UNIVERSITÀ DEGLI STUDI DI SASSARI
Dipartimento di Architettura Design e Urbanistica
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Tesi di Dottorato:

CORALLIGENOUS AND BEACH ROCKS AS (PALAEO) ENVIRONMENTAL INDICATORS

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SUMMARY

1 INTRODUCTION

The continental shelves of the Mediterranean Sea, from ~20 m down to 120 m depth, can be characterized by the presence of the 'coralligenous habitat', a biogenic concretion that thrives exclusively in Mediterranean waters (Ballesteros, 2006; Çinar et al., 2020; Piazzi et al., 2021). Coralligenous habitat is considered as a hard substratum produced by the accumulation of calcareous coralline algae growing in low light conditions of 0.05% and 3% of the surface irradiance (Ballesteros, 1992; Ballesteros, 2006). Coralligenous growth is also influenced by nutrient concentration in the sea water (Piazzi et al., 2011), sedimentation (Piazzi et al., 2012) and temperature and salinity conditions (Ballesteros, 2006). Moreover,the coralligenous habitat is the result of interactions between the building activities of algal and animal constructors and biological and physical erosive processes (Martin et al., 2014).

The coralligenous communities, as well as other marine communities such as the meadowof *Posidonia oceanica* (L.) Delile (De Falco et al., 2017; Simeone et al., 2018), can be considered a carbonate-producing ecosystem, because of the presence of calcifying organisms (Canals & Ballesteros, 1997; Sartoretto et al., 1996). Knowledge of the distribution of coralligenous habitats along the continental shelves of the Mediterranean Seais crucial for the management and conservation of marine resources (Bracchi et al., 2017; Cogan et al., 2009; Çinar et al., 2020; Piazzi et al., 2021). Two main coralligenous types may be defined: coralligenous cliffs over littoral rocks, and coralligenous banks or platforms on continental shelves (Ballesteros, 2006; Montefalcone et al., 2021). Martin et al. (2014) reviewed the available data of coralligenous habitat distribution in the whole Mediterranean Sea, highlighting that the mapped polygons of coralligenous outcrops amounted to

2763.4 km^2. They applied a probabilistic model of coralligenous occurrence, estimating that as much as 95% of coralligenous habitat had still to be mapped (Martin et al., 2014).

In recent years, the mapping effort of coralligenous habitat increased under the European Marine Strategy Framework Directive (MSFD; EC, 2008). The MSFD aims to improve the environmental status of the seas and coralligenous assemblages are considered ‘special habitat types’ that should be monitored. Direct observations of coralligenous banks are often prevented by water depth. To avoid these difficulties, geophysical acoustic data, coupled toground truth data obtained with seabed sampling or video images of the seabed, have been more frequently used to map the seafloor (Brambilla et al., 2019; Costa & Battista, 2013; De Falco et al., 2010; Di Martino et al., 2021; Innangi et al., 2019). Although new data of seabed mapping of the circalittoral zone have been locally produced (e.g. Bracchi et al., 2015; Bracchi et al., 2017; Cánovas Molina et al., 2016; De Luca et al., 2018; Georgiadis et al., 2009), the knowledge of coralligenous habitats in the Mediterranean distribution is largely incomplete.

The aim of the thesis research is to map the occurrence of ridges that could be potential substrate of coralligenous banks as well as indicators of the sea level fluctuations occurred post Last Glacial Maximum (LGM); that is, post the last 20 ka. The selected areas are on the northwest continental shelf of Sardinia in a depth range of ~40- 100 m. They represent the largest shelf sector of the Mediterranean Sea where extended mapping of coralligenous banks and seafloor has been performed.

2 OBJECTIVES

The main objectives of the PhD project consist of:

- creation of biocenotic and geomorphological maps through the integrated use of these instruments;
- surveying and mapping Coralligenous through the integrated use of ROV (suitably modified), Multibeam and Side Scan Sonar;
- mapping the presence of ridges that could be potential substrate of coralligenous beds and indicators of sea-level fluctuations that occurred after the Last Glacial Maximum (LGM), i.e., after the last 20 ka. The selected areas are located on the northern and western continental shelf of Sardinia, in a depth range of ~40 to 160 m. They represent the largest shelf area in the Mediterranean Sea where extensive mapping of coralligenous beds and seafloor has been performed.

3 MATERIALS AND METHODS

Marine data sensing systems aimed at acquiring high and very high-resolution data.

3.1 Side Scan Sonar

The recent development of military sonar-type technologies applied to the study of the seafloor has made it possible to make detailed maps of the seafloor and, in particular, to detect objects on the seafloor (such as wrecks) of metric and, in some cases, sub-metric dimensions (Bai, Y., Bai, Q., 2018).

The sonar commonly used for bottom analysis is of the side scan type: Side Scan Sonar (SSS) (Fig.1). This instrument makes it possible to obtain morpho-acoustic images (sonograms) of the seafloor in many respects comparable to terrestrial aerial photos. Images are acquired by emitting 255 simultaneous acoustic pulses (pings) according to a beam-oriented transverse to the direction of navigation (slate range). Return waves (backscatter) from the seafloor are picked up, recorded, and transformed into images. Acoustic images record the different intensities of the pulse reflected from the seafloor.

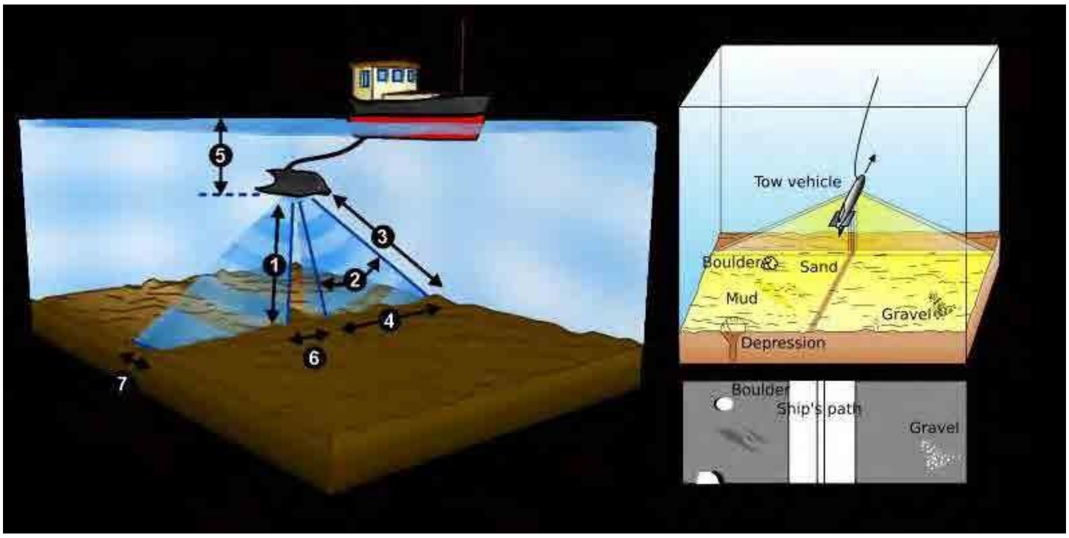

Figure 1 - Principle of SSS operation. (1) SSS height from the bottom; (2) vertical beam; (3) maximum acoustic range-lateral beam; (4) slate range; (5) depth; (6) right and left channel separation-no-acquisition zone; (7) beam width.

Data sheet of the Side Scan Sonar used.

MODEL: KLEIN 3000 digital dual frequency 500 and 100 KHz Specifications of the underwater unit (Fig. 2)

TOWFISH

1) Pulse transmission: Tone burst, operator selectable from 25 to 400 µsecs. Independent pulses with frequency control; has two transducers (Fig.2) per side consisting of a transmitting (transmitter) and a receiving (reiceiver) unit

2) Horizontal Beams. 0.7° @ 100 kHz, 0.21° @ 500 kHz

3) Vertical Beams: 40°

4) Beam tilt 5, 10, 15, 20, 25° down, adjustable;

5) Scale range: 15 settings - 25 to 1,000 meters

6) Maximum range 600 meters @ 100 kHz; 150 meters @ 500 kHz

7) Operating depths: 1,500 m

8) Towfish construction: stainless steel;

9) Length of the Towfish: 122 cm (48 in)

10) Diameter of the Towfish: 8.9 cm (3.5 in)

11) Weight (in air) 29 kg (63.9 lbs)

12) Standard Sensors: roll, pitch, heading

Figure 2 - The Towfish and detail of the transducer.

Surface Unit Specifications.

TRANSCEIVER PROCESSOR UNIT (TPU)

1) VxWorks® with custom application;

2) Standard 19-inch rack or table mount, VME bus structure;

3) Outputs 100 Base-Tx, Ethernet LAN;

4) NMEA 0183 navigation input;

5) Power (including towfish) 120 W @ 120/240 VAC, 50/60 Hz;

6) Power supply: 1600 W generator.

3.2 Remotely Operated Vehicle

Remotely Operated Vehicle (R.O.V) is a sub robot that functions only when connected by cable to the relevant remote location. Remotely controlled from boats, ships, or oil platforms, the sub robot has applications in numerous and very different fields: from oil extraction to seabed monitoring for marine environmental protection, from wreck recovery to mine and underwater ordnance detection.

Figure 3 - The ROV Velociraptor model.

The ROV we used is the Velociraptor model (Fig. 3) complete with monitor and console. This instrument, weighing about 50 kg in the air, is capable of operating up to 400 meters depth and has two lateral motors for horizontal propulsion and one vertical motor for elevation and sinking. Two halogen spotlights, two laser pointers and two cameras, capable of making HD movies, complete the equipment.

