University of Cagliari

DOTTORATO DI RICERCA IN SCIENZE DELLA TERRA

Ciclo XXVIII

UPPER SLOPE GEOMORPHOLOGY OF SARDINIAN SOUTHERN CONTINENTAL MARGIN, APPLICATIONS TO HABITAT MAPPING SUPPORTING MARINE STRATEGY

Scientific disciplinary field: GEO/04

Presented by:	Dott. Enrico Maria Paliaga
PhD coordinator:	Prof. Marcello Franceschelli
Tutor:	Prof. Paolo Emanuele Orrù

academic year 2014 - 2015

REGIONE AUTONOMA DELLA SARDEGNA

FSE 2007-2013
POR
SARDEGNA
obiettivo competitività regionale e occupazione

UNIONE EUROPEA
Fondo sociale europeo

Enrico M. Paliaga gratefully acknowledges Sardinia Regional Government for the financial support of his PhD scholarship (P.O.R. Sardegna F.S.E. Operational Programme of the Autonomous Region of Sardinia, European Social Fund 2007–2013—Axis IV Human Resources, Objective l.3, Line of Activity l.3.1.)

Sommario

GEOGRAPHIC LOCALIZATION

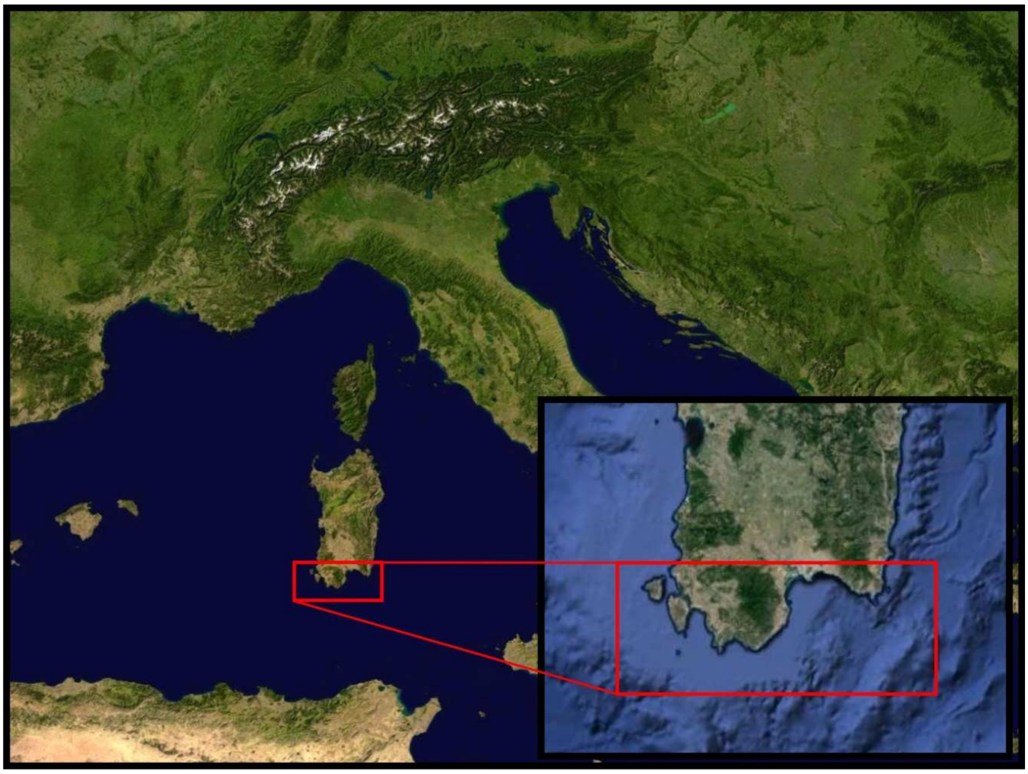


Fig. 1 - Study area localization

Study area is located in the western Mediterranean sea, more particularly includes the areas of the continental shelf and upper slope of southern Sardinia (Fig. 1), located at depths ranging from -40m and -200m, limited onshore to the west from Cape Altano and to the east from Cala Pira.

REGIONAL GEOLOGICAL SETTING

Sardinia is divided into three large geological complex which outcrops for approximately equivalent extensions: the Palaeozoic metamorphic basement, the late Palaeozoic intrusive complex and the late Palaeozoic volcano-sedimentary covers, and in the alternative by granitic rocks and covers not metamorphic. In the study area, given its size, crop up both the Varisican metamorphic and intrusive complex that the Cenozoic volcano-sedimentary covers (Fig. 2).

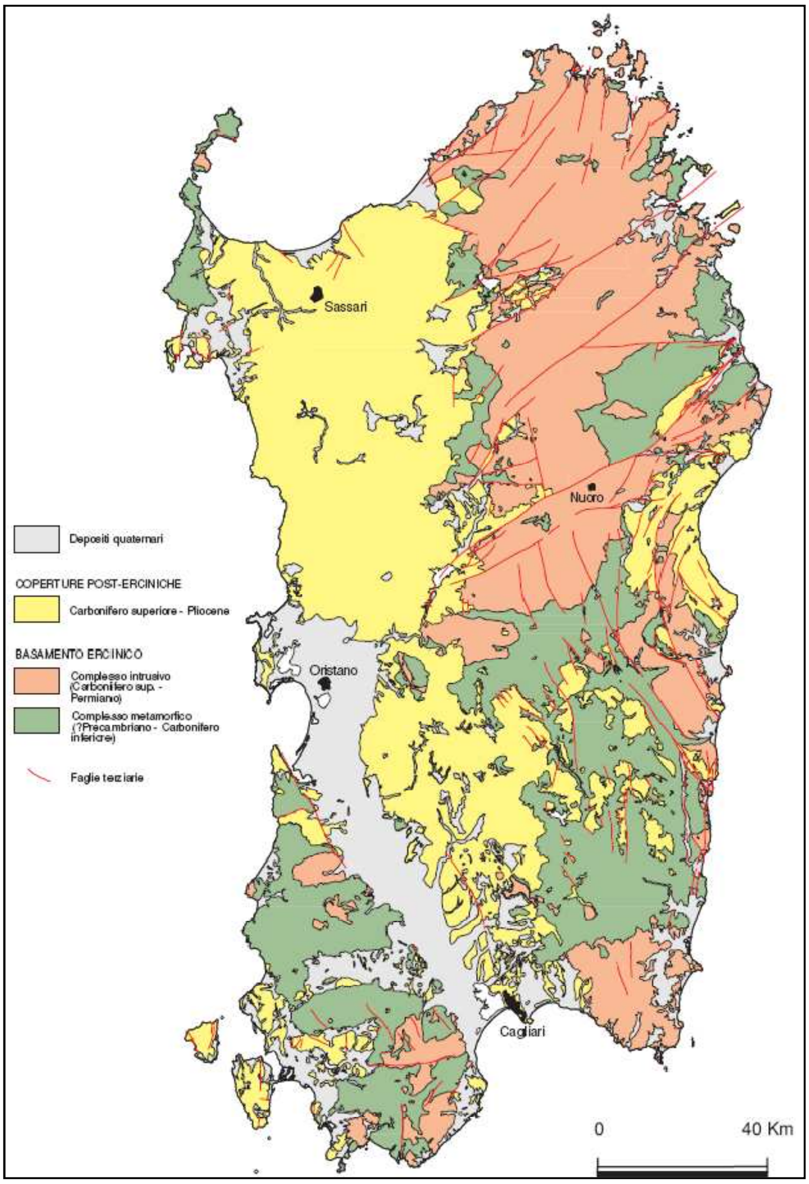


Fig. 2 - Sardinia main geological complex (Carmignani et al. 2001).

In Sardinia are known deformations (Fase Sarda *Auct.*) and sub-alkaline magmatism of eocaledonian age; it is possible that this deformation is not of collisional type, but linked to a tectonic transpressional and / or transtensional who has not developed significant shortening (Barca *et alii*, 1984).

However, the footprint of the basement comes from the Variscan (Hercynian) orogenesis, which produced deformation, metamorphism and an important intrusive and effusive magmatism. The age of the Variscan deformation (Lower Carboniferous) is well defined on both stratigraphic (Cocozza, 1967; Oliver, 1969), that radiometric bases (Di Simplicio et al, 1975; Ferrara et al, 1978). Tectonics characterized by normal and transcurrent faults are associated with the final stages of exhumation of the metamorphic basement and the emplacement of the calc-alkaline batholiths and contemporary Stefanian-Permian deposits. The post-Variscan tectonics has limited effects in Sardinia. Discrepancies are known at various levels of the succession, but until the middle Eocene evolution of Sardinia seems only characterized by slow movements that determine vertical deep transgressions and regressions on the Variscan peneplan. Oligocene Apennine collision reactivates Sardinian Corsican block, with strike-slip faults generally controlled by old Variscan features and especially late-Variscan (Alvarez & Cocozza, 1974). To this tectonics, in Miocene and Pliocene-Pleistocene follows relaxing phases correlated with the opening of the Balearic basin and the southern Tyrrhenian Sea, which are associated with normal faults N-S and NW-SE oriented in eastern and western Sardinia respectively (Carmignani et alii, 1992).

2.1 PALEOZOIC METHAMORFIC BASEMENT

The metamorphic basement of Sardinia (Figure 4) is a segment of the European Variscan chain, separated from Europe only in the early Miocene (Burdigalian). Restoring the Sardinian-Corsican block miocenic pre-drifting position, the fundamental structures of the base of the two islands find their continuation in Provence and Catalonia (Alvarez, 1972; Arthaud & Matte, 1966; 1977; Cherchi & Montadert, 1982; Edel et al. , 1981; Gattacceca et al., 2007; Matte, 2001; Ricci & Sabatini, 1978; Westphal et al., 1976). The various reconstructions of the pre-Mesozoic geometry of this chain (Matte, 1986;) are generally agreed defining a curved orogenic belt that ranges from Spain to the Massif Central in France (Ibero-Armorican arc). The Variscan orogeny affected the entire basement of Sardinia with intense deformation, metamorphism sin-kinematic and a major post-collisional magmatism. The age of the Variscan deformation is well defined on both bases stratigraphic that radiometric because:

a) in the southern areas with low and very low grade metamorphism, terrains from the Cambrian to the Lower Carboniferous (Boat & Oliver, 1991; Maxia, 1983; Oliver, 1969; Spalletta, 1982) are deformed, weakly metamorphosed and unconformably covered by sediments (?) Westphalian Stefanian, not deformed and not affected by regional metamorphism (Cocozza, 1967; Del Rio, 1973; Funds, 1979);
b) in the northern areas the age of isotopic migmatites stripes closure of Gallura is 344 ± 7 Ma and the radiometric age of the metamorphic minerals is between 350 and 284 Ma (Del Moro et al., 1991; Di Vincenzo et al. , 2004; Ferrara et al., 1978);
c) the intrusive complex spread throughout the Island has aged from 311 to 274 Ma (Cocherie, 1978; 1985; Del Moro et al., 1972; Del Moro et al., 1975; Ghezzo & Orsini, 1982; Oggiano et al., 2005).

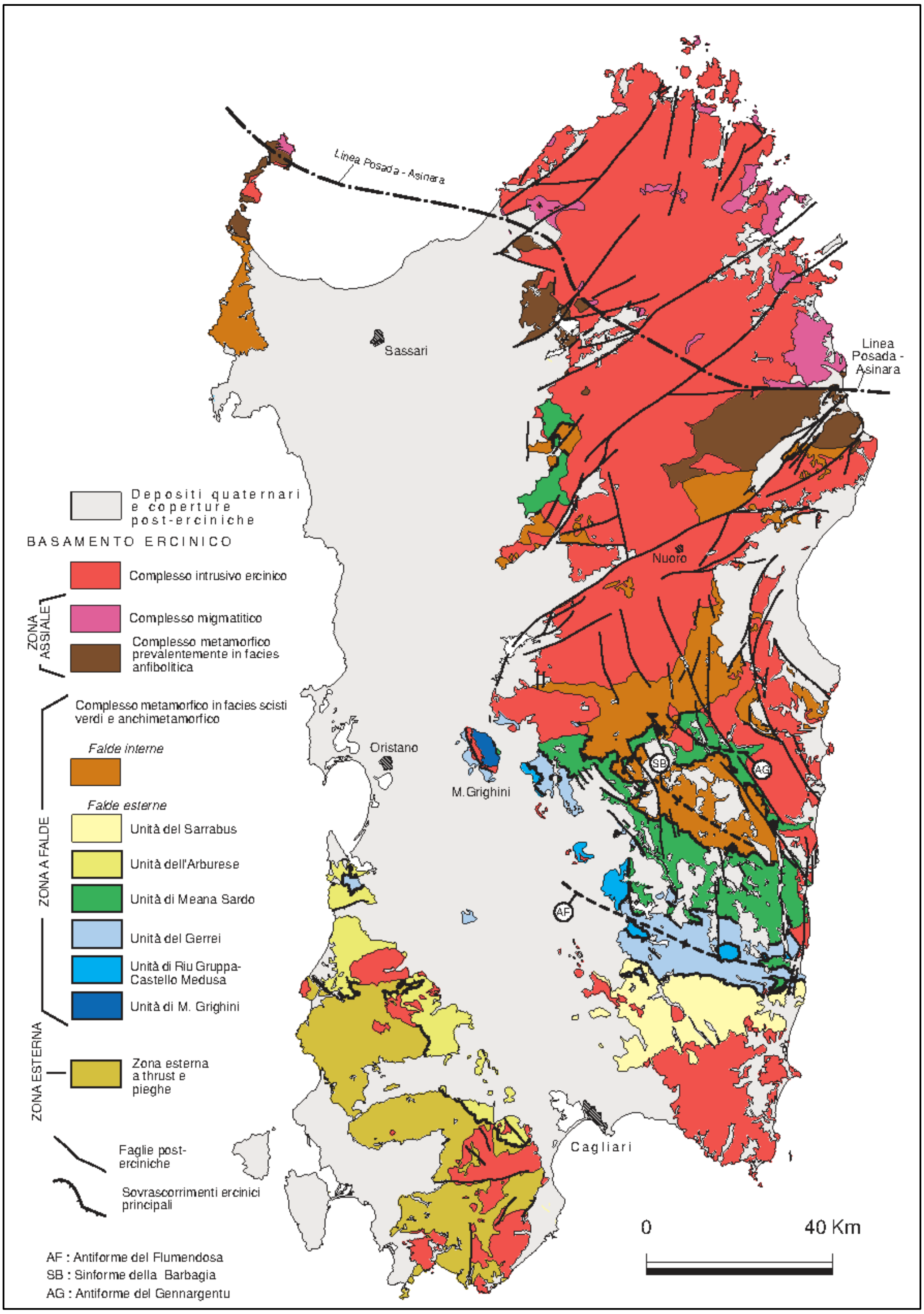


Fig. 3 - Tectonic sketch of the basement (Carmignani et al. 2001).

In Sardinia outcrops a complete section of the Variscan chain: from outer areas that emerge in SW Sardinia, to the inland areas that emerge in the north-east of the island and continue in Corsica. The chain has NW-SE direction and is characterized by shortening and a tettonic-methamorphic zoning typical of continental collision orogeny. The metamorphic polarity varies continuously from SW Sardinia anchizone, the amphibolite facies in the NE of the island (Di Simplicio et al., 1974; Franceschelli et al., 1982), and by an equally sharp change in the structural style (Carmignani et al., 1979; 1982b).

The Sardinian basement is characterized by Variscan nappes converging towards SW ("nappes zone" Carmignani et al., 1987), interposed between the amphibolite facies metamorphic complex, mainly in the north of Sardinia and an outer area with thrust and folds ("outer zone "Carmignani et al., 1987) intensely deformed, but substantially autochthonous, that emerges in the SW part of the island.

The failure to recognize remnants of oceanic crust involved in the orogenesis led for a long time to completely ensialic chain evolution interpretations: reversal zones of continental rifting (Carmignani et al., 1979) or large active transcurrent movements from the Cambrian to the top Carboniferous.

These interpretations were also incurred by the opinion, then widespread, that the European Variscan orogeny was devoid of important " crystalline flapsr" and ophiolitic associations with metamorphism of high pressure, so that the ideas mobilistiche of plate tectonics have been very slow to establish itself. Nearly three decades of research has shown that many characters instead of orogens "alpinotipi" and "ercinotipi" are not as conflicting.

According to Cappelli et al. (1992) and Carmignani et al. (1994b) similar associations at the foot of the internal crystalline Massif Central (Burg & Matte, 1978; Burg et al., 1989), emerge in northern Sardinia along the Posada-Asinara line (Fig. 3), which separates the complex from the Variscan migmatitic Variscan metamorphic complex predominantly in amphibolite facies (both included in the "axial zone" Carmignani et al., 1987).

The Posada-Asinara line is a strongly deformed belt, characterized by the presence of bodies of limited extension of amphibolites with relics of granulite, eclogite paragenesis (Oggiano & Di Pisa, 1992) and the wrecks of mylonitic textures typical of high grade metamorphic conditions (Elter et al., 1990; Carosi & Palmeri, 2002 Franceschelli et al., 2007).

Geochemical and geochronological data that indicate MORB origin and an age of about 950 Ma for protoliths amphibolites with relics eclogitic had suggested in Sardinia (Cappelli et al., 1992) the assumptions made by some authors to the French French variscid:

a) a long-term ocean basin between the plates of Gondwana and Armorica (Perroud & Bonhommet, 1981), a basin that began to open in the Precambrian and was subducted definitely in the Devonian;
b) an oceanic crust obduced during Precambrian or Lower Palaeozoic orogenic cycles n (Bernard-Griffith & Cornichet, 1985; Paquette et al., 1985) and metamorphosed under eclogitic conditions during the Variscan orogeny.

According to Cappelli et al. (1992), in fact, the Posada-Asinara line divides two terrane welded together during the Variscan orogeny and represents a paleo-oceanic suture tectonically transported between a crystalline basement, perhaps Precambrian, constituted by Armorican decompressed crust (represented by the complex migmatitic Variscan), and covers the continental margin of Gondwana, stacked in the pitched chain.

Thus abandoning the completely ensialic evolution interpretation of the chain made in the 70s, Cappelli et al. (1992) propose a hypothesis that provides for the closure of an oceanic basin, as already postulated for other regions from low 80s. In this model the evolution of the Sardinian basement, with its polimethamorfic polideformated chain characters, is reflected in a complete Wilson cycle, from the Cambrian, provides:

a) an expansion of the ocean floor between Gondwana and Armorica passive continental margin (?) Precambrian up to lower Ordovician (Fig. 4);
b) a long period of convergence between Gondwana and Armorica (Fig. 4b), with -type B subduction direct below the margin of Gondwana and witnessed by the spread of volcanic products with chemistry from intermediate to medium-acid of the Ordovician, due to a volcanic arc on continental crust (Andean type) (Fig. 4c); then a subducting oceanic

plate below the Armorican, from the Silurian, while the plate boundary of Gondwana remains passive until the Devonian (Fig. 4d);

c) the Lower Carboniferous continental collision between the margin of the Andean type of Gondwana and the crust of the plaque Armorican, following the closure of the oceans and crustal stacking in different tectonic units (Fig. 4e);

d) gravitational collapse of the orogenic wedge thus realized, with ascent of the deeper metamorphic cores (Fig. 4f) (Carmignani et al., 1994b). Distension is associated to crustal the emplacement of granitoid calcalcalini, who are from the Westphalian simultaneous to the formation of continental basins and late Paleozoic volcanism.

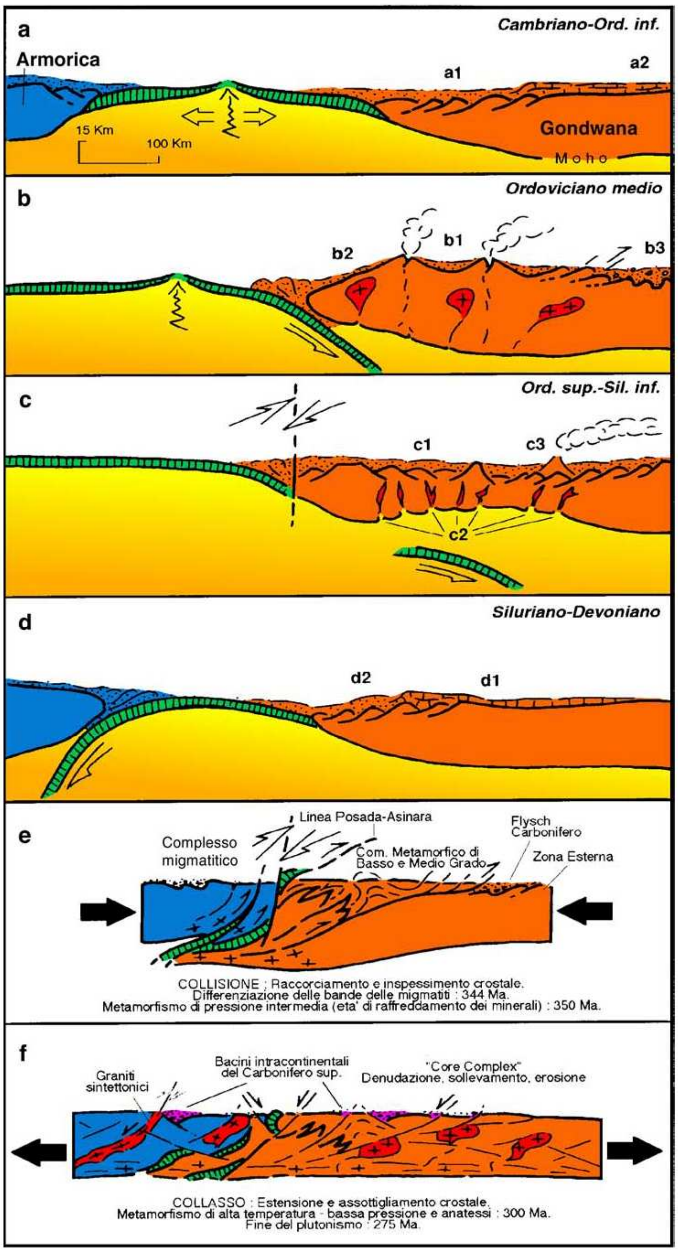


Fig. 4 - Geodynamic evolution scheme of Sardinian Variscan Basement: (a) Cambrian- lower Ordovician; (b) average Ordovician; (c) Upper Ordovician - Lower Silurian; (d) Silurian-Devonian; (e) lower Carboniferous; (f) Upper Carboniferous - Permian (from Carmignani et al., 2001).

This model, still relevant today as it provides closure of oceanic space between the northern edge of Gondwana and Armorica or Armorica Terrane Assemblage, or Hun Superterrane (Franke, 2000; von Raumer et al., 2003), should be updated with U / Pb geochronological data meanwhile produced in Sardinia, Corsica and Mauri. In these areas, attributable to the same sector of the chain, the age of the oceanic protoliths are generally Ordovician and those of their Silurian Devonian eclogitic metamorphism (Cortesogno et al., 2004; Palmeri et al., 2004). Recent works tend to exclude Posada-Asinara line identification with a suture zone, interpreting it as a brittle-ductile shear zone late-Varisic.

2.2MESOZOIC AND PALAEOGENE COVERS

Ceased orogenic movements, during Mesozoic, Sardinia enjoys a relative tectonic quiet and an almost total absence of magmatic activity. In this era the island was therefore not affected by major deformation phases (Barca et al, 2005). Throughout the Triassic and Lias Sardinia constituted a largely emerged structural high that in the Alpine paleogeography probably represented a part of the Brianzonese Dominion (Barberi & Cherchi, 1981).

This high structure was widely transgressed only from the Dogger, whose dolomitic and neritic environment limestone deposits covers unconformably both the Hercynian basement, than the continental Stefanian-Permian or Permotriassic succession (Barca et al, 2005).

This transgression interests first western Sardinian sector (Muschelkalk of Nurra and Sulcis) and later extends to the east (Gulf of Orosei Dogger). Only in the Middle Jurassic marine conditions prevailed throughout the region. In the central part of the island, carbonate covers lies flat on the Paleozoic basement, often separated by a basal quartzitic conglomerate (Barca et al, 2005).

2.3 OLIGO-MIOCENE TECTONICS

During the Tertiary, between late Oligocene and middle Burdigalian there has been a sequence of critical tectonic events for the geodynamic context of the Mediterranean region and Sardinia in particular. The western Mediterranean area in this period is characterized by extensional tectonics, interpreted as a response to compressive phenomena on the Alpine front. So that form several micro-continents, such as the Balearic Islands or the Corsica-Sardinia block, which is separate from the European continent and begin their drift towards the south-east, leaving portions of the continental crust thinned or small ocean basins (Carmignani et al, 2001).

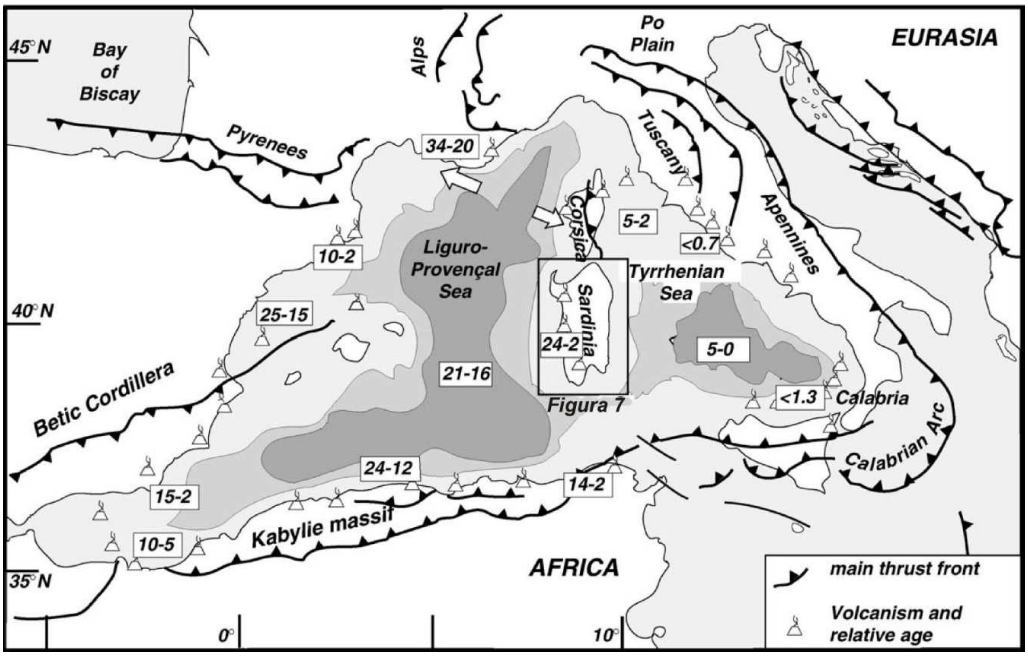


Fig. 5 - Western Mediterranean chart showing volcanism and kinematics derived from deformational analysis, upper Oligocene to the present. Numbers describe the age of beginning and end of Liguro Provencal basin extension (Oligocene-Burdigalian) and Central - Southern Tyrrhenian (Tortonian-present). Note the magmatism eastward gradual rejuvenation, resulting in an eastward migration of compressional and extensional phenomena. Sardinia being in intermediate position, between the two basins, recorded Oligo-Miocene calc-alkaline volcanism, related to the opening of the Liguro-Provencal basin and anorogenic volcanism connected with the opening of the southern Tyrrhenian Sea (from Faccena C. et al, 2002).

During the Tertiary period, between late Oligocene and middle Burdigalian there has been a sequence of tectonic events critical to the geodynamic context of the Mediterranean basin and Sardinia in particular. The Mediterranean basin in this period is characterized by extensional tectonics, interpreted as a response to compressive phenomena on the Alpine front. So several micro-continents were formed, such as the Balearic Islands or the Corsica-Sardinia block, which is separate from the European continent and begin his drift towards the south-east, leaving portions of the continental crust thinned or small ocean basins (Carmignani *et alii*, 2001).

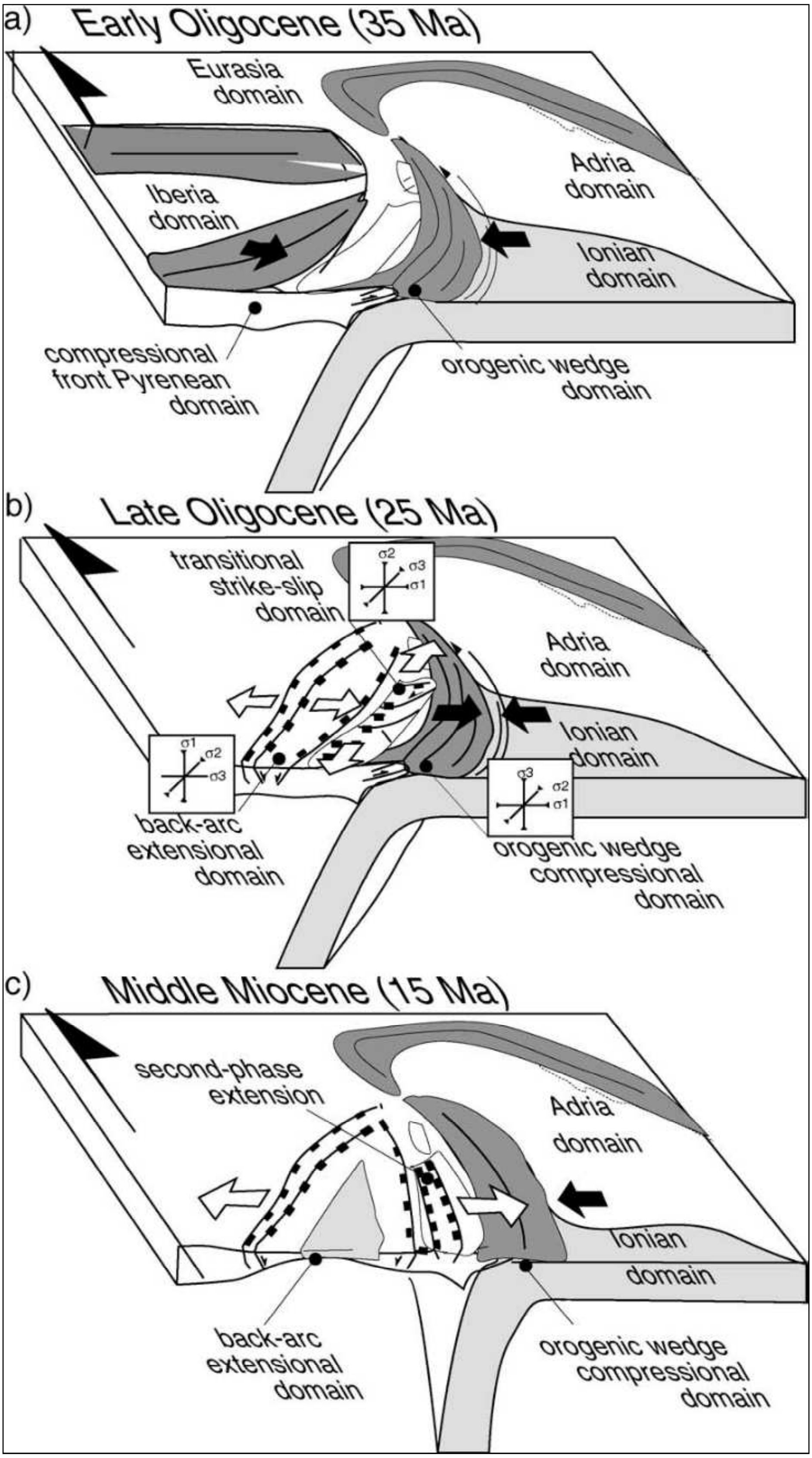


Fig. 6 - Schematic block-diagrams showing the tectonic setting of the western and central Mediterranean in three stages from 35 to 15 Ma (from Facenna et al, 2002).

In a 1,5Ma period there was the separation of the continental Sardinian-Corsican microplate from the European continent and the simultaneous opening of the back-arc basin of the western Mediterranean. This tectonic phase has been related with the orogeny of the Northern Apennines and the Sicilian Maghreb chain (Rims & Montardert, 1982; Sowerbutts A., 2000; Sau et al, 2005; Casula et al, 2001).The subduction of the neotetid oceanic plate under the european continental plate, together with the convergence between Africa and Europe, produced an extensive calc-alkaline volcanism (Fig. 6).

