Tavolara Island (Marine Protected Area 'Tavolara-Punta Coda Cavallo' – Sardinia NE)

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ABSTRACT

In this document a geological – geomorphological map in scale 1: 25,000 is presented. The study area is located inside the Protected Marine Area Tavolara – Punta Coda Cavallo, in north-eastern Sardinia. The study was done through integrated analysis of multibeam bathymetric and very high-resolution side scan sonar data, acquired in an area of 163 km² with the purpose of mapping the main biocoenoses and with particular reference to the coralligenous bioconstructions and the distribution of *Posidonia oceanica*. The interpretative hypotheses, based on the analysis of geophysical data, have been validated through diving surveys. This map represents a fundamental knowledge base and it constitutes an important technical-scientific support for long-term planning and management of the studied seabed.

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1. Introduction

Marine habitat mapping provides the spatial framework for ecosystem-based management (EBM). Its increasing prominence, in international policy and regional and national management organizations, highlights its growing acceptance especially as a tool for designing and delineating MPA (Marine Protected Area). The management priorities of protecting biodiversity and developing sustainable use solutions, need to be implemented with the use of credible scientific information. One of the main goals of marine spatial management is to promote a sustainable use of marine resources while not putting marine biodiversity and habitats at risk. Objectives for marine biodiversity and habitats are stated in the Biodiversity Convention, Habitat Directive and the Marine Strategy Framework Directive (EC, 2008a; EEC, 1992; UN, 1992).

Effective planning which aspires to be 'representative' and 'adequate' requires spatial knowledge of biota, habitat, or suitable surrogates at a scale relevant to an MPA (Leslie, Ruckelshaus, Ball, Andelman, & Possingham, 2003; Lombard, Cowling, Pressey, & Rebelo, 2003; Roberts et al., 2003; Williams et al., 2008; Williams & Bax, 2001). Biodiversity conservation is a major objective for MPAs globally. It is necessary to know the composition and distribution of benthic communities, the characteristics of a natural and healthy state, and the effects of different human activities (e.g. EC, 2008b; epbrs, 2013; Steltzenmüller et al., 2013).

It has been estimated that only 5–10% of the seafloor is mapped at a comparable resolution to similar studies on land (Wright & Heyman, 2008). Furthermore, marine ecosystems are poorly described compared to their terrestrial counterparts. On land, the proportion of unknown habitats has been estimated as 17% whilst for the marine realm it has been estimated as 40% (EC, 2007). Numerous research highlight the strong relationship between habitat and biocoenosis (Curley, Kingsford, & Gillanders, 2002; Friedlander & Parrish, 1998; Gratwicke & Speight, 2005; Moore, Van Niel, & Harvey, 2011; Williams et al., 2008). Information about benthic habitats and biological communities are important for the implementation of ecosystem-based management of the sea and in assessing the consequences of human activities, and assessment has to have a clear link to the management objectives (Buhl-Mortensen et al., 2012; Steltzenmüller et al., 2013). Habitat mapping is a support for government spatial marine planning, management, and decision making; and to support and underpin the design of marine protected areas.

Using acoustic technologies such as multibeam echosounder and side scan sonar (SSS), very high-resolution data with total coverage of the seabed are acquired. The resulting bathymetric data and the geomorphological characteristics of the seabed, derived from their acoustic properties, represent an excellent base for the geomorphological and geological classifications of the seabed (Buhl-Mortensen,

Buhl-Mortensen, Dolan, & Holte, 2015). These physical classifications of the seabed in turn form an essential component in benthic habitat mapping that integrates biological properties and has been widely used (Brown, Smith, Lawton, & Anderson, 2011 and references therein). Marine habitat mapping has been defined as ‘Plotting the distribution and extent of habitats to create a map with complete coverage of the seabed showing distinct boundaries separating adjacent habitats’ (MESH, 2008).

In 1992, the first geomorphological map (Orrù & Pasquini, 1992) and the first biocenotic map of seabed in the MPA has been created. Subsequently, previous morphological knowledge has been investigated with the acquisition of new multibeam and side scan sonar data acquired full coverage under an agreement between MPA and Agence de L’eau Andromede Océanologie (France). A new geomorphological map has been created in the MPA in which the distribution of incoherent sediments, rocky outcrops and the main morphologies has been mapped; this document implements the knowledge bases about the seabeds habitats mapping.

2. Geological setting

The seabed of the Marine Protected Area Tavolara is dominated by the crystalline basement associated with the Hercynian emplacement of the Corsica-Sardinia batholiths and is comprised of granites, rose monzogranite and biotite leucogranite (Ghezzi & Orsini, 1982). The dyke system has a mainly acidic composition with quartz porphyry (Andreolli et al., 1971).

The Mesozoic is formed by dolomite and limestone, at the base it is characterized by Middle Jurassic siliciclastic to carbonate successions of the Genna Selole Formation with a the rich macroflora and palynoflora of the lower middle Jurassic (Costamagna et al., 2018) which have been studied in the last 150 years (Costamagna et al., 2018).