3.2.1 Modifications made

The ROV was suitably modified, through the placement of a GoPro hero camera 5 that allows 4k video capture, bringing the number of cameras present to three. The camera inserted inside a diving suit (capable of withstanding the pressure of 200 ATM) was placed on a specially made stainless steel bracket. Inside this, two lasers were placed 10 cm apart to detect the size of objects/organisms on the seabed (Fig.4A). In addition, a low-cost positioning system consisting of a Bluetooth GPS antenna placed inside a float on the surface, connected directly to the ROV.

The antenna transmits data to the laptop PC in the boat, so its position can be detected, without resorting to the more expensive USBL positioning systems, which can cost tens of thousands of euros. The comparisons made between the low-cost system and the USBL we normally use (MicroNav System - Tritech) (Fig. 4B) allowed us to define the deviation in accuracy of the two systems as minimal.

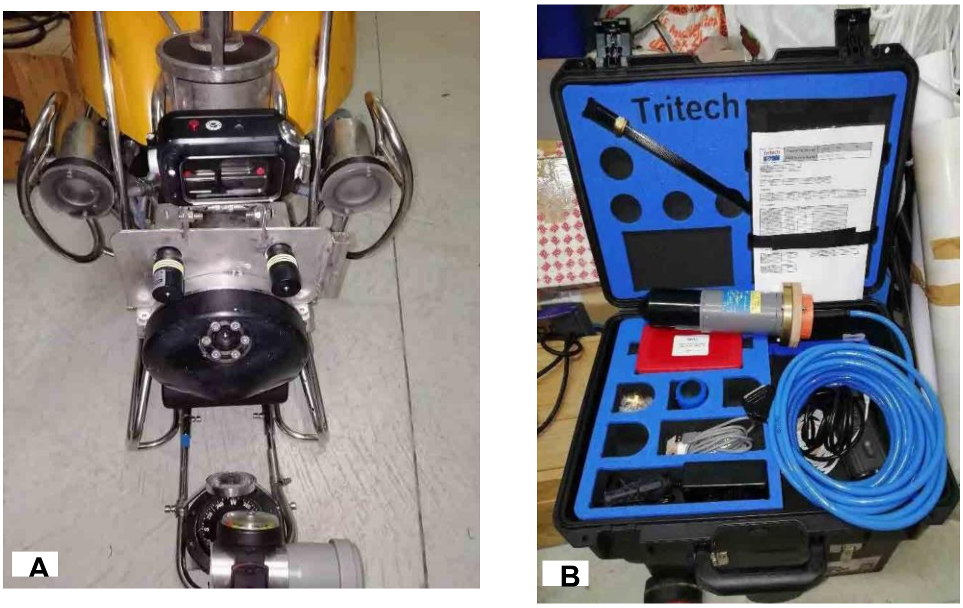

Figure 4 - **A**-stainless steel plate with underwater lasers and hull for Go Pro - **B**-USBL Micronav System-Tritech

3.3 Multi Beam

The multibeam represents the most accurate technology available today and is widely used for many high-resolution bathymetric studies; the use of the multibeam to perform detailed bathymetric studies is now common practice in most application fields (Renard, V., & Allenou, J.-P., 2015).

A multibeam (Fig.5) emits sound waves perpendicular to the direction of motion of the vessel, in a simultaneous fan of pulses that propagate as sound waves at a maximum coverage angle of about 150º: in this way, 100% coverage of the seafloor can be obtained by making transects parallel to each other; the frequency of the pulse is between 100 and 455 kHz The instrument emits acoustic waves through a large number (e.g. 120 to 240) beams, or beams, acquiring for each energization a large number of data transverse to the route followed by the ship. In this way, total coverage of the seafloor is obtained; for depths less than 100 m, the extent of coverage averages 2-3 times the depth. For proper use of the instrument, it is necessary to interface it with on-board instrumentation and calibrate it against environmental conditions, using:

- a motion sensor, to balance the effects of roll, pitch and changes in the vessel's altitude (pitch, roll, heave);
- a gyroscope that defines the orientation of the boat with respect to magnetic north;
- A multi-parameter probe that allows calibration of the instrument with respect to the speed of acoustic waves in the water;
- a high-precision tide gauge that allows calibration of the depth measurement with respect to sea level variation; and by carrying out specially designed calibration lines made prior to the survey and repeated periodically.

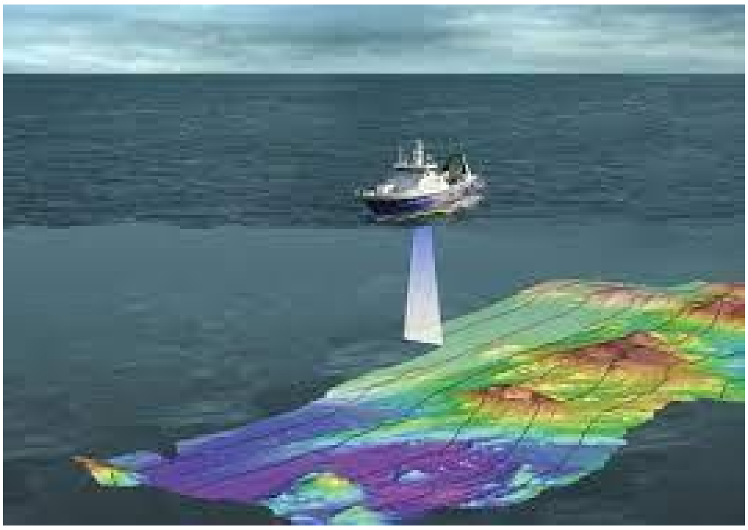

Fig.5: Multi beam echosounder

3.4 The Coralligenous

Coralligenous stands are the main biogenic constructions of the Mediterranean Sea and they are considered indicators of the ecological quality of coastal systems and of “seafloor integrity” by the Marine Strategy Framework Directive. The two main coralligenous morphologies are the cliffs and platforms, the former developing in shallow waters (about 20–50 m) on vertical/subvertical rocky substrate and the latter built over horizontal substrates below 50 m depth also on detritic bottoms.

The coralligenous blocks were formed at the end of the last transgression (about 8,000 years ago), at a time when the sea level was several meters lower than it is today. This explains why the inner mass of coralligenous is now subfossil. Bioconstructing organisms, both animal and plant, produce a calcareous skeleton that remains fixed to the substrate after death. The accumulation of dead skeletons can lead to the formation of a permanent rock structure in which only the outermost layer is alive (Laborel, J., 1987).

The algal element is fundamental to the formation of bioconcretions, but the animal component contributes, in part, to the formation of concretions (bryozoans, serpulids, madreporaria, etc.) and in part to the very breakdown of the coralligenous (porifers, polychaetes, bivalves, etc.) by controlling and contributing to its balance.

Many algal species colonize and characterize coralligenous stands, the most relevant ones for coralligenous development being Corallinaceae and Peyssonneliaceae, which create a secondary concreted substrate for the subsequent establishment of other plant and animal species within the coralligenous (Bianchi, N., Morri C., 2001). The coralligenous physiognomy is often characterized by many animal species, some of which are important for the growth of the bioconcretion itself, since they are fixative organisms, such as porifera, cnidarians and ascidians.

The large gorgonian forests (Fig. 6) are the most representative species of the coralligenous, such as: *Paramuricaea clavata*, *Eunicella cavolinii* and *Eunicella singularis*. These tend to grow perpendicular to the water flow in order to intercept nutrients carried by the currents: the orientation of the fans can thus provide indications of the direction of the prevailing current. The stand is thus formed by a vertical stratification of settled organisms, resulting in significant substrate cover and high biodiversity (Ross, J.H., 1984).

Figura 6: Gorgons (photo by Mario De Luca).

Coralligenous is a mature ecosystem with high biodiversity and characterized by a complex ecological structure (Laubier, L.; 1966). The intensity of substrate colonization is very high, leading to a complex ecological network with intraspecific and interspecific interactions among colonizing organisms. Despite its complexity, the coralligenous system is considered fragile because its persistence is related to the maintenance of particular biotic and abiotic factors (Hong J.S., 1983). Impact of pollution on the benthic community. Environmental impact of the pollution on the benthic corralligenous community in the Gulf of Fos, northwestern Mediterranean. Bulletin of Korean Fishery Society 16: 273-290).

As in other ecosystems, increased turbidity, siltation and sediment deposition can pose threats.

3.5 The Beach rock

Beach rock (Figure 7) can be defined as a paleo-beach, the sediments of which have been preserved on the platform as a result of submergence processes in the cemented state. All authors agree in defining beach rock as a littoral clastic, arenaceous or conglomeratic deposit cemented by calcitic-magnesian or aragonitic carbonates precipitated in the intertidal environment.

Fig. 7: Beach rock

This results in the exclusion of all lithotypes due to supralittoral sediment cementation (colluvial sands, alluvial sands, dunes, etc.) or exclusively biogenic (red algae bioconstruction, coral bioconstruction, etc.). Both the sediment deposition environment and the primary cementation area correspond to the shoreline zone, meaning altitudinally the tidal limits and transversely the limits of maximum breaker expansion. Although Jurassic and Cenozoic beach rocks are known in the literature (Bernier 1984), these deposits are characteristic of subcurrent or recent littoral environments. Particularly represented beach rocks are related to the last sea-level rise.

3.5.1 Geomorphologic features

The sedimentary structures of a beach rock are typical of a littoral environment (such as parallel, wedge-shaped, sigmoidal, and inclined lamination) and are truncated by interlayer erosional surfaces.