The study of the syn-rift sediments in the Gulf of Lion and in the Ligurian Basin shows that the rifting phase occurred between 30 and 21 Ma, which was followed by a translation with counterclockwise rotation of at least 30 °, in a time interval from 21 to 16 Ma, with center of rotation on the current Gulf of Genoa.Recent paleomagnetic studies, show a rotation of the Sardinia and Corsica block, since upper Oligocene, of 45-55 degrees (Sowerbutts A., 2000). This was followed by a post-rift phase characterized by a general transgression, subsidence and basins filling, pursued until late Miocene. These events are the main cause of the current structure of the continental shelf and the structure of the Sulcis continental margin (Lecca, 2000 and references therein). The current structure of the continental margin of Sulcis is to be linked with the structuring of the Continental Margin of Sardinia Western (Lecca, 2000).

2.3.1 Sardinian Rift Setting

The structure of the Sardinian rift does not qualify as a unit but is divided into different basins of half-graben involving a system of blocks and tiltati horst. On a smaller scale, the relative movements between the tectonic blocks that make up the Sardinia, have reactivated the fault systems of the late Hercynian basement of Sardinia, which is already reactivated during the Mesozoic and Paleogene. (Sau et al, 2005).

The subsequent evolution of the entire Rift Sardo (Cherchi & Montadert, 1982), follows a propagation strain from south to north, thanks to a strike-slip fault system from simple to transtensive until extensional, which gave rise to a regional system of tectonic blocks separated by depressions branched, according to regional tectonic, oriented roughly NW-SE and NE-SW, within which was possible to establish that a sedimentation from continental has assumed marine characters (Casula et al, 2001). The evolution of the Mediterranean Geodynamic reactivated in several stages the initial structure of the rift in the upper Oligocene, with different characteristics between the central-southern and northern Sardinia due to different sub-regional and local conditions (Casula et alii, 2001). The differences among the various basins rift of northern and central-southern persist until the onset of a general marine sedimentation, which peaked in upper Burdigalian the prevalence of extensional movements (Cherchi, 1985; Assorgia et al, 1995; et Lecca et al., 1997).The rift heterochrony is attested by biostratigraphic data; starts first in southern Sardinia (Cherchi & Montadert, 1982), where is located the study area, while in northern Sardinia, despite oldest products of andesitic volcanism are documented, the transgression is more recent.

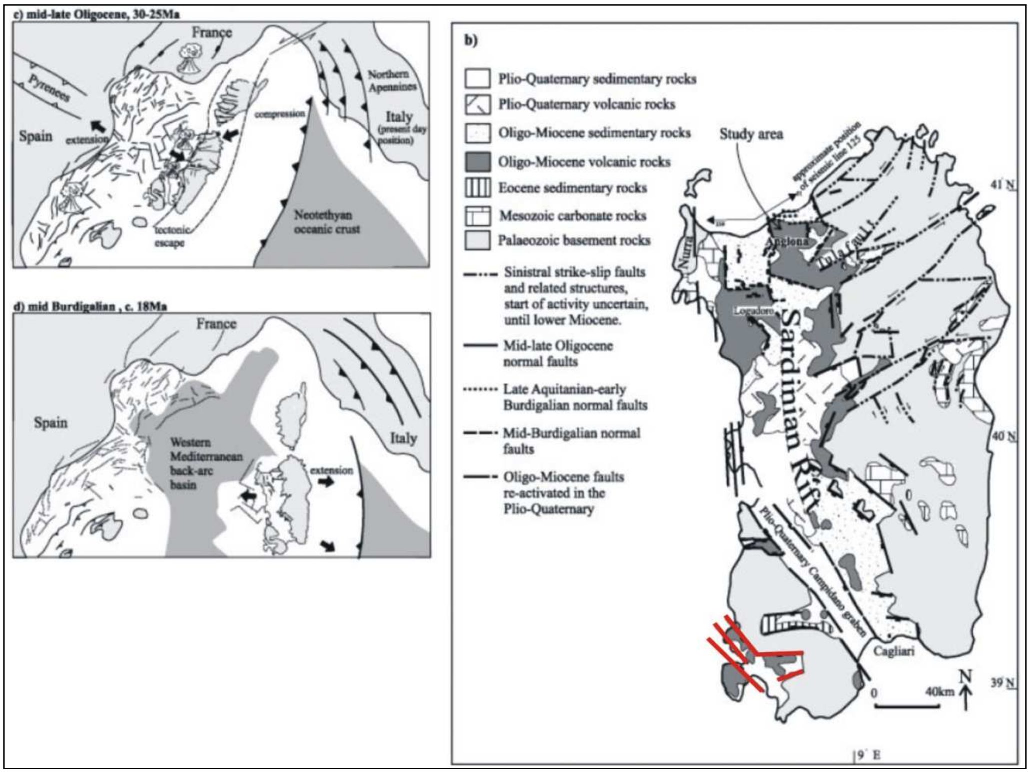


Fig. 7 - b) Simplified Sardinia geological scheme with the location and age of the main structures activated during the formation of the sub-basins of the Oligo-Miocene rift. South-western Sardinia structures have been highlighted in red. c) reconstruction of the early-stage paleogeography, mid-upper Oligocene, 30-25 Ma. d) final stage of rifting middel, Burdigalian, 18 Ma (modified from Sowerbutts, 2000, taken from Cherchi & Montardet 1982 Assorgia et al 1995 Roca & Desegaulx 1992 Millard & Mauffret 1993).

2.4 Upper Miocene – Pliocene

In the middle Miocene NNE-SSW oriented faults were reactivated in conjunction with the opening of the northern Tyrrhenian basin. The beginning of this process is likely, before the middle Miocene, perhaps 18 Ma (Sau et al 2005 Lick et al 1997), however, the phase of maximum extensional activity was reached in late Tortonian. After major geodynamic evolution phases of the Mediterranean and the Sardinian rift, several recent episodes have affected the filling of basins formed before and erosion of adjacent emerged areas (Lecca et al., 1997). The outcrop of Miocene sedimentary cover in Sardinia is limited, due to intensive erosion during Messinian and middle-upper Pliocene regressions (Marini & Murru, 1983). In addition, the discrepancy between transgressive Pliocene on Messinian substrate demonstrates the existence of a late Miocene compressive phase which created major distortions detectable, however, only in southern Sardinia (Carmignani et al, 2001). In the period between the Tortonian and Pliocene, at the regional scale, we observe the partial reactivation of the faults of the rift with two distinct behaviors between south-central Sardinia and northern Sardinia.

The formation in central-southern Sardinia, during upper-middle Pliocene, of the Campidano Graben is related to the extension towards S-E of the coeval extensive tectonic of southern Tyrrhenian. The structures of this phase will overlap with NNW-SSE orientation on the N-S Oligo-Miocene rift; Campidano low, that was forming, was filled with several hundred meters of syntectonic deposits, produced from horst’s erosion consisting of oligo-Miocene sedimentary rocks and the Hercynian basement. Subsidence connected with the Campidano graben probably continued up to the present in the offshore of Cagliari and Oristano Gulfs. Almost simultaneously, in central Sardinia and on the east coast, begins an anorogenetic volcanism without further subsidence (Sau et al, 2005). The new volcanic cycle starts in the Messinian (5.2-5 Ma; Assorgia et al 1976), mainly develops during Pliocene and continued until the Pleistocene (0.14 Ma). This volcanism, was in connection with the extension of the Tyrrhenian basin. In western central Sardinia and eastern Europe, can observed the tabular reliefs, the top of which is protected by Pliocene-Pleistocene basaltic flows, called "Giare". The fluid lava occupied depressions preserving them upon cooling; the current topographic position can be justified with the inverse relief process accompanied by up-lift phenomena that accelerated demolition processes against the slopes of the paleo-valleys, while preserving the valley talweg protected by the lava spread.

2.5 Pleistocene

Pleistocene is characterized globally by phases of expansion and reduction of the ice sheets and associated high frequency eustatic variations. It can be divided according to the "curve of the global variation of stable isotopes of oxygen" based on the isotopic ratio of O^{16}/O^{18} oxygen content in the carbonate shells of ocean foraminifera (Shackleton et al 1973, 1983; Bard et al 1990). Intervals of temperature rise of the oceanic water surface and reduction of glacial extention (and the resulting mean sea level) are represented by positive peaks in the curve and odd numbered. Among these the most important and representative Sardinia is the isotopic stage (positive peak) MIS 5 (127,000 to 70,000 years) with a maximum interglacial 5e, corresponding to the Euthyrrenian and two secondary peaks 5c and 5a, separated by minors cold peaks. Even isotopic stages (maximum negative of isotope O^{16} / O^{18} curve) are cold oscillations; the latest and most important is represented from the MIS 2 (29,000 to 11,000 years), associated with the glacial Würm.

Transgressions have left their mark primarily on the continental shelf and in the vicinity of its edge. During the Würmian ice age occurred the Pleistocene largest regressive event, with traces of deposits and littoral forms to about 130 meters below the current sea level, as observed on the edge of Sardinia western shelf (Ulzega et al 1979) this level is dated about 18,000 years BP. Among the depths 0 and -130 meters have been highlighted various shore lines (Fig. 11), the dating of which is made in reference to the similar Mediterranean and by comparison with the levels of the eustatic curves calibrated in stable areas (Bard et alii 1990).

Numerous studies documenting evidence of transgression both on land and on the continental shelf (oceanographic cruises between 1974 and 1980) where was detected various shorelines (beach rocks) between 0 and -150 meters (Ulzega & Hearty, 1986). Although was not made any absolute dating, through correlations with other shorelines in the Mediterranean, can be reported, for example, the shore line - 100 m (well preserved in Sardinia) to 15,000 years B.P.

2.6 Holocene

In agreement with what emerges from the numerous eustatic rise curves, sea level start to rise 15/18 Ka (Bard et alii, 1990) in a continuous manner, up to about 10/12 Ka when it undergoes a stasis in which beach-rock of -35 / -45 meters below actual sea level have been reported (De Orrù & Wall, 1998). This period is documented by several authors as a new cold phase called Yunger Dryass.Thereafter, the level of the sea resume to rise a continuous manner up to 8 Ka BP where there was a decrease of speed; from that moment the ascent continues up to the present in an asymptotic. On the Sardinian continental shelf are preserved extensive evidence of the Holocene sea level stationing both in depositional facies, beach rock and relict littoral sediments, than erosive facies, abrasion surfaces and frames etched into the substrate (Orrù & De Muro, 1998). Recent bibliography shows that during the Holocene, the whole island had a considerable tectonic stability (Lambeck et al, 2004; Antonioli et al, 2007; Alessio et al 1994); marine deposits related to the Middle and Upper Pleistocene remain at consistent and linkable (Ulzega & Ozer, 1982) except for a few rare sites where were observed mild vertical block movement (Carobene, 1982); one hand can justify the particularly conservative characters of Sardinian shelf in respect to shorelines, on the other side qualifies Sardinia as a key area in the reconstruction of the lifts mechanisms the post-glacial sea, for the Western Mediterranean sea (De Muro & Orrù, 1998).

GEODYNAMIC CONTEXT

Central - Western Mediterranean sea is floored by several sub-basins (Alboran, Valencia, Provencal, Algerian and Tyrrhenian basins), which substantially develops during the last 30-40 Ma. This area is geologically younger than eastern Mediterranean, which is probably floored by Mesozoic oceanic crust with a thick sedimentary cover, or with thinned continental crust (Robertson e Dixon, 1984).

Central-western Mediterranean basins became younger moving from the west towards the east (Fig. 8). The geologic evolution of this area is related with relative movements of three main plates (Africa, Adria and Europe, Fig.)plus an unspecified number of small continental terranes, oceanic or transitional basins. Paradoxically, the development of many basins occurred in a relative convergent context between Africa and Europe.

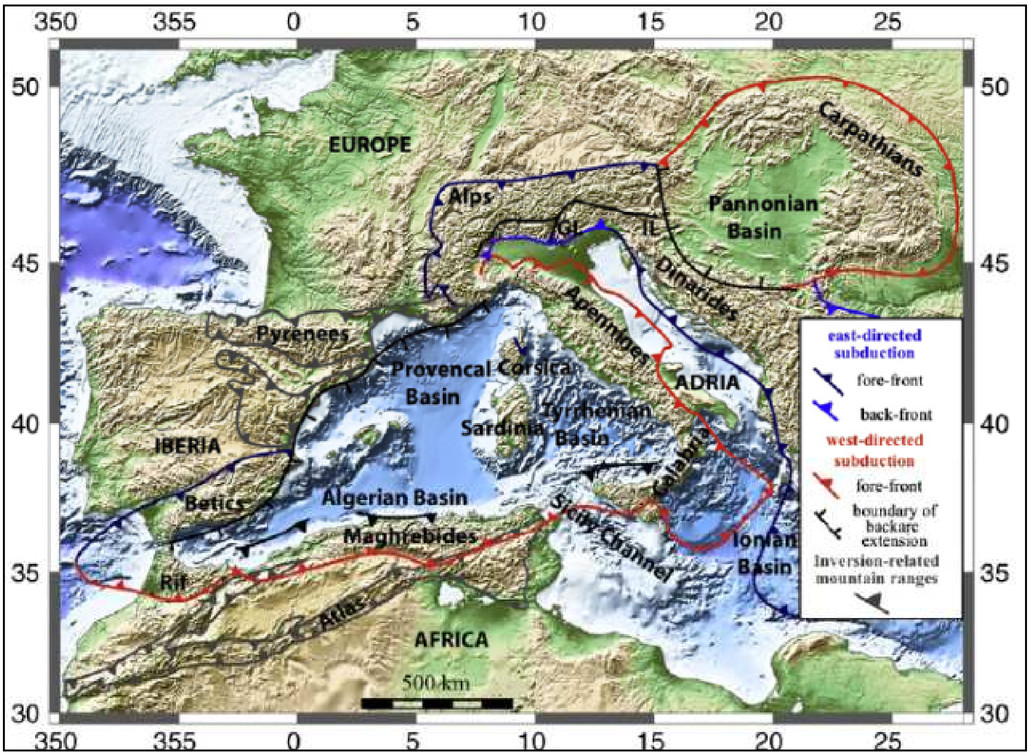


Fig. 8 - Simplified geodynamic scenario of central-western Mediterranean sea overlaid to topography and bathymetry (E. Carminati et al.,2012).

The maximum amount of relative North-South / Africa–Europe movement at Tunisia longitude was of 135Km in the last 23Ma, namely more than five times shorter than the entire Apennines' arc which moved towards east more than 700Km in the last 23Ma. For this reason we assume that the migration towards east of the Maghreb - Apennine's arc is not a consequence of the relative N-S/Africa-Europe convergence, but rather a consequence of Apennine-Maghreb rollback subduction (Carminati et al., 2012).

CENTRAL-WESTERN MEDITERRANEAN SEA FORMATION.

The beginning of the Apennine-Maghreb subduction direct towards the west is not know in his details, many hypothesis vary from late Cretaceous (~ 80 Ma) to lower Oligocene (~ 33 Ma;. Lustrino et al, 2009 and references).

The fast radial roll-back of Adriatic plate along the northern sector of subducing Apennine-Maghreb plate and the asthenospheric lifts are responsible for high heat flows value (> 100 mW / m2) observed in central Mediterranean (Zito et al., 2003).

Central- western Mediterranean is constituted by a series of V-shaped sub-basins, developed from Oligocene than in the extension back-ark context contemporary to the roll-back of the Maghreb - Apennine's subduction zone (Auzende et al, 1973;. Carminati et al, 1998a, 1998b, 2010).

The discontinuous thinning process increases towards east, south-east and south from a central zone located along actual Provencal coast (Southern France), bringing to relevant thickness side variations. The insulation of the ribbons, during the migration from the east to the south of Maghreb - Apennine's thrust front, indicates discontinuous extensional processes in back-arc area.

From Langhian onwards active extension moves from west to east of Corsica and Sardinia, and leads to the structuring of the actual Tyrrhenian basin (Sartori et al, 2001;. Trincardi e Zitellini, 1987).

Sardinia-Corsica continental block is the largest lithospheric strip of central-western Mediterranean. The boudinage arrived to complete the thinning of the continental lithosphere with probable formation of new oceanic crust in Liguro-Provencal basins (~ 20-15 Ma), Algerine (~ 17-10Ma), Vavilov (~ 7-3,5 Ma) and Marsili (~ 2 Ma-Present) (Beccaluva et al, 1990; Serri et al, 2001).

Only for Vavilov and Marsili basins was established the true oceanic nature of the crust. During the back-arc basin opening, the blocks moved radially, from a northeastern direction to the south, and rotated both clockwise (southern wing) than anticlockwise (northern wing). Sardinia-Corsica continental block rotated for approximately 60° anti clockwise (Gattacceca et al, 2007;. Montigny et al, 1981;. Speranza et al, 2002.), while the Balearic promontory rotated 20° clockwise. Recent evolution stages of central-Mediterranean region are complicated by diachronic contractions of south Algerine basin(~ 8 Ma) and in southern Tyrrhenian sea (~ 2 Ma).

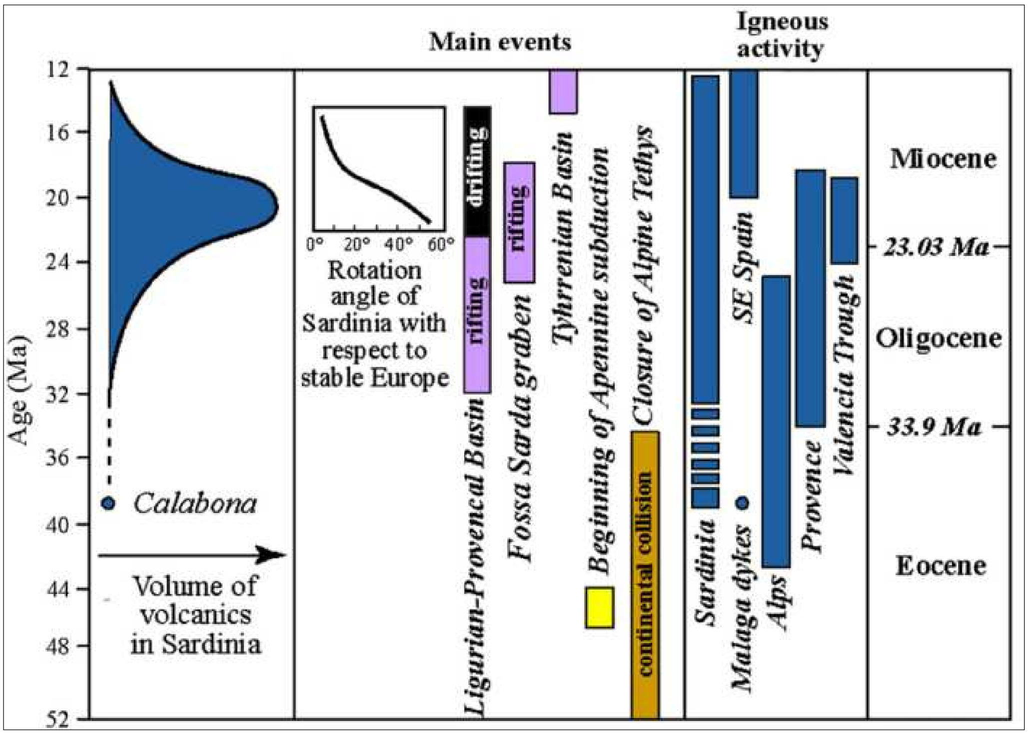


Fig. 9 - Chrono diagram of the period from 52 to 12 showing the approximate volume of igneous rocks of Sardinia, the speed of rotation of the Corsica-Sardinia block (Gattacceca et al., 2007) and the main tectonic and magmatic events of the western and central Mediterranean (Carminati et al ., 2012).

According to Carminati et al.,2012, this tectonic inversion can be attributed to Africa-Europe convergence. Sicily channel has been characterized since Pliocene to present by a rifting NW-SE trending, which push for the Malta, Pantelleria and Lampedusa graben formation. Towards NW, this fracture maybe propagated to Pliocene graben of Campidano in south eastern Sardinia (Corti et al., 2006).

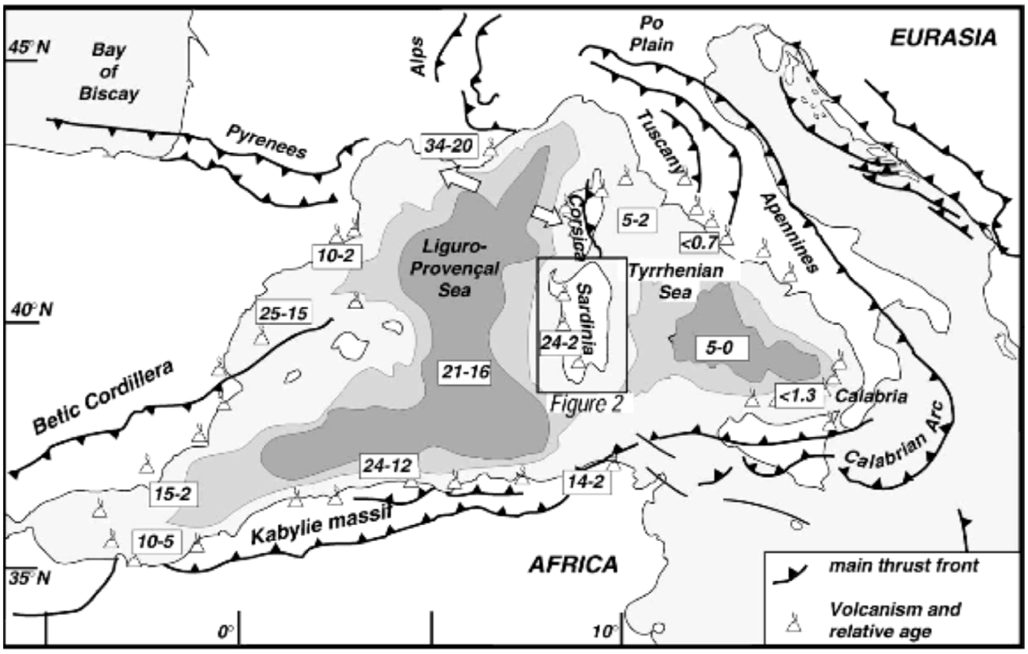


Fig. 10 – Central-Western Mediterranean chart showing volcanism and kinematics, derived from deformation, analysis from upper Oligocene to the present. The numbers describe the age of beginning and end of Liguro Provencal (Oligocene-Burdigalian) and Central-Southern Tyrrhenian (Tortonian-present) basin extension. Note the gradual rejuvenation of the age of magmatism eastward, resulting in an eastward migration of compressional and extensional phenomena. Sardinia being in middle position, between the two basins, recorded the Oligo-Miocene calc-alcaline volcanism, related to the opening of the Liguro-Provencal basin and anorogenic volcanism connected with the opening of southern Tyrrhenian Sea (from Faccena C. et al, 2002).

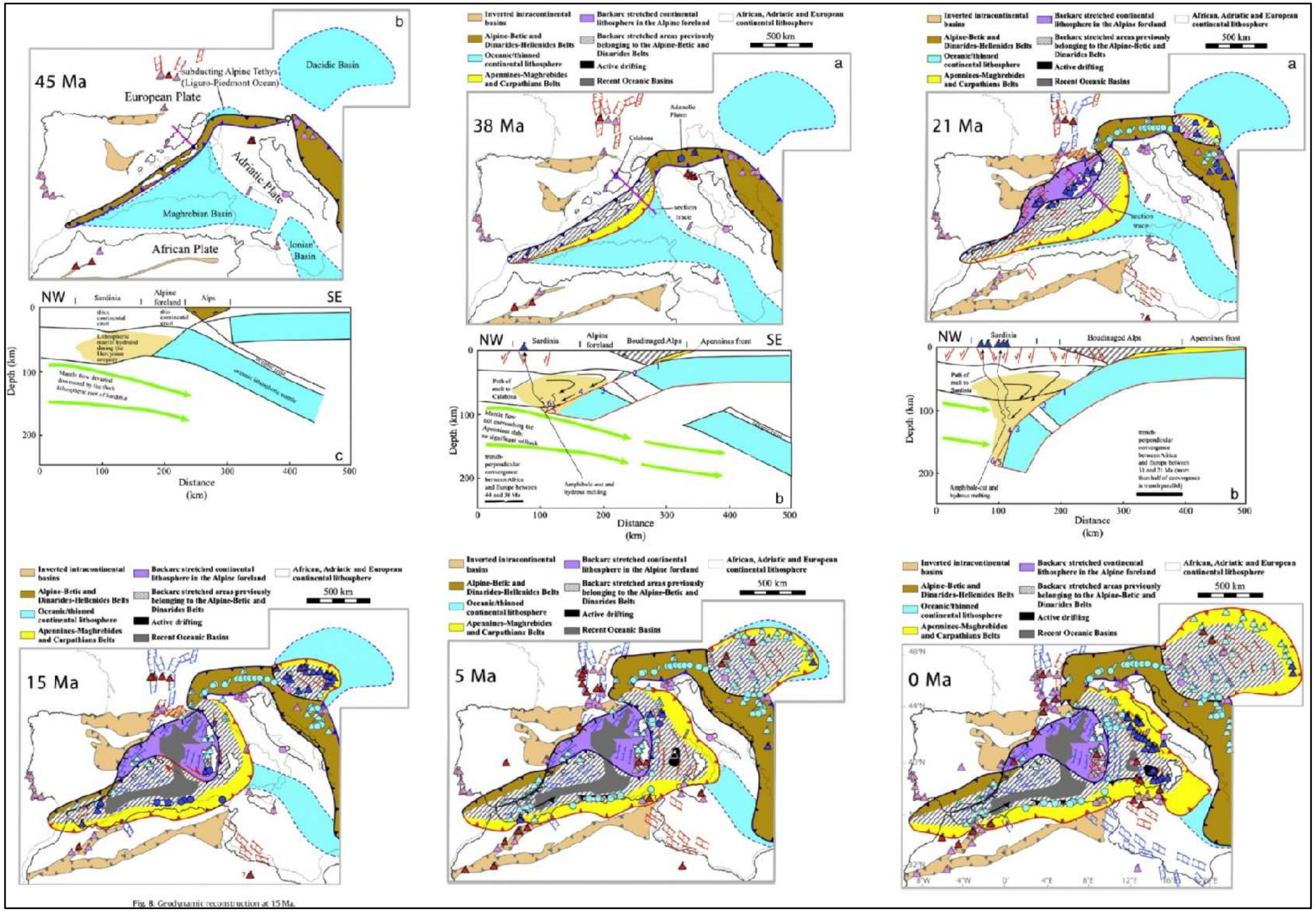


Fig. 11a – Geodynamic reconstruction at 45-38-21-15-5-0 My and relative cross sections (Carminati et al.,2012, modified)

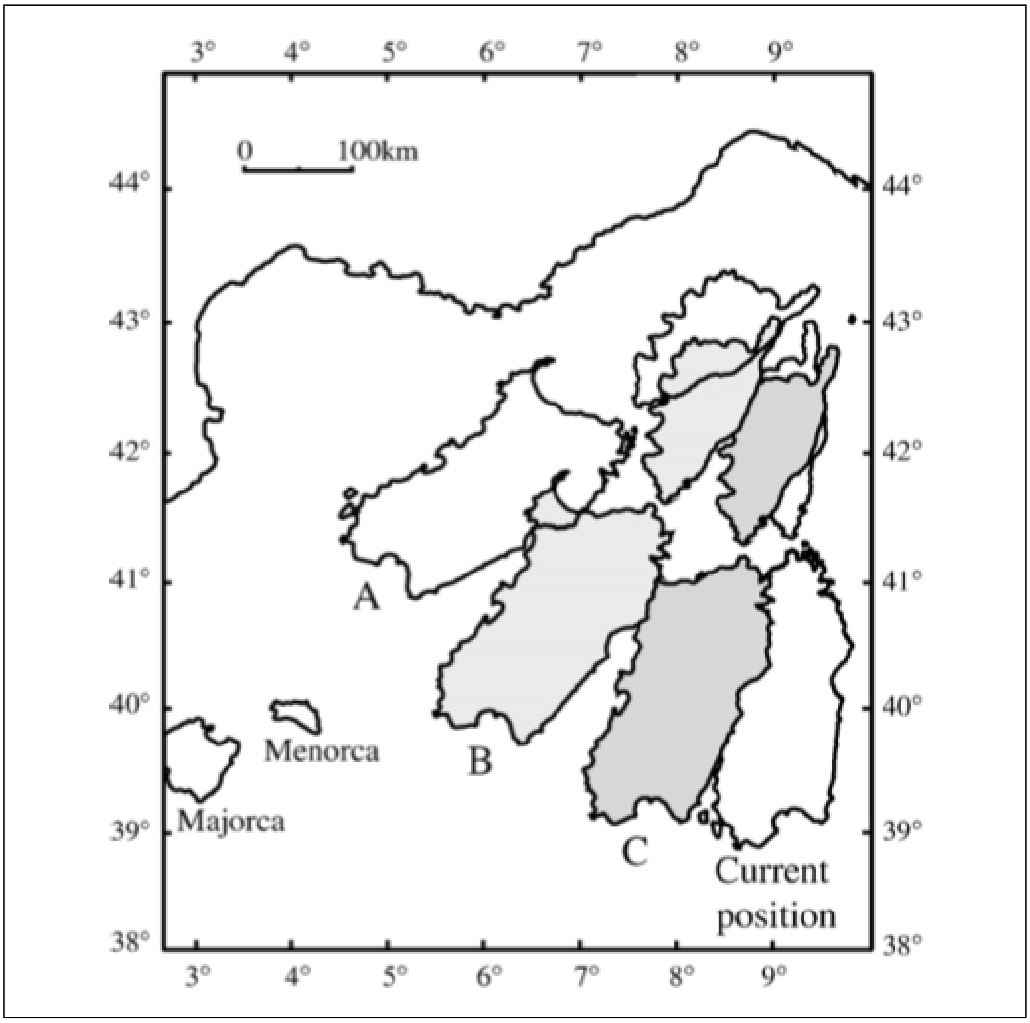


Fig. 11 - Reconstruction of the Liguro-Provençal basin showing the various positions pre-rift / post-rift (21.5 Ma) taken from the Sardinian- Corsican block based on: (A) morphological concordance of the continental margins of the basin; (B) Determination of the oceanic domain from seismic information; (C) palaeomagnetic data of Corsica and Sardinia and magnetic anomalies of the basin. (J. Gattacceca et al. - Miocene rotation of Sardinia, 2007).

GENESIS AND GEOMETRY OF "RIFT SARDO"

The structure of the Sardinian rift does not qualify as a unit but is divided into different basins of half-graben involving a system of blocks and tilted horst.

On a smaller scale, the relative movements between the tectonic blocks that make up the Sardinia, have reactivated the fault systems of the late Hercynian basement of Sardinia, which is already reactivated during the Mesozoic and Paleogene (Sau et alii, 2005).

The consequent evolution of the whole Rift Sardo(Cherchi & Montardert, 1982), follows a strain propagation from south to north, thanks to a strike-slip fault system from simple to transtensive until extensional, which gave rise to a system of regional tectonic blocks separated by branched depressions, according to regional tectonic, roughly oriented NW -SE and NE-SW, within which it was possible to establish that sedimentation from continental has assumed marine characters (Casula et alii, 2001).

The evolution of the Mediterranean Geodynamic reactivated in several stages the initial structure of the upper Oligocene rift with andesitic volcanism, with different characteristics between the central-southern and northern Sardinia due to different sub-regional and local conditions (Casula et alii, 2001).

The differences among the various rift basins of northern and central-southern persist until the onset of a general marine sedimentation, which peaked in upper Burdigalian with the prevalence of extensional movements (Cherchi, 1985; Assorgia et al, 1995; et Lecca alii, 1997). The heterochrony of the rift is attested by biostratigraphic data; it starts first in southern Sardinia (Cherchi & Montadert, 1982), where is located the study area, while in northern Sardinia, despite documented products of andesitic volcanism oldest, the transgression is more recent.