In the Permian and Triassic, the lowering of the sea level has formed a continental Permo – Triassic surface smooth, on which the powerful Mesozoic carbonate cover rests, and Tavolara Island is a residual limb. The Last Glacial Maximum (LGM) can be connected to the slope deposits ‘éboulis ordonnées’ (slope deposits made up of alternating layers of well-sorted angular stones and finer material primarily composed sand, silt, and clay material of Tavolara Island (Ozer, 1976; Ozer & Ulzega, 1981) and the aeolian sandstones to the cross-bedding of Molara Island (Ginesu, 1988). The grèzes litées are Alpine tectonic lineations, trending NW-SE and NE-SW (Ghezzi & Orsini, 1982) and erosive processes have led to the evolution of engravings, platforms, relief and depressions. The dyke system contributes in a decisive way to the

articulation of the seabed which is highlighted by the differential erosion.

The main river valleys reflect the characteristics of a paleo – hydrographic with tectonic control, which is connected to the coastal rias (De Muro & Ulzega, 1985); depressions with an parallel elongation axis to the coast, interpretable as paleo – lagoons connected to the late Pleistocene sea levels are also recognized (Ulzega, Lecca, & Leone, 1981).

The Quaternary deposits such as the fossil conglomerates detected in the Spalmatore Peninsula (Tavolara Island) and attributed to the last interglacial locally known as Tyrrhenian (Ulzega & Ozer, 1982), rest on the Jurassic transgressive succession, which is represented by calcareous conglomerates and dolomitic limestone up to bioclastic limestones.

3. Methods

Geophysical survey methods were used to derive data about the geomorphology and lithology of the seabed, which was acquired by side scan sonar (SSS) and multi-beam echosounders (MBES). These instruments acquired data on the seabed’s reflectivity (SSS), bathymetric data at a high resolution (MBES) and a combination of the two. Acoustic reflectivity (acoustic backscatter) is a complex function of many factors: the acoustic frequency, the angle of incidence, the slope of the seabed, the roughness scale, the particle size distribution, the presence of fauna and flora on the bottom, and bioturbation. This process goes under the name of segmentation and is more commonly known as the acoustic classification of the seabed (Acoustic Seabed Classification ASC, Anderson, Holliday, Kloser, Reid, & Simard, 2008; Brown & Blondel, 2009). As part of the morphometric analysis, quantitative information derived from bathymetry such as the Bathymetric Position Index (BPI) are extracted. The BPI is a second order derivative of the surface that defines the elevation of a point in relation to the surrounding landscape. The result is a map of geomorphological features such as ridges, depressions, flat areas and slopes, which are automatically extracted from the digital terrain model (DTM). These models can be managed through GIS software, enabling the three-dimensional visualization of the seabed, in great detail.

In particular, very high-resolution ultrasound findings were obtained using both MBES (Kongsberg-GeoSwath Plus 250 kHz) and SSS (Klein 3900 – 445/900). These were supplemented with video surveys and underwater photography (both to depths of –75 m, using rebreeder closed-circuit) rather than with a driven camera and ROV.

All the different types of data were entered into a GIS database to facilitate our interpretations and the multidisciplinary and multiscale assessments.

The geomorphological map was created on a cartographic reference basis UTM WGS84 – Zone 32N, through the use of the Esri ArcGIS/ArcMap. Cartography of the studied area was created through analysis and interpretation of geophysical data in scale of 1:5000 in order to allow a final refund with high detail and accuracy.

The bathymetry has been elaborated through the analysis of acquired multibeam data; while for the sector emerged the DTM with 1 m × 1 m cell size of the Autonomous Region of Sardinia was used (<http://www.sardegnaeoportale.it/areetematiche/modellidigitalidielevazione/>).

4. Results

The seabed of the inner continental shelf has morphological characteristics that are closely linked to the morphostructural elements of the emerged sector. Capo Ceraso, Punta Greca and Capo Coda Cavallo promontories, like Tavolara Island, are iso-oriented.

The submerged karst landscape of limestone and dolomite surrounding Tavolara Island is characterized by landslides of collapsed, paleo platforms, wave cuts, isolated reliefs (Secca del Papa), and the underwater granitic landscape of Molara Island, with residual inselberg and tor reliefs.

The continental shelf, subject of this study, extends for approximately 10 nautical miles: the convexity of the edge, which is generally just accentuated, is home to prograding sediments. The heads of Molara Canyon to the north and Posada to the south, are an exception with an edge to sub-outcropping substrate. The two canyons are differentiated by genetic and morphological characteristics: the incision of the Molara Canyon is clearly a river setting and is linked to the evolution of the Olbia ria, while the heads of Posada Canyon show the retraction evidence that is typical of the dynamics of a submarine canyon, in the strict sense, with gravitational processes (creep and slumping) along slopes and a turbidity flow (Bouma, Normark, & Barnes, 1985).

Holocene sedimentation in the external shelf is extremely low. This allows the surfacing of submerged shorelines in facies of beachrock with a littoral ridge developed for several kilometers (Ulzega, 1988).