Some forms of erosion agree with the pattern of preservation of littoral cords in continental shelves according to the process of Transgressive submergence (Penland et al, 1988), this mechanism involves submarine reworking of the littoral sedimentary body in the absence of cementation to produce the landward displacement of the paleo-beach (Colantoni et al, 1990).

In the case of submergence of a beach rock, the sedimentary complex retains its original position, but is subjected to erosional processes that partially alter its geometric characters; often the stratum surfaces are truncated by a channeled summit erosion surface, testifying to the partial removal of the upper part of the original sedimentary stock. Along the edges, erosion processes follow different patterns: the layered setting exposes to a greater extent to retreat the bank heads along the inner (landward) boundary, while along the outer boundary undermining phenomena at the base, with offshore migration of sediments, cause settlement fractures to which block basculations are related.

The scaling processes may also produce particularly pronounced inclinations of the strata; The original sedimentary body, therefore, may be significantly reduced in both thickness and transverse extension and exhibit a characteristic sub-orthogonal network of fracturing. In some cases, driven erosional processes may alter the original geometry of the beach rock, to the point of evolution into residual plates or disruption of continuity of outcrops.

Dislocations can occur along the main fractures, due to subsidence of underlying compressible sediments; this process can evolve according to a stepped structure leading to a total subsidence of about 10 metri (Orrù & Ulzega, 1987). Often the summit erosion surface masks even important lithological differences.

3.5.2 Cementation modes

Beach rock cementation processes require at least temporary immobilization of a beach sediment body, generally dynamic. Generally, complete fossilization of the beach for long periods does not appear necessary.

These processes develop between the lower and upper limits of the tide, in fact the total power of cemented strata is several meters in areas of high tidal ranges, 4 meters for beach rocks in the Great Barrier Reef of Australia (Davies & Kinsey, 1973), while in microtidal areas such as the Mediterranean the outcrops show modest thicknesses, generally less than a meter (Alexandersson, 1972; El Sayed,1988).

In the Sardinian platform (Figure 8), the power of the deposits averages between 4 and 5 meters (Ulzega et al, 1984) despite being in the microtidal area.

Current beach rock formation is generally restricted to latitudes of 30° north and south, above the latitudinal ranges of living coral formations (Hopley 1982). Precipitation of cements occurs in the vadose/marine/air water table interface zone, with a polyphasic and polymorphic character, and can have a rapid evolution, even on the order of ten years

(Frankel,1968; Alexanderson, 1972; Guo & Friedman, 1990).

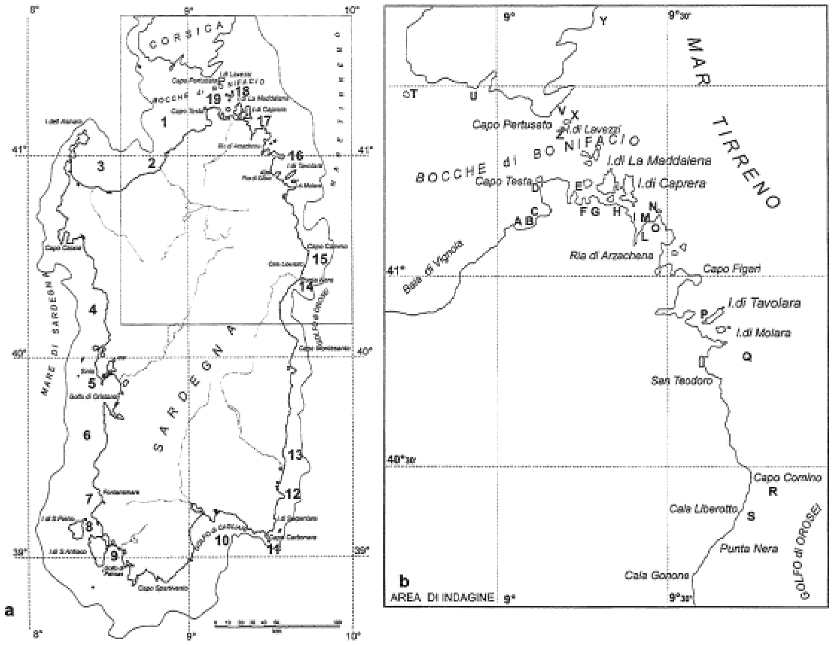

Fig. 5a - Distribuzione degli studi sulle beach-rock nella piattaforma continentale sarda: 1) Fanucci et al., 1974; Ozer et al., 1980; 2) Ozer et al., 1983; 3) Ulzega et al.,1984; 4) Carboni e Lecca, 1993; 5) Forti e Orrù, 1995; 6) Carboni et al., 1989; 7) Ulzega e Orrù, 1984; 8) Orrù e Ulzega, 1989; 9) Segre,1969; 10)Ulzega et al., 1986; 11) Orrù et al., 1994; 12) Ulzega et al., 1984; 13) Lecca et al., 1979; 14) Orrù e Ulzega, 1987; D'Angelo et al., 1996; 15) Ulzega et al., 1980;Grillo et al.,1984; 16) Orrù e Pasquini, 1992; 17) De Muro e Ulzega, 1985; De Muro, 1994; De Muro et al., 1996; 18); De Muro et al., 1996; Cespuglio 1996; Camin,1997 pers.com.; 19) De Muro e Ulzega, 1988; De Muro; 1990; Brambati e De Muro, 1992; De Muro 1994; De Muro et al., 1996.

Distibution of beach-rocks studies in sardinian continental shelf: 1) Fanucci et al., 1974; Ozer et al., 1980; 2) Ozer et al., 1983; 3) Ulzega et al.,1984; 4) Carboni and Lecca, 1993; 5) Forti and Orrù, 1995; 6) Carboni et al., 1989; 7) Ulzega and Orrù, 1984; 8) Orrù and Ulzega, 1989; 9) Segre,1969; 10) Ulzega et al., 1986; 11) Orrù et al., 1994; 12) Ulzega et al., 1984; 13) Lecca et al., 1979; 14) Orrù and Ulzega, 1987; D'Angelo et al., 1996; 15) Ulzega et al., 1980;Grillo et al.,1984; 16) Orrù and Pasquini, 1992; 17) De Muro and Ulzega, 1985; De Muro, 1994; De Muro et al., 1996; 18); De Muro et al., 1996, Cespuglio 1996; Camin, 1997; 19) De Muro and Ulzega, 1988; De Muro; 1990; Brambati and De Muro, 1992; De Muro 1994; De Muro et al., 1996.

Fig. 5b - Distribuzione delle beach-rock in corso di studio avanzato, ubicate nel settore Nord-orientale nella Sardegna e nella Corsica meridionale: A) Baia di Vignola; B) Naracu Nieddu; C) Capo di Monti Russu; D) Capo Testa; E) Isola di Spargi; F) Isola dei Gabbiani; G) Palau; H) Poltu Mannu; I) Barca Brusciata; L) Canniggioni; M) Poltu Cuatu; N) Liscia di Vacca; O) Cala Ghiaia; P) Tavolara; Q) San Teodoro; R) Capo Comino; S) Cala Liberotto; T) Moines; U) Figari; V) Cala Lunga; Z) Lavezzi; X) San Bainzo; Y) Palumbaggia.

Distribution of advanced studies about beach-rocks, located in north-east Sardinia and southern Corsica: A) Baia di Vignola; B) Naracu Nieddu; C) Capo di Monti Russu; D) Capo Testa; E) Isola di Spargi; F) Isola dei Gabbiani; G) Palau; H) Poltu Mannu; I) Barca Brusciata; L) Canniggioni; M) Poltu Cuatu; N) Liscia di Vacca; O) Cala Ghiaia; P) Tavolara; Q) San Teodoro; R) Capo Comino; S) Cala Liberotto; T) Moines; U) Figari; V) Cala Lunga; Z) Lavezzi; X) San Bainzo; Y) Palumbaggia.

Fig.8: Distribution of Beach rock studies in the Sardinian continental shelf

Carbonate cementation in a beach rock (Milliman,1974) generally follows the following steps:

- Concretion of granules by a cryptocrystalline film of calcitic or magnesian calcite composition.
- Second fibrous or acicular generation to magnesian calcite or aragonite
- Micritic or globular biogenic filling, calcite magnesian.

Magnesian calcite occurs predominantly in the Mediterranean Sea.

Recent studies have shown that primary cementation to aragonite (Holail & Rashed, 1992), in fibrous-acicular and cryptocrystalline facies is due to precipitation of seawater carbonates at the interface zone with air within the intergranular pores, where calcitic precipitation related to meteoric waters may occur (Bernier & Dalongeville, 1996).

The shorelines of the Versilian transgression in Sardinia.

Numerous evidences of Holocene marine level stationing are preserved on the Sardinian continental shelf, both in depositional facies, beach rock and relict littoral sediments, and in erosional facies, abrasion surfaces and frames incised in the substrate. Recent bibliography suggests that the whole island during the Holocene had considerable tectonic stability; marine deposits related to the Middle and Upper Pleistocene are maintained at consistent and correlated elevations (Ulzega & Ozer, 1982); this on the one hand may justify the particularly conservative characters of the Sardinian platform with respect to shorelines, and on the other qualifies Sardinia as a key area in the reconstruction of post-glacial sea uplift mechanisms, for the western Mediterranean.