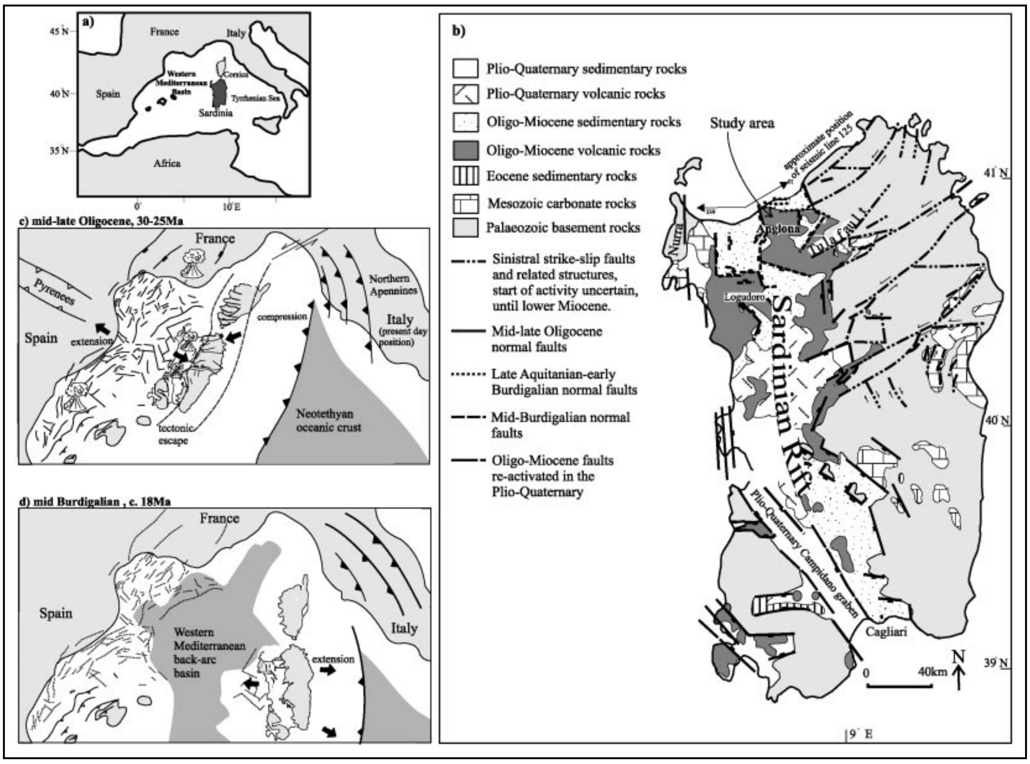


Fig. 12 - Figure (a) Sardinia geographical location. (b) simplified summary of Sardinian geology showing the location and age of higher sub-structures of delimitation. Changed after Cherchi & Montadert (1982a, b), Assorgia et al. (1995). (c, d) Oligo-Miocene palaeogeographic reconstructions of the western Mediterranean changed from Sowerbutts (2000). Fault traces outside of Sardinia (= active solid, dashed = inactive) and areas of probable oceanic crust (dark gray) changed since Desegaulx & Roca (1992), & Mauffret Maillard (1993), Mauffret et al. (1995), and Vially & Trémolières (1996).

RIFTING PHASES ASSOCIATED VOLCANISM

Several volcanic cycles are associated with the evolution of the Cenozoic Sardinian graben.

Associated lava products were changing composition and characteristics as the geodynamic context changes, highlighting a poly-phase of the rifting, recognized as the first in the basins of northern Sardinia (Asinara Gulf) (Genneseaux & Thomas, 1986), later extended to the whole system of the Rift Sardo (Lecca et al 1997).

Several authors(Lecca *et alii*, 1997; Sau *et alii*, 2005) recognised following events:

- Stage 1, proto-rift phase (Lecca et alii, 1997), pre-Aquitanian (28-24Ma): is rapresented by gabbroid and tonalithic bodies and/or massive domes with intermediate chemistry and basalts. During this phase, ignimbritic sequences are vacant. Initial extensional phase favour the half-graben geometry with sin-rift clastic deposits coming from topographically lifted horst blocks, separated by faults(Sowerbutts, 2000). Clastic deposits laterally change to lacustrine marls. Voluminous masses of pyro and epiclastic materials, coming from emission centres along side faults of the half-graben, deposited in marginal to marine environments, inside the depressions, exploiting disposable accommodation space.
- Stage 2, Acquitanian-Burdigalian volcanic-sedimentary phase: is characterized by the extensive deposit of ignimbrites interleaved with andesites. Pyroclastic deposits are mainly sub-aerial and looks connected to fissure eruptions along fault zone NE-SW oriented. Volcanic activity reaches his peak around 20-21Ma. This evolution step of the rift is connected with a second faulting phase occurred during Sardo-Corsican micro plate rotation to actual position, during the western mediterranean back-arc basin spreading (Sowerbutts A., 2000).

- Stage 3, upper Burdigalian-Langhian phase (18-14Ma): is a major extensional phase, occurring along the Oligo-Miocene Rift Sardo, following the back-arc basin opening due to the extensional tectonic migration towards fore-arc zone. The volcanic activity, subordinated respect to the neritic marine deposits, involve the western sector of the rift; ignimbrites are mainly deposited in south western Sardinia.

Submarine volcanism has been particularly active during lower Miocene. Pillow-lavas outcropping in central-southern Sardinia belongs to this cycle. Volcanic sands, tufite and ialoclastites are often interleaved in Aquitanian and Burdigalian sediments, testifying the submarine volcanic activity relevance. It was hypothesized that the drifting of Sardinia and Corsica didn't happen in solidarity. Hypothesis of a contemporary drifting is surrounded by following observations:

- Permo-Carboniferous granitic intrusion orientation is parallel in Sardinia and Corsica;
- Late Varisican fracture lines are parallel;
- Sardinian and Corsican vein systems presents same density and orientation (Orsini *et alii*, 1980);
- Palaeo magnetism of Permian veins in the Bocche di Bonifacio strait shows an almost rigid rotation of Corsica and Sardinia (Vigliotti & Langenheim, 1995).

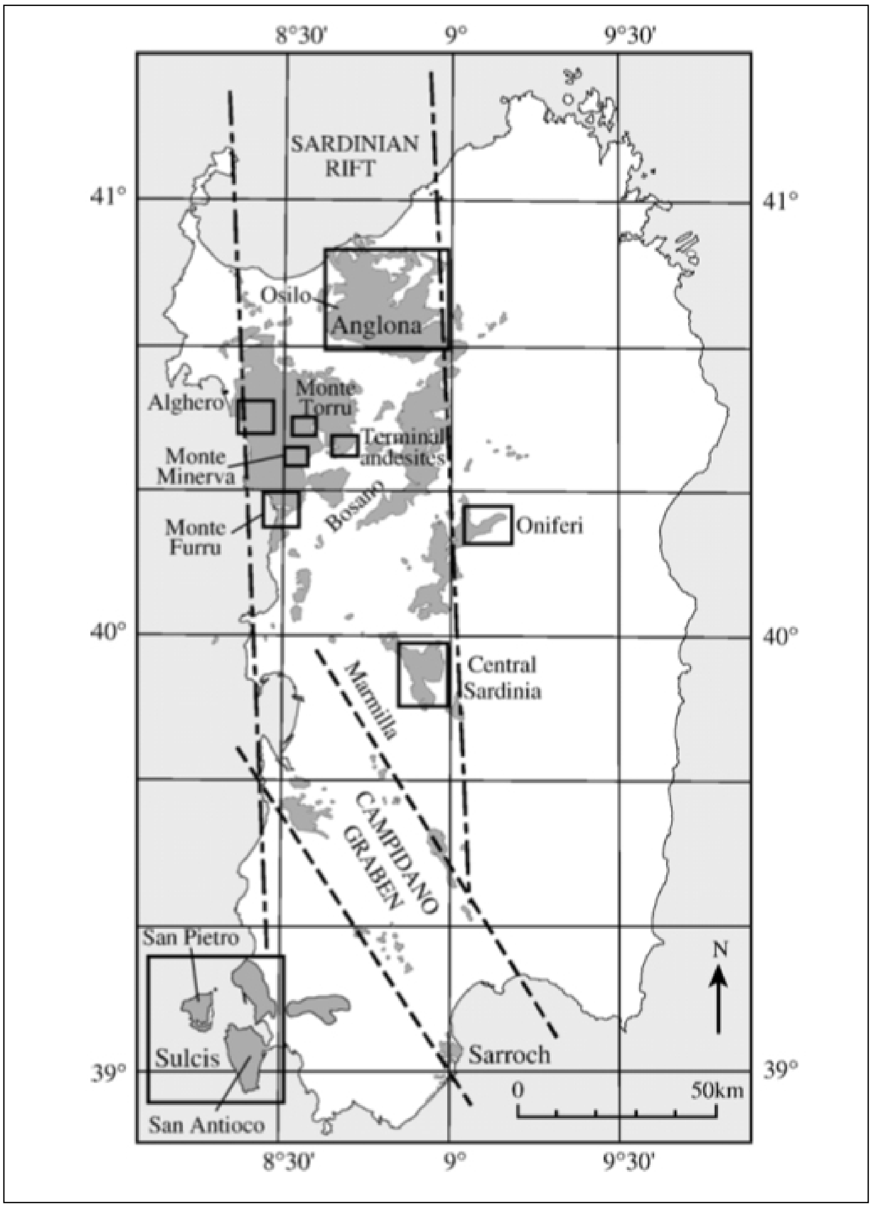


Fig. 13 - Sardinia Chart showing Miocene calc-alkaline volcanic outcrops (J. Gattacceca et Al. - Miocene rotation of Sardinia, 2007)

In middle Miocene, NNE –SSW oriented faults have been remobilised concurrently with north Thyrrenian opening. The beginning of this process is probably previous to middle Miocene, maybe 18Ma (Sau *et alii* 2005, Lecca *et alii* 1997), anyway maximum extensive activity has been reached at the end of Tortonian. Following main phases of Rift Sardo and Mediterranean sea geodynamic evolution, several more recent episodes influenced the filling of previously formed basins and adjacent emerged areas erosion (Lecca *et alii* 1997). The outcrop in Sardinia of upper Miocene sedimentary covers is limited due to intensive erosion during Messinian regression and emersion phases in medium-upper Pliocene (Marini & Murru, 1983). Transgressive lower Pliocene discordance on Messinian substrate demonstrate the existence of a late Miocene compressive phase which creates relevant deformations, noticeable only on southern Sardinia (Carmignani *et alii*, 2001).

Between Tortonian and Pliocene, on a regional scale, can be observed the partial reactivation of rift’s faults with two different behaviour in central-southern Sardinia and northern Sardinia. The making in central-southern Sardinia during medium-upper Pliocene of Campidano graben is to be put in relation with the extension towards SE of the southern Tyrrhenian distensive tectonics. This phase structures are superimposed with NNW-SSE trend on the Oligo-Miocene rift ones, N-S oriented; Campidano trough, under formation, was filled by hundreds meters of syn-tectonic deposits produced at the expenses of the horst constituted by Oligo-Miocene sedimentary rocks and by the Varisican basement.

Subsidence linked with Campidano graben probably until actual time in the off-shore area of Cagliari Gulf and Oristano. Almost simultaneously, in central Sardinia and on eastern coast, start a new anorogenetic volcanism without any further subsidence (Sau *et alii*, 2005). The new volcanic cycle, starts in the Messinian(5.2-5 Ma; Assorgia *et alii* 1976), develops mainly during the Pliocene and continues till Pleistocene (0.14 Ma).

This volcanism, with prevailing fissure basaltic character, was related with Tyrrhenian basin. In western and eastern central Sardinia, can be observed tabular reliefs, which top is protected by Plio-Pleistocene basaltic lavas, and they are definite “Giare”.

Fluid lava occupied low areas, freezing at the time of cooling; actual topographic position can be justified with relief inversion process, together with up-lift phenomena which accelerate erosive processes on palaeo valleys sides, while preserving the valley bottom protected by the lava spreading.

OCEANOGRAPHIC SETTING

The Oceanographic setting of the area is dominated, as regards the most superficial sectors by the Western Sardinian Current WSC (Figure 6) which flows towards the SE with an average value of about 0.08m / s but that, for morphological causes, in the Western San Pietro Island sector accelerate up to 0.16 m / s (Olita et al. 2013). After rounding Cape Sperone, the WSC flows eastwards over the continental shelf of southern Sardinia.

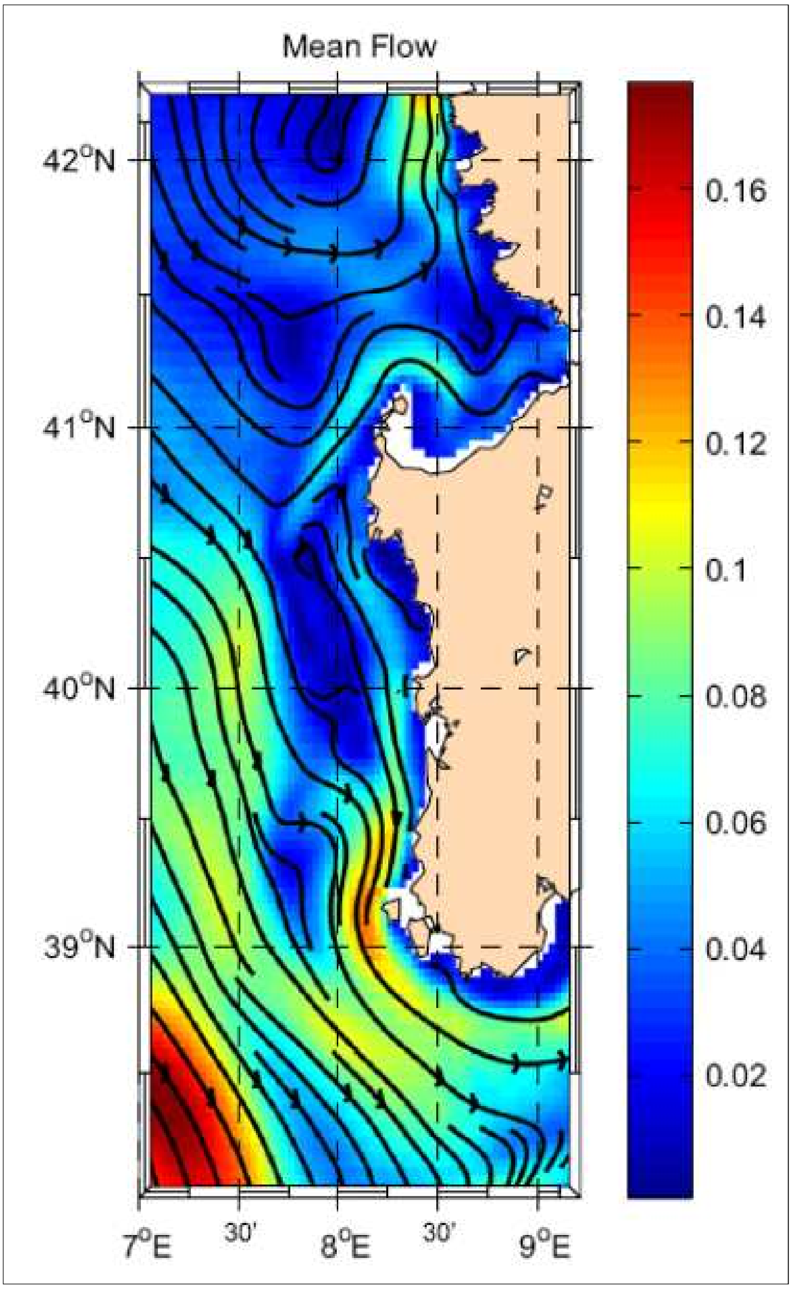


Fig. 14 - WSC surface circulation from Olita et al., 2013.

Otherwise, in upper and lower slope sectors water masses movements is dominated by the fluxes of Levantine Intermediate Water and Tyrrhenian Dense Water (Fig. 15), which goes around the Sardinian southern continental margin in a clockwise direction.

These flows are firstly direct towards SW in the south eastern sector of Sardinia continental margin, than turns to the West and NW once reached western side of the continental margin (Millot, 1999).

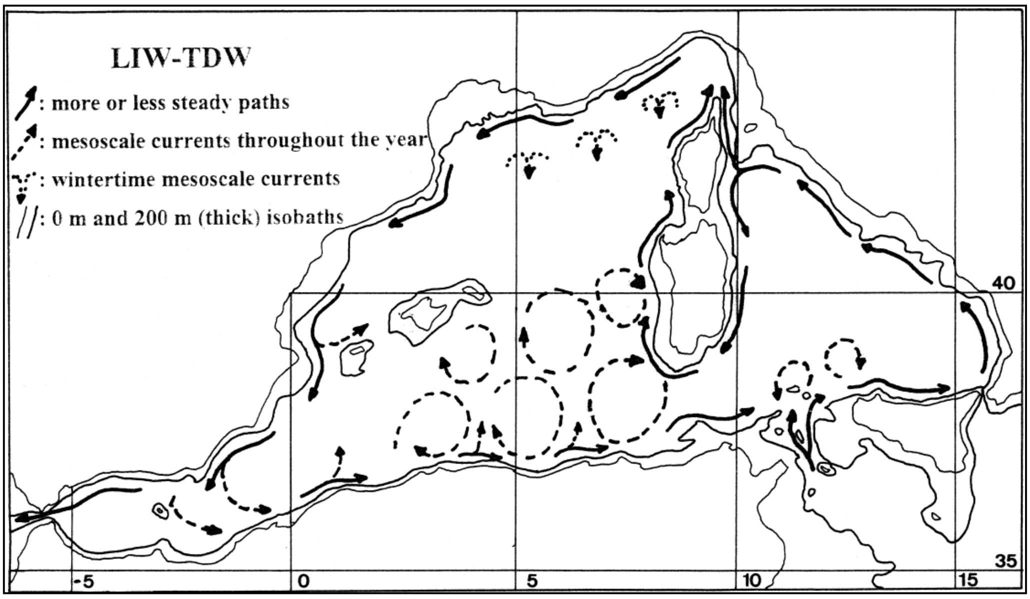


Fig. 15 - Circulation of Levantine Intermediate Water (LIW) and Tyrrhenian Dense Water (TDW) from Millot, 1999.

EFFECTS ON CIRCULATION AND ECOSYSTEM FUNCTIONING

Submarine canyons can affect general and local scale circulation patterns by deflecting the in-coming and out-coming flows (Flexas *et al*., 2008). Several key factors play a role by enhancing or reducing the canyon effect, i.e. the canyon's relative position (distance) from the coast, its size and morphology, general circulation and local currents, the in-coming flow direction (Klinck, 1996), the presence, intensity and amount of river outputs and wind stress strength, water mass stratification, etc. The result is a great variety of situations and effects which can occur for each single canyon (or each canyon system) set along the continental margin of the Mediterranean, and which are, in some cases, very different from what could be expected through oceanographic process modelling. The tendency of geostrophic circulation to follow bathymetric contours limits the cross shelf-break exchanges. Canyons cutting the bottom topography can reduce the rotational effects of the current (geostrofic effect such as Coriolis force) and significantly force the flow to cross isobaths, leading to enhanced mixing through upwelling and downwelling (Allen and Durrieu de Madron, 2009).

Mediterranean circulation is mainly characterized by a large cyclonic gyre of in-coming Atlantic waters, which can generate anticyclonic eddies on the coastward right side of the flow, strongly affecting current patterns within the continental shelf. On the left side of the gyre flow cyclonic eddies are generated, which can affect circulation in the pelagic domain from the continental margin to far offshore. Bottom morphology (seamounts, submarine canyons, gullies, trenches, valleys, steep slopes, etc.) as well as wind forcing and increasing density processes can alter and deeply modify the above patterns, thus a high time-volume variability is the main feature of Mediterranean circulation Würtz M. *et al., (2012).*

The abundance and diversity of marine life can be enhanced by canyons through their effect on local circulation, by funneling sediment transport and by providing more varied and complex physical habitats than surrounding slope areas, because canyons often have steep slopes, rocky outcrops, and faster currents that can support fauna with diverse habitat requirements.

By concentrating organic detritus moving along continental shelf and slope, submarine canyons concentrate sediments rich in organics and contain denser deposits of phytodetritus (Garcia *et al., 2008).* Given such enhancement of trophic resources, canyons may be favourable habitats for benthic consumers and suspension feeders. Würtz M. *et al., (2012).*

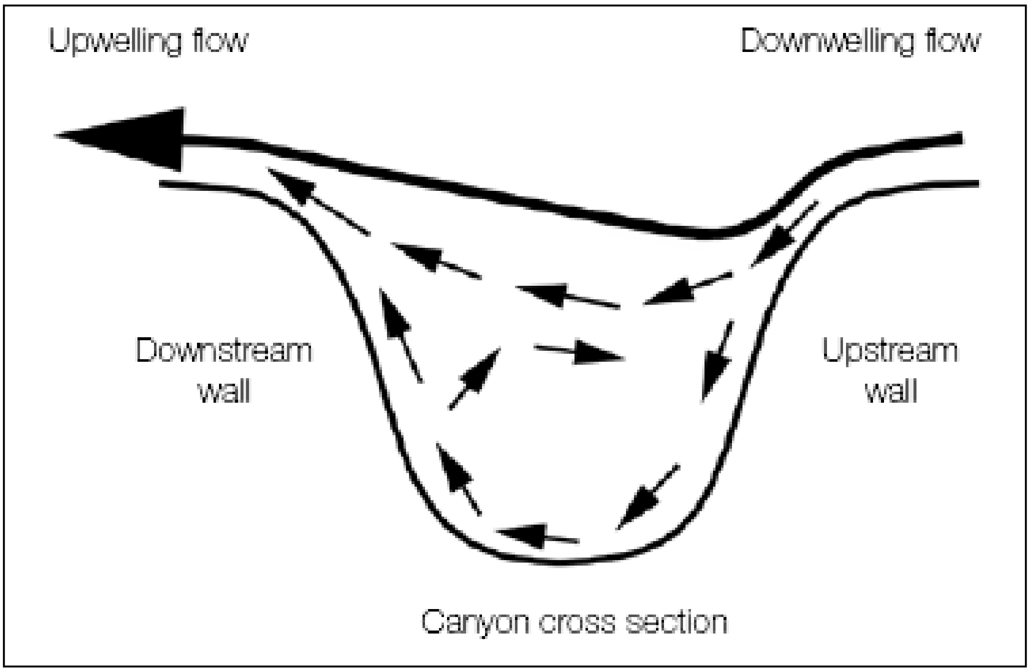


Fig. 16 - Schematic representation of a right-bounded flow (when the flow has the coast on its right): current-canyon interaction causes asymmetry in the vertical velocity field; downwelling is forced over the upstream wall, whereas upwelling is forced over the downstream wall. Modified from Allen and Durrieu de Madron (2009).

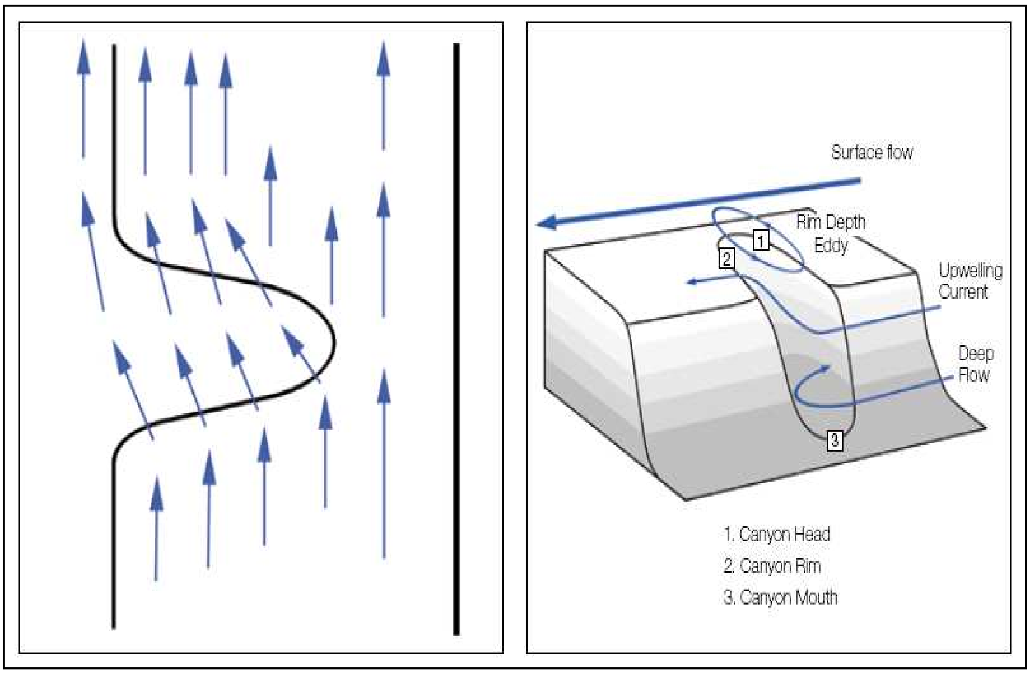


Fig. 17 – On the left: Positive flow in the Northern Hemisphere. Plan view sketch showing net flux through a canyon onto the shelf, accommodated by an increasing along-shelf flux. The black line is the shelf-break isobath, straight hatching on the right indicates the coast, and the blue arrows represent the flow. Modified from Allen and Durrieu de Madron (2009).

On the right: Wind-driven shelf-break or slope currents lead to upwelling or downwelling flows within the canyon, with the strongest effects at the canyon rim especially at shelf-break depth (modified from Allen and Hickey, 2010).

MATERIALS AND METHODS

DATA ACQUISITION CAMPAIGNS

The dataset discussed here was collected during two cruises carried out in the framework of the “MaGIC” project (MArine Geohazard along Italian Coasts) in 2009 and 2010 by CoNISMA’s R/V Universitatis, using different acoustic systems: I) RESON SEABAT 8160 50 kHz multiBeam Echo-Sounder (MBES)and II) GEOACOUSTIC CHIRP II Sub-Bottom Profiler (SBP).

Fig. 18 - Research Vessel “UNIVERSITATIS” (actually R/V Minerva I)

Onboard the R/V Universitatis, the integrated system used an IXSEA OCTANS motion sensor a gyro compass and a Satellite Differential GPS (SDGPS). The datum was WGS84 and the UTM projection was chosen for navigation and display, fuse 32 N, providing a detailed data coverage of South Sardinia continental margin geomorphology through high resolution morpho-bathymetric maps. Data collected during the survey were integrated with CARG project (Official National Italian Geological Cartography).

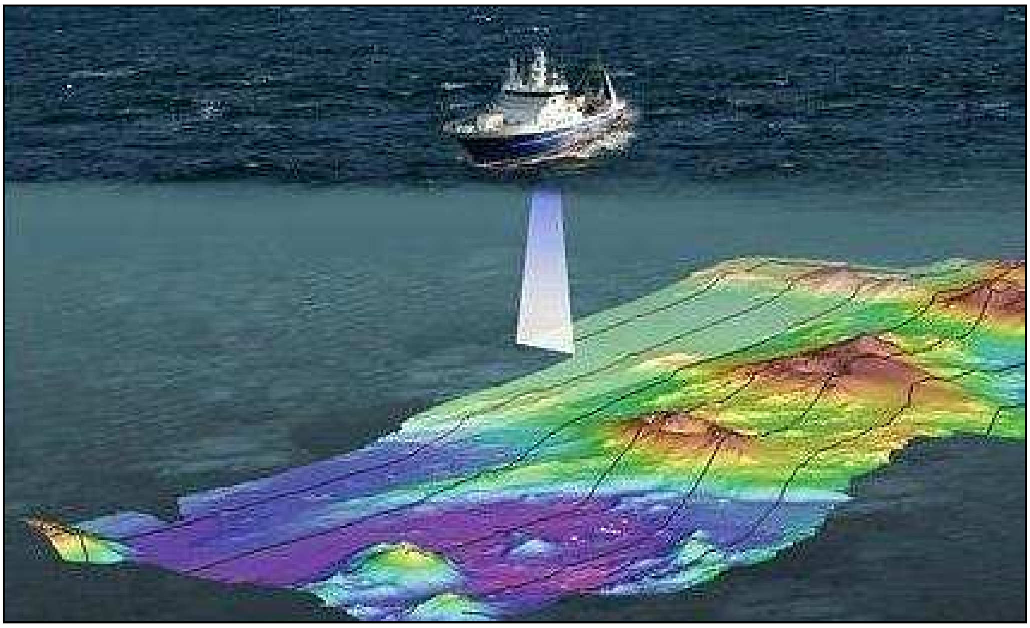


Fig. 19 - A multibeam echo sounder (MBES) emits a range of acoustic pulses at high frequency transverse to the ship's course and, backscattered from the bottom, came back to the source and are converted to spot heights. The data obtained are processed through complex calculation procedures and then displayed as a map of the depth contours, shaded relief or three-dimensional surfaces.

The geomorphologic analysis provided a useful guideline to plan the further ROV survey, as data obtained through Multibeam echosounder were used to create different maps where ROV transects are reported.

The video material was obtained during two ROV surveys conducted along the south Sardinia continental margin in October 2011 and June 2013 (Table 1). Two different ROVs were used: (1) the ROV “Pollux III” equipped with a digital camera (Nikon D80, 10 megapixel), a strobe light (Nikon SB 400), a high definition video camera (Sony HDR-HC7) and (2) the ROV “Seaeye Falcon” equipped with three cameras: (1) a default color camera, (2) a color camera equipped with laser beams, over a 180° tilt platform and (3) an independent high definition video camera (GoPro 3+). Both ROVs were equipped with track-link system, depth sensor, compass, and two parallel laser beams providing a constant 10-cm reference scale in the video frame, for the measurement of the frame area. Each of the five rocky pinnacles was investigated through a different number of ROV dives (from a minimum of 1 to a maximum of 3), within the same day, to collect enough video material for the further image analysis (Table 1). The software DVDVIDEOSOFT was used to extract video frames every 30 s; overall, a total of 11 h of ROV footage were analyzed. After discarding the extractedframes with non-clear visibility, compromised resolution/ focus or not-suitable substrate (i.e., soft bottoms), 9 h of filming were used for final stage of the image analysis. The analysis was performed with the CPCe software (Kohler and Gill 2006) in order to obtain for each frame: (1) coral abundance (number of colonies per m−2 ± SE, henceforth col m−2 ± SE); (2) species composition of the coral community; and (3) sediment coverage of the substrate, classified from 1 to 5, referring to 5 % ranges (1 = 0–20 %; 2 = 20–40 %; 3 = 40–60 %; 4 = 60–80 %; 5 = 80–100 %)

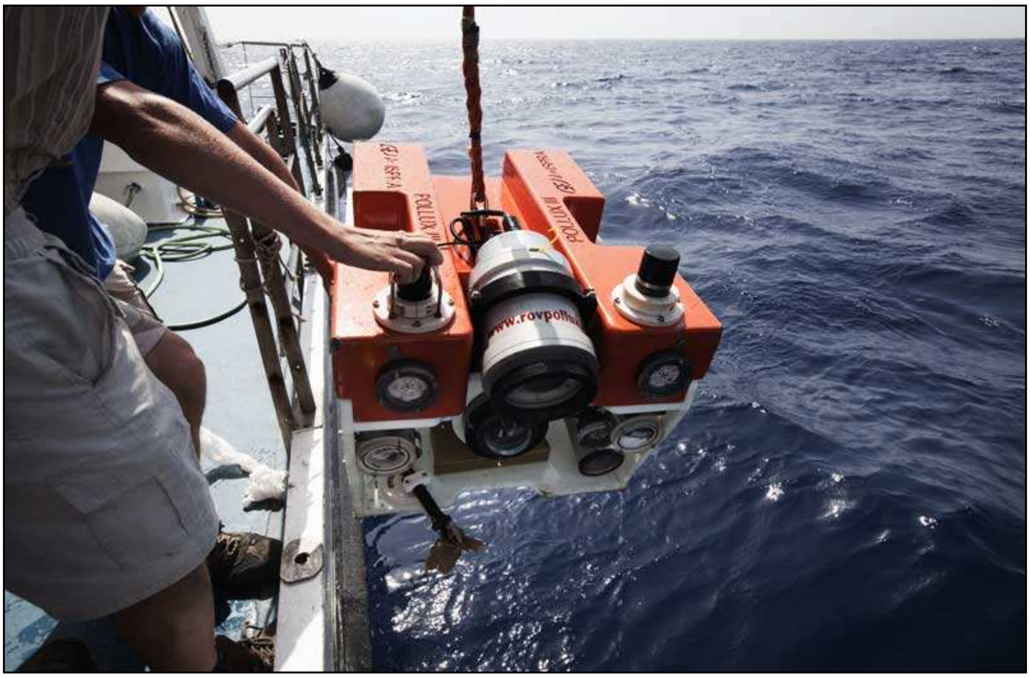


Fig. 20 – POLLUX II R.O.V deployed from the deck of m/v ASTREA.