The resulting marine system, in the bays and channels, is very conservative. This explains the anomalous abundance of submerged paleo forms in a territory dominated by erosive processes.

Submerged Pleistocene shorelines at different bathymetry were detected, while inherited morphologies evolved in a sub-aerial environment, of the pre-Quaternary era, are distinguished on granite abrasion platforms.

4.1. Geomorphology of the unlithified substrates

Quartz-feldspathic sands characterize the submerged beaches, between the shoreline and the seaward of

the abrasion platform of the rock platforms or the *Posidonia oceanica* mat.

Bedforms were detected in the submerged beach (ripple and mega-ripple). In the beach of Porto Taverna and San Teodoro ‘La Cinta’, two orders of littoral bars are detected, with asymmetrical trends.

After the lower limit of the *Posidonia oceanica* meadow (−30/−40 m), the bioclastic sediments plains extend. In the area near to this limit, the biogenic component of the sediments is mainly represented by bryozoans, foraminifera and other organisms with a carbonate shell, that come from the meadow.

Below 45 m depth, offshore, the dominant biogenic fraction is represented by advanced red algae in *mäerl* and *praline*, these sediments are often site of dunes with sorted grain size ($l = 50$ m, $h = 2$ m). They are characterized by a strong selection of particle size bioclast, fine sediments, silty sands and sandy silts.

Using side scan sonar data a sedimentary distal plain has been recognized northwest of Molarotto, where there is a granite isolated outcrop, medium fine bioclastic sediments from an external continental shelf and biogenic gravels ‘*maerl* and *pralines*’.

4.2. The morphotypes of the granite rocky bottoms

The continuity of the rocky outcrops is interrupted by covers of quartz – feldspathic sand in submerged beaches that correspond to small creeks.

In a submerged environment, the Permo-Triassic smoothed zone has been recognized, on this, the Jurassic Sea has transgressed and the carbonate sequence of the Tavolara Island rests.

The discontinuity surface was detected at a depth of −50 m and −60 m and this separates the granite from the limestones of the southern cliff.

The presence of paleo residual forms, such as inselbergs, highlights the subaerial setting of this smoothing surface, subsequently affected by marine abrasion.

Fine sediments of cover are less powerful, except for the axial zone, where the engraving of a paleo channel is identifiable.

In Figure 1, the deep plane to the northwest of Molara Island is shown, where outcrops of granite substrate are present, which are organized into isolated residual reliefs, tor and inselberg.

Shallow abrasion platforms (−5 m/−10 m), extend between the islands of Molara and Molarotto. Here, the fracturing channels, particularly obvious and numerous, give these morphotypes freshness characters attributable to a late-Pleistocene evolution.

The granite rock outcrops surrounding the Molarotto Islet, appear in the Side Scan Sonar images strongly fractured, with sub-parallel fracturing network, trends N 90 E and off the northwest coast