The first shorelines attributed to Versilian transgression were reported for the Italian seas by Segre in 1969, among them the relict littoral cords at -40 meters in the Gulf of Palmas (southwestern Sardinia); later following the discovery of a beach rock at a depth of less than 70 meters in the Bocche di Bonifacio (Fanucci et Al, 1974), a complex system of submerged shorelines at elevations between -55 and -145 meters was detected perfectly preserved along the northeastern Sardinian platform; based on such evidence of deglaciation sea-level changes, the transition between Sardinia and Corsica to the present-day elevation of -75 meters was recognized (Ozer et Al., 1976, Ulzega & Ozer, 1982).

Geophysical survey techniques were fine-tuned (Lecca et Al.,1979), the first mapping experiments were carried out (Carboni et Al., 1979), and the first underwater sampling of a beach rock at Cala Liberotto was performed (Ulzega et Al., 1980).

The extension of geophysical surveys and sampling over the entire platform completed the cognitive picture on the geographic and bathymetric distribution of beach-rock, indicating the eastern platform as more conservative than the western one (Palomba & Ulzega 1984; Grillo et Al., 1984; Carta et Al.,1986); the data complex was represented in the first cartographic-geomorphological synthesis of the entire Sardinian platform (Ulzega,1988).

Depositional complexes of cordon-lagoon characterized by beach-rock were found in the Gulf of Cagliari at -25 and -40 and -55 meters (Ulzega et Al., 1986), in the San Pietro channel at -5 meters (Orrù & Ulzega, 1989); in the northern sector of the Gulf of Orosei at -35, -40 and -55 meters (Orrù & Ulzega, 1987; D'Angelo et al., 1994).

The scarcity of beach rock reports for the bathymetric range between -10 and -30 meters appears to be related, for the seas of Sardinia, to the masking of outcrops by Posidonia oceanica; as part of the investigations aimed at the establishment of Marine Reserves, mapping of seagrass beds has allowed the detection of beach-rock discontinuously outcropping from plant bioconstructions, in Tavolara Bay at -5, -25, -28 meters (Orrù & Ulzega, 1991; Orrù & Pasquini, 1992), in the Capo Carbonara area (Orrù et al. , 1994), in the Sinis Peninsula, Gulf of Oristano (Forti & Orrù, 1995).

On the mechanisms of post-glacial sea-level rise and related interstadials, it has been possible to read the isotopic ratios of Oxygen and Carbon from paleoclimatic and paleoenvironmental perspectives in the beach-rock cements of northeastern Sardinia and southern Corsica. These studies led to the definition of a Holocene sea-rise curve, constructed from beach-rock data only, proposed for the central Tyrrhenian Sea (De Muro et al., 1996).

3.5.3 Indirect survey methods

Shoreline mapping on the continental shelf was mainly carried out on the basis of geophysical surveys: high-frequency echographic surveys (KRUPP-ATLAS DESO 20, 33 Khz and ELAK LAZ 51, 66 Khz) aimed at detailed bathymetric reconstruction; low-frequency echographic surveys (Sub Bottom Profiler EDO 3.5 Khz) allow to highlight, for unconsolidated depositional bodies the geometric characters and facies of sedimentation, thus allowing to resolve the relationships between beach rock and associated paleo-environments (paleo-lagoons, paleo-reefs and fan-deltas).

Side scan sonar surveys (Side Scan Sonar KLEIN 150 Khz) are aimed at outcrop mapping, shape recognition, reconstruction of fracture networks, and planimetric definition of the relationships between different sedimentary facies.

3.5.4 Direct survey methods

For the Sardinian continental shelf, the first experiments in underwater inspection and sampling of a beach rock were carried out using professional divers (Ulzega et Al.,1980); the modest results especially in the reliability of the survey recommended the use of underwater geologists (Orrù & Ulzega, 1986).

The advancement of underwater survey techniques allowed the parallel evolution of detailed geomorphological mapping methods first in the proximal shelf (Orrù & Ulzega, 1984; Demuro & Ulzega, 1985) later extended to the deeper bathymetric belts (Ulzega et Al., 1984; Orrù & Ulzega, 1986; De Muro, 1990).

3.5.5 Analytical Methods

The analytical procedure for beach-rock samples is along two main lines: sedimentological, exoscopic and mineralogical analyses on the clastic fraction; mineralogical and geochemical analyses on cements.

3.5.6 Sediment analyses

Polarized light optical microscope petrographic analyses on thin sections can be used to determine the lithology of the pebbles, the mineralogical composition of the sandy fraction, and the ratio of clastic fraction to carbonate cementation matrix. Scanning electron microscope images can detect on the surface of quartz grains the signs of processing from different environments: infralittoral, intertidal, high beach or aeolian and to highlight phenomena of recrystallization or silica dissolution due to polycyclic processing (Forti & Orrù, 1995).

4 ACTIVITIES CARRIED OUT TO DATE

4.1 Coralligenous banks mapping along the western and northern continental shelf ofSardinia Island

Mapping of coralligenous banks was carried out along the continental shelf of the northern and western margin of Sardinia Island (Italy, western Mediterranean Sea) in the context of the European Marine Strategy Framework Directive (MSFD, 2008/56/EC). Seafloor mapping was carried out through multibeam echosounder surveys and video transects, using a Remote Operating Vehicles (ROV), in areas not formerly explored. A high-resolution digital terrain model of the seabed (DTM) was obtained from multibeam data. A total surface of 436 km^2 of sparse patches of coralligenous banks was mapped in the depth range ~40-160 m. A final map of coralligenous habitat distributions along the western and northern continentalshelf of Sardinia (scale 1:250,000) was produced. The base-map is formed by the shaded DTM of the seabed. Other mapped features include the edge of the continental shelf and the distribution of rocky seabed.

4.1.1 Methods

Multibeam echosounder (MBES) data were collected along the western and northern marginof the Sardinia Island (western Mediterranean Sea), from ~40 m down to ~500 m depth, covering a total area of 9930 km2 (~25,000 km of total line length) (Table 1 and Figure 9).

MBES data were acquired during several oceanographic cruises on the R/V Maria Grazia, R/V Urania and R/V Minerva Uno of the National Research Council. The MBES used were: (i) Kongsberg EM 3002D (293-307 kHz, resolution 1 cm) for shallow areas, and (ii)Kongsberg EM 710 (200 kHz) and Sea Bat Reson 7111 (100 kHz) for deeper ones.

Shallowerdata (ranging from 30 m of depth) were collected along a limited sector facing the Sinis Peninsula (Figure 1) using the Sea Bat Reson 7125 (400 kHz). Multibeam data were processed using the software Caris Hips and Sips, and a Digital Terrain Model (DTM) at 2.5 m cell resolution was obtained for the whole investigated area. Backscatter data were also obtained by the multibeam data (Innangi et al., 2019b). The analysis of seabed morphologycoupled to backscatter data was used for a primary classification of the seabed to discriminate soft vs hard substrates. A detailed analysis of seabed morphological features coupled with terrain analysis of the DTM was performed to identify the areas potentially covered by coralligenous banks. The terrain parameters used for the analysis were slope and roughness and were extracted using the software Quantum-Gis (www.qgis.org). The slope is the angle of inclination to the horizontal for any cell. Roughness is the degree of irregularity of the surface. It is calculated by the largest inter-cell difference of a central pixeland its surrounding cell (https://docs.qgis.org/).

The patches of coralligenous banks were then manually mapped using the software Global Mapper and exported as shapefile areas at 1.25,000 scale. Ground truth data were collected during two oceanographic cruises on the R/V Minerva Uno in 2013 and 2016. Video images of the seabed were recorded by usingthe Remote Operating Vehicle (ROV) Pollux 3, equipped with a high-resolution camera. The ROV was equipped with an acoustic positioning system for geo-localization of the video images. Seabed images were collected in 19 transects, distributed in six sectors at 60-140 m depth. The transects were positioned over the coralligenous patches previously identifiedby the DTM analysis. The correspondence between seabed classification and ground truthdata was tested using 88 snapshots randomly extracted from the video collected along the transects (4–5 images for each transect).

4.1.2 Conclusions

The map of coralligenous banks of the western and northern continental shelf of Sardinia was produced at a 1:250,000 scale. The map contains the digital terrain model of the seabed in the depth range 40-160 m, the position of the continental shelf edge, the polygons enclosing the rocky substate on shelf, and the polygons enclosing the coralligenous banks.The map provides new insights on the coralligenous habitat distribution in the MediterraneanSea revealing its huge extent over the shelf, thus contributing to the knowledge of the habitatdistribution requested by the European Marine Strategy framework directive. The map provides new information on habitat characteristics. Specifically, (i) the maximum depth where the banks were detected was 160 m, that is among the greatest depth recorded for this habitat, and (ii) the coralligenous banks are mostly associated with rocky outcrops related to beach rocks developed in the continental shelf during the post LGM sea level rise.