The ROV was also equipped with an underwater acoustic tracking position system (Tracklink 1500 MA, LinkQuest Inc.) providing detailed records of the tracks along the seabed; transects could not be linear as the survey was focused on a target species, *Corallium rubrum*, which is distributed in patches in semi dark caves, steep walls and boulders. The precise measure of the length of each track was obtained, assuming a constant speed of the ROV; soft bottoms and low visibility frames were discarded in the initial stage of video analysis. When patches of red coral were found (a patch is defined as per Follesa et al., 2013 a group of >2 colonies), a representative number of frames were taken. Within each frame, randomly positioned 50×50 cm squares (used as Useful Sampling Unit) were obtained with CPCe Software (Coral Point Count with Excel extensions) (Kohler & Gill, 2006). Through the ROV laser beams, a scale for CPCe software calibration was provided. The number of Useful Sampling Units (henceforth called USU) was proportional to the patch extension, in order to better represent it; a minimum of 4 USU was taken per each patch, always covering a minimum surface of 1 m_2 (i.e. four 50×50 cm squares). Although considerable distances separated patches, a minimum of 10 meters was used as a reference to define two patches distinct.

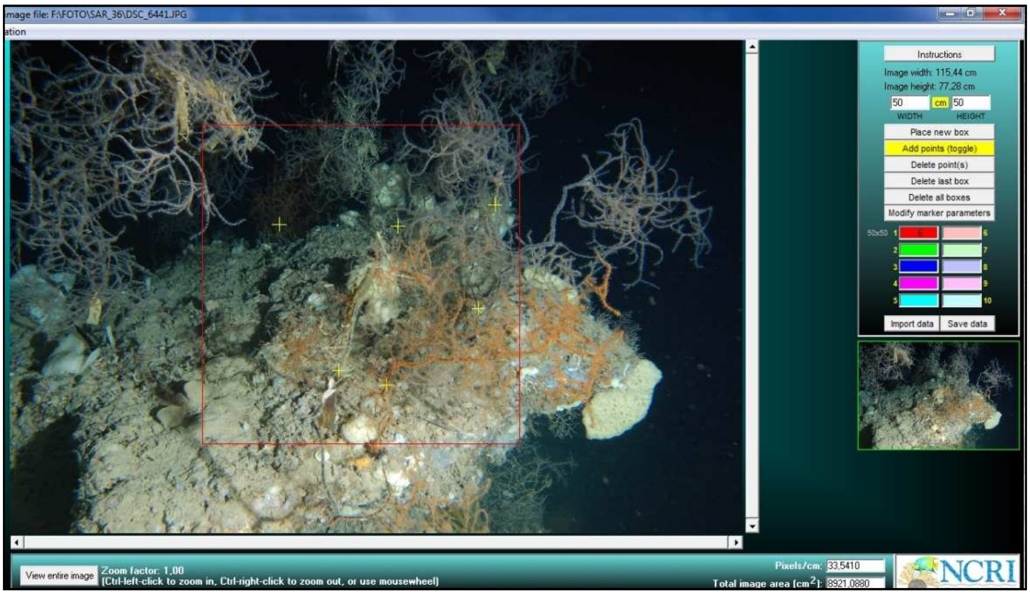


image file: F:\FOTO\SAR_36\DSC_6441.JPG

Image width: 115,44 cm

Image height: 77,28 cm

WIDTH: 50 cm

HEIGHT: 50 cm

Zoom factor: 1,00

(Ctrl-left-click to zoom in, Ctrl-right-click to zoom out, or use mousewheel)

Pixels/cm: 33,5410

Total image area (cm2): 8921,0880

Fig. 21 – CPCe Software screenshot showing USU square within which is operated the automatic colour count (in this case red for Red Coral).

WHAT IS HABITAT MAPPING? WHAT METHOD IS USED FOR HABMAP?

Marine environment is under increasing pressure from human activities. Fishing, mining, pollution and other human activities are causing serious damage to deep sea ecosystems and reducing benthic biodiversity. Without immediate action to mitigate these impacts, it is expected that by mid-21st century, the commercial fish stocks will collapse beyond the point of recovery (Worm et al., 2006). In addition, it is estimated that on a global scale no area of the oceans is not influenced by human activities, and that a large fraction (41%) is strongly affected by many human impacts. Our knowledge of the extension, geographical location and ecological functioning of benthic habitats is still extremely low because of the limitations posed by the traditional methods of investigation of the seabed, and it is estimated that only 5-10% of the ocean floor is mapped with a resolution similar to the studies on the ground (Wright and Heyman, 2008). Consequently, it is difficult to manage resources effectively, protect ecologically important areas and set the legislation to protect the oceans. **To address this need for management, there is an urgent need to develop reliable methods for mapping of marine ecosystems to determine their location, extent, and condition** .

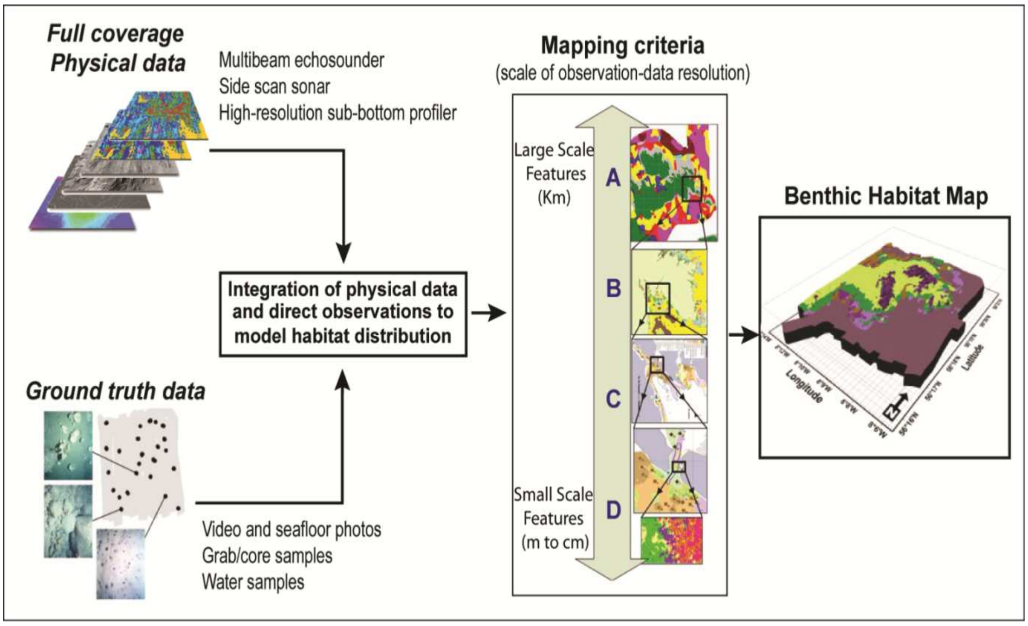


Fig. 22 - Generalized approach for the production of benthic habitat maps (modified from MESH, 2008a). Example data from Stanton Banks, UK (McGonigle et al., 2009) .

Marine habitat mapping shows the distribution of the habitats interpreting layers of physical data, often derived from remote sensing, using information obtained from biological habitats direct sampling and observation of the seabed. Only a small part of the seabed can be directly observed, the total coverage of habitats is deducted by the association data of habitat and physical samples from the sea floor so that the final maps can provide the habitat distribution of the seabed. **Habitat mapping represents our best estimation of the distribution of habitats in a place and at a particular time.**

Marine habitat mapping is also required for the implementation of various EC Directives and Regulations in that it is the baseline for environmental assessment and monitoring requirements as well as for the enactment of protection measures for marine habitats and species.

Benefits of a broad-scale habitat map

In order to most benefit from the potential offered by the European marine basins in terms of growth, employment, and to protect the marine environment, we need to know more about the seafloor. European Directives, such as the Marine Strategy Framework Directive (MSFD), call for a full-coverage seabed habitat map of all European seas. In general, habitat maps are very costly and time consuming to produce from survey (EMODnet, H. Ellwood, 2014). The creation of a detailed habitat map involves surveying the seafloor with sonar, MBES equipment and collecting samples or photos of the seabed, before analysing and integrating these data types to generate a map. It can take several years from planning a survey to complete a detailed map. By contrast, broad-scale mapping of seabed substrate at a low resolution combined with using modelling techniques to classify habitats in terms of physical parameters is an efficient way to meet the need for a full coverage habitat map at a reasonable cost. Broad-scale products have been used for assessing and reporting the status of European seas, designing ecologically coherent Marine Protected Area networks, establishing monitoring programmes for seabed habitats and informing marine planning.

Principles behind making broad-scale seabed habitat maps

It is possible to produce a 'predictive map' of expected seabed-habitat types by combining a series of measurements, such as water depth and light levels, morphology complexity and water circulation amongst others, using statistical analysis and Geographical Information System modelling.

In particular in this work the advantages of a **multiscalar approach** (Fig. 22) have been used in order to extend the information verified in a limited number of ground truth check points, to large areas with same geologic, geomorphologic and oceanographic conditions, enabling the creation of broad-scale predictive maps for habitat distribution along the continental shelf and upper slope regions. Surely, in a successive stage, would be desirable to increase the number of check points in order to increase the confidence with the final products.

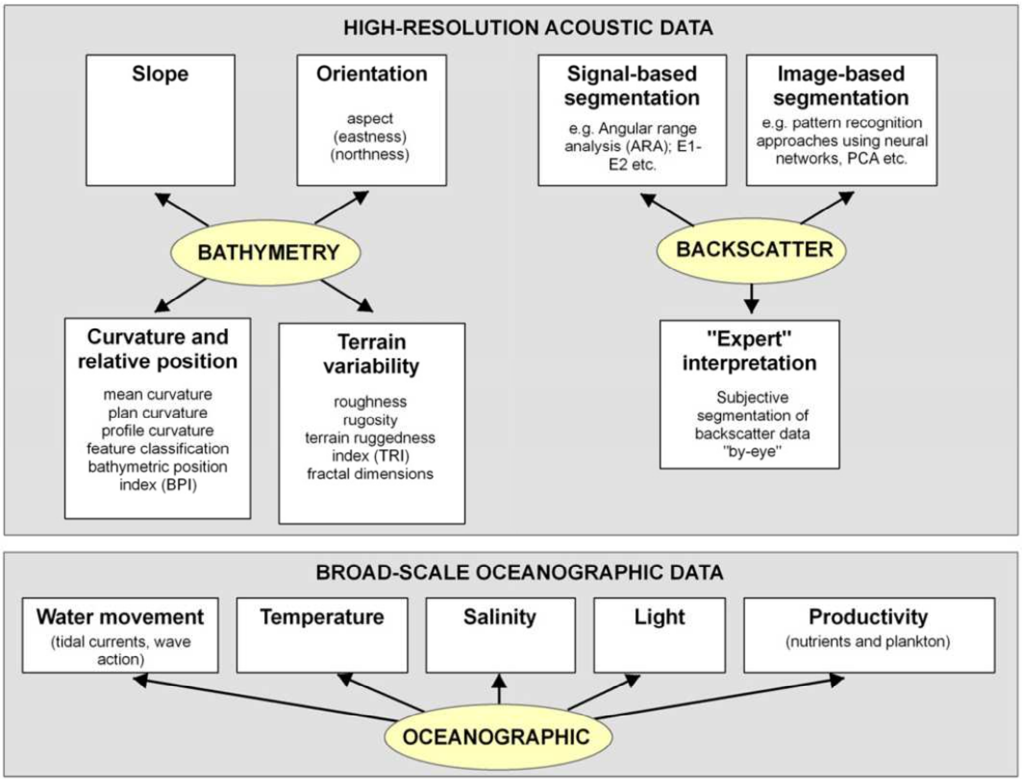


Fig. 23 - Spatial data sets used for habitat segmentation. Primary data (bathymetry and backscatter), and secondary layers (white boxes). Oceanographic data can also be used, but ismore difficult to measure at a spatial scale required for effective habitat delineation. Modified from Wilson et al. (2007).

Principal drivers for seabed habitat distributions include the type of seabed substrate (rock, mud, mixed sediment, etc.), depth, light availability and the energy of water movements. To describe the variation in environmental conditions with depth, EUNIS divides subtidal habitats into zones: Infralittoral, Shallow Circalittoral (or Circalittoral), Deep Circalittoral and Deep Sea. Another factor that can be fundamental in driving habitat types is the degree of exposure to wave and water-current energy.

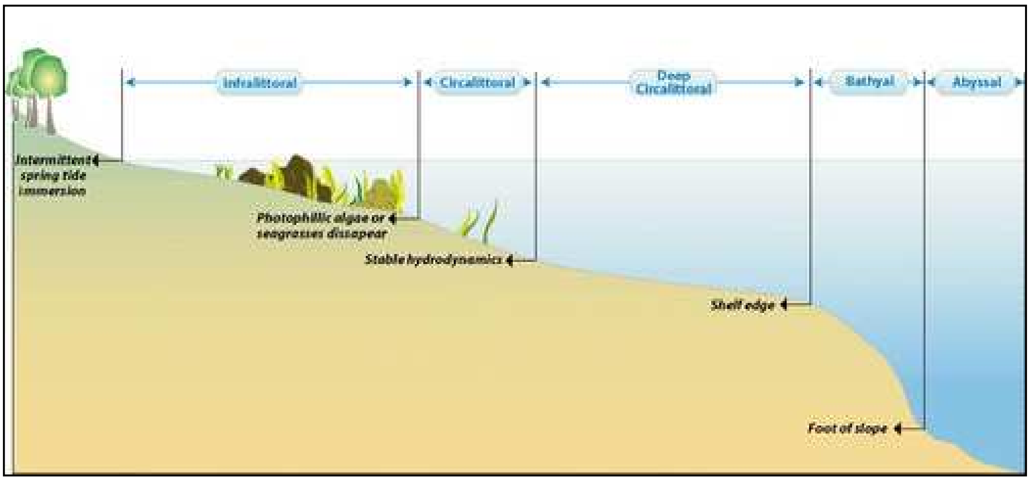


Fig. 24 - The division of marine sublittoral habitats into biological zones (©MESH Atlantic Blue Box, 2013).

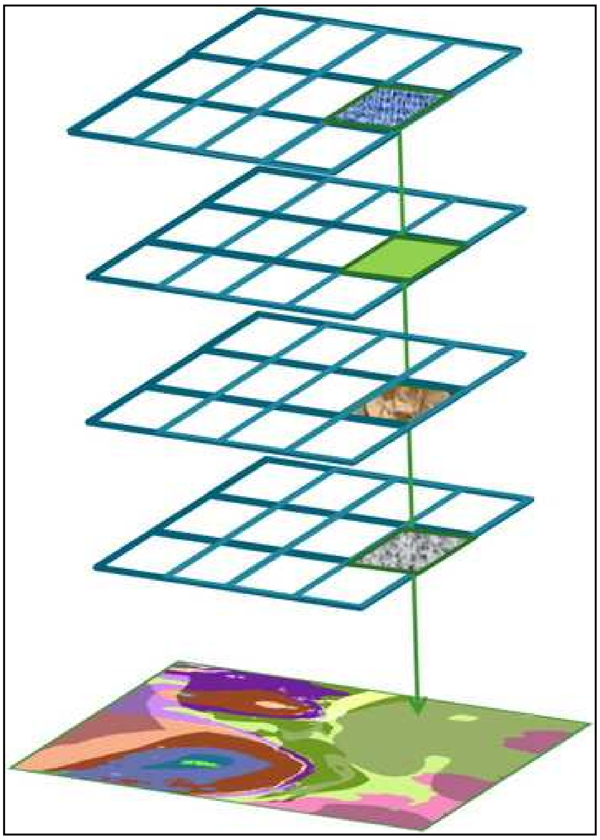


Fig. 25 - Illustration of how a predictive habitat map can be created by 'layering' data in GIS

The principal input layers are the type of seabed substrate and the biological zones. Depending on the basin, layers of hydrodynamic energy levels, salinity and/or temperature are also produced.

The map model was developed in ESRI™ ArcGIS and Quantum Gis and can be saved and executed multiple times, which ensures that the systems are repeatable and easily updated when new layers or methods are available. As well as careful evaluation of contributing data, and refining statistical methods for its interpretation, during the creation of the maps it is necessary to define meaningful thresholds for likely changes in habitats: in each input layer these are used to define the boundaries between classes, where the change in the physical conditions reaches a critical point that defines an expected change in habitat type.

This work started within the Marine Strategy project framework and has been carried out by the Geology and Biology operative units of the Cagliari University, preliminary focused on the Coralligenous Habitat mapping on

Sardinia’s continental margins. Coralligenous assemblages habitat mapping was made reprocessing MBES raw data. From a five meters bin size resolution DTM (terrain model of the seabed), these data will be splitted into "spatial units" representing discrete or continuous "habitat units" (Dunn et al. 2003) before being integrated with the "in situ" information.

Starting from these primary data you can derive a set of secondary data by applying mathematical analysis algorithms, obtaining: gradient (slope), orientation, variability of the seabed: roughness, acoustic classes, hardness, curvatures but especially the reflectivity or acoustic back-scattering (acoustic backscatter) useful for individuation and mapping of complexes habitat and then the preparation of a predictive model of habitats distribution (Diesing, 2009). This process, called segmentation (Cutter et al. 2003) or also commonly known as acoustic classification of the seabed (Acoustic Seabed Classification ASC) (Brown et al. 2011) produces the result of second order derivatives thematic data. An automatic data processing (automatic segmentation) has been tried unsuccessfully, mainly because of the data unsuitableness due to poor data resolution for this kind of automatic interpretation, software are still unable to discriminate real data from the “background noise”. The results obtained in such way, after verification, suffered severe limitations of reliability of the interpretative model, so, at the end all the interpretation has been carried out with the traditional “expert interpretation” done by eye, examining the full data coverage of Sardinia southern continental margin.

Integration with other nature geophysical data (high resolution seismic Sub-bottom Profiler CHIRP) and the comparison with previous knowledge, can make it a more "robust" forecast model of distribution for target habitat, helping limiting the number and the extension of the key areas to be submitted to new Multibeam (MBES) surveys and the ROV (Remotely Operated Vehicle) calibration visual survey. In this framework we will adopt a multiscalar analysis approach that will allow, starting from a knowledge framework for large areas, to detail the mosaic of biotic components in relevant test areas for the different “coralligenous” facies: bioconstructions coralligenous assemblages (-40 / -90 m); deep coralligenous assemblages(-90 / -120m); Deep rocky coral assemblages rock (Cp) semi dark caves biocoenosis (SDC), *Corallium rubrum* facies (-100 / -130m); *Rouche du Large* Biocoenosis (RL) *Leiopates glaberrima* facies (- 130 / -230m) and white bathyal corals (Cold coral) Biocoenosis, *Madrepora oculata* and *Ophelia pertusa* facies (not yet reported in Sardinia).

Theory of multibeam data interpretation

The geomorphologic structure of the seabed controls the distribution of the different habitats, in particular benthic species show a preference for certain depths and morphologies of the fund, then the bathymetry can be used to "segment" an area in regions that reflect distinct biological characteristics. This type of "segmentation" is called "morphometric analysis" or "quantitative geomorphology".

As part of the analysis morphometric are extracted quantitative information derived from bathymetry (such as slope, orientation, curvature, roughness, etc.). Which may be useful to divide the sea floor and to extract relevant biological units automatically and objectively all the geomorphologic features on the seabed. This approach also allows to quantify the morphological parameters of the elements and derive useful statistical information on the characterization of the underwater landscape, geomorphologic structure and then to marine habitats.

After converting raster DTM, the terrain analysis was performed in a GIS environment (Quantum GIS and Global Mapper). The variability or the complexity of the land was attached to the distribution of fauna by several researchers (Kostylev et al 2005), and, at appropriate scales, can be an important parameter in distinguishing suitable habitat for particular fauna. On a local level, some species require a complex habitat with a strong structural component (eg, rocky outcrops), while others tend to occupy a flat terrain typical of the soft sediment areas. On a larger scale, indices of variability of the ground reflect the relative changes in seabed morphology.

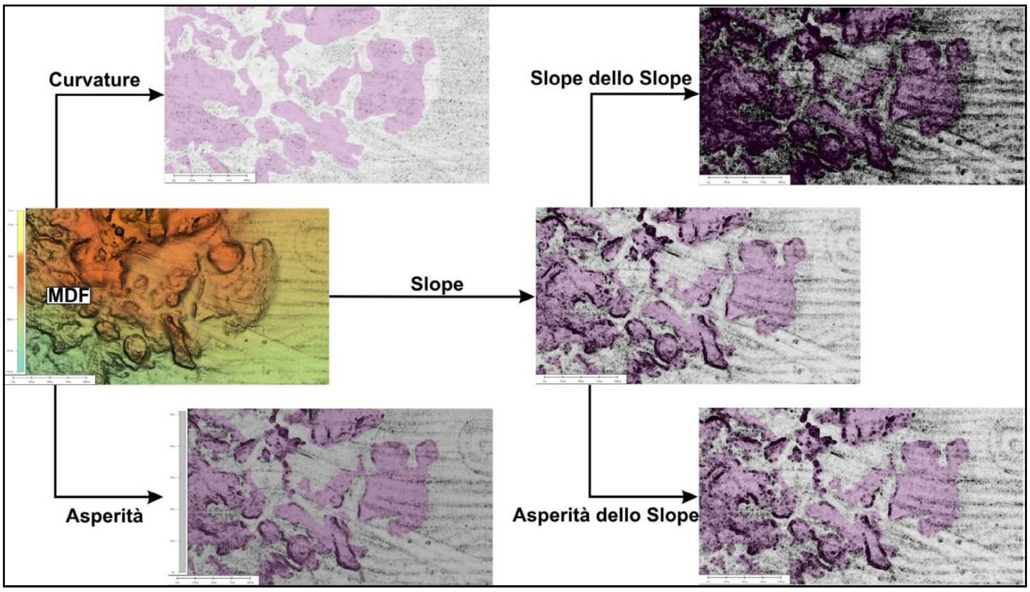


Fig. 26 - Selected variables for determining the areas occupied by coralligenous assemblages from seabed Digital Elevation Model (DEM). The areas occupied by coral reefs are filled in purple.

Description of selected variables for the Coralligenous assemblages habitat individuation:

Asperity

The Asperity (Roughness) index is a quantitative measure of the heterogeneity of the soil described by Riley et al (1999). It is calculated for each area by summing the change of elevation within the grid of 3x3 pixels.

Dartnell (2000) has used the statistics focal available in ArcInfo to compute the depth value of the minimum and maximum nxn within an area defined by the user of rectangular shape surrounding the central pixel. The roughness is then calculated as the difference between the maximum and minimum values. The roughness is understood as an expression of the variability of a topographic surface at given scale, where the scale of analysis is determined by the size of the morphology and the geomorphologic characteristics of interest. The variations of the surface of the seabed are associated with changes in habitat and colonization of particular importance for studies of habitat mapping.

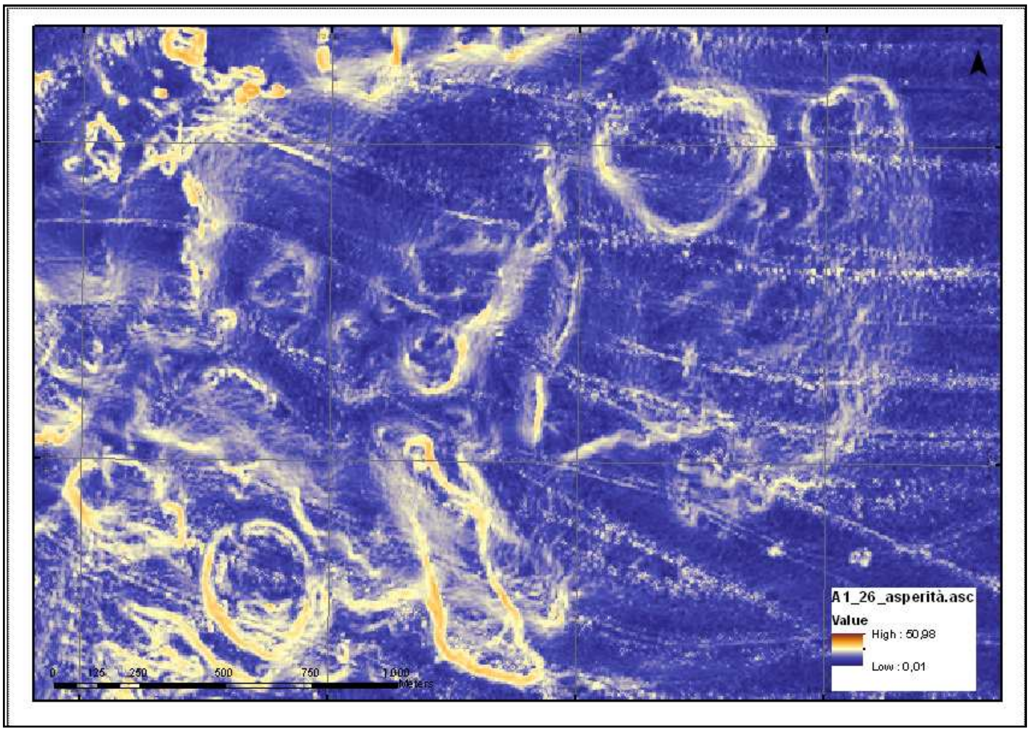


Fig. 27 – Toro Island, Roughness map calculated from a 5m bin size DTM. Roughness is calculated as variation of min/max values inside an area starting from a DTM allow to better identify even the less evident morphologies.

Asperity on Slope

This index calculates the asperity instead of starting from the depth data from the slope raster data. Dartnell (2000) has used the statistics focal available in ArcInfo to compute the depth value of the minimum and maximum within an area defined by nxn ' member of rectangular shape surrounding the central pixel.

The roughness is then calculated as the difference between the maximum and minimum values. The roughness is understood as an expression of the variability of a topographic surface at given scale, where the scale of analysis is determined by the size of the morphology and the geomorphologic characteristics of interest. The variations of the surface of the seabed are associated with changes in habitat and colonization of particular importance for studies of habitat mapping.

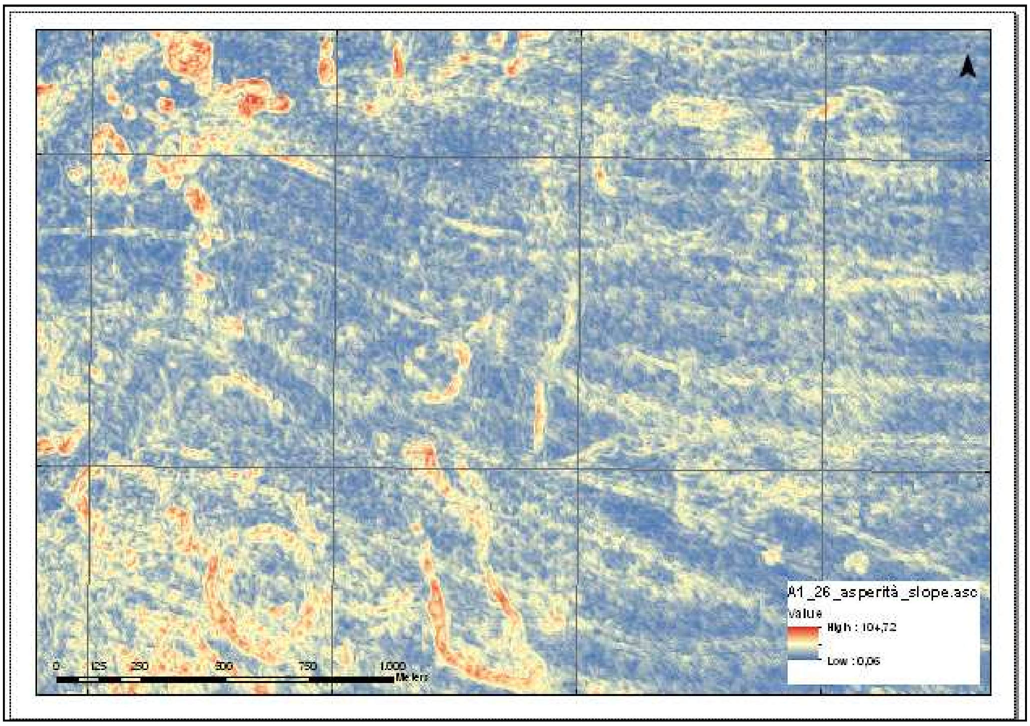


Fig. 28 – Toro Island, same area as previous example, in this case the change of min / max values within an area was calculated starting from the slope dataset with 5m resolution rather than by the DTM.

Slope

The Slope (slope) is the measure of the slope or degree of inclination of a surface with respect to the horizontal plane, the function calculates the maximum rate of change of each of its cell around. The function is calculated over a set of 3 x 3 cells and can be expressed both in terms of angular degrees (0 ° - 90 °) and in percentage.

Slope cards are designed to be an important factor in determining benthic habitats and colonization in the deep sea at a variety of scales. Flat areas tend to show different facies of the seabed and to host communities that are different from those of areas on steep slopes.

The Slope can also contribute to the amplification of current flow (Mohn and Beckmann, 2002), which has consequences for the supply of food for the benthic fauna.

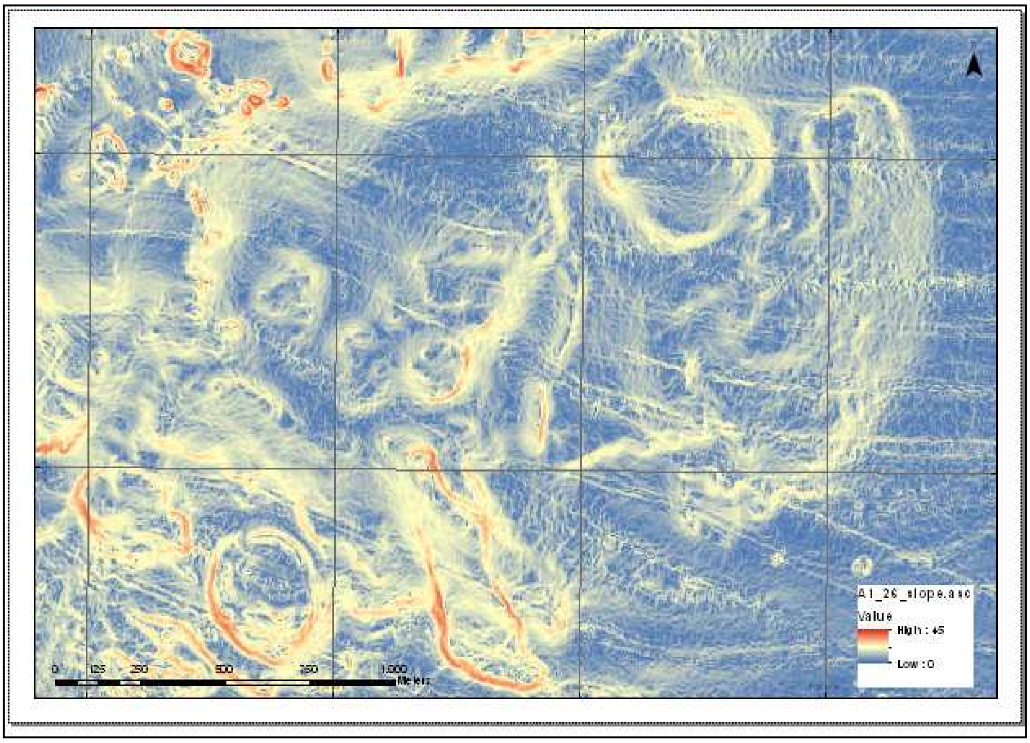


Fig. 29 - Toro Island, same area as previous examples,map of the slope calculated from DTM with 5m resolution. The result highlights the different slope classes, allowing to identify the steeper walls (red) and the flat areas (blue).

Slope II

The slope II is the second derivative of the slope which allows to filter the data of the slope and have a noise reduction as well as a highlighting of steeper slopes.