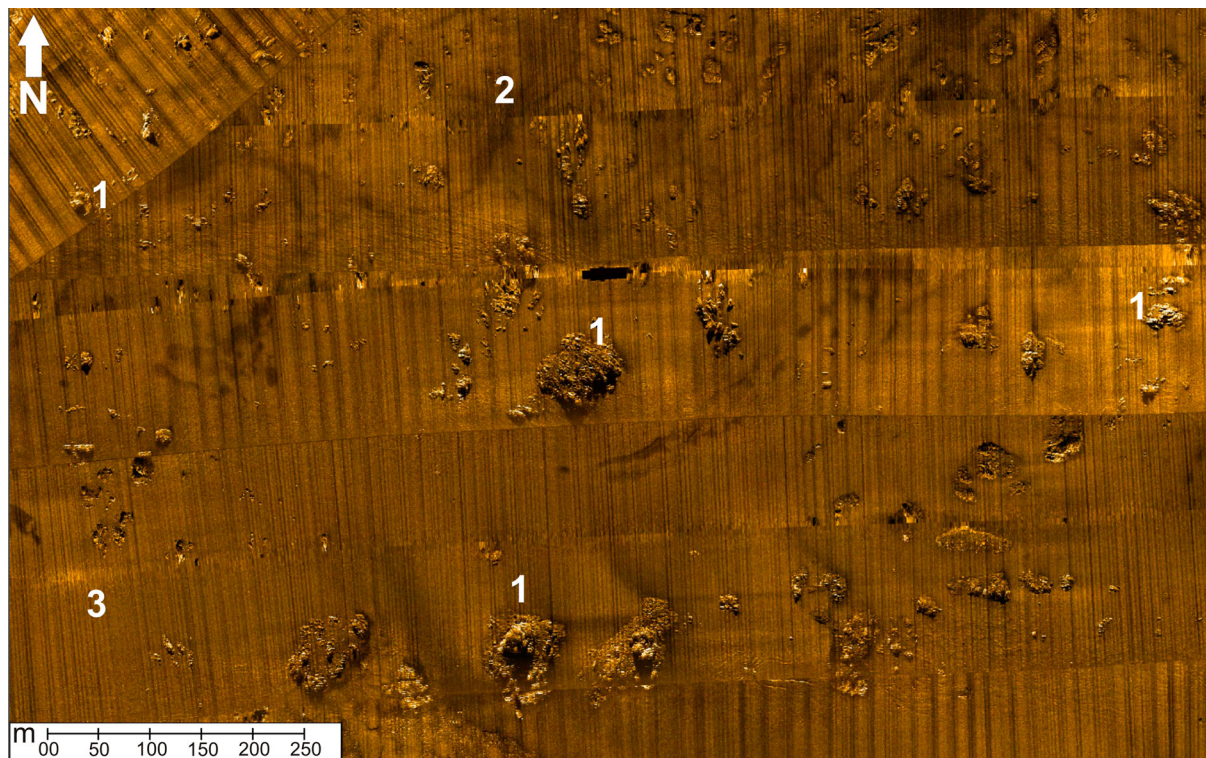


Figure 1. Side Scan Sonar image of a deep flat north west of Molaria Island: (1) outcrops of the granite substrate, organized in isolated residual reliefs in the tor and inselberg; (2) medium thick bioclastic sediments from the outer continental shelf; (3) medium-fine bioclastic sediments of the intermediate continental shelf.

of the Molaria Island. Tor morphologies are controlled by a dense diacase grid to the prevailing N 130 E trend. Similar platforms that are interpretable as paleo-cliffs detectable at greater depths: -50 m to -60 m to the north of Molaria Island and -30 m to -40 m to the south of Capo Coda Cavallo.

Subaerial morphological characteristics unite the very steep rocky seabed of Capo Ceraso and the northern side of the Molaria Island: residual paleo forms, such as inselbergs and tors, are found in relief for selective erosion.

4.3. The morphotypes of beach rocks

In the Sardinian continental shelf, numerous evidence of stationing of the Holocene sea level are preserved, both in depositional facies, beach rock and coastal sediments that in erosion facies, abrasion surfaces and frames are etched into the substrate.

The marine deposits related to the Middle and Upper Pleistocene are at consistent and correlated depth (Ulzega & Ozer, 1982). Some rare sites are the exception, where bland vertical movements in blocks were observed. This justifies the particular conservative character of the Sardinian shelf towards the shorelines in relation to the low tectonic mobility, the other what qualifies Sardinia as a key area in the reconstruction of post-glacial sea-level rise for the Western Mediterranean (Lambeck et al., 2011).

Tavolara – San Teodoro is an area in which shorelines in facies of beachrocks are concentrated from -65 m to -2 m. The overall look of the beachrock outcrops, often characterized by obvious forms of erosion both on the summit surface and the edges of the outcrop suggested an erosional origin to early scholars (Orrù & Pasquini, 1992).

On the deeper outcrops, the beach sand banks appear to be undamaged, though they are affected by an orthogonal fractures network.

The slightly inclined position towards the open sea, typical of these outcrops, resumes the characteristics of the sedimentary body of a beach; the sedimentary structures represented are typical of the shoreline environment.

Some forms of erosion of the beachrocks confirm the submersion model and the conservation of littoral bar in the continental shelf according to the process of transgressive submergence (Penland, Suter, & Boyd, 1988). This mechanism provides the submarine reworking of the sedimentary coast body, in the absence of cementation, producing a shift towards the land of a paleo-beach.

The cementation processes of the beachrock require at least the temporary immobilization of a sedimentary body of beach and they are responsible for the formation of the current beach-rocks that have developed between the lower and upper limits of the tide. In microtidal areas such as the Mediterranean