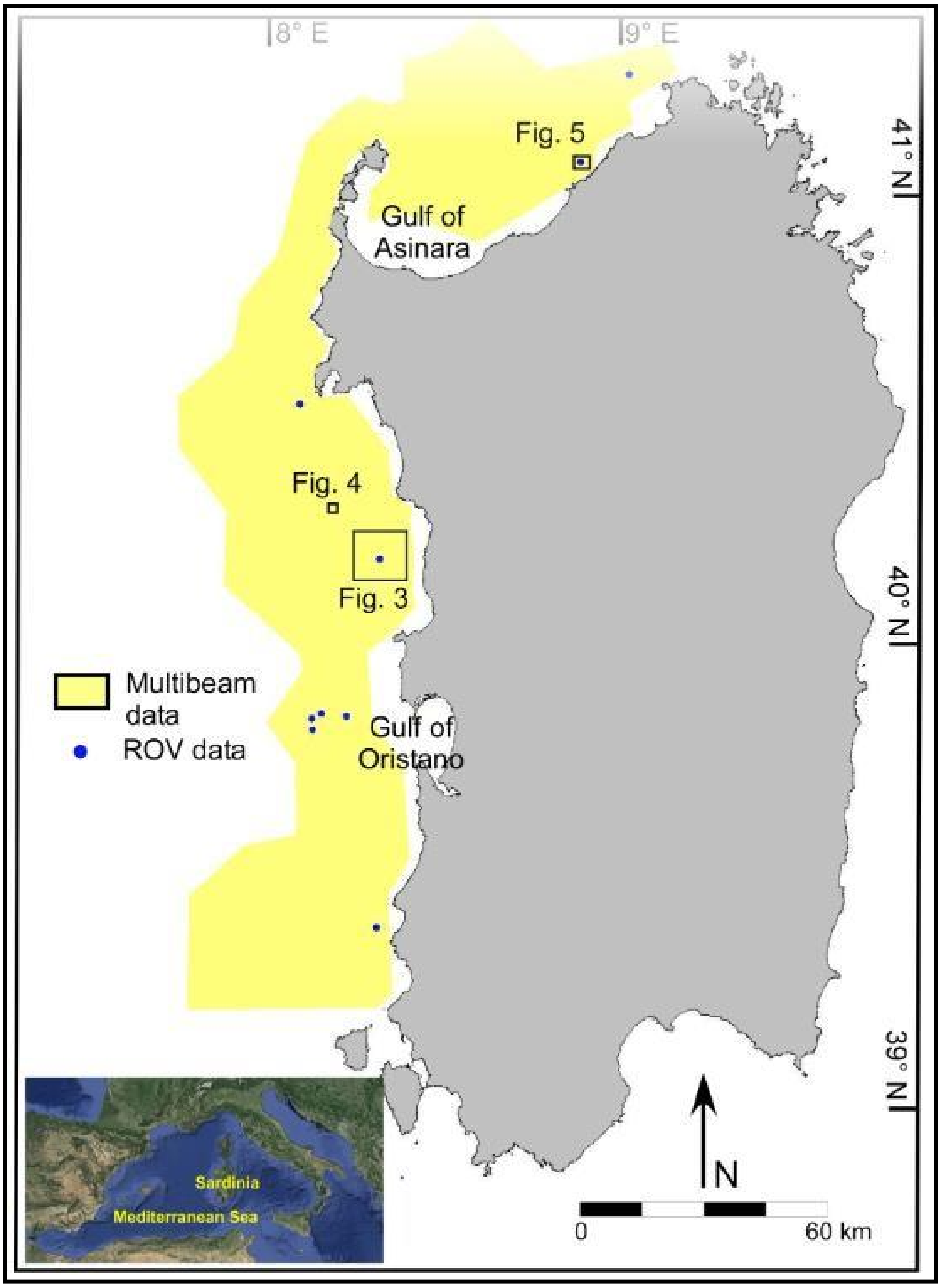

Figure 9. Used data set.

4.2 Sea Floor of the Marine Protected Area of the Asinara Island

The Asinara Island Marine Protected Area (MPA) (Sardinia, Italy) represents one of the mostuncontaminated areas of the Mediterranean Sea and, therefore, but misses of an accuratemapping of the biocenoses and associated lithologies present on the sea floor. The providedmap has highlighted the presence of 21 biocenoses laying on rocky or sandy substrate if shallower or deeper respectively. The most recurring are: the *Posidonia oceanica* L (Delile)and the coralligenous. The good state of conservation the P. oceanica meadow characterizing the eastern part of the island, and the diffuse presence Coralligenous reefs on the western side, are indicative of the well conditions of the marine ecosystem of the Asinara Marine Protect area. Moreover, the Coralligenous reefs developed on beach rockshave allowed defining which was the paleogeography of the Asinara Island during the time interval comprised from 12.9 to 10.0 ka Before Present (BP).

4.2.1 Methods

The sea floor map of the MPA of the Asinara Island was made by the integrated use of SideScan Sonar (SSS), ground truth points acquired with Remote Operating Veichles (ROVs) and direct observation of the shallower part of the MPA. These data have been integrated with Multi Beam (MB) data. SSS and MB data were acquired by Istituto Nazionale di Oceanografia e di Geofisica Sperimentale (OGS) for the Asinara National Park during two campaigns 2015 and 2016 (Romeo et al., 2019). The used SSS is a DF-1000/DCI Digital with a dual frequency of 100 and 500 KHz (EDGE TECH, Massachusetts, USA). The used MB is a Teledyne Reson SeaBat 7125, which operates with a dual-frequency of 200– 400 KHz, and is composed of 512 beams in equidistance or equiangular mode. The survey wasmade with a slate range of 120 m and a line spacing of at least 20%. The SSS and MB were towed with a 15 m longboat (BT 1428 SIRIUS), equipped with a GPS RTK Geodetic System Trimble DSM 232 modular receiver DGPS. Two Remote Operating Vehicles (ROVs)'Velociraptor' (Enne Elettronica, Savona, Italy) and Minirov Mod. DeepTrekker DTG3, wereused during the thesis research to acquire videos and photos of the seafloor features. Bothwere equipped with a high-quality video camera with grand angular lens providing a field view of 80° and with two 50-W halogen spotlights, and with a Tritech MicronNav position System.

Twenty-one ROV transects, at least 1 km long, have been surveyed. From, each of them, nine transects of 200 m in length were subsequently extrapolated (Figure 2(A)). Forany of these, high-definition video and photographic material were processed with the aid ofspecific software: VideoLAN VLC for frame extraction and Seascape for image analysis. The latter is developed specifically for underwater digital photography of benthic community (Teixidó et al., 2011). The used aerial photos are Ortophoto 2008 (Regione Sardegna, RAS)and BaseMap Esri images (Digital Globe) with a resolution of 0.5 m and accuracy of 10.2 (Fig.10). Each data was a layer and GIS tools were used in the production of differentmaps. Side Scan Sonar data were in part reprocessed using the software SeaView Mosaic (Mogasoftware).

The SW provided a high-resolution seafloor acoustic mosaic interpreted using qualitative backscatter values based on different backscatter intensities. The backscatter signal is a function of the topography, in particularly of the seafloor slope, whichinfluences the angle of incidence and the nature of the seafloor, and of the roughness of thematerial. This has allowed us to generate a map based on different acoustic facies. Facies where controlled with video ROV inspections. Inspections have proved that generally fine sediments exhibit lower backscatter, higher is typical of coarse sand and/or rocky substrate, medium/high patchy backscatter identifies the *Posidonia oceanica* meadows. These considerations have allowed us to distinguish biocenoses and abiotic features present on the seafloor.

The acoustic mosaic has higher backscatter intensity corresponding to darker color and lower backscatter intensity the lighters. Multi Beam data were mostly used to define the limits and continuity of the abiotic features. These has allowed us to make paleogeographic considerations of the Asinara Island during the Holocene. The final map was edited at a scale of 1:25,000 interpreting to 0.250 m pixel resolution SSS mosaic integrated with ROV images. Aerial photo interpretation and direct observation of the infralittoral zones were used in the shallower areas. MB data were complimentary used withSSS to obtain a morphological description of the seafloor.

4.2.2 Results

The Marine Protected Area has been ideally subdivided according to its physiography in western and eastern parts. These are also characterized by a different geology, morphology, ecology and main biocenoses. Twenty-one different biocenoses have been mapped on the base of direct observation and photo interpretation the shallower part and their acoustic facies in the deeper.