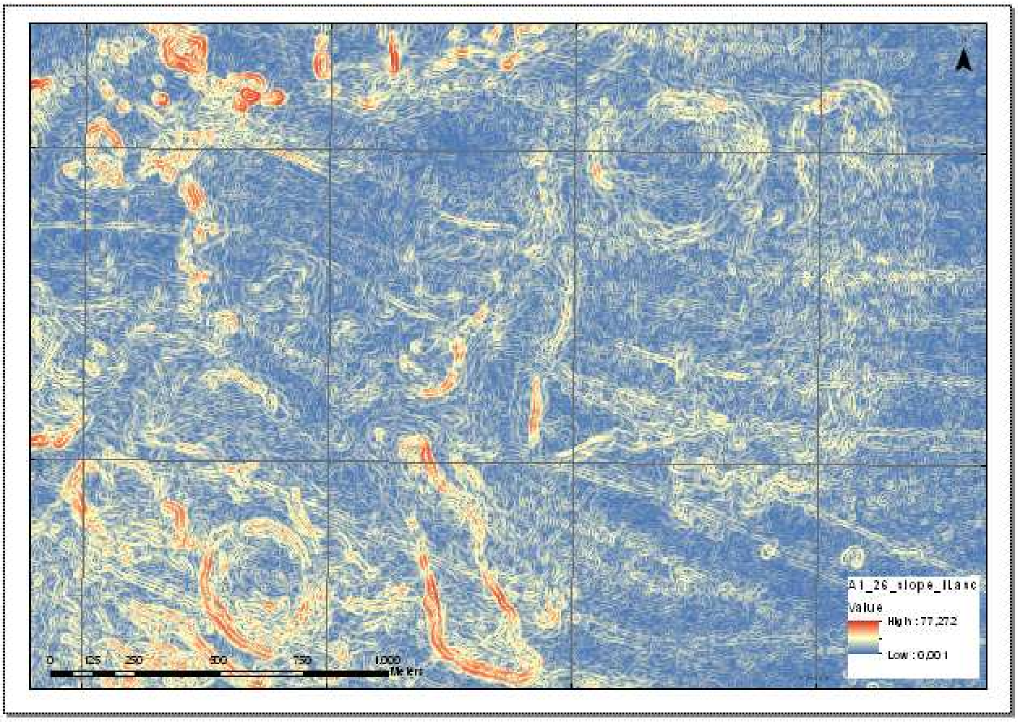


Fig. 30 - Toro Island, same area as previous examples, The second derivative emphasizes the extremes of the scale of the different slope classes as well as minimize the interference.

Planar Curvature

The curvature planar capture local variations of curvature and displays a simulated lighting. This is very useful to identify areas of rapid change in slope or exposure, technically bending plane is the second derivative along the perpendicular to the maximum slope, measure convergence or divergence topographical or the curvature of a profile designed around the pixel central and it describes the variation of exposure in the plane along the surface and may be useful to define ridges, valleys and slopes.A positive value indicates that the surface is convex with respect to the cells that are located laterally to the center cell, while a negative value indicates that the surface is concave with respect to the cells that are located laterally to the center cell. A value of zero indicates the surface is linear. The measures of curvature describes the relative position of the elements of the seabed and are important for the characterization of benthic habitats in terms of exposure to the currents and can also be connected to the nature of the seabed, the seabed characterized by the presence of coarse sediment, while the areas clearer are in fine sediments (high backscatter).

The measures of curvature describes the relative position of the elements of the seabed and are important for the characterization of benthic habitats in terms of exposure to the currents and can also be connected to the nature of the seabed. The planar curvature is the 'curvature of a profile designed around the central pixel. It describes the variation of exposure in the plane along the surface and may be useful to define ridges, valleys and slopes.

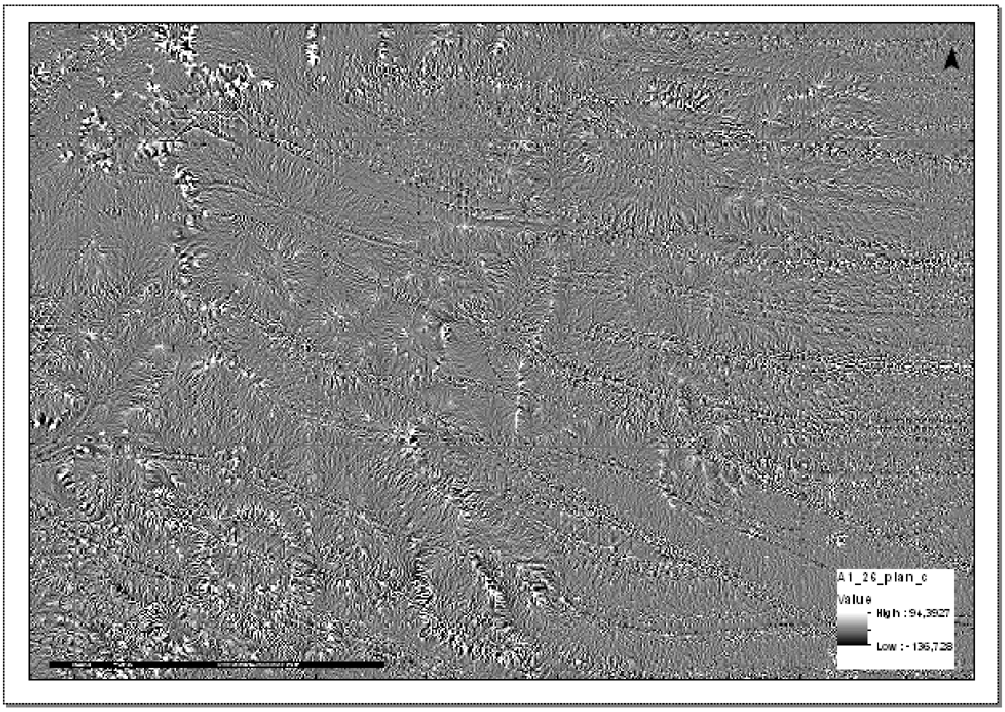


Fig. 31 - Toro Island, same area as previous examples, planar curvature calculated from DTM with 5m resolution. The curvature is useful for the detection of isolated peaks and ridges in the process of interpretation.

Backscatter

The acoustic reflectivity (acoustic backscatter) is a complex function of many factors, such as the acoustic frequency, the angle of incidence, the slope of the bottom of the stairs roughness, particle size distribution, the presence of flora and fauna on the bottom, the Bio-turbation and glare caused by penetration into the sediment.

Therefore, sound resolution (bathymetry and reflectivity) can be divided into "spatial units" representing "habitat units" discrete or continuous before being integrated with the information "in situ".

The morpho-acoustic image of the seabed (sonogram) expresses the variations in intensity of the backscatter, in terms of gray tones, associated with morphological changes, weaving / composition of the sediments and the presence of rocky outcrops.

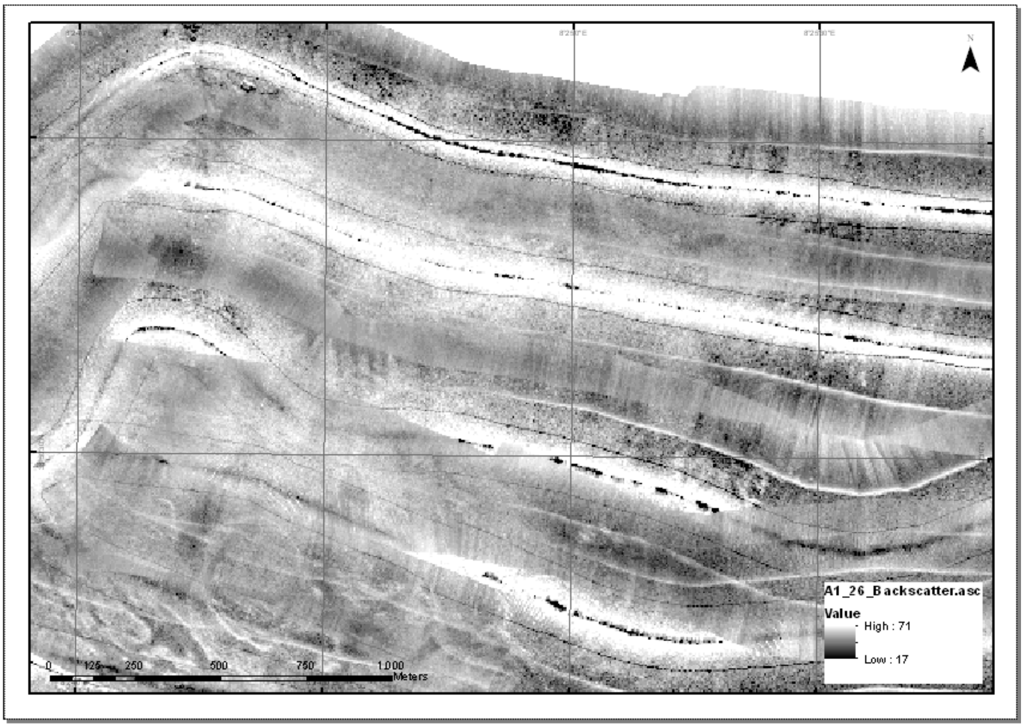


Fig. 32 - Toro Island, same area as previous examples , the backscatter image highlights the differences in reflectivity of the substrate. Rocky outcrops have a dark / dull response (low backscatter) as well as areas of seabed characterized by the presence of coarse sediments, while the lighter areas are characterized by fine sediments (high backscatter).

Working steps:

Coralligenous assemblages habitat mapping have been developed as follows:

1. STEP 1 - Critical evaluation of all available information, published and unpublished, about the distribution of coralligenous assemblages in the study area, extrapolation of polygons distribution model and restitution on DSM (digital surface model) from Multibeam (MBES). First screening based solely bathymorphologic of habitats that can accommodate the biotic "coralligenous", discrimination of the different facies based on preliminary analysis of the images backscattering (backscatter).

2. STEP 2 - Automatic analysis, unattended of Multibeam (MBES) data. Restitution of derivative products such as gradient (slope), orientation, seabed variability, roughness, acoustic facies, hardness, and curvature in a GIS environment; Segmentation analysis of acoustic facies.

3. STEP 3 - High resolution seismic data analysis (Sub-bottom profiler) on significant sections crossing areas of distribution of Coralligenous assemblages, with particular reference to algal bioconstruction facies.

4. STEP 4 - Cartographic synthesis, sample areas localization, ROV (Remotely Operated Vehicle) and detailed morphobathymetric survey planning for "sea truth" process.

5. STEP 5 – High detail multibeam survey of sample areas, processing and restitution of the new morphobathymetric data, segmentation analysis and backscatter in geo-habitat perspective.

6. STEP 6 - ROV Survey (Remotely Operated Vehicle). Based on the detection of detailed Multibeam survey, will identify areas of interest for ROV investigations. The ROV dive will be fully videotaped in HD, with underwater precise positioning of the vehicle through on board instrumentation. Geo-referenced high definition videos and photos will be the dataset for the next phase.

7. STEP 7 - Image analysis: the photos and videos captured in HD, will be processed with the help of CPCE software: image analysis performed with this specific software, ensures both the same method of analysis (Random Point Count) is the standardization of the sampled area for individual image. They will be obtained the following indices: number of species, surface cover, abundance, morphometry.

8. STEP 8 Sampling and analysis of species of particular interest / importance, to explore into details on what are the dynamics and structure of the population

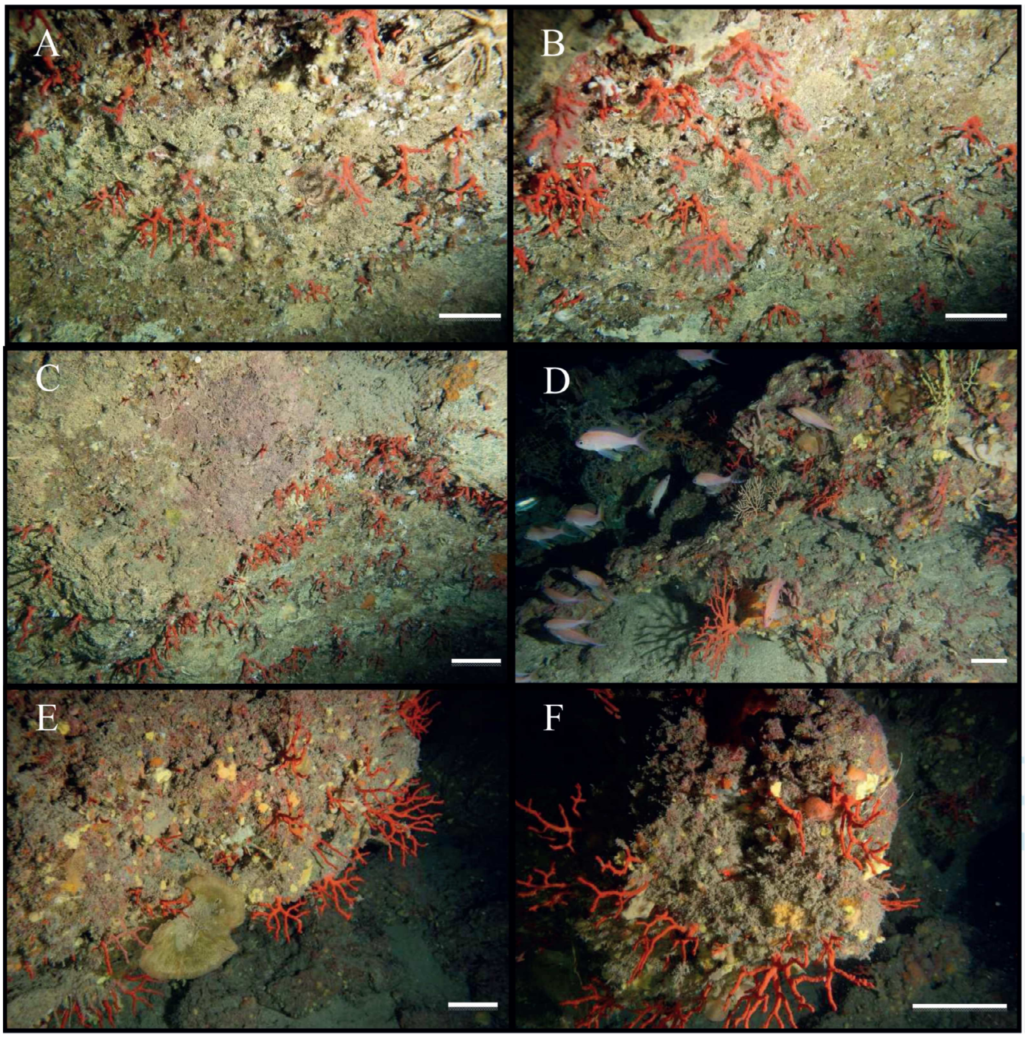


Fig. 33 –Several Red coral colonies identified during ROV surveys offshore San Pietro Island and Capo Carbonara. The execution of ROV surveys allowed us to validate our interpretative methods and model, efforts focused on Coralligenous biocoenosis can be extended in a later stage to different biocoenosis with significant confidence (from Cau, Paliaga et al., 2015).

Legislation: the Marine Directive in the EU, in Italy and Sardinia

The aim of the European Union's ambitious Marine Strategy Framework Directive is to protect more effectively the marine environment across Europe.

The Marine Directive was adopted on 17 June 2008, after several years of preparation and extensive consultation of all the relevant actors and the public, and came into force on 15 June 2008. It was due to be transposed into national legislation by 15 July 2010 then implemented in Italy by Legislative Decree. N. 190 of 13 October 2010.

Article. 4 from Legislative Decree N 190 / 2010 states that for Italy the authorities responsible for the Marine Strategy, according to the Directive, both the Ministry of Environment the territory and the sea (MoE), with functions of coordination national activities.

For coordination MoE uses a special technical committee, set up under article 5 of Legislative Decree 190 / 2010. To the Technical Committee, as well as representatives of the Ministry of the Environment, take part: a representative for each Region and Autonomous Province; a representative of the Union of Italian Provinces; a representative of the Italian National Municipalities. Are then represented the Ministries involved: Ministry of Agriculture and Forestry; Ministry of Infrastructure and Transport, Ministry of Health, Ministry of Defense, Ministry of Foreign Affairs, Ministry of Education University and Research, Ministry of Heritage and cultural Activities, Ministry of Economic Development and the Department for Regional Affairs.

To support the scientific and technical coordination of the activities of the Ministry of the Environment employs Institute for the Protection and Environmental Research (ISPRA), with whom he signed a special convention.

The Commission also produced in 2010 a set of detailed criteria and indicators to help Member States implement the Marine Directive. Marine Strategy Directive is based on an integrated approach and aims to become the environmental pillar of the future Maritime Policy for the European Union.

The MSFD calls for an assessment of the environmental status based on a list of characteristics listed below. The monitoring programme also addresses ‘physical loss’ and ‘physical damage’. Qualitative descriptors for determining good environmental status (referred to in the MSFD):

1) Biological diversity is maintained. The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions.
2) Non-indigenous species introduced by human activities are at levels that do not adversely alter the ecosystems.
3) Populations of all commercially exploited fish and shellfish are within safe biological limits, exhibiting a population age and size distribution that is indicative of a healthy stock.
4) All elements of the marine food webs, to the extent that they are known, occur at normal abundance and diversity and levels capable of ensuring the long-term abundance of the species and the retention of their full reproductive capacity.
5) Human-induced eutrophication is minimized, especially adverse effects thereof, such as losses in biodiversity, ecosystem degradation, harmful algae blooms and oxygen deficiency in bottom waters.
6) Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.
7) Permanent alteration of hydrographical conditions does not adversely affect marine ecosystems.
8) Concentrations of contaminants are at levels not giving rise to pollution effects.
9) Contaminants in fish and other seafood for human consumption do not exceed levels established by Community legislation or other relevant standards.
10) Properties and quantities of marine litter do not cause harm to the coastal and marine environment.
11) Introduction of energy, including underwater noise, is at levels that do not adversely affect the marine environment.

Most relevant descriptor, from the Earth Sciences point of view is Descriptor 6.

Descriptor 6: Sea-floor integrity is at a level that ensures that the structure and functions of the ecosystems are safeguarded and benthic ecosystems, in particular, are not adversely affected.

The objective is that human pressures on the seabed do not hinder the ecosystem components to retain their natural diversity, productivity and dynamic ecological processes, having regard to ecosystem resilience. The scale of assessment for this descriptor may be particularly challenging because of the patchy nature of the features of some benthic ecosystems and of several human pressures. Assessment and monitoring needs to be carried out further to an initial screening of impacts and threats to biodiversity features and human pressures, as well as an integration of assessment results from smaller to broader scales, covering where appropriate a subdivision, sub-region or region.

6.1. Physical damage, having regard to substrate characteristics

The main concern for management purposes is the magnitude of impacts of human activities on seafloor substrates structuring the benthic habitats. Among the substrate types, biogenic substrates, which are the most sensitive to physical disturbance, provide a range of functions that support benthic habitats and communities.

— Type, abundance, biomass and areal extent of relevant biogenic substrate

— Extent of the seabed significantly affected by human activities for the different substrate types

6.2. Condition of benthic community

The characteristics of the benthic community such as species composition, size composition and functional traits provide an important indication of the potential of the ecosystem to function well. Information on the structure and dynamics of communities is obtained, as appropriate, by measuring species diversity, productivity (abundance or biomass), tolerant or sensitive taxa and taxocene dominance and size composition of a community, reflected by the proportion of small and large individuals.

- Presence of particularly sensitive and/or tolerant species
- Multi-metric indexes assessing benthic community condition and functionality, such as species diversity and richness, proportion of opportunistic to sensitive species
- Proportion of biomass or number of individuals in the macrobenthos above some specified length/size
- Parameters describing the characteristics (shape, slope and intercept) of the size spectrum of the benthic community

Locally, the Autonomous Region of Sardinia with the Regional Agency of the Hydrographic District of Sardinia, protection and management of water resources service, took a coordination role, delegating scientific and technical activities to Universities and research institutes.

More in detail have been involved CNR – IAMC and IMC foundation (Oristano) operative unit and the Cagliari and Sassari universities units, both for the biological and geological issues. The department of chemical and geological sciences and the department of life sciences and environment of the Cagliari university, were responsible to restitute preliminary, intermediate and final charts of Coralligenous biocoenosis distribution for the southern Sardinian and Bonifacio Strait / La Maddalena area, SBP profiles interpreted in habitat mapping key, ROV transects and results and metadata sheets.

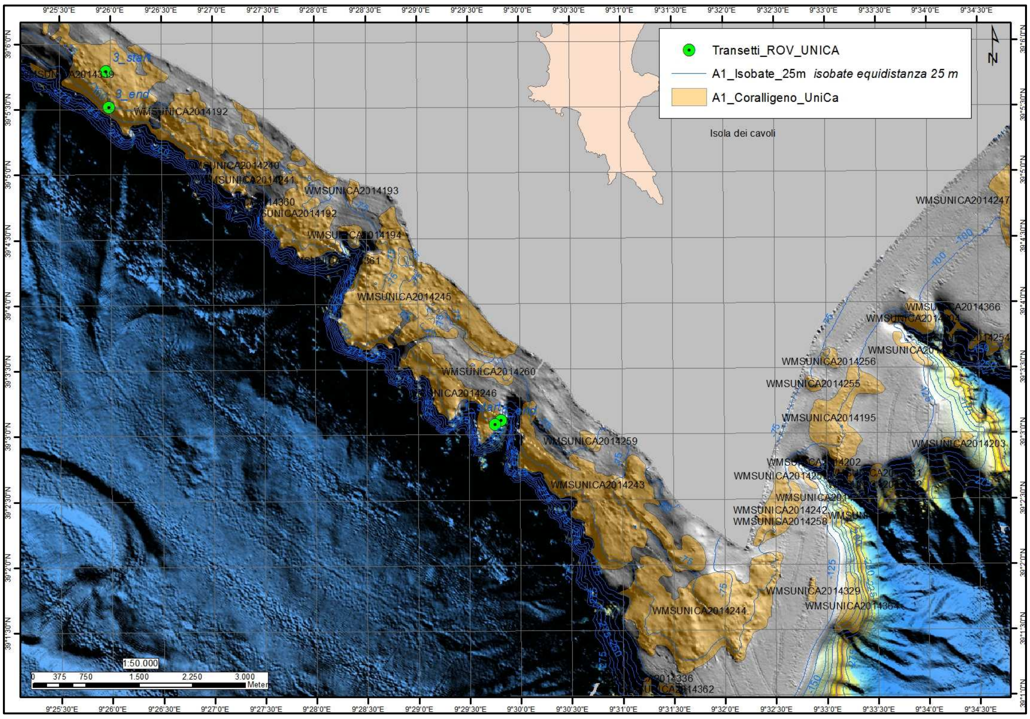


Fig. 34 – Assessment area 1, Sardinian southern margin, Capo Carbonara area. Marine strategy intermediate Coralligenous Biocoenosis charting example with foreseen Coralligenous biocoenosis distribution and ROV proofing surveys (green dots).

Broad area mapping 1: 50.000 scale

Area 1 - from Cape Altano to Cala Pira (southern Sardinia)

Area 2 - from Torre Vignola to Li Nibani (Strait of Bonifacio - North-eastern Sardinia)

Test sites, detailed mapping 1: 25.000 scale

a) Shelf edge and Toro Canyon head
b) Shelf edge and continental shelf of Capo Boi - Isola dei Cavoli
c) Shelf edge at La Maddalena - Caprera Canyon

The coralligenous habitat mapping have be done by reprocessing and re interpreting multibeam (MBES) data from an high resolution DTM (cell size 5m), these data have been divided down into "spatial units" representing discrete or continuous "habitat units" before being integrated with "in situ" information.

Within these primary data you can derive a set of secondary data by applying mathematical algorithms of analysis: gradient (slope), roughness, planar curvature but especially the reflectivity or acoustic back-scattering (acoustic backscatter). Useful for discriminating and mapping of habitat complexes and then for the preparation of a forecasting model of distribution. This process, called image segmentation (Cutter et al. 2003) or also commonly known as acoustic classification of the seabed (Acoustic Seabed Classification ASC) (Brown et al. 2011) produces the restitution of second order derivative thematic data.

The processes of unmanned “ automatic elaboration " if on one hand allow to reduce the computation time by following objective criteria, suffer from severe limitations of reliability of the resulting interpretive model (A <50%), which can be overcome only with the transition to the " expert interpretation" (Ehrhold et al., 2006).

In particular, the integration of other geophysical data (Sub bottom Profiler CHIRP high resolution seismic) and the comparison with the budget of previous knowledge, can make more "robust" the distribution forecast model of target habitat and help limiting the number and extent of the key areas to be subject to new Multibeam and ROV surveys. In this framework has been adopted a multiscalar analysis approach that will allow, starting from a wide area knowledge to detail the mosaic of biotic components in test areas significant for the presence of "Coralligenous" in different facies (EUNIS nomenclature): **A4.26** Continental shelf Mediterranean coralligenous communities moderately exposed to hydrodynamic action (-40 / -90 m); deep Coralligenous assemblages (-90 / -120m); **A4.713** Caves and overhangs with *Corallium rubrum* (-10 / -200m); **A5.11** Biocenosis of rocky bottoms substrates, bathyal zone (RL) facies *Leiopates glaberrima*. (- 130 / -230m) and **A5.63** Coral communities of the bathyal plan (white corals biocoenosis) (Cold coral), facies *Madrepora oculata* and *Ophelia pertusa* (not yet reported in Sardinia).

Concretely, what is the aim of the Marine Directive and how does it work?

The Marine Directive aims to achieve Good Environmental Status (GES) of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. It is the first EU legislative instrument related to the protection of marine biodiversity, as it contains the explicit regulatory objective that "biodiversity is maintained by 2020", as the cornerstone for achieving GES. The Directive enshrines in a legislative framework the ecosystem approach to the management of human activities having an impact on the marine environment, integrating the concepts of environmental protection and sustainable use.The Directive has divided the European marine waters in four regions: the Baltic, North East Atlantic Ocean, **Mediterranean Sea** and Black Sea, and for some of these took steps to further breakdown identifying sub-regions.

In the Mediterranean sea have been identified three sub-regions:

a) the Western Mediterranean sea

b) the Adriatic Sea

c) the Ionian Sea and the Central Mediterranean.

Italian waters belong to all three sub-regions. Given the nature of cross-border area of the marine environment, Member States are required to cooperate to ensure that their strategies are developed in a coordinated manner for each marine region or sub region. Also to ensure healthy and productive marine waters clean is vital that such strategies are coordinated, consistent and properly integrated with those provided by existing Community legislation (such as transport, fisheries, tourism, infrastructure, research) and international agreements.

The Framework Directive requires Member States to design a marine strategy that is based on an initial assessment, the definition of good environmental status, on the identification of environmental targets and the establishment of monitoring programs. For good environmental status of marine waters is the ability to preserve the ecological diversity and vitality of the seas and oceans so that they are clean, healthy and productive while maintaining the use of the marine environment to a sustainable level and safeguarding the potential for uses and activities by current and future generations.

What does a Marine Strategy include?

- The initial assessment of the current environmental status of national marine waters and the environmental impact and socio-economic analysis of human activities in these waters (by 15 July 2012)
- The determination of what GES means for national marine waters (by 15 July 2012)
- The establishment of environmental targets and associated indicators to achieve GES by 2020 (by 15 July 2012)
- The establishment of a monitoring programme for the ongoing assessment and the regular update of targets (by 15 July 2014).
- The development of a programme of measures designed to achieve or maintain GES by 2020 (by 2015)
- The review and preparation of the second cycle (2018 – 2021)

States must draw up a program of concrete measures directed to achieving these objectives. Such measures shall be developed taking into account the consequences that will have on the economic and social. To enable Member States to achieve the objectives, the directive has developed 11 descriptors that describe the ecosystem once the good environmental status has been achieved, Art. 19 of the Directive provides that the Member States involve the public and all stakeholders through a public consultation. Cooperation between the Member States of one marine region and with neighboring countries which share the same marine waters, is already taking place through these Regional Sea Conventions.

The main goal of the Marine Directive is to achieve Good Environmental Status of EU marine waters by 2020. The Directive defines Good Environmental Status (GES) as:

“The environmental status of marine waters where these provide ecologically diverse and dynamic oceans and seas which are clean, healthy and productive”

GES means that the different uses made of the marine resources are conducted at a sustainable level, ensuring their continuity for future generations.

In addition, GES means that:

- Ecosystems, including their hydro-morphological (i.e. the structure and evolution of the water resources), physical and chemical conditions, are fully functioning and resilient to human-induced environmental change;
- The decline of biodiversity caused by human activities is prevented and biodiversity is protected;
- Human activities introducing substances and energy into the marine environment do not cause pollution effects. Noise from human activities is compatible with the marine environment and its ecosystems.

The Directive aims to Member States to reach by 2020 the good environmental status (GES, "Good Environmental Status") for its marine waters. Each state must therefore put in place, for each marine region or sub region, a strategy that consists of a "preparatory phase" and a "program of measures".

In order to achieve GES by 2020, each Member State is required to develop a strategy for its marine waters (or Marine Strategy). In addition, because the Directive follows an **adaptive management** approach, the Marine Strategies must be kept up-to-date and reviewed every 6 years.

SARDINIAN SOUTHERN CONTINENTAL SHELF GEOMORPHOLOGY

BACKGROUND KNOWLEDGE

The knowledge on Sardinia surrounding seabed have been extremely poor until the second half of the 70's, series of physical oceanographic information have been acquired by the Italian Navy Hydrographic Institute, published in pilot books, and in charts at various scales. However these documents have been drawn for navigation scope, with particular reference to safety, especially close the coastline, so seabed beyond the -20 meters isobaths is represented with by quoted points, hardly useful for the reconstruction of submerged morphologies.

For these reasons, when in the second half of the '70s the CNR's research project "Oceanografia e fondi marini" started, the systematic study of the continental shelf of Sardinia in order to reconstruct the morphology, geomorphologic evolution and geological structure were set on an almost void base knowledge. Purpose of the Project, was to identify the evolutionary conditions on the continental shelf, both current and past, that could have favored the formation of "placers", i.e. concentrations of minerals, which have already been detected in some beaches (Ulzega, 1980).

The western continental margin of Sardinia have been explored by geophysical surveys and drillings (Finetti & Morelli, 1973; Ryan & Hsu, 1973), the first investigations on the continental shelf were carried out by the University of Trieste (1970) and by the University of Genova (1974 -75) (Fanucci et al, 1976). Subsequent seismic reflection data were collected during the PF Oceanography and Marine bottoms (Sparker-Uniboom the 0.5-kJ, Scient. Resp. A. Ulzega), on the occasion of a collaboration between the University of Paris and the University of Cagliari (Resp . Scient. Gennesseaux M. and L. Lecca, Countryside oceanografica "Marge Sarde" of 1985 (Thomas et al, 1988) and, finally, during different seismic campaigns (1983-1991, Sparker 1-3.5 kJ) and samplings in the framework of the research project Continental Margin of Sardinia held by the University of Cagliari (performed by research vessels of the CNR, Resp. Scient. L. Lecca).

Since 1976 a number of oceanographic cruises have been carried out with CNR's O/V Bannock, organized and conducted by the operative unit connected with the Institute of Geology of the University of Cagliari, interesting the major part of the continental shelf of Sardinia up to the -200 meters bathymetric line. During the cruises were carried out High Frequency Narrow Beam, 12 kHz echographic surveys, Side Scan Sonar, high-resolution 800-1000 J Sparker, Uniboom and Sub Bottom Profiler 3.5 kHz and magnetometric surveys in addition to a number of sampling stations of seabottom sediment using buckets, dredges, gravity corer and direct withdrawals with divers. All operations were performed with radio positioning system Loran C. Ulzega (1980), basing on the data acquired during oceanographic cruises performed under the Project on " Oceanografia e fondi marini", defines the main structural and morphological features characterizing the continental shelf of Sardinia: at first glance purely physiographic highlights the differences between the eastern and western margin (Fig. 35).