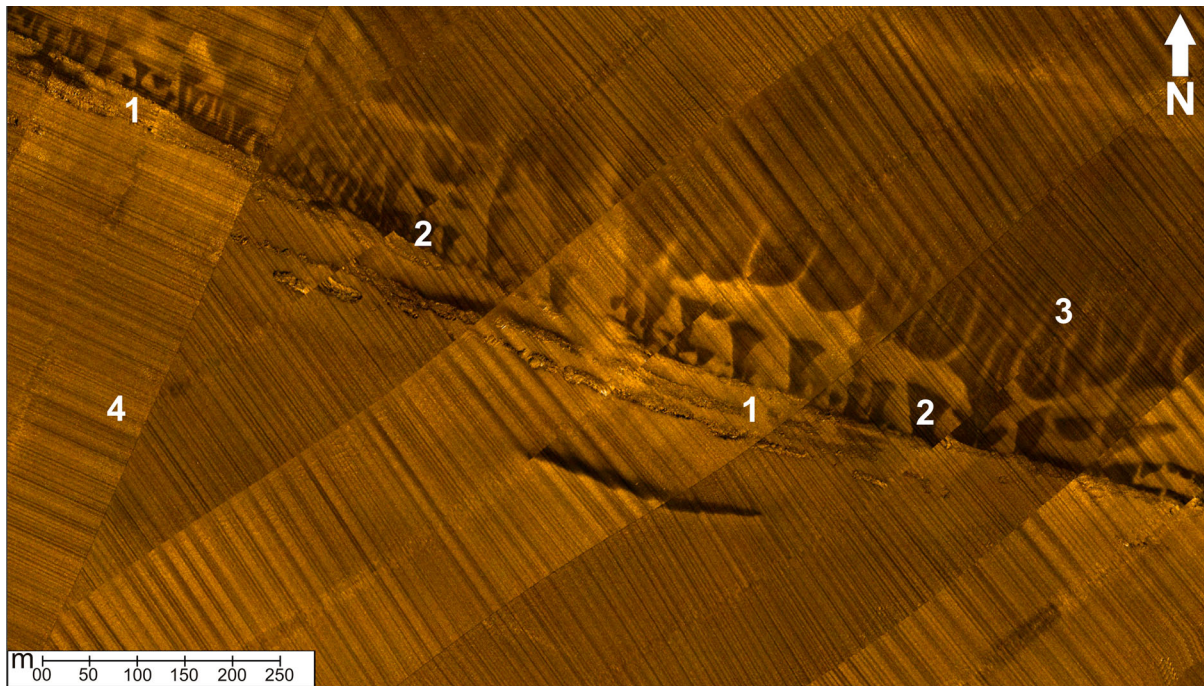


Figure 2. Side Scan Sonar image of the distal sedimentary plains off Spurlatta Bay: (1) conglomeratic sandstone beach rock; (2) biogenic gravels 'maerl' and 'pralines'; (3) dunes scalloped organization; (4) medium-fine bioclastic sediments of the outer continental shelf.

the outcrops are of limited thicknesses, typically below 1 m.

Most of the beach rock detected along the Sardinian shelf, where the power of the deposits is on average between 4 and 5 m (Ulzega & Orrù, 1984) do not seem to follow the same rule.

An explanation may be found in the synsedimentary cementation processes that follow the transgression (Guerra, Kiang, & Sial, 2005; Kitano & Hood, 1965; Taylor & Illing, 1969).

The dating of the shell of an organism through carbon isotopes indicates the date of death of the organism, to which one must add the processing time of the bioclasts, the transportation time and emplacement within the sedimentary stock and possible reworkings.

The cementation subsequent to the stabilization and partial burial of the sedimentary stock can be extremely rapid in some cases (Kelletat, 2006).

The deepest shore line from -62 to -65 m, found off the coast of San Teodoro Bay is attributable to a period between 12,000 and 11,500 years to the present day, in the Pleistocene-Holocene transition. The beach rocks at depths between -54 m and -50 m, detectable off of Spurlatta Gulf and San Teodoro are attributable to a period between 11,000 and 10,500 BP that corresponds to the Last Glacial Maximum (LGM) between the Late Pleistocene and Holocene (Younger Dryas) (Figure 2).

Other beachrocks are preserved on the seabed of the Spurlatta Gulf. In the proximal shelf, four rows of beachrocks at different depths can be observed: -40 m, -25 m, -5 m and -0.5 m. Those at

depths between -40 and -25 m are dated in the period between 10,000 and 8000 years BP.

The beach rocks at shallow depths, (-5 m and -0.5 m) north and south of Spalmatore, are highly evolved forms of erosion. The summit area of the conglomeratic sandstone outcrops are home to deep channels and erosional potholes.

The shallow water shore lines were detected in Spalmatore at -4 m (Figure 3), in both the north and south bay, they are attributable to 4500–4000 years BP. In these shallow water areas the beachrock have largely been dismantled by coastal waves; the only exception is the Cala Girgolu outcrop near Porto Taverna. While in the submerged beach of Porto Taverna and in some adjacent beaches, beach rocks are present a -2 m.

Other beach outcrops of sandstones and conglomerates were detected in the southern sector of the area in question, south of Molara; here, the littoral bars are arranged in two rows at depths of -50 m and -45 m, respectively. The closed depression, filled by fine sediments and located between the two littoral bars, can be interpreted as a paleo-lagoon.

4.4. The morphotypes of the limestone dolomite cliff foot

Tavolara Island is surrounded by active cliffs carved into the limestone and dolomite.

In the southern side, the cliffs reach heights of over 200 m, the cliff of the northern side has a modest height and acclivity.