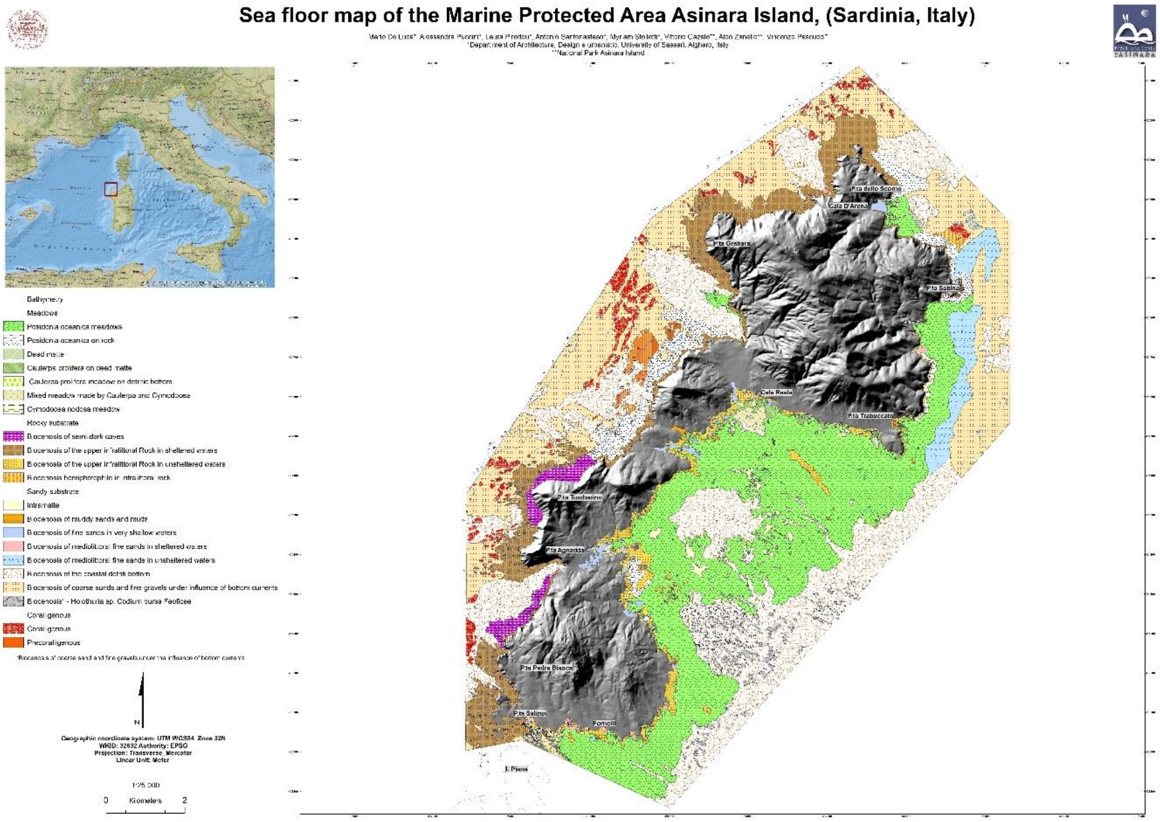

Figure 10. Sea floor map of the Asinara Island. After De Luca et Al. 2020

4.3 Inconsistency in community structure and ecological quality between platform and cliff coralligenous assemblages

Coralligenous reefs are the main biogenic constructions of the Mediterranean Sea and they are considered indicators of the ecological quality of coastal systems and of “seafloor integrity” by the Marine Strategy Framework Directive. The two main coralligenous morphologies are the cliffs and platforms, the former developing in shallow waters (about 20–50 m) on vertical/subvertical rocky substrate and the latter built over horizontal substrates below 50 m depth also on detritic bottoms. The present study aims at assessingwhether patterns of spatial variability and ecological quality of the coralligenous cliff assemblages reflect those of platform assemblages.

At this aim, six geographic areas around Sardinia (western Mediterranean, Italy) were considered and, within each area, thestructure of both the coralligenous cliffs and platforms was investigated by SCUBA and ROV methods, and their ecological quality was assessed by ESCA and CBQI indices, respectively. Overall, 20 morphological groups (seven macroalgae and thirteen invertebrates) were found but differences in community structure were evident both spatially and between systems, platforms vs cliffs. In fact, spatial variability in assemblages structure changed between the two morphologies across the areas. Moreover, a different spatial pattern in the ecological quality was found between platform and cliff assemblages. The results of the present study corroborate the individual peculiarity of coralligenous platformsand cliffs, highlighting the importance of the concurrent assessment of both systems in monitoring programs.

4.3.1 Methods

This study was performed in Sardinia (Italy, Western Mediterranean Sea) where coralligenous platforms develop on a surface of several hundreds of km^2 between 50 and 170 m of depth (De Falco et al., 2022). Six areas (Catalano = CAT, Bosa = BOS, Alghero = ALG, Asinara = ASI, CapoTesta = CTE and Tavolara = TAV) were selected; each of them corresponds to about 25 km of coastline. All areas are characterized by low human pressure (Piazzi et al., 2021a) and only BOS does not include a Marine Protected Area (MPA) in the coastal zone. In each area, both coralligenous platforms (60–110 m of depth) and cliffs (35 m of depth) were sampled.

Figure 11. The six studied ares

The distance from the coast of coralligenous platforms varied between 6 and 12 km. Coralligenous platforms were sampled through Remote Operated Vehicle (ROV) surveys performed between 2014 and 2020. ROVs were equipped with a high-resolution camera and an acoustic positioning system for geo-localization of the video images. The ROV moved along linear tracks, in continuous recording mode, at constant slow speed (<0.3 m s^{-1}) and at a constant height from the bottom (<1.5 m). In each area three sites were randomly selected at a distance from the coast greater than 5 km, and in each site two transects 100 m long were sampled. Within each transect, 10 pictures targeting hard bottom were randomly selected from footages.

The percent cover of all sessile organisms was quantified in each image by superimposing a grid of 100 equal-sized squares (Dethier et al.,1993). Soft bottom zones or portions covered by motile organisms were subtracted from thetotal surface of images while computing the percent cover. Fishing pressure was assessedas percentage of frames presenting fishing gear (longlines, nets, and other lost gear, such as anchors, ropes, moorings, etc.), while fishing impact was estimated as percentage of frames presenting fan coral colonies with necrosis/epibionts and gear covering/entangling coralligenous habitat (Ferrigno et al., 2017). Substrate slope was also estimated for each picture.

Coralligenous cliffs were sampled by SCUBA divers. In each area, three sites several kms apart were chosen. At each site, three plots of about 4 m^2 where randomly selected on a vertical rocky substrate at 35 m depth. In each plot, 10 photographs of 0.2 m^2 areas were taken by a framed camera (Piazzi et al., 2019b). The percentage cover of the main groups was assessed by manual contour technique using the ImageJ software (Cecchi et al., 2014).Groups of species belonging to the same taxon and showing similar morphology were merged into morphological groups (Ferrigno et al., 2017, Appolloni et al., 2020), for both coralligenous platforms and cliffs.

4.3.2 Results

The study highlighted differences in both spatial variability of assemblages and ecological quality between the two systems. Interestingly, the spatial variability in structure of both cliffand platform assemblages did not correspond with spatial patterns of ecological quality. Thisfinding confirms the ability of the two indices to evaluate the ecological quality of the habitat independently from geographical differences in the structure of assemblages, and thus by the dominance of different organisms. This requisite is crucial for indices which are to be employed at large spatial scale. Overall, the results of the present study corroborate the single peculiarity of coralligenous platforms and cliffs, highlighting the importance of the concurrent assessment of both systems in monitoring programs.

4.4 Post-Late Glacial Maximum costal evolution of the north Sardinia

Marine mapping can provide very important information regarding sedimentary bodies deposited as consequence of past sea level changes.

The integrated use of Side Scan Sonar (SSS) Multibeam (MB), ground truth points acquired with Remote Operating Vehicles (ROVs) were indispensable to discover and describe rocks at different depths in different areas of northern Sardinia. In particular, to recognize ridges interpreted as beach rocks. Within this aim, the North Sardinia has been surveyed with the aim to define continuity, nature, and depth of the underwater beach ridges.

We present the seabed map of the Tavolara Island where the presence of beach rocks at depths of -90, -70 and -50 m laying parallel to each other has been recognized. Beach ridges are associated with other geological and morphological features, such as paleo-rivers, paleo-lagoons and paleo-delta systems. This made possible to define which has been the paleogeography of the area surrounding Tavolara Island during the interval comprised between the Late Glacial Maximum (LGM, 20-19,000 y BP) and the Present. The shape of these beach rocks is similar to that described in other parts of Sardinia (Li et al., 2014; De Muro, S., & Orrù, P.E., 1998; De Luca et al., 2022; Mauz et al., 2015). references.

4.4.1 Area of study

Tavolara Island is located of the northeast coast of Sardinia (Italy) (figure 12). It is a Marine Protected Area (MPA) not far from Olbia and near San Teodoro. Forming by a giant rock formation, the Island is easy to spot, and it is the largest island within this area. A limestone massif 6 kilometers long and 1 kilometer wide, with very scenic steep cliffs on all of the eastern coastline. Its highest point is 585 meters above sea level with space of about 5,9 Km^2. The shelf edge is at about -90 m below the present level.