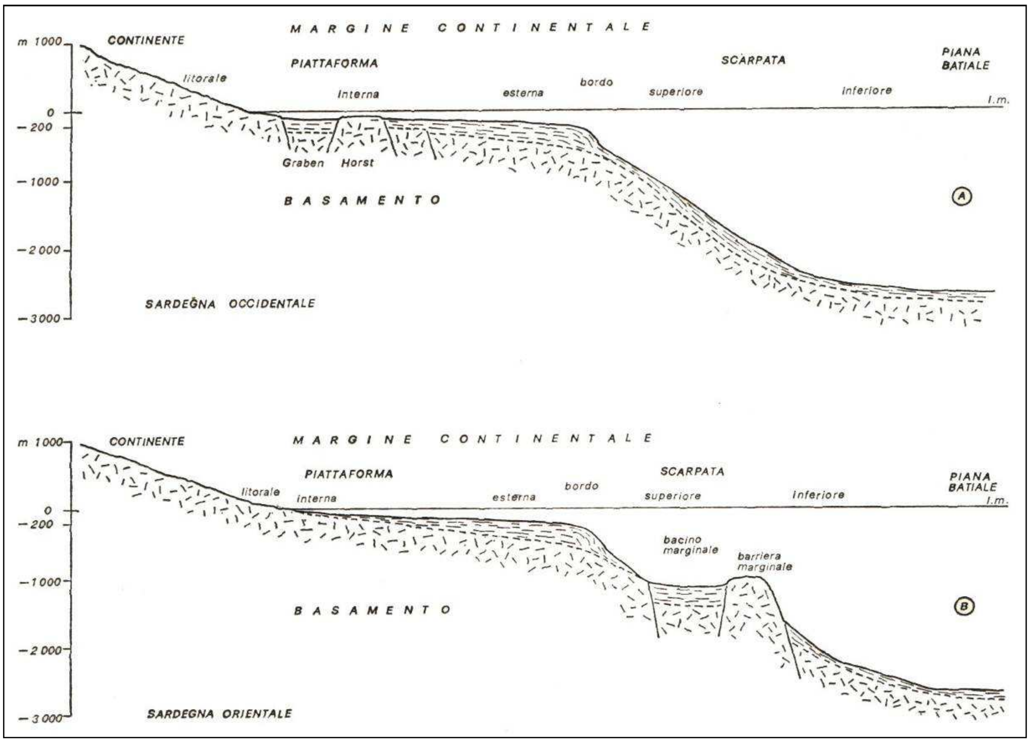


Fig. 35 - Representative profiles of the continental margins of western (A) and Eastern Sardinia (B). The covers are represented by Pliocene-Quaternary sediments (from Ulzega, 1980).

The first has an average width of a few kilometers, with a very steep slope that ends at the depth of -1000 meters approximately in correspondence with the Sardinian basin, while the second has an average width variable up to about 50 kilometers and a steep slope that stretches to the abyssal plain of the Sardinian Sea at a depth of about -2800 meters. More complex are the geomorphologic and geological characteristics, the nature of which is strictly related with the stratigraphic and structural setting of emerged lands (Ulzega, 1980). The continental shelf of western Sardinia, from the Sulcis archipelago (south) to the Nurra (north), has a varying morphology shows a complex structure with tectonic highs and trenchs parallel to the coast, with occasionally outcropping bedrock. Totally different are the characters of the eastern platform, from Sarrabus (south) to the Gallura (north)region.

The width is extremely limited (from less than 2 Km to about 15 Km), due to a series of tectonic features trending north-south parallel to the shore line which affects the upper slope and the shelf edge (Ulzega, 1980). A series of deep canyons, east-west oriented, deeply affect both the slope than the shelf (San Lorenzo, Orosei, Posada canyons etc.). Shelf edge lies at the constant depth of about -125 meters coming up at lower depths in correspondence of the retreat for regressive erosion of the heads of the canyons.

Based on the data acquired during the Project "Oceanography and Marine Seabottoms", Ulzega et al. in 1988 produced the Geomorphological Marine and Continental Chart of Sardinia " scale 1: 500.000; mapping for the first time continental margins of Sardinia. In the seismic lines of the entire margin, Lecca (2000) recognizes the stratigraphic characters of the upper Miocene sequence and in which the lower parts, consisting of continental and littoral units, are not highlighted by seismic data or are often confused with the underlying basement . At this moment the only certain stratigraphic data come from the results of the DSDP 133-134 (Ryan & Hsu, 1973), which documented over Ercinic phyllites the presence of different Miocene facies. Therefore, in the seismic lines it is possible to recognize that the lower margin tectonic blocks have been extensively covered by the Miocene turbiditic succession, which continues up to the bathyal plain where is called Miocene infrasalino (Rehault et al, 1984). While the lower Miocene sequence located within the half graben, is correlated with the sin-rift unit (Cherchi & Montadert , 1982) (Thomas et al, 1988).

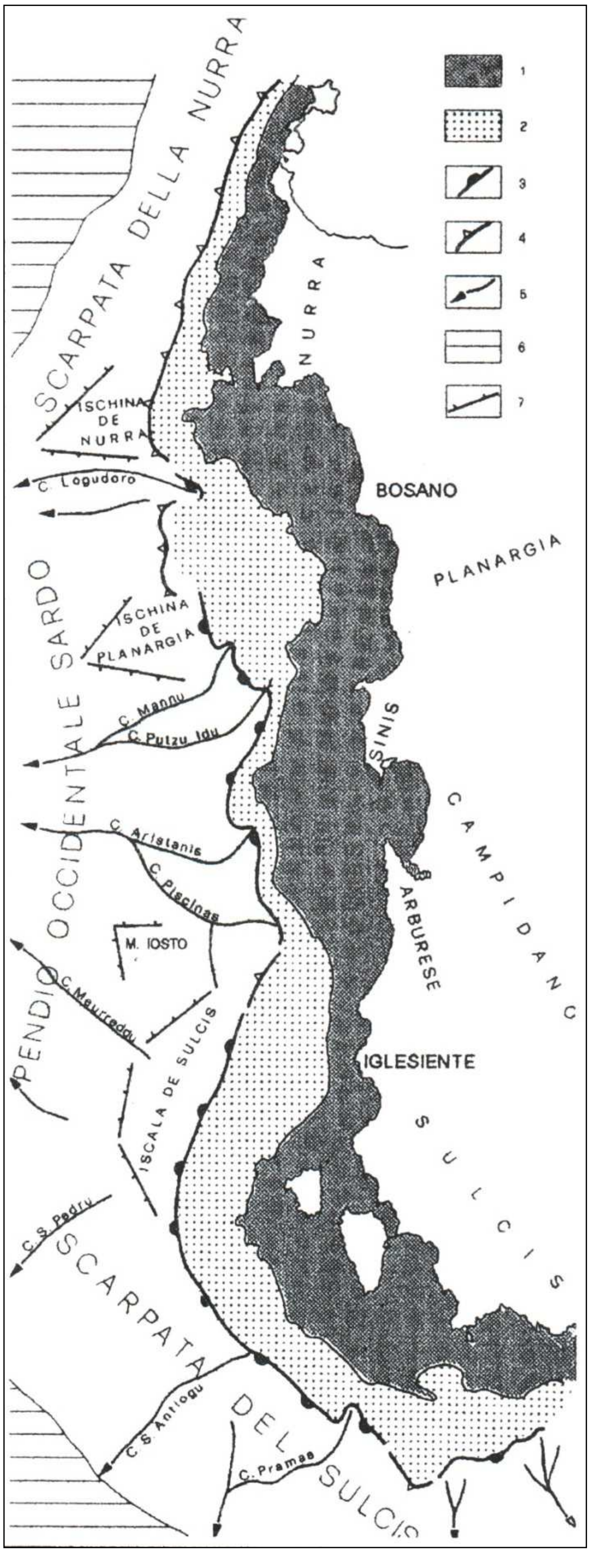


Fig. 36 - Geomorphologic sketch of the continental shelf and upper-intermediate slope of western Sardinia: 1) inner shelf, 2) outer shelf, 3) prograding shelf-break, 4) structural shelf- break, 5) canyon, 6) abyssal plain, 7) structural slopes (Lecca, 2000).

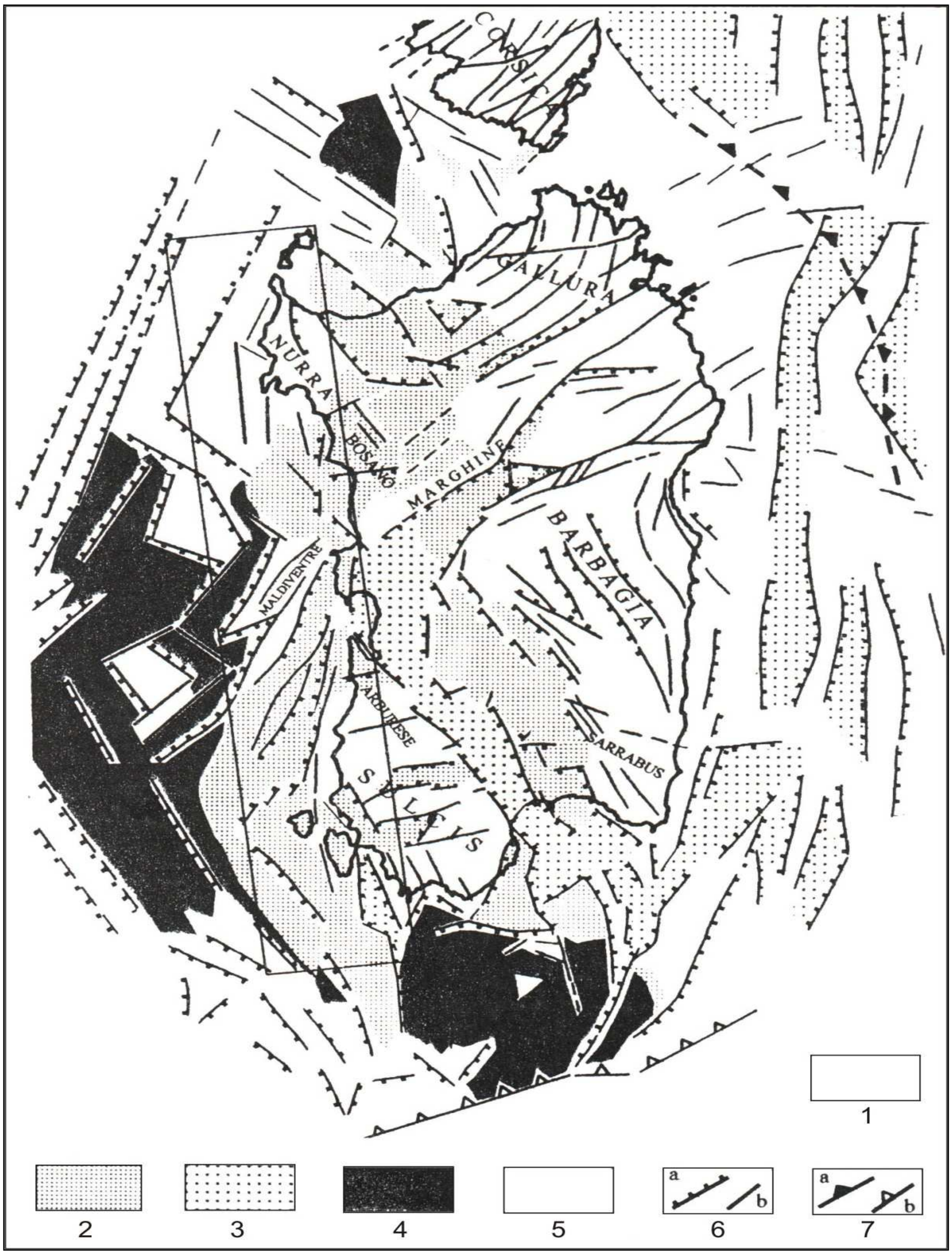


Fig. 37 - Tectonic structure and Neogene basins of Sardinia and continental margins. 1) pre-rifting blocks constituted by Hercynian basement with limited Mesozoic and Paleogene covers; 2) semi-graben basin or asymmetric graben "Rift Sardo" filled by volcanoclastic and continental sedimentary sequences and by epicontinental marine sequences, terminal Oligocene medium upper Miocene, dislocated by various stages of extensional tectonics; 3) reactivated extensional basins associated with the opening of the Tyrrhenian Sea and filled by middle-upper Miocene and Pliocene-Quaternary sequences; 4) Miocene basins of the western and southern margins of Sardinia, probably partly belonging to the Oligo-Miocene Rift Sardo system, covered by Pliocene-Quaternary sequences; 5) Western Mediterranean bathyal plain below which are Miocene infra-evaporitic sequences, Messinian evaporitic and Plio-Quaternary; 6) fault zones: (a) extensional and (b) transtensive; 7) (a): flaps front of the Alpine Corsica, (b) limit of Blocco Sardo with Maghrebian Chain. The box indicates the position of the continental shelf of western Sardinia (Lecca, 2000).

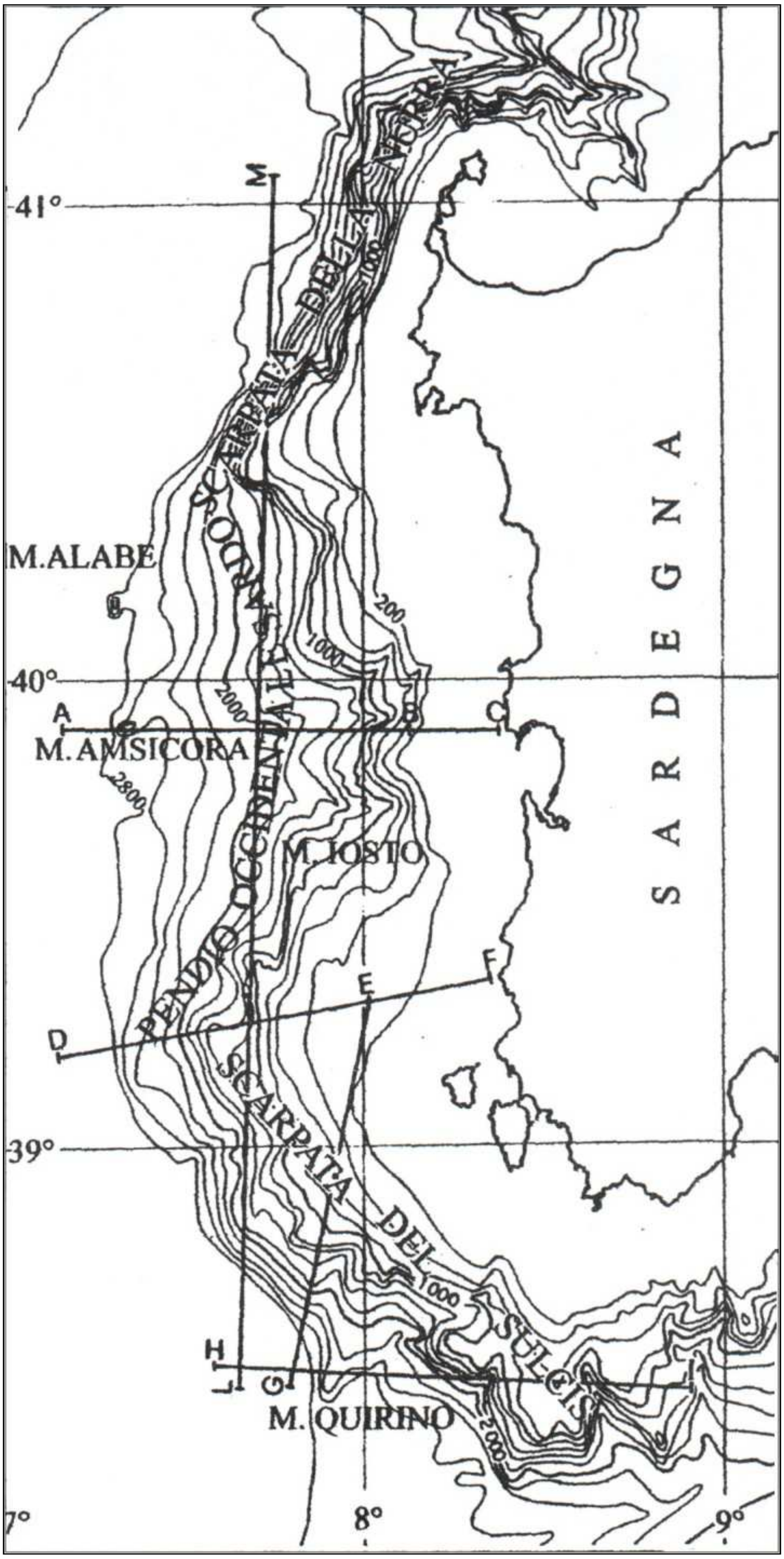


Fig. 38 - Bathymetric sketch of western Sardinia continental margin with interpreted seismic lines (Lecca, 2000).

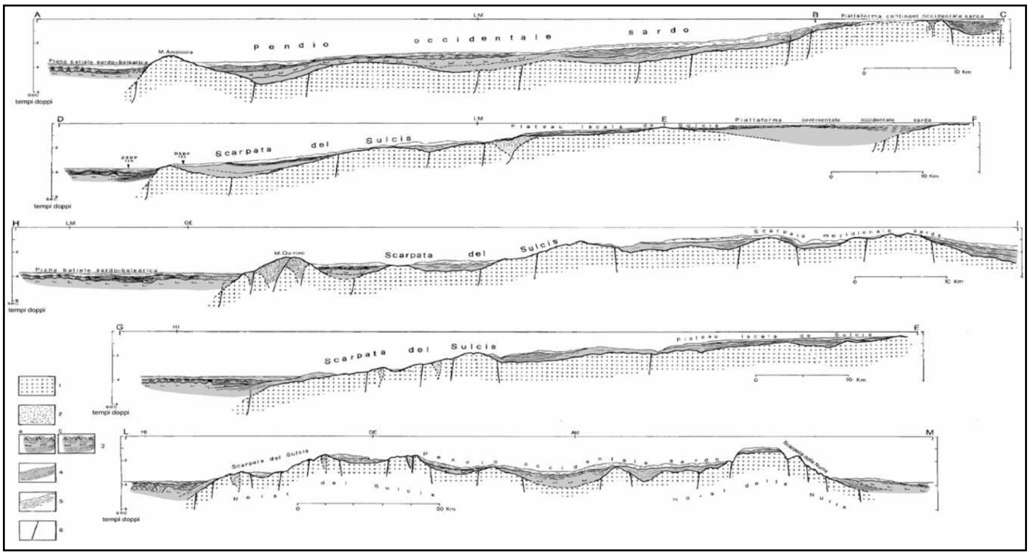


Fig. 39 - Geological interpretation of Flexotir, Aquapulse and Sparker seismic lines (Lecca 2000). 1) Base pre-rift: Hercynian basement with local covers by Mesozoic and Paleogene; 2) Oligo-Miocene volcanic assumed on the basis of the presence of magnetic anomalies, β) Pliocene-Quaternary basalts; 3-4) Miocene marine sequence: 3a) Messinian evaporite sequence with evidence of diapirims in abyssal plain, 3b) sequence with reduced Messinian evaporites, at the base of the margin, 4) pre-Messinian part: infra-salt in the abyssal plain and turbiditic sequence in intermediate and upper margin; 5) Pliocene-Quaternary sequence; 6) fault zones.

The transition to the bathyal plain is often marked by the culmination of the last tilted blocks of the margin, which interrupt the continuity of the Miocene infrasaline sequence between the lower margin and the bathyal plain (Lecca, 2000). In the upper margin the Miocene turbiditic sequence is limited upwards by the erosive surface correlated with the Messinian eustatic-evaporitic regression and caused, as is known, by the separation of the Mediterranean from the Atlantic probably for tectonic closure (Hsu et al, 1972). Otherwise, the base of the lower margin, on the Miocene turbiditic sequence lies, often in para-correlation, the Messinian sequence with reduced thickness compared to that of the bathyal plain. In the bathyal plain sequence the saline unit is always present, while in the lower part of the margin (between the base and 2.5 to 2.75 sec TWT, that means approximately between 2800 and 2131 to 1937 meters deep) is observed a reduced Messinian sequence, likely with side associations of more proximal facies, and no clear evidence of chlorides unit with the exception of some rare cases (Lecca, 2000).

In addition to Oligo-Miocene structuring and the continuation of an extensional phase during the middle Miocene, can be recognized post-Messinian extensional tectonic reactivations located throughout the various levels of the margin and especially at its base, correlated with the opening of the Tyrrhenian Basin (Lecca, 2000). Above all these sedimentary units lies the Pliocene-Quaternary turbiditic sequence with parallel stratification in middle and lower margin regions, and with clinoform prograding setting in the upper margin and the outer continental shelf. The basis of this sequence is sometimes highlighted by reflections with on lap geometries interpretable as littoral products. Can also be identified a maximum floding surface topped by seismically almost transparent sediments, little stratified, which vary upwards to better stratified sediments, probably emipelagites and sandy turbidites. Therefore, regarding Messinian eustatic event, which can be considered a third order event, amplified by evaporitic phase. Using the concepts of sequence stratigraphy (Wilgus et alii, 1988) can be identified: a truncation of falling sea level and subaerial erosion, a low stand sistems tract, a transgressive sistems tract (usually recognizable in the lower margin), a discrepancy of transgressive surface, a maximum flooding surface, and finally a high stand sistems tract corresponding to Pliocene-Quaternary (Lecca, 2000). Sardinia southern continental shelf, in the area that extends to the west from Cape Altano till Cala Pira to the East, reflects at sea the structural and sedimentary features of adjacent emerged areas. From West to East different morphological styles take turn, the sectors overlooking the islands of San Pietro, Sant'Antioco and the Gulf of Palmas, are mainly characterized by a particularly wide platform that gently degrades to the shelf edge located at a depth of about -180m.

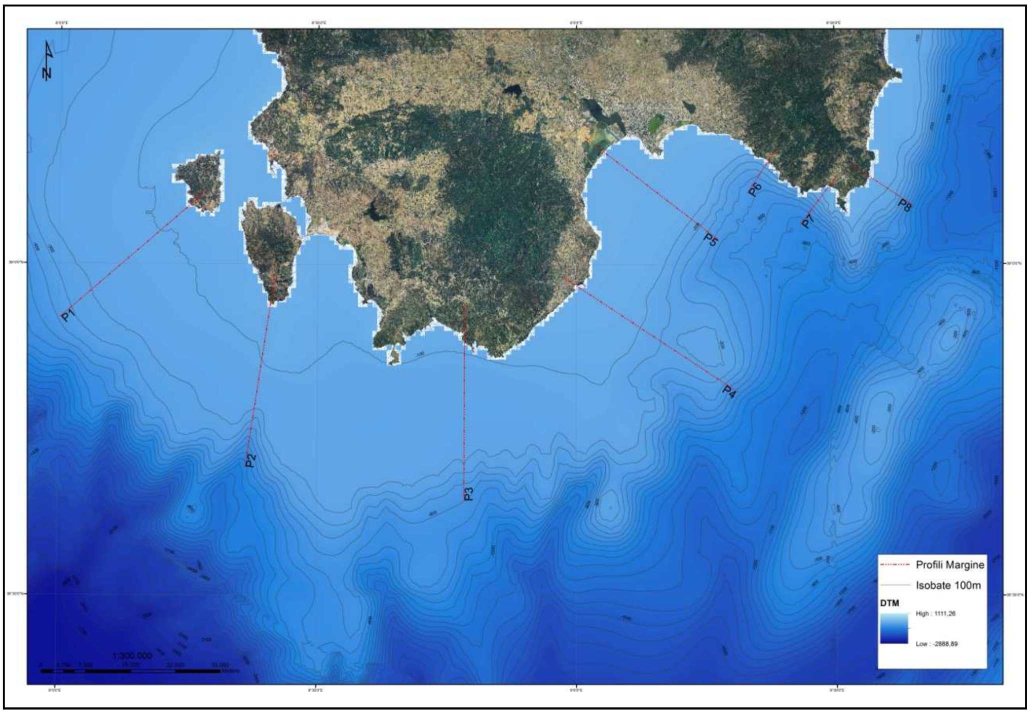


Fig. 40 - Morphometric profiles localization along south Sardinian continental margin acquired on the basis of GRID 30s GEBCO.

The sector of the continental shelf between Capo Teulada and Capo di Nora, is also characterized by regular morphologies, and is home to the volcano-sedimentary series of outcrops oligo-Miocene, the edge of the platform lies at a depth of approximately -130m and is interested indentation of the many heads of the Canyon Teulada, Teulada and Nora. Within the Gulf of Cagliari, in the area between Cape of Nora and Cala Regina, attitude morphostructural the continental shelf, and in general of the continental margin, are strongly influenced by the continuation of the main tectonic features of the Campidano graben. The edge of the platform lies at an average depth of -120m in the west borders the platform of the southern Sulcis and to the east with the platform of the Sarrabus. The style that characterizes the continental shelf in the area between Regina and Cala Cala Pira affected, in the inner Gulf of Cagliari the tectonic control of the continuation of a mare important tectonic features of southern Campidano, while the eastern sector, from Cape Carbonara to Cala Pira, reflects the structural setting of the eastern edge of Sardinia, characterized by an average width of a few kilometers, with very steep escarpment that stops at the depth of -1000 meters at the Sardinian basin.

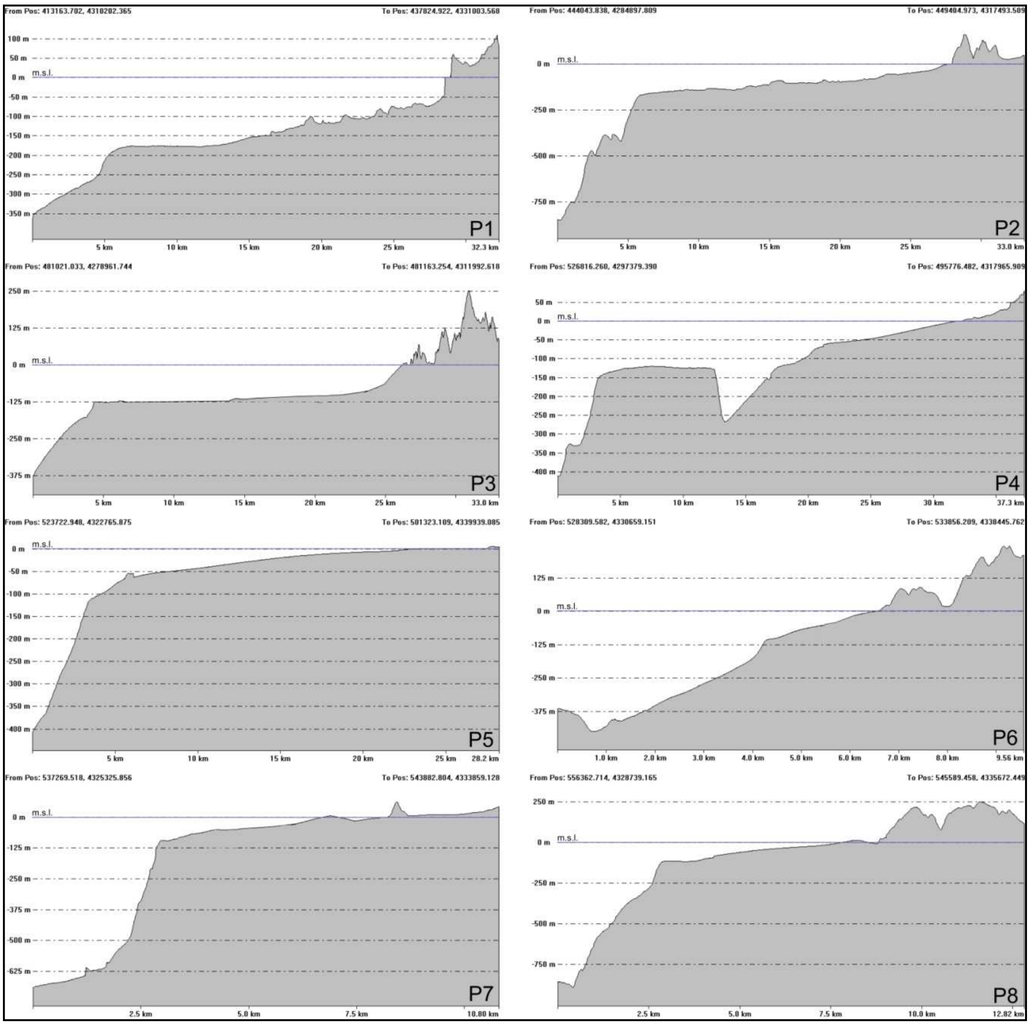


Fig. 41 - Morphometric profiles of south Sardinian continental margin extracted from the 30s GEBCO DTM. Localization is in Fig.8

Here below the study of the four previously distinct areas of the continental shelf will be deepened.

Sector 1 –Capo Altano to Capo Teulada

South Western Sardinia continental shelf morphology is the result of the structural control by major tectonic features characteristic of the western continental margin. The special character of the Sardinian western edge is represented by a strict conditioning by the structural elements; tectonic and neo-tectonics movements affect the sedimentation and mask the effects of a normal morphogenesis linked to erosion and depositional (Ulzega, 1980). In this area, as in all the continental margin of western Sardinia, the continental shelf is particularly extended, with a width that reaches 20 NM, and whose edge lies at depths ranging between -200 and -180m, on this shelf section are indented the Sant ‘Antioco canyon head, and to the south of Toro island, the Palmas canyon head

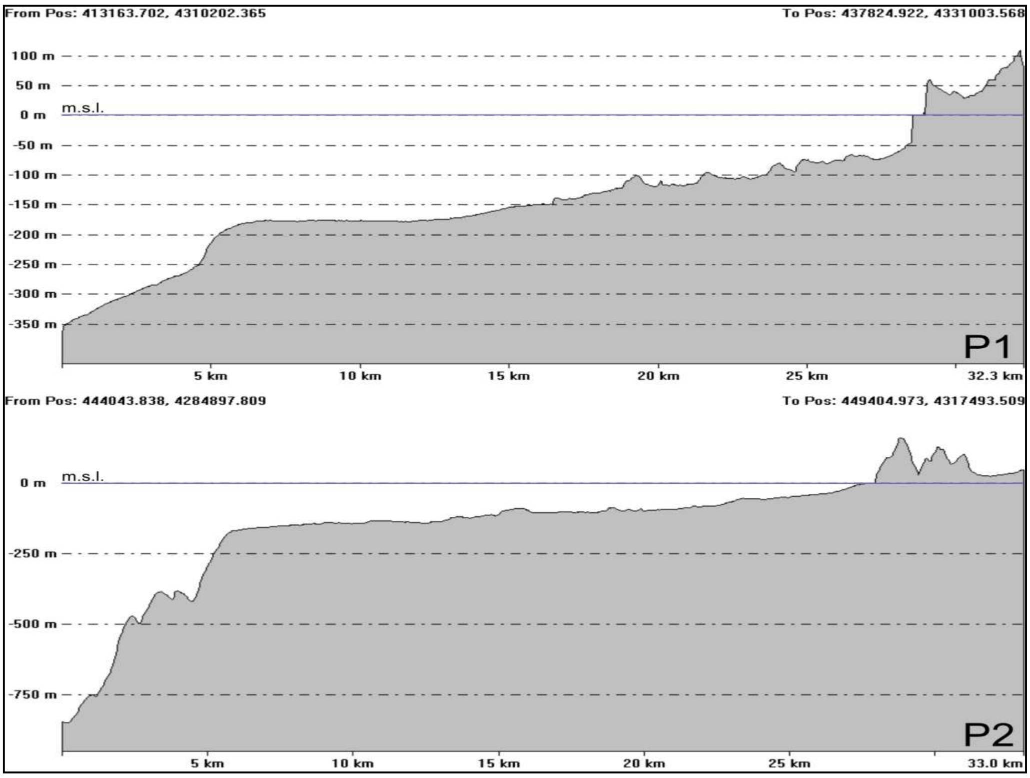


Fig. 42 - P1 and P2 Sardinian south western margin profiles, there is the considerable extension of the continental shelf in this area and the inner platform is characterized by an articulated morphology determined by extensive outcrops of Oligo-Miocene volcanic sequences, the shelf edge lies at depths between -180 and -200m.

In 1989, Orrù and Ulzega with the "Carta geomorfologica della Piattaforma Continentale e delle Coste del Sulcis" in scale 1: 10000 (Fig. 43), show that the continental shelf of the south-western Sardinia presents itself sharply divided in an inner sector, most articulated where some of the most obvious signs of volcanic events Oligo-Miocene and Pleistocene eustatic oscillations of level can be noticed, and an outer sector with a certain regularity. The most significant inner platform morphological highs are represented from the Corno island and the top surfaces of lava flows of San Pietro island, the islands of Toro and Vacca, Banco Pomata and Cala sapone, Tabacco and Mastrili shoals, while in outer shelf particularly evident is the San Pietro trench.