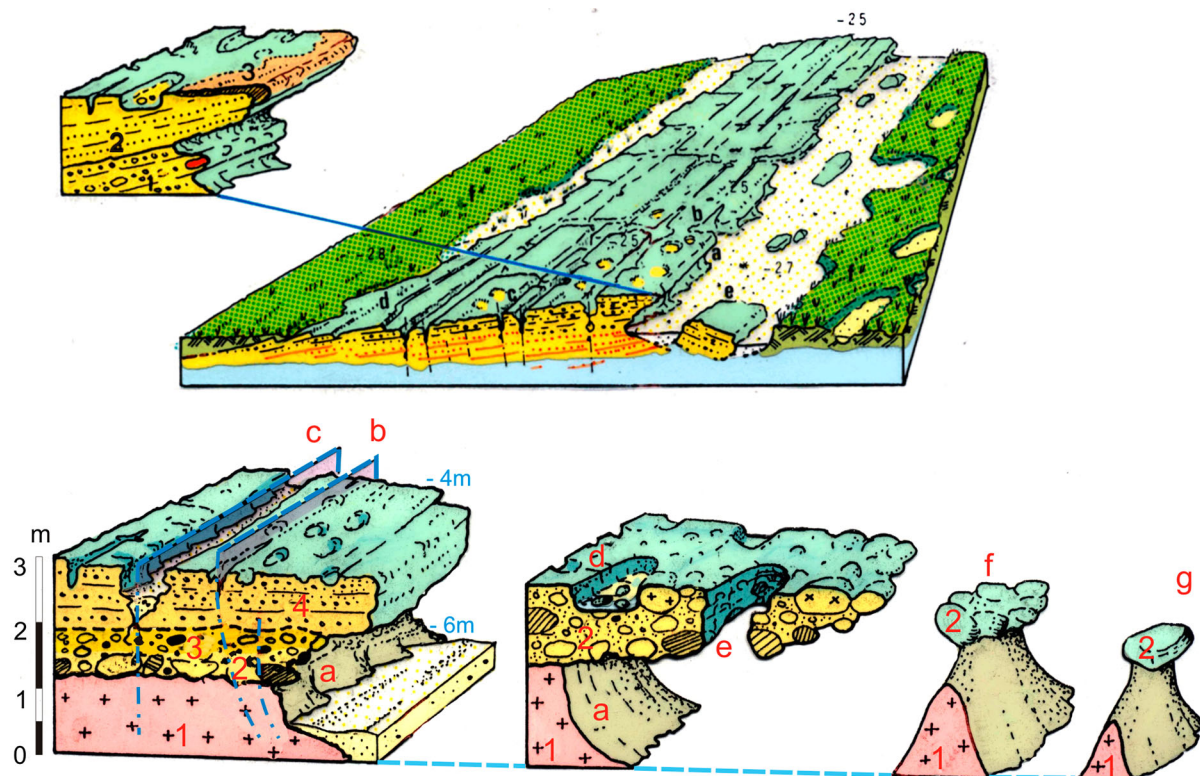


Figure 3. Block diagram of the underwater geological survey, beach rock off Spalmatore di Fuori, -4 m (above image); Stages of evolution of the frames of the internal edge (to earth), by the landslides until the residual isolated reliefs (below image). (1) fractured and altered granite(substratum); (2) transgressive conglomerate with granitic and calcareous pebbles; (3) polygenic and poorly sorted beach-conglomerate; (4) micro-conglomerate and quartz-feldspar sandstones; (a) selective scour in bedded of different grain size; (b) parallel fractures; (c) erosional channel along open fracture; (d) sub-active erosional pothole; (e) pothole; (f) pyramidal relief in altered granitic substratum; (g) residual pillar with boulder on.

In the northern and western side, the cliff is partially buried by extensive scree and Late Wurmian éboulis ordonnées (Ozer & Ulzega, 1981).

In the southern side, the submerged cliff is completely exposed and developed up to -25 m , extending for 5 km without continuity. The base of the submerged cliff is often covered by the collapse products in subangular blocks that are greater in size than 10 m^3 .

At times, basal abrasion platforms are detected, such as those located at depths of -7 m , -10 m and -25 m , they are characterized by forms of abrasion, karst littoral and potholes.

The transition between the rocky outcrops, the collapse deposits and deep plains in the organogenic sediments is underlined by littoral bars and bioconstructed platforms at calcareous algae. Isolated reliefs are also detectable on the bottom, the most important is the Secca del Papa, located north-east of Tavolara Island and it is characterized by a pattern of fracturing N 110° E and N 40° E .

4.5. The bioconstructions of red algae (Coralligenous)

Off the north cliff of Tavolara Island and near the Secca del Papa (Figure 4) a bio-construction platform of calcareous ‘coralligenous’ algae is present. In the base of

‘Secca del Papa’, the bio-concrections reach values of 1 m of high.

The coralligenous of the inselbergs is thinner, with a lower biodiversity than the coral of the deep beachrocks that are hotspots of biodiversity.

4.6. Geoarchaeology

In 2011, during archaeological excavations sponsored by AMP Tavolara – Punta Coda Cavallo (Scientific Responsible Dott. Paola Mancini) uncovered a third millennium a.C, Monte Claro culture settlement, an extended settlement emerged off the entire peninsula of Spalmatore, full of decorated ceramic material that is typical of the era.

The structure of the prehistoric village suggests that the town could have developed towards the shoreline, and was then partly submerged during the latter stages of the Holocene sea level rise.

The morphobathymetric data can be compared with the sea-level curve developed by Lambeck et al. (2011) and tested with recent chrono-isotope analyses in the survey of Malfatano, southern Sardinia and the Gulf of Oristano (central-western Sardinia).