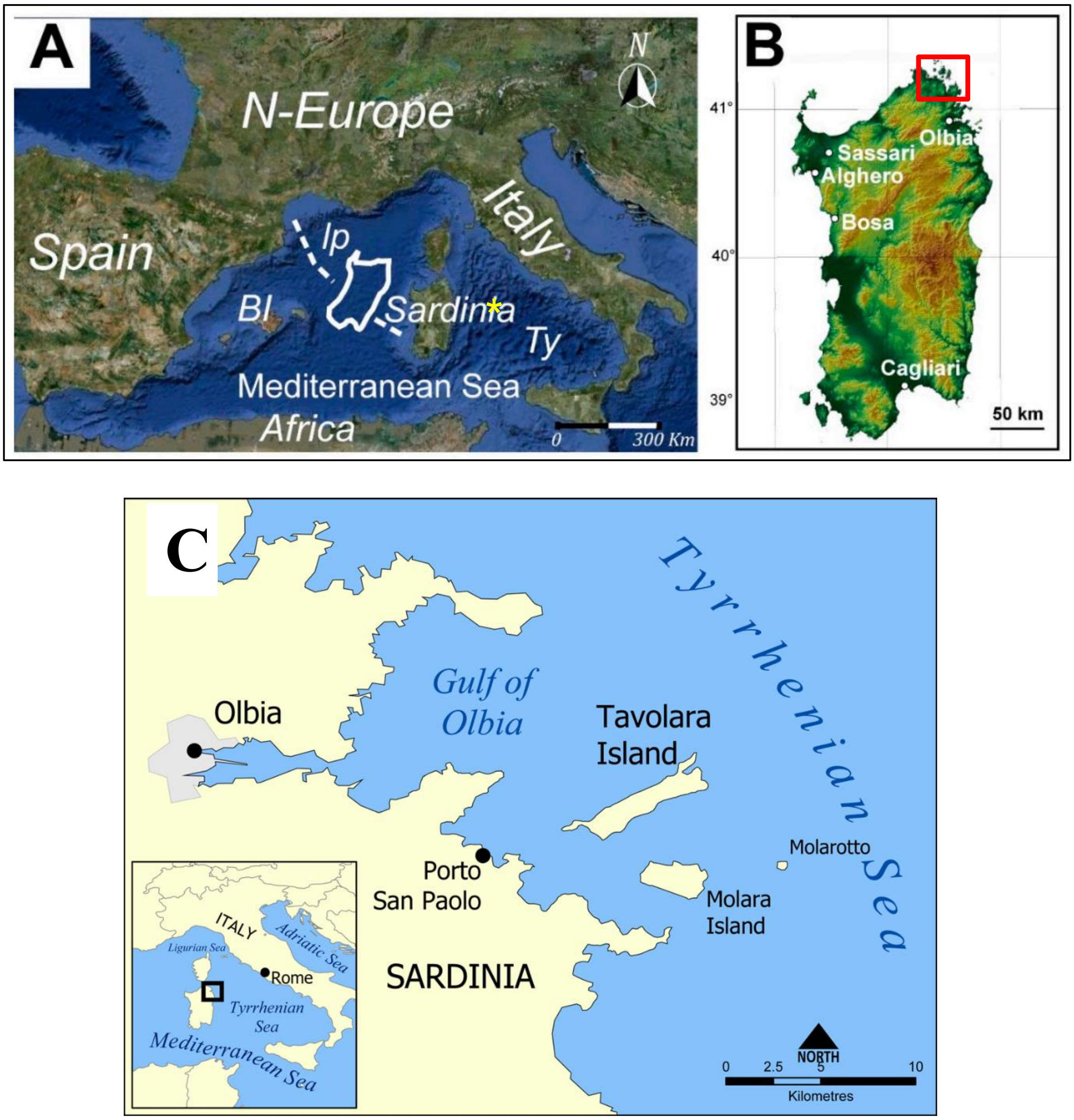

Figure 12: Sardinia. **A)** Satellite view of the Mediterranean region where Sardinia occupies a central position. Dashed line indicates the Sardinia anticlockwise rotation of the island occurred that in the Neogene time; BI = Balearic Islands; lp = Liguro–Provençal Basin; Ty = Tyrrhenian Sea; **B)** Digital elevation model of Sardinia; in the map are reported the main cities. With square is indicated the area close of Tavolara. The image can be freely downloaded at: https:// commo ns.wikimedia.org/wiki/ File: Sardinia_ topo. png# file) (Image details: horizontal resolution = 118.11 dpc, Vertical resolution = 118.11 dpc, File change date and time 11:03, 20 November 2012; **C)** Location of Tavolara Island.

4.4.2 Geological setting

Sardinia is one of the biggest Island of the Mediterranean Sea (Figure 1) and represents a segment of the south-European plate that was separated from the European continent during the early Miocene (Cherchi & Montadert, 1982; Doglioni et al., 1999).

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 (Ghezzo & Orsini, 1982). The Tavalora island, instead is dominated by Mesozoic limestones (Costamagna et al., 2018; Deiana et al., 2019; Bosellini A., 2020).

4.4.3 Methods and data set

The geomorphological map and the cartography of the seafloor of Tavolara Island have been entered into a GIS software (Geographic Information System) database, to facilitate the interpretations and multidisciplinary and multi-scale assessments, in which the distribution of sediments, rocky outcrops, have been re-drawn in order to get information about the paleo-environment and the paleo-dynamics of this area to defined the coastal evolution during most of Holocene and latest Pleistocene.

Obtained results from high-resolution multibeam conducted by the Italian CNR for the MAGIC project (Chiocci et al., 2021).

The resulting bathymetric data and the geomorphological characteristics of the seabed represent an excellent base for the geomorphological and geological classifications of the seabed.

4.4.4 Results

The Sea Floor Map of the Tavolara Marine Protected area highlights diffuse presence of beach rocks forming a sort of lines. *Posidonia oceanica* has been observed and remapped on the base of SSS data were acquired by Environment Ministry (M.A.T.T.M., 1999). In the shallower parts of the area at -90 and -50 beach rocks have been observed on the seafloor forming a sort of lines (beach ridges) (figure 13).

Paleo-deltas systems are distinguished, which consists of a delta front and strand plain with associated paleo shorelines. On the delta plain depressions have been interpreted as a small lagoon formed on the back of beach ridges.

4.4.5 Interpretation

The coralligenous reefs are one of the most important benthic ecosystems in the Mediterranean and their conservation is a major challenge for the conservation and management of nearshore marine systems (Goodwin, 2011; Mumby & Steneck, 2008).

Because these reefs are composed of calcareous organisms, they are sensitive to anthropogenic influences and climate change, which tend to act simultaneously and are therefore particularly threatened on a global scale (Pezzolesi et al., 2017)

Beach rocks have been founded at depth between of −50 and −90 m (Fig.13) and have allowed defining which was the paleogeography of the sea floor in particular close to Tavolara island. They are similar to those described for beach rocks in other parts of Sardinia. These beaches formed during still stands of the post Late Glacial Maximum Sea level rise (Meltwater pulse 1 & 2).

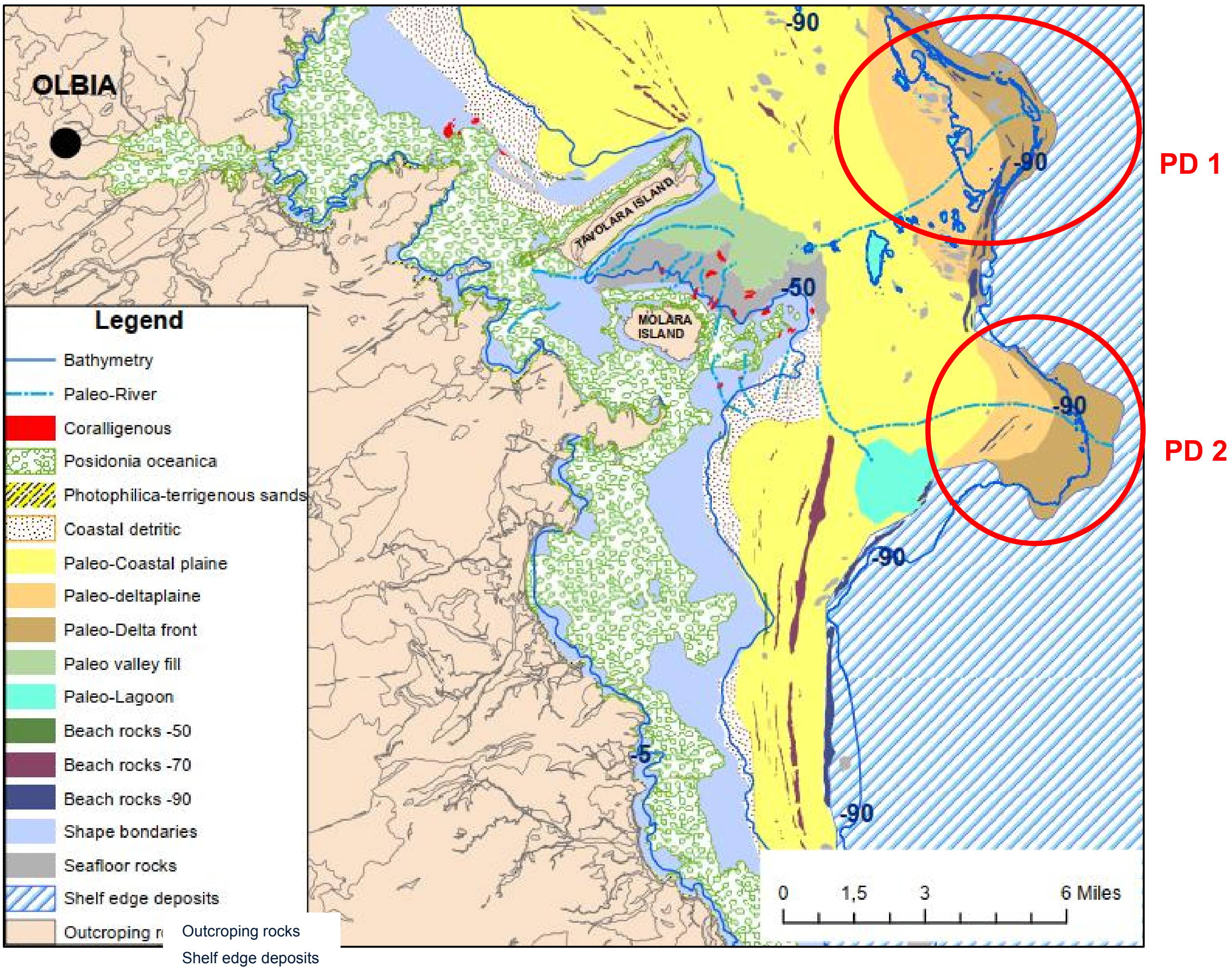

Figure 13: Geomorphological and habitat map of the seafloor area of Tavolara; PD1: Paleo-delta1, PD2: Paleo-delta2.

A several Beach rocks whatever it is the nature of the substratum that supports them (mostly made up by granites). By their presence, they have allowed us to reconstitute paleo-shorelines (figure 14). This feature formed when relative sea levels was -90 to -50 m below the present. In this period most likely the coastal plain was characterized by lagoons fed by rivers and connected to the open sea by relatively deep channels, forming small deltas that form a series of beach systems. This could also explain the abundance of linear rocks located in this area.