Outer continental shelf is generally characterized by a Plio-Quaternary sediment cover prograding on the edge (at a depth of -180 meters). The rocky outcrops are constituted sometimes by the Miocene sedimentary sequence, but more frequently from tertiary volcanic calc-alkaline rock types which build up on the islands of S. Antioco and San Pietro lying on the Mesozoic substrate outcrops in S.Antioco. While the continental shelf in the Gulf of Palmas, is a relative low along an extensional tectonic fault zone, probably with weak transcurrent component and whose filling happened in the Middle-Upper Miocene. Within this depression the Messinian erosion and subsequent full filling occurred during Pliocene and Quaternary. The structural high, continuation of the Toro island, separates the inner shelf, where we observe an Pliocene initial phase of accretion inside the depression, from the outer platform constituted by a reduced prograding prism (Lecca, 2000).

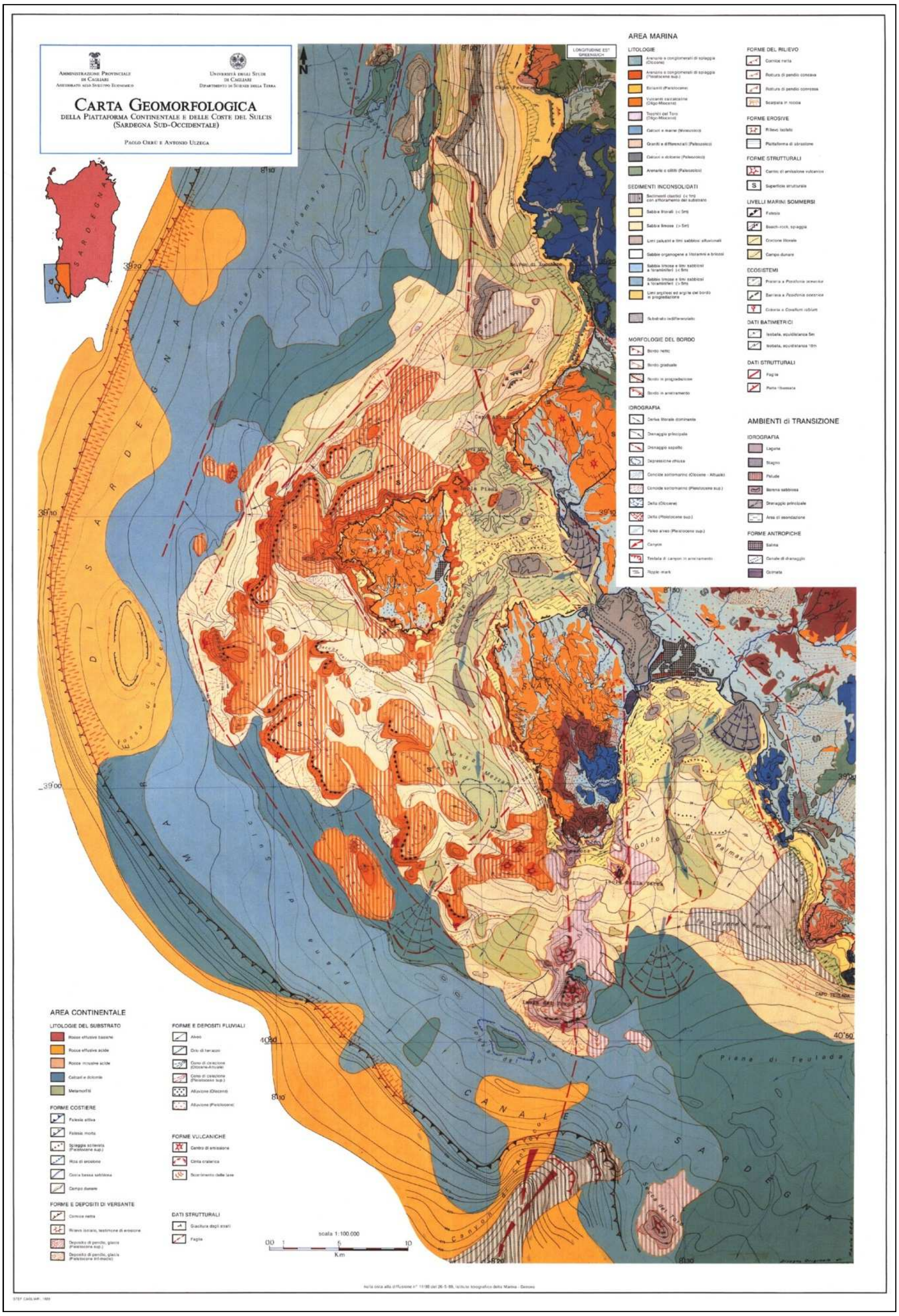


Fig. 43 - "Continental Shelf and Sulcis coasts geomorphologic chart" scale 1: 10000 from Orrù & Ulzega (1989).

NEW FINDINGS

On south western Sardinia continental shelf, 10 miles off Cape Sandalo, the boundary between internal and distal platform is identified, represented by a series of volcanic paleo-cliffs engraved on the volcanic substrate (Fig. 13), as observed by Orrù & Ulzega in 1989. It seems obvious that these morphologies are controlled by tectonic lineation NNW-SSE and NE-SW oriented. Similar morphologies can be observed along the coastline in the area between Capo Altano and Porto Paglia, where the same volcanic formations outcrops.

On rock walls can be observed a complex paleo-landslide with his detachment niche and a large deposit of blocks collapse at the base. These large structurally affected morphologies, whose foot is located at an average depth of -140 meters and the top at -90 meters, probably evolved in sub-aerial environment during Messinian age and then reactivated during subsequent emersions.

The hypothesis that the gravitative and erosive morphologies observed may be related to the last phase of stationary low sea level during the last glacial maximum (MIS 2), was confirmed by sampling a littoral thanatocoenosis close to the island of San Pietro.

C1 Beta – 310989 - D2 - Mytilus cf galloprovincialis 15360±280 BP cal.

C2 Beta – 310992 - D5 - Acmaea virginea 19100±270 BP cal.

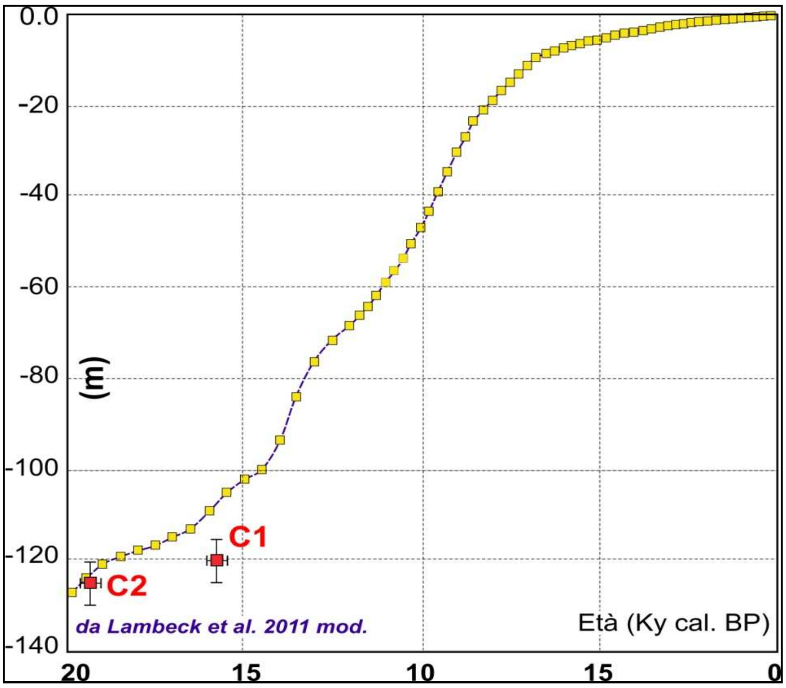


Fig. 44 - C1 and C2 samples comparation with glacio-hydro-isostatic curve predicted for western Sardinian shelf for the last 20.000years (Lambeck et al., 2011).

On the DTM has been identified a palaeo ria, that breaks the continuity of the rock frames at -130 m; the inner bay opens into a large amphitheater, rising up to -120m. On the bottom, now filled by fine sediments, there should be a palaeo-lagoon during MIS 2 sea low standing, it is unclear whether this morphology is the result of erosion or if it is part of a volcanic caldera or submerged crater, like others nearby. The samples of the seabed, taken by dredging, showed a black-gray sandy silt full of molluscs belonging to a littoral thanatocoenosis, lagoon and shallow water and some sort of shelf habitats, which have not yet been completely classified.

Some fossils were analyzed through a C14 dating tests at Beta Analytics, Miami USA. The results allow to relate the thanatocoenosis with a sea level that can confirm the presence of a lagoon during the LGM.

The inner shelf area is characterized by large mesas, cuestas and other typically volcanic morphotypes (Fig. 9) such as calderas and necks (Fig. 10, Fig. 11), separated by deep incisions, often filled by coarse sediments both of bioclastic and terrigenous origin (partly due to the productivity of seagrass meadows). The mega-dykes system, highlighted by the differential erosion, affect the whole area of the emission centers and follow a tangential trend that continues for more than 6 km without solution of continuity (Fig. 45).

The emplacement of this great mega-dykes system, the geodynamic context of the Tertiary rifting, has similarities with such incidents, at least as regards the characteristics of size, with areas of active rifting (Wright et al., 2006; Ayele et. al., 2009).

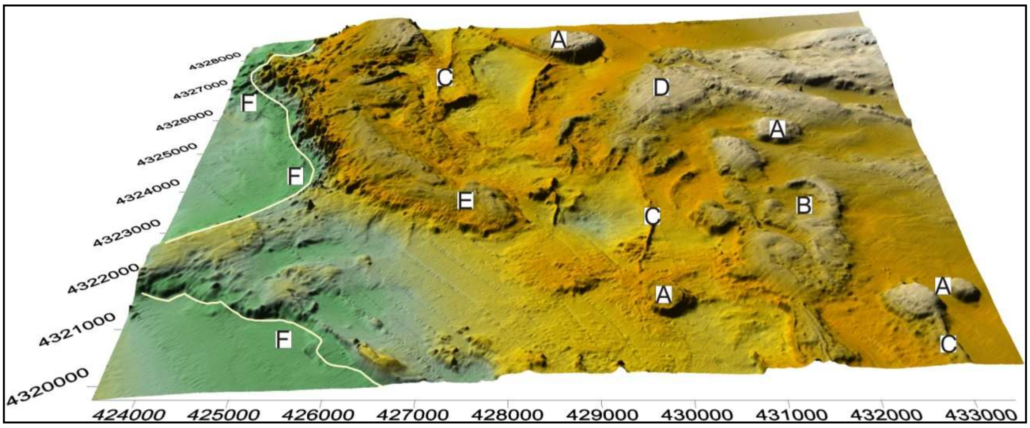


Fig. 45 - - The DTM shows the main in the area: A) Several Necks are highlighted from selective erosion; B) the edge of a collapsed caldera can be identified in the area; C) A mega-dykes system, mainly N-S oriented, goes through the whole volcanic district. Mesas (D) and cuestas (E) are also present in this area. A cliff alignment, about 50metres high define the limit between inner and outer shelf, the cliff foot lies around -140m (F), retracing the paleo sea-level of the MIS 2.

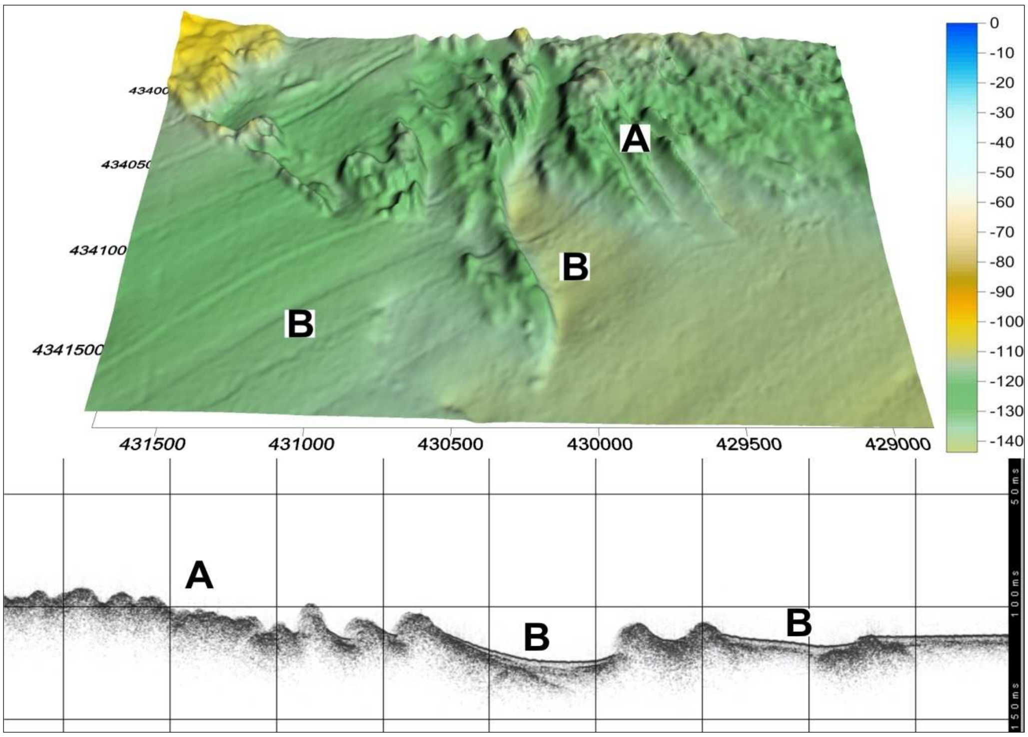


Fig. 46 - DTM and SBP 3,5 kHz echographic profile acquired north of S.Pietro island showing; A: Top surface of the outcropping Oligo-Miocene volcano sedimentary succession with morphologies related to the volcanic emplacement; B: Depressions filled by outer shelf Plio-Quaternary loose sediments.

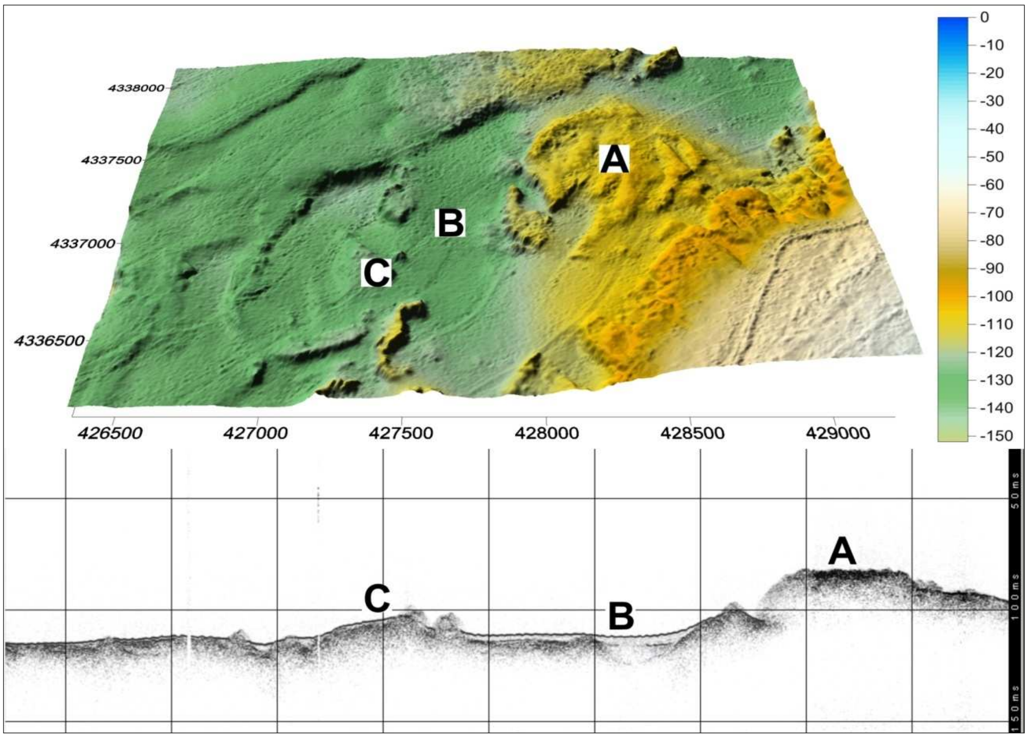


Fig. 47 - DTM and SBP 3,5 kHz echographic profile acquired northwest of S.Pietro island showing; A: Eroded volcanic neck top surface belonging to the outcropping Oligo-Miocene volcano sedimentary succession; B: Depressions filled by outer shelf Plio-Quaternary loose sediments; C: Outcropping Oligo-Miocene volcano sedimentary succession.

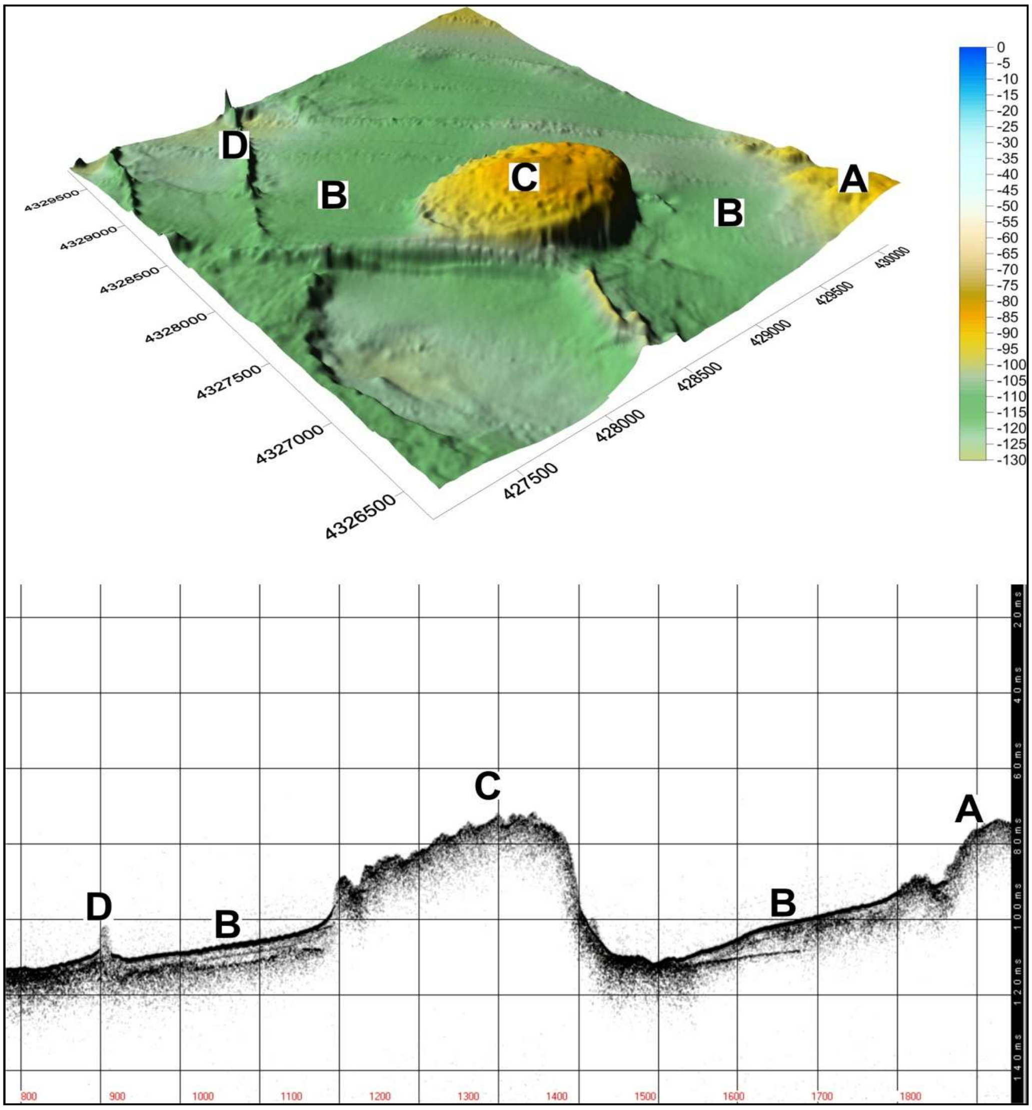


Fig. 48- DTM and SBP 3,5 kHz echographic profile acquired west of S.Pietro island showing: A: undifferentiated volcanic outcrop; B: Thick cover of intermediate shelf loose Plio-Quaternary sediments; C: 1000m radius neck with associated radiating dykes; D: 6m high and 30 thick dykes which extends seamlessly up to 6 Km on the inner continental shelf.

Same tectonic control may be assumed for the Cala Fico palaeo valley incision, thanks to the study of the Sparker seismic traces acquired during the "Sardinia Channel 2009" campaign (Fig. 49) it was possible to identify a palaeo river bed subject to polycyclic evolution, was identified an undifferentiated volcanic substrate affected by an irregular erosive surface attributable to MIS2, above the erosive surface was observed an opaque seismic facies interpreted as a filling with silt-sandy sediments related to the closing stages of Versilian transgression, MIS 1, covered by marine sedimentation of the transgressive cycle closing.

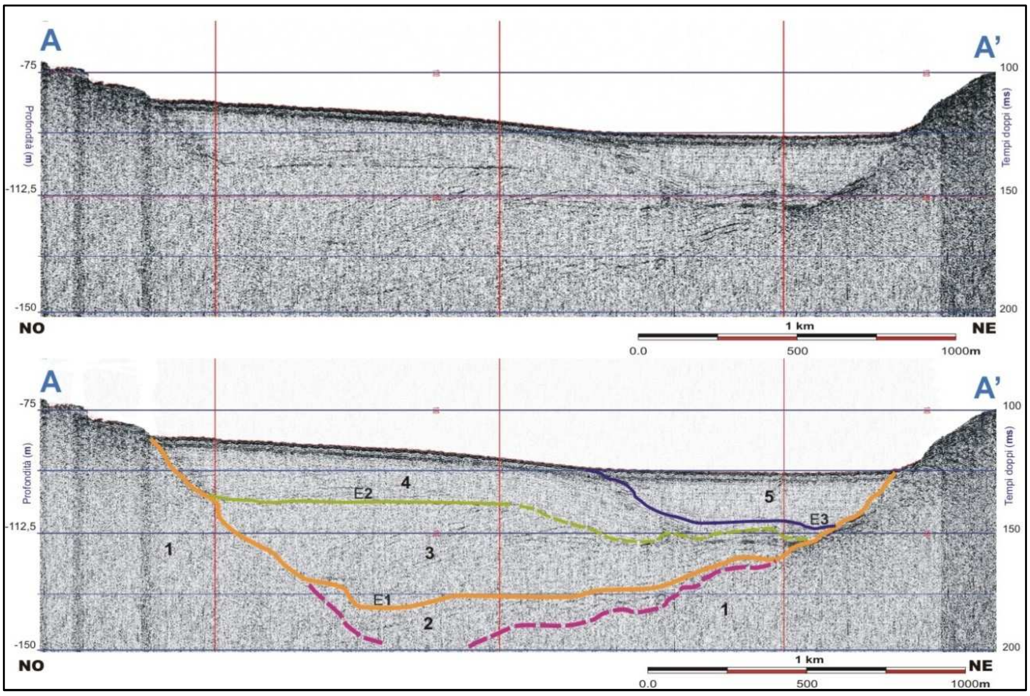


Fig. 49- In the seismic section A-A' recorded inside Cala Fico palaeo valley (sparker record 0.5/1 kJ) are shown: 1) Volcanic comenditic and ignimbritic substrate; 2) Parallel reflectors lower sedimentary sequence (pre-Messinian); E1) Messinian erosion surface; 3) Wavy lamination upper sequence (Pliocene); E2) Erosion surface (Pliocene Plestocene sup.-inf.); 4) Inclined lamination sedimentary sequence (lower Pleistocene. - Upper Pleistocene.); E3) Last Glacial Maximum erosive surface (MIS 2); 5) Fine sediment filling with Plano-parallel laminations (Holocene).

In the inner shelf area comprised in the Gulf of Palmas many submerged shorelines document the permanence of the sea level at depths below the current, starting from great depths (approximately -130 m), relating to 'last eusthatic regression (MIS 2, Chappel & Shackleton, 1986), will meet the shallower depths testifying stops during the last Versilian transgression. Often in correspondence with palaeo shorelines, which occur in facies of sandstone/conglomerate beach rock, can be identified other typical coastal morphologies. These include palaeolagoons behind the ancient beach ridges, highlighted by depressed and closed morphologies, and finally the dune fields, always of backshore area, as detected in the inner Gulf of Palmas at a depth of -20 meters (Orrù & Ulzega, 1989). The distal area, slightly sloping, (0.6 ° - 0.8 ° degrees) is Regularized by the Miocene sedimentary sequence at the basis and by the prograding Plio-Pleistocene sequence constituted by many system tracts of clinoform patterns (Lecca, 2000) . The Sulcis continental shelf extends gently sloping up to the shelf edge, locally little pronounced and in smooth transition with the upper slope, which is found at an average depth of about -170/-180 m. The shelf edge is particularly jagged due to the presence of several canyon heads in recession affecting the below slope.

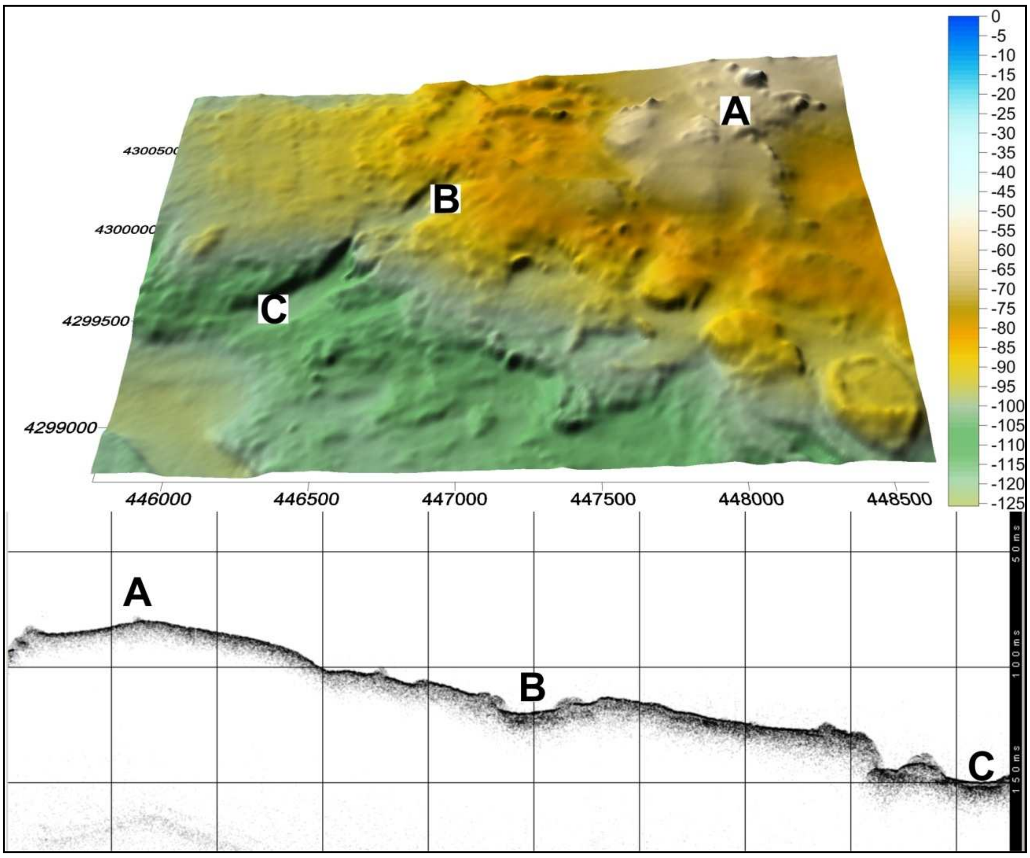


Fig. 50 - DTM and SBP 3,5 kHz echographic profile acquired 1,5Km southwest of Toro island showing; A:Acoustic basement outcrop belonging to the Oligo-Miocene volcano sedimentary succession; B: Small depressions filled by outer shelf loose slimy sands (Holocene); C: Outer shelf loose Plio-Quaternary sediment cover.

These are the heads of the smaller canyons that flow into the two main canyon S. Antioco and Palmas. Important tectonic features were observed in correspondence with the edge of the continental shelf; it is a probable fault which presents orientation N130, partially masked by the Holocene sediments drape. The fault slope associated with the lineation would seem to be exhumed by erosion. In the canyon head area, at the average depth of - 350 m, several sub-circular depressions with diameters between 150 and 250 meters and a maximum depth of up to 70 meters has been found. The origin of these morphologies in an area of upper slope, first put in relation with mechanisms of erosion-type plunge pool inside of thalweg canyon was reconnected to subsidence for leakage of fluid from the underlying fine sediments coming from the Plio-Quaternary prograding body (Deiana et.al, 2014).

Sector 2 –Capo Teulada to Capo di Nora

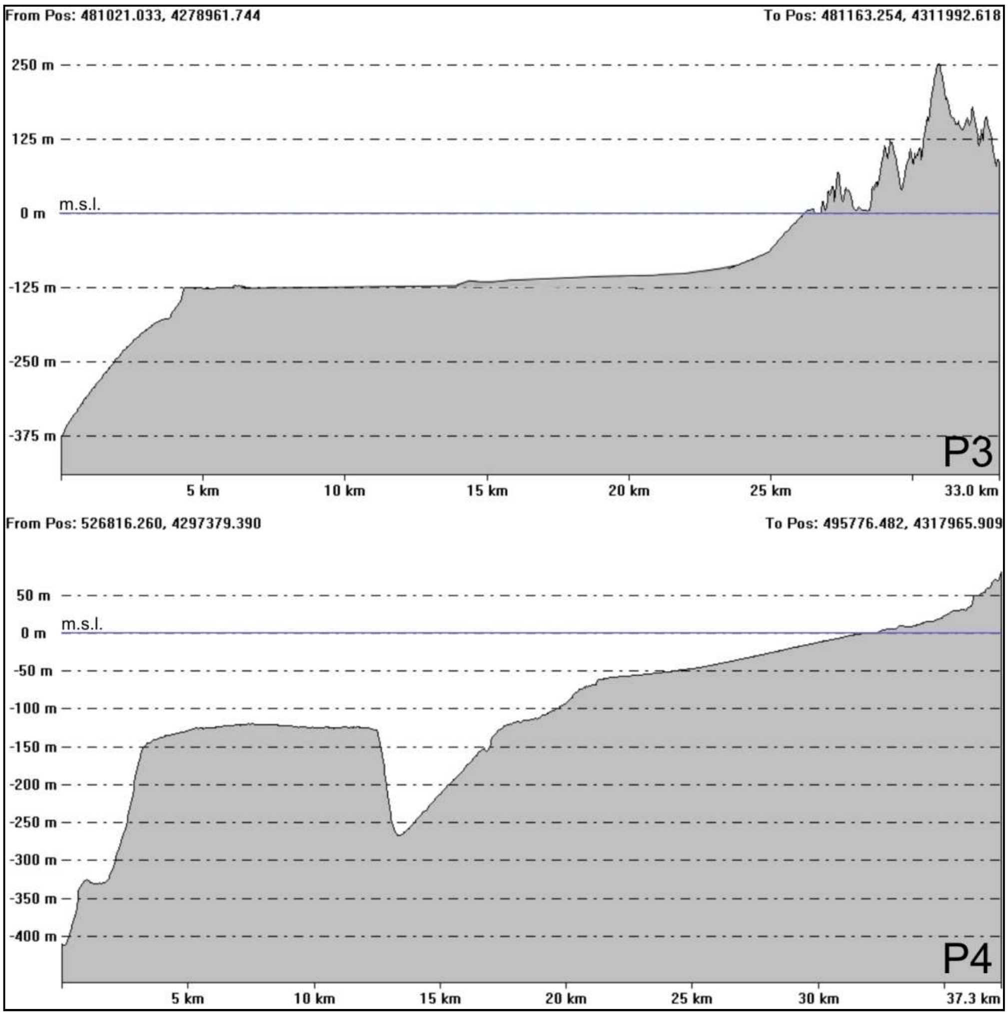


Fig. 51 - Profile P3 and P4 showing different styles of Southern Sardinian continental margin, P3 traced in the Capo Spartivento area shows an almost flat and regular sea bottom while P4, traced off Capo di Nora shows a steeper profile of the continental shelf and the separated residual strip of continental shelf of "Su Banghittu" in distal Cagliari Gulf area. For profile localization see Fig. 40

South Sardinia continental margin is characterized by a submarine depositional system controlled by the Pliocene extensional tectonics subdivided into several marginal basins (Wezel et al. 1981), in which arrive the sedimentary contributions of the various segments of the continental shelf (Lecca et al, 1998) . The continental shelf in the area between Capo Teulada and Capo di

Nora, is characterized by regular morphologies, and is home to the outcrops of the Oligo-Miocene volcano-sedimentary series, the shelf edge lies at a depth of -120m and is interested indentation of a number of canyon heads of the Teulada, Spartivento and Nora Canyons. In the distal area of the submarine valleys, fan shaped sedimentary bodies extend to junction with the Sardinian-Algerian bathyal plain (Auzende et al, 1974). In upper slope are recognizable traces of gravitational slipping and turbidite flows not channeled affecting roofing Plio-Quaternary sediments and which give rise to accumulations of base slope.