This indicates that the paleo shoreline is related to the Eneolithic settlement of Spalmatore and the Monte Claro culture 4.5/–4.1 Ky BP, at a depth of $-4/-5\text{ m}$.

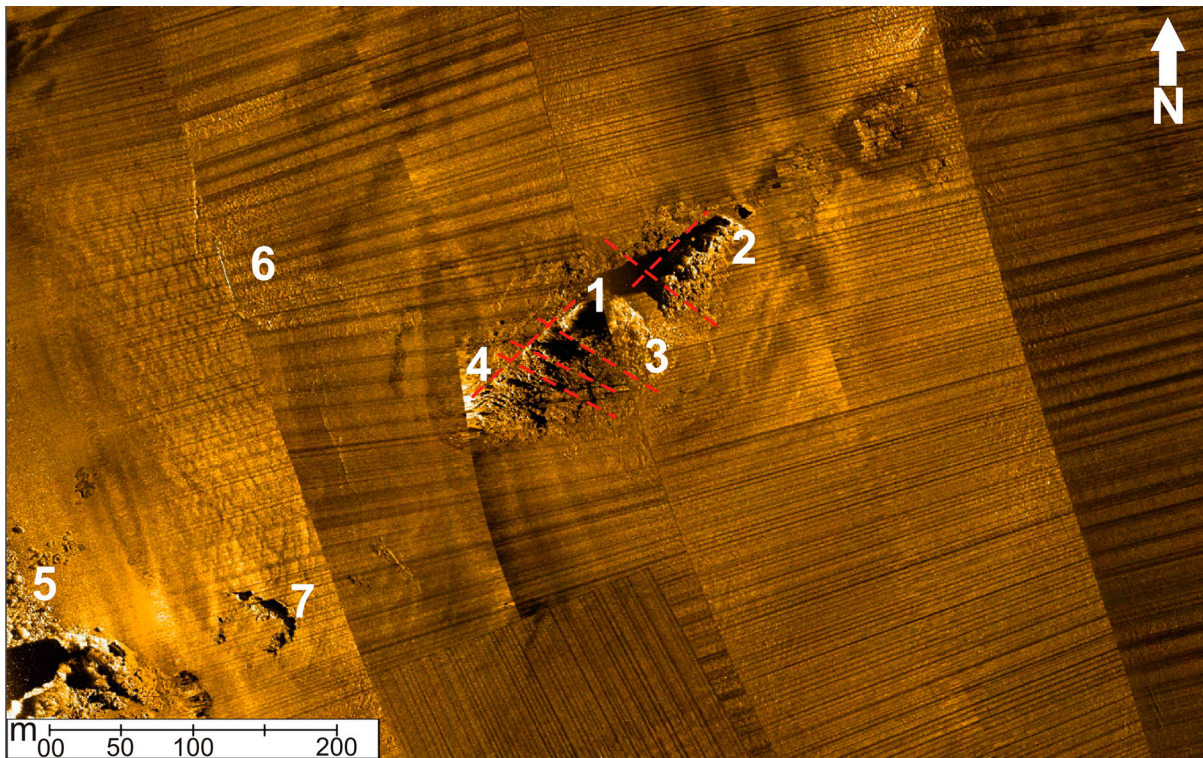


Figure 4. Side Scan Sonar image, northern sector of Tavolaria Island, 'Secca del Papa': (1) isolated relief in dolomitic limestone, main relief; (2) secondary relief; (3) bioconstructions of 'coralligenous' red algae (C); (4) fracturing pattern N 110 ° E and N 40 ° E; (5) collapse landslide to the foot of the limestone cliff; (6) bedforms 'sand ribbons'; (7) bioconstructed terraces of calcareous algae – Coralligenous.