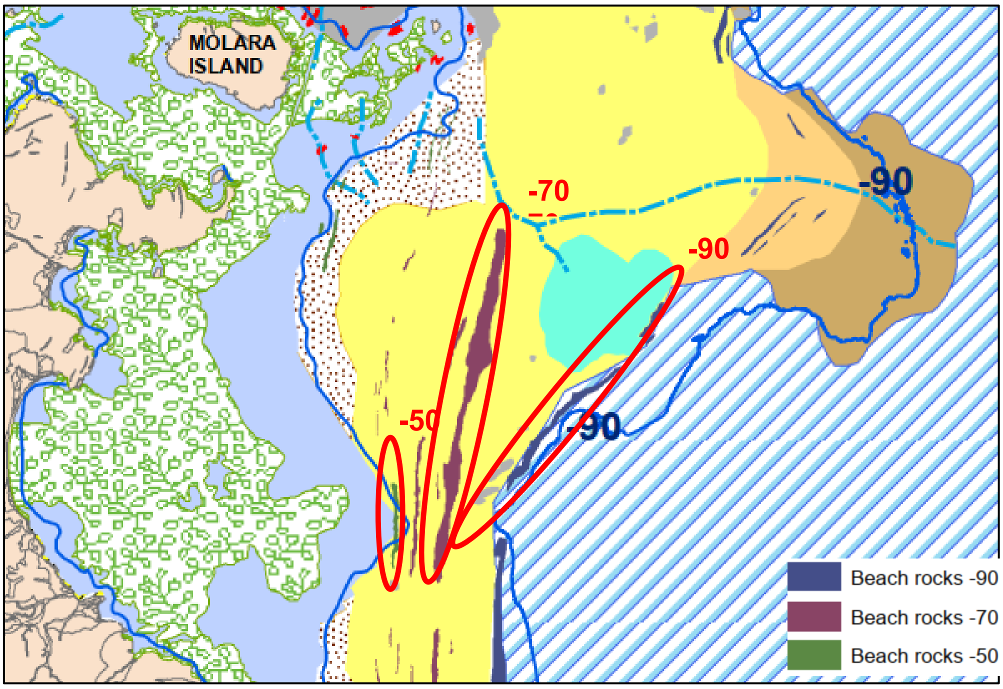

Figure 14: Paleo-shorelines forming at -90, -70 and -50.

At -90-80 that more less associated still stand preceeding the with the Meltwater Pulse 1 (MWP1) and known as oldest dryas or Heinrich event 1 (H1) (Alvarez-Solas et al., 2011).

The H1 cold event was followed by the melting water pulse (WP1A) associated with the warm Bölling-Allerød interstadial (BA) (Su et al., 2016; Naughton et al., 2023).

Beach rocks observed betwwen 50-70 could be related to the Younger Dryas cold event (Bard et al., 2010). Time during which sea level rise decreased. This was followed by a new Meltwater Pulse 2 (MWP2) (Bard et al., 2010) (Fig. 15).

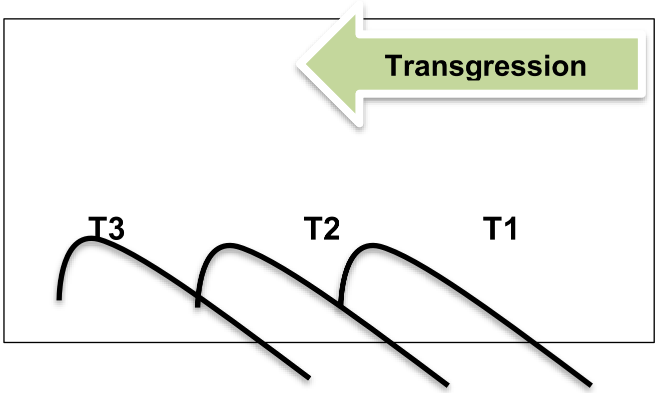

Figure 15: Several Beach rocks of -70 (MWP2).

All those Beach rocks are very close events their deferent time of construction indicates time of reduced sea level rise occurred during the post LGM sea level transgression.

5 DISCUSSION

5.1 Coastal evolution from LGM 10 years to the present:

1. Late Glacial Maximum (LGM) (-20 000 years ago). Sea level was at low stand stage during which delta systems developed at the present shelf egde; that is, at depth of -120-130m

2. Post Last Glacial Maximum (LGM) (-20 000 years ago) sea level rose from -120 to -90 (fig 17).

3. At -90 most probably during the Oldest Dryas-H1 (between -17 000 and -15 000 years ago) sea level rise stopped allowing the formation well developed beach systems. This was followed by the Meltwater pulse 1A (MWP-1A), associated with the Bolling Allerod (BA) interstadial (between -14 690 to -12 890 years ago), and responsible of a new fast sea level rise.(fig.17)

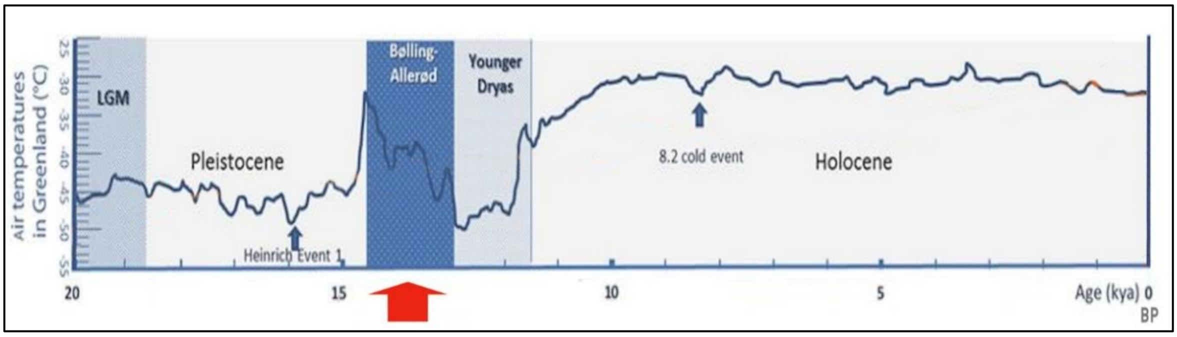

Figure 17: The Bolling – Allerod warming within the Post-Glacial period that followed the Last Glacial Maximum (LGM). Evolution of temperature in the Post-Glacial period according to Greenland ice cores (Li et Al., 2014)

4. A new still stand occurred from 12,9 and 11,6 ka BP. During this time sea level remained between -60 to 40 for about 1500 y allowing the deposition of new beach ridges. The time was not enough to form delta systems (Fig. 17).

5. From 12 000 to 2500 y BP sea level rose continuously but with some pulses during which beach ridges developed.

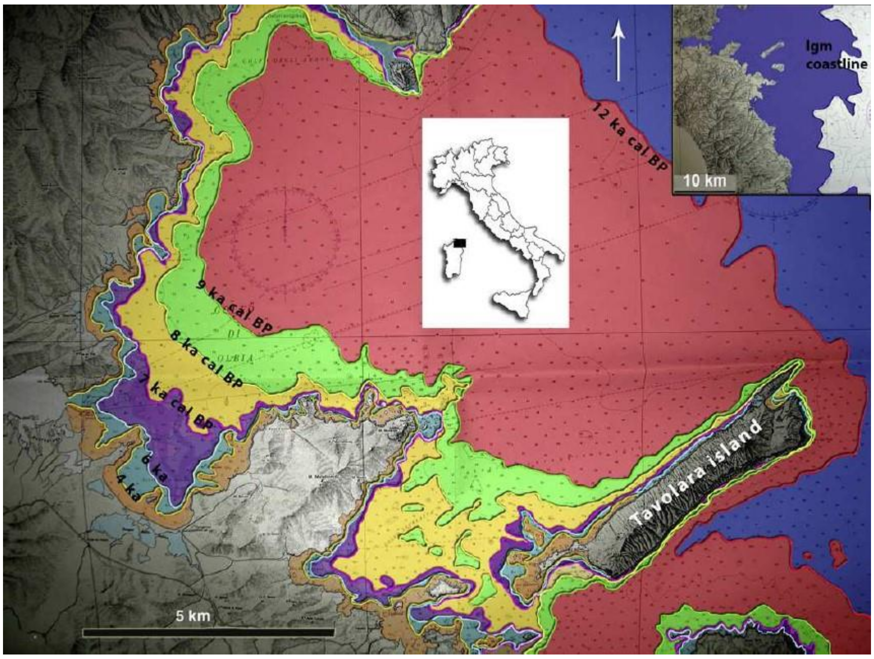

Figure 18: Tavolara coastline during the last 12 000 years ago (Porqueddu, 2024).

6. 9 000 years ago, the coast was located at -24.5 meters. Tavolara forms a pronounced promontory, while to the north there is still a long, flat coastal area that allows access to the NE tip, to the south Tavolara is already sheer to the sea (Fig. 18).

7. 8 000 years ago, the coastline was at -13 meters. Tavolara just "broke away" from Sardinia and became an island. We are just before the Neolithic period; man is able to navigate; 8500 years ago, in fact with a sea level of -15.5 m Tavolara was still joined to Sardinia (Fig.18).

These reconstructions were possible thanks to a model specially calculated for this area of Sardinia in which both the eustatic (ice melting) and isostatic contributions due to the lowering of the coasts by the weight of the sea water column varied by 148 meters from 22000 years ago to the present are considered (Porqueddu et al., 2010).

6 CONCLUSIONS

Basing on the geomorphological study of the seabed and the knowledge of the coastal sector, we claim that the beaches occurring in the Tavolara Island were formed during the sea-level rise subsequent to the Late Glacial Maximum. In particular the about -90 may be associated with relative sea level still stand occurred after the Melting Water Pulse (MWP) 1A (~14,650 y BP), the about -50 may have been formed during the cold Younger Dryas; that is, between 12,900 and 11,700 y BP.

The collected data and obtained insights in these areas of Sardinia will be very important to create a model of sea level rise and still stand occurred post the LGM.

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