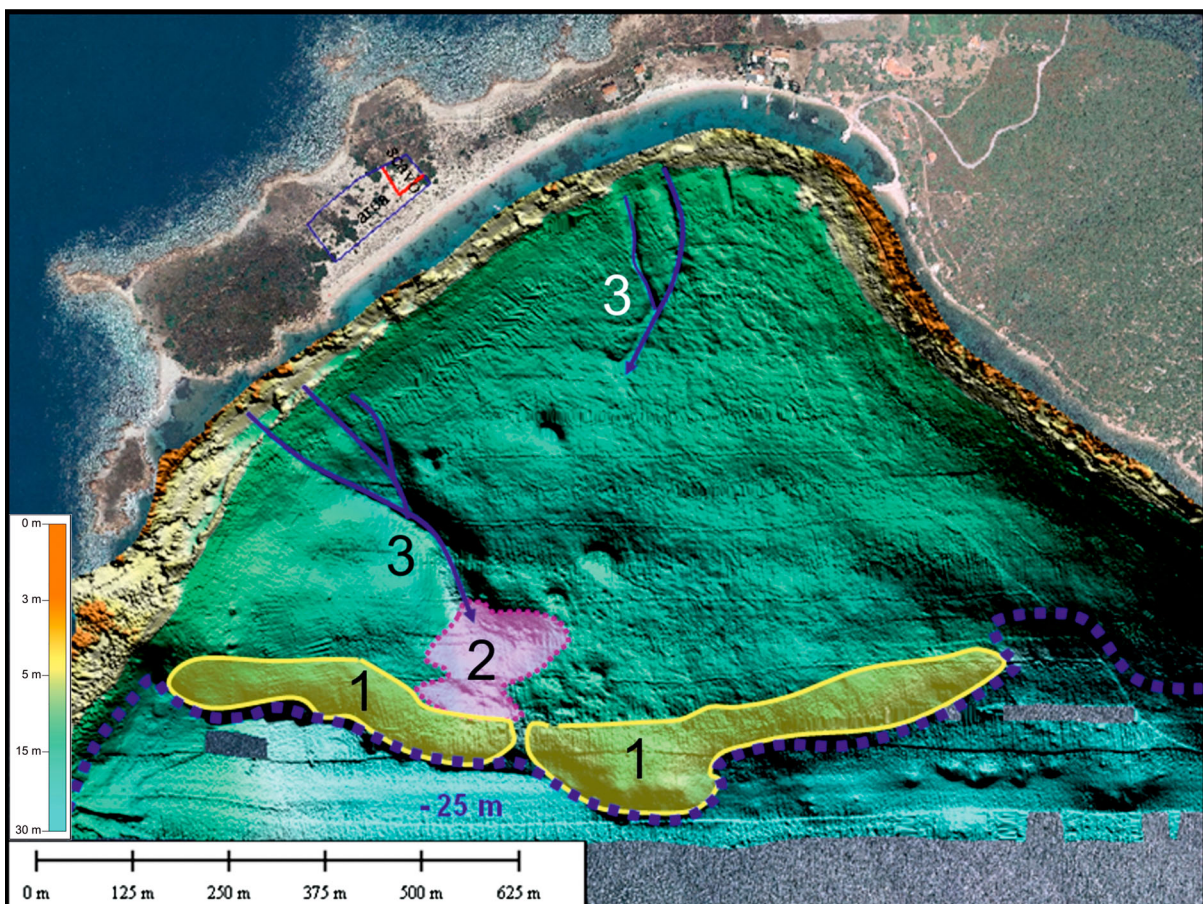


Figure 5. DTM from high-resolution multibeam (cell at 1 m), Baia di Spalmatore di Terra, Tavolaria Island; paleoenvironmental reconstruction of the paleo sea level to -25 m (9.5 Ky BP – Late Mesolithic period): (1) littoral bars and dunes; (2) lagoon; (3) drainage channels.

In the **Figure 5**, the paleoenvironmental reconstruction of the paleo sea level to -25 m (9.5 Ky BP – Late Mesolithic period) is shown.

5. Conclusions

Basing on the geomorphological study of the seabed and the knowledge of the coastal sector, some hypotheses on the evolutionary scheme of the area surrounding Tavolara Island have been proposed.

The formation of a wide valley south of Tavolara occurs simultaneously with the engraving of the main rias in the north east Sardinia, in the upper Miocene (Vail & Hardenbol, 1979).

In the late Pliocene and early Pleistocene, a very intense erosive phase generates a deepening of the valleys, modeling the relief with the retreat of slopes (Ulzega & Ozer, 1982; Vardabasso, 1956).

During a hot-humid interglacial (Tyrrhenian) a transgression generates an incision of tidal notch up to $+6.5$ m above present sea level (MSL) and the deposition of the beach sediment (Antonioli et al., 2015; Ulzega & Ozer, 1982). The climate stiffening, with the lowering of the sea level down to -120 m, reactivated the river incision of Tavolara Valley. Important retraction processes of the slopes lead to the formation of Eboulis ordonnées deposits (Ozer & Ulzega, 1981) which extend to -60 m below current sea level.

At the base of these, dune fields developed during the Würmian of which blocks of sandstone with cross-bedding in Tavolara Island and filled some channels in the northern side of the Molara Island (Ginesu, 1988) with sand and eolian sandstone, are preserved.

The consequent pulsations and the stationing characterizing the Versilian transgression lead to the construction and cementation of beach rocks at different depths.

At the same time, the submergence and fossilization of backshore depressions, abrasion platforms and karst tubes (Holocene) can be identified.

The anthropic changes also involve the *Posidonia oceanica* meadow, with repercussions for type and dynamics of deeper sedimentation.

Software

All the different types of data have been entered into a GIS (Geographic Information System) database, to facilitate the interpretations and multidisciplinary and multi-scale assessments. The Global Mapper and ArcMAP software were used for the cartography of the multibeam data.

Digital models can be derived using Global Mapper software tools, with a series of rasters processed as the slopes map, the shaded model, the representation of contour lines and the statistical

analysis of the survey (hypsographic curves, exposures slope, etc.).

Disclosure statement

No potential conflict of interest was reported by the authors.

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