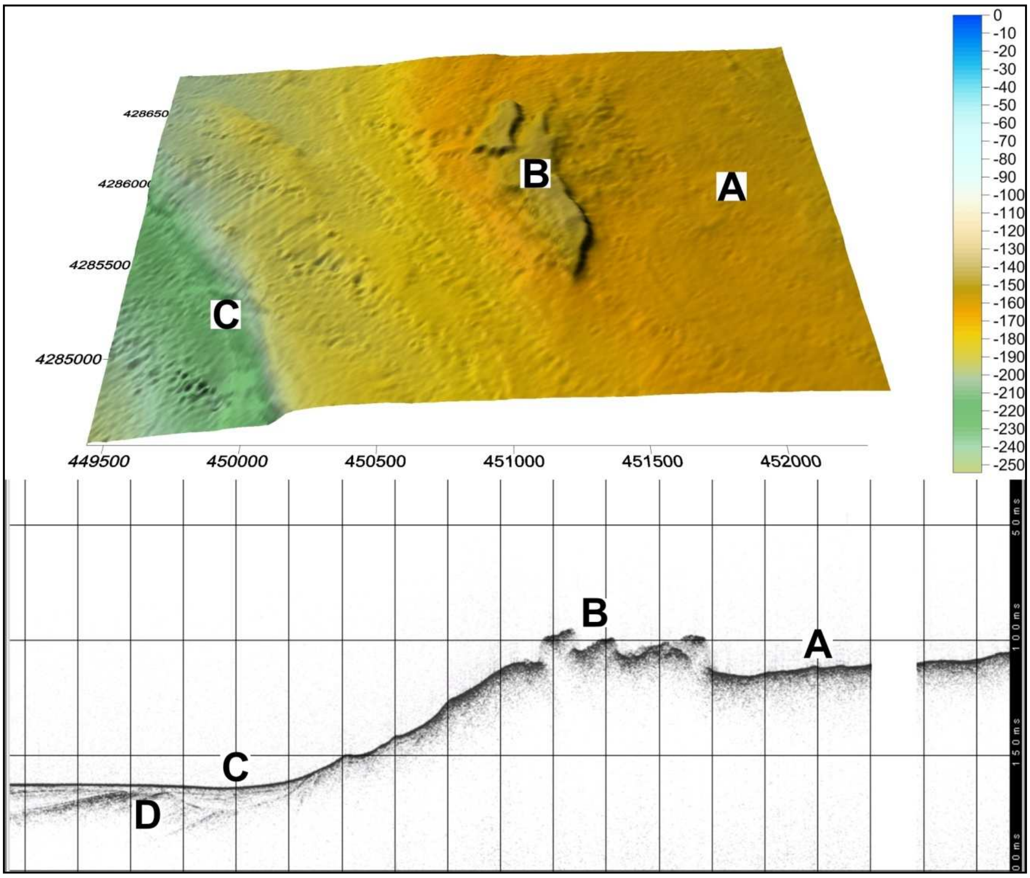


Fig. 52 - DTM and SBP 3,5 kHz echographic profile acquired 24 Km south Cape Teulada showing; A:Acoustic basement belonging to the Oligo-Miocene volcano sedimentary succession; B: Outcrop of the Oligo-Miocene volcano sedimentary succession; D: Pliocene (?) stratified sediments covered by (C) outer shelf loose slimy sands (Holocene).

The slope sector dominated by the Toro and S.Antioco Canyons which engraves the continental shelf in an area dominated by wide rocky outcrops correlated with the oligo-Miocene volcanics (Toro Island and Secca 103) . The head of the Toro canyon is indented on the edge of the continental shelf for about 7 km along the western fault of Palmas Gulf. To the southeast of the Toro Island, submerged palaeo shorelines are shown in beachrock facies, related to Last Glacial Maximum (LGM), while near the Canyon head an expanded field of mega dunes documents the activities of important tractive current. On the edge, at the heads of the S.Antioco Canyon are some closed depressions correlated to fluids release processes (Deiana G. et al., 2014). The detected pockforms can be grouped into three groups according to the morphology that characterizes them: elongated (sub-circular), irregular and circular. Elongated pockforms have “elliptical plan”, with the major axis oriented about NW-SE. The maximum size of these pockforms is approximately 2.8 km (major axis) per 0.8 km (minor axis); the depth reaches about 50 meters. In cross section they show a V-shape with predominantly symmetrical morphology with irregular bottom, sometimes, the pockforms affects the whole thickness of the Pliocene-Quaternary covers up to exhume the underlying bedrock. Pockforms with this morphology are detectable only in the upper slope of the north-western margin. The irregular pockforms have sub-circular plan, probably originated from the coalescence between two adjacent smaller pockforms and feature typical irregular perimeter; in cross section the profile of major depression is asymmetric V to U type. The average size for most significant pockforms reach diameters of about 1.5 km and a maximum depth of about 60 meters (Deiana G. et al., 2015).. Most of these pockforms were detected in the north-west of the study area, in correspondence with the heads of the main S. Antioco Canyon; however some isolated cases are detectable in peripheral areas. Circular pockforms are very variable in size: the smaller ones, detectable only in the outer continental shelf and at its edge (the north-western studied area), have a diameter of about 8 to 10 meters and a depth of about 2 to 3 meters; the pockforms with larger dimensions have a diameter which reaches 900 meters for a depth up to 95 meters. The cross profile is typically symmetrical V and U shaped, only rare exceptions are asymmetric. Circular pockforms are those that appear most extensively studied in the area: in particular, the density of these forms is detectable in correspondence of the Toro high where, in an area of about 50 sq km were detected 25 pockforms, sometimes following well defined alignments. In intermediate slope, a major complex landslide involving Quaternary sediments loose covers can be detected, the total area affected by the landslide complex reaches approximately 73.5 square kilometers. The structural high of Toro high defines the southern limit of the western sector. To the east the continental slope is engraved by the Teulada and Spartivento Canyons. Spartivento Canyon is the westernmost part of a major canyon system that affects the southern slope of Sardinia; the geomorphological structure of each canyon head, characterized by apparent asymmetry between the sides of the thalweg, seems to be correlated with the incision along tectonic lineaments with transcurrent component approximately north-south oriented. Teulada Canyon is defined by three main ribbon shaped channels affecting the Pliocene-Quaternary sequence up to the edge of the continental shelf at a depth of -150 meters. The morphology of the areas of the escarpment is articulated by the presence of two significant landslides affecting the loose Quaternary sediments cover; their detachment niches are defined by sharp frames high up to 30 meters.

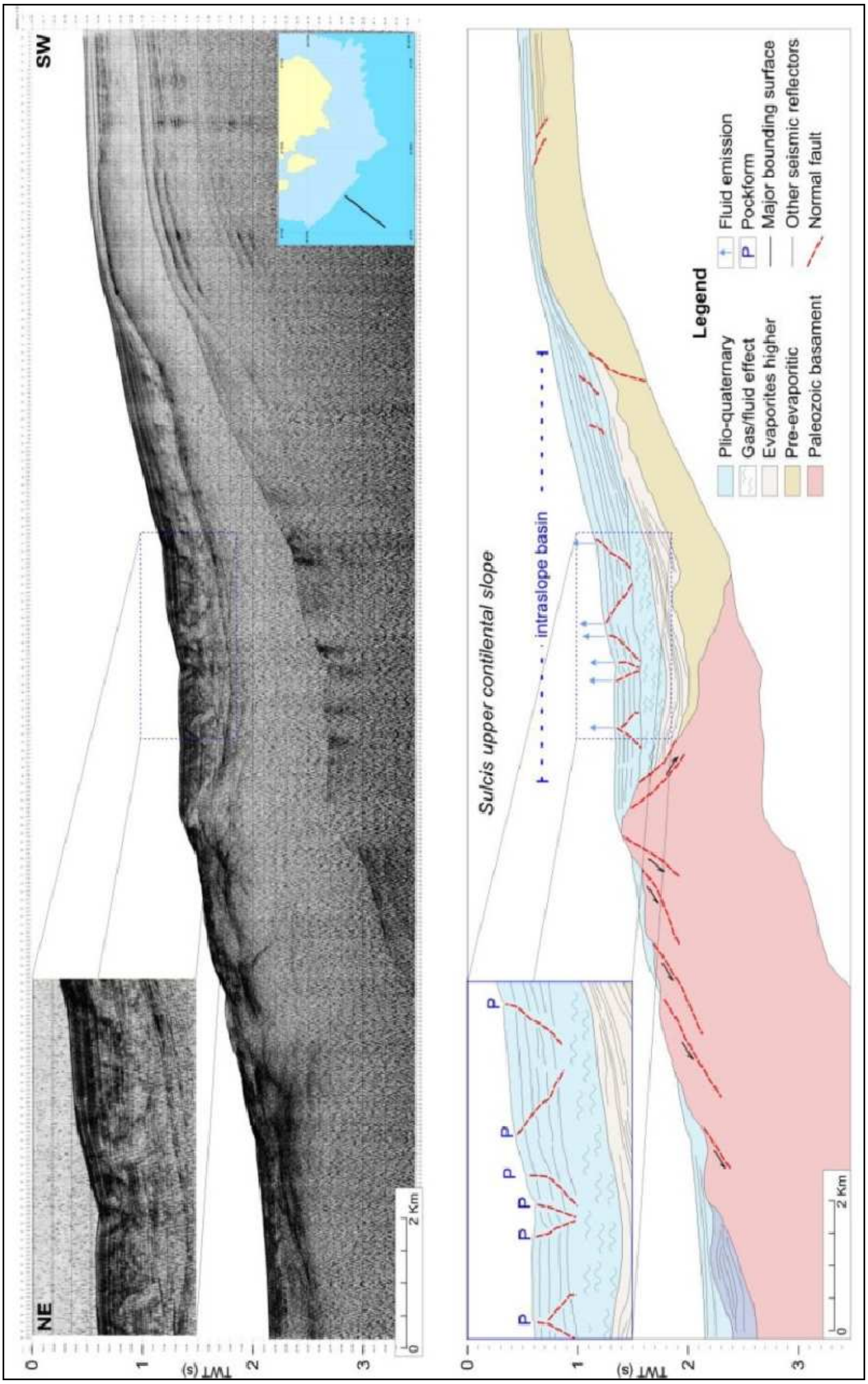


Fig. 53 - Multichannel seismic section acquired in upper continental slope, showing main seismic unit of the Sulcis margin. Highlights a intraslope basin filled by Oligo-Miocene sediments; Pliocene-Quaternary sequence is characterized by the presence of a based seismic facies correlated with water saturated sediment or organic material. The pockforms detectable on the surface appear to be correlated with escape process from the basal part of the sequence Pliocene-Quaternary (from Deiana et al., 2015).

Sector 3 –Capo di Nora to Cala Regina

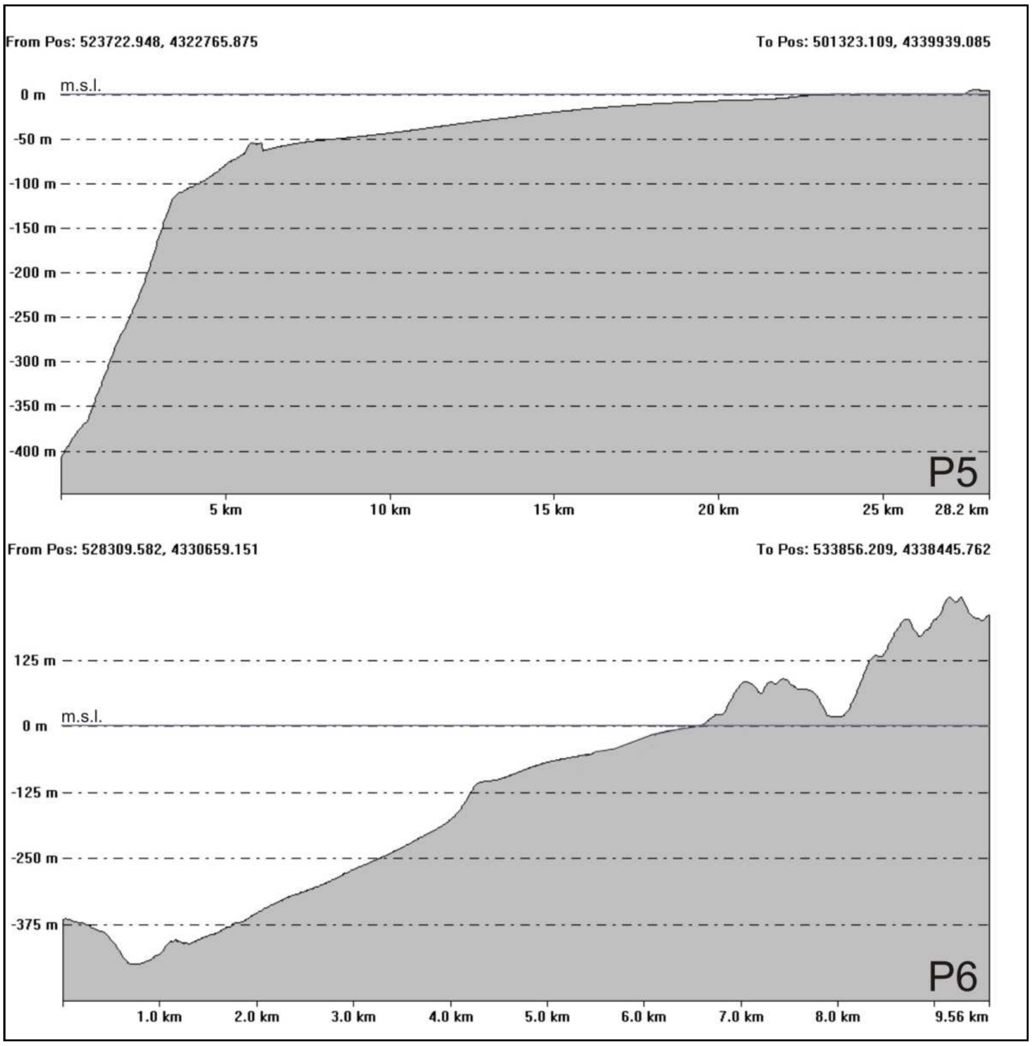


Fig. 54 - Profiles P5 and P6 traced inside Cagliari gulf, the first, P5 shows the wide (10,5Nm) and slowly degrading continental shelf (slope values ranging from 0.6° to 2°), a fossilized palaeo shoreline is identified around -55m and the shelf edge, often house of depositional terraces lies at an average depth of -120m slightly rising up in correspondence with Sarroch canyon head scarp. On the eastern side of Cagliari gulf, P6 point out the differences with western side, the continental shelf is extremely small extended and steep (less than 1Nm and with slope values ranging from 3° to 7°) due to the continuation at sea of a Campidano Graben eastern master fault. For profile localization see Fig. 40

Cagliari basin is the innermost part of the sedimentary system of the whole margin, defined and controlled by tectonic blocks of southern Sardinia continental margin, in particular by the movements of Mount Ichnusa and Su Banghittu submarines blocks (Fanucci et al., 1976). These marginal basins close to the south Rift oligo-Miocene (Cherchi & Montadert, 1982) in southern

Sardinia, reactivated during the Pliocene-Quaternary extensional movements related with the opening of the southern Tyrrhenian Sea (Cherchi et al., I978; Casula et al., 2001). The morphology of the Sardinian Channel is articulated due to the tilting of tectonic blocks approximately NS and NNW – SSE oriented, the most important is the Ichnusa Seamount, wich rises up to an altitude of -140 m and It consists of Paleozoic metamorphic and granitic lithologies, with post - Paleozoic volcanic and sedimentary covers.

The continental slope is incised by extensive canyon systems; the edge of the continental shelf lies at the average depth of -120 m to go back to lower altitudes in correspondence of the retreat for regressive erosion of canyon heads (Ulzega et al, 1986); in the distal area of the submarine valleys sedimentary bodies extend to bathyal fan sedimentary bodies, at the junction with the Sardinian-Algerian bathyal plain (Auzende et al, 1974). In upper slope are recognizable traces of gravitational slipping and not channelled turbidite flows affecting roofing Plio-Quaternary sediments and which give rise to accumulations of base slope. In accordance with the shelf edge, continuous depositional bodies has been detected and interpreted al Submerged Depositional Terraces (Ferraro et alii. 1998) related to the last sea level low standing at -120m, MIS 2 (Chapel & Shackleton, 1986). The main terrace extends for approximately 8 nautical miles, while his width perpendicular to the edge is reduced to only 200-300m in correspondence with active S.Elia canyon heads (APAT, Atlas of submerged depositional terraces, 2004). Cagliari gulf outer continental shelf is house of an important accretionary prograding prism on the upper slope; in this area sediments buildup are constituted by limitated terrigenous siliciclastic inputs from southern Sardinia and by an important bioclastic component produced on the continental shelf, moreover, to tractive bottom currents reduction is associated the fine sediments deposition (silts and clayey silts) (Lecca et alii, 1998).

The morphological high of "Banghittu "is a residual strip of continental shelf located in the central sector of the Gulf of Cagliari. The edge of the relief is affected by gravitational movements involving the bedrock; the resulting deposit mainly consists of blocks of considerable size (up to 250 m) (Deiana et al., 2012). The morphology of the relief is influenced by tectonic features, a faults system N 136° oriented and a nearly orthogonal to them N 27° oriented, which displace and tilt portions of residual discards vertical platform with around 160 meters. The most significant movements affects block sizes up to 250 meters in length that migrate from the detachment point up to several kilometres away on a weakly inclined plane, according to the Debris Avalanche dynamics. The landslide body is divided into four distinct areas, to the main body of the deposit to the foot of the slope follows a zone characterized by the presence of scattered blocks, from which branch paths of translation of the main shifted blocks. The sedimentary input of the many rivers that flow into the Gulf of Cagliari is severely limited by the fact most of these flow into the lagoon of Santa Gilla (Rio Cixerri, Flumini Mannu) west of the promontory Cape San'Elia or east of it, within Molentargius pond (Rio Is Cungiaus, Rio di Selargius), which before the recent changes was also a man-made lagoon, filling and thus constituting a real sedimentary trap (Orrù et al., 2004, Orrù et al., 2011).

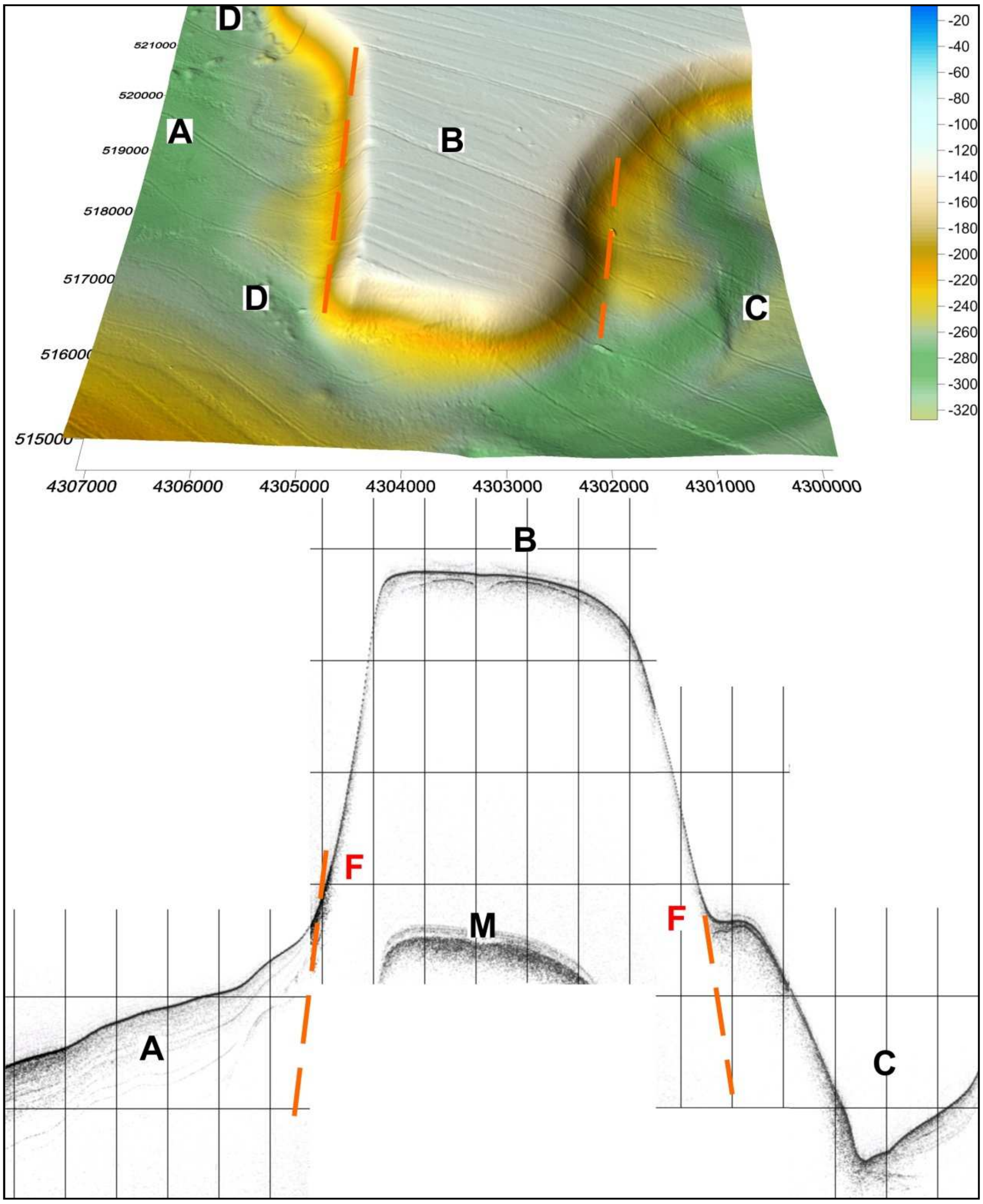


Fig. 55 - DTM and SBP 3,5 kHz echographic profile acquired 18 Km southeast Nora Cape showing; B: Acoustic basement belonging to the Miocene sedimentary succession; A: Hemipelagic drape constituted only by carbonatic – bioclastic sedimentation due to Banchittu's relief isolation from outer shelf; C: Pula Canyon talweg; D: Block fall deposit derived from recent Banghittu's edge dismantling; F: Faults; M: Multiple reflection.

Cagliari Gulf continental shelf is fed by terrigenous contributions from three different inland areas. The eastern sector receives mainly sediments derived from the alteration of the Hercynian low-grade metamorphites, from late Variscan plutonites and, in the coastal region, from clastic continental and marine Miocene and Quaternary sequences. The western sector, adjacent to the coastal area is characterized by granitic rocks of the Variscan basement, locally Palaeogene terrigenous sedimentary cover and, in the vicinity of the Campidano Graben western fault, important Oligo-Miocene andesitic volcanic systems. The area within Campidano Graben, shows in the east a succession of marls and sandstones of lower - middle Miocene, shelf bioclastic sandstones and limestone of the upper Miocene; the western part is constituted by the Pliocene - Holocene continental and transitional complex of southern Campidano.

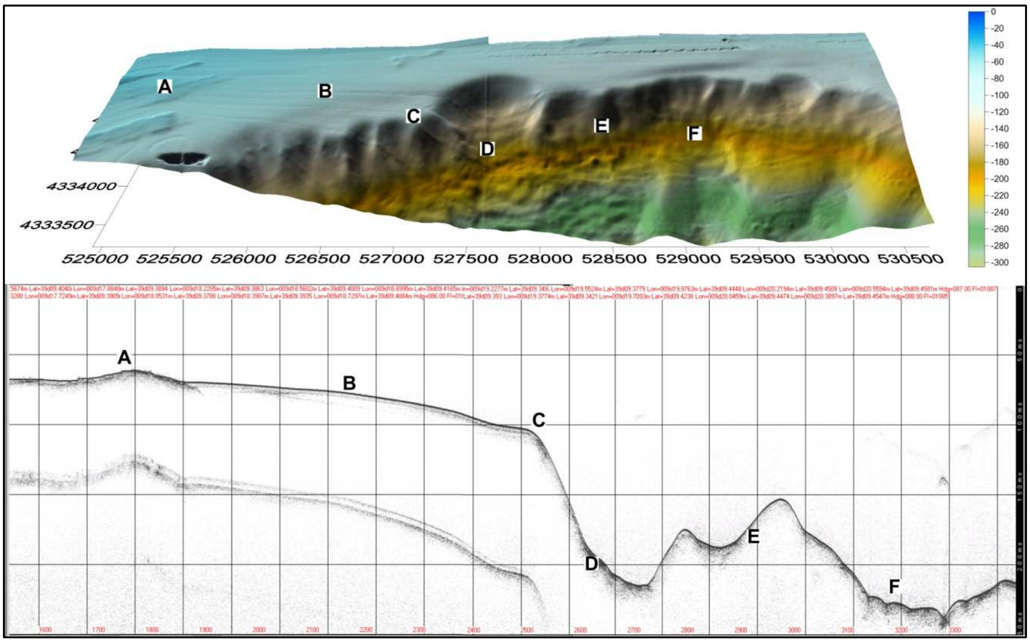


Fig. 56 - DTM and SBP 3,5 kHz echographic profile acquired in the Gulf of Cagliari; A: sandstones and conglomerates represent the shoreline (beach-rocks) lithology correlated to the Versilian transgression; B: the sandy silt which constituted the submerged depositional terrace are characterized by an opaque-transparent signal; in the terrace are noticeable rare sub-parallel and prograding reflectors with convex geometry; C: Continental Shelf edge located at -92m; D: deformed structures, interpretable as landslide's deposits, characterized by an opaque seismic facies and by ondulated reflectors; E: The bedrock, is often covered by the Holocene transparent facies which fills the depressions and presents a seismic deaf facies with absence of sedimentary geometries. F:Intracal landslide deposit.

Sector 4 –Cala Regina to Cala Pira

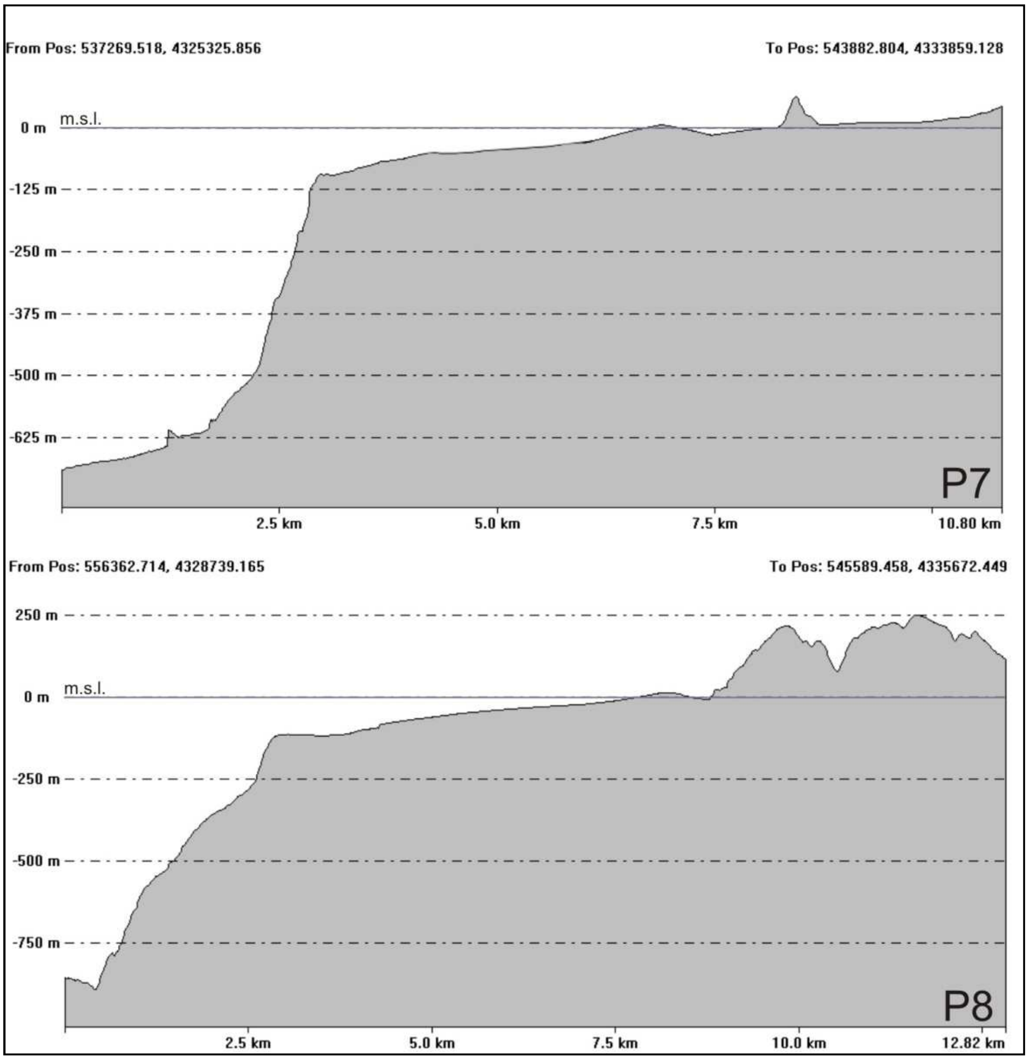


Fig. 57 - Profiles P7 and P8 are localized, the first inside Cagliari Gulf, on the eastern side, showing the narrow continental shelf, the shelf break which lies at approximately -100m and the steep upper slope often characterized by vertical rocky walls. P8 is instead localized outside Cagliari gulf, on Sardinian eastern continental margin where continental shelf is approximately 3Nm wide, not really steep, (1°-3°) with an articulated morphology showing many outcrops of the crystalline basement and two major canyon heads.

The Sarrabus narrow continental shelf portion, which characterizes the east side of Cagliari Gulf is based on the homonymous horst structure and is fed by contributions from the granitic and schist inland. The profile of the shelf shows conditions of undernourishment, and a break of slope is detectable at -10 m for structural control. The shelf break is present at depths ranging from -70m in correspondence with Carbonara Canyon head and others minor channels due to retrogressive erosion processes which interest this portion of the continental shelf and upper slope, in other to -110m for the low sediment supply which reflects the physical and structural properties of a basin elderly and tectonically stable.

In the upper continental slope sector there are significant size gravitational phenomena , in particular were found two main systems, generated by various events which affects not only the upper slope but also the shelf edge area. These landslides interests large volumes of sediments, in order of tens of millions of m3 each. showing deposits characterized by gibbous surface and creep which spills over the landslide foot, inside an erosive meandering canyon system. In the sparker seismic record is shown a system of normal faults that displace sediments related to the Plio-Pleistocene depositional series. In red are highlighted erosional surfaces related to low standing sea levels.

The main feature of Sardinian eastern continental shelf, as opposed to the west, is the considerable coverage of Pliocene-Quaternary sediments, which is in an almost continuous stand. For this reason, the morphology is generally more regular, with almost constant steepness from the shore to the edge, which has a decisive shelf break and is characterized by strong accumulations of prograding sediments. On this morphological-structural particularly conservative basis Ulzega (1980) recognized and studied with particular attention the effects of glacio-eustatic sea level variations events related to Quaternary climate changes. Specifically, the moments of the sea level stationing, both in the regressive phase that especially during transgressions, are defined by morphologies referable to palaeo-beaches (Beach Rocks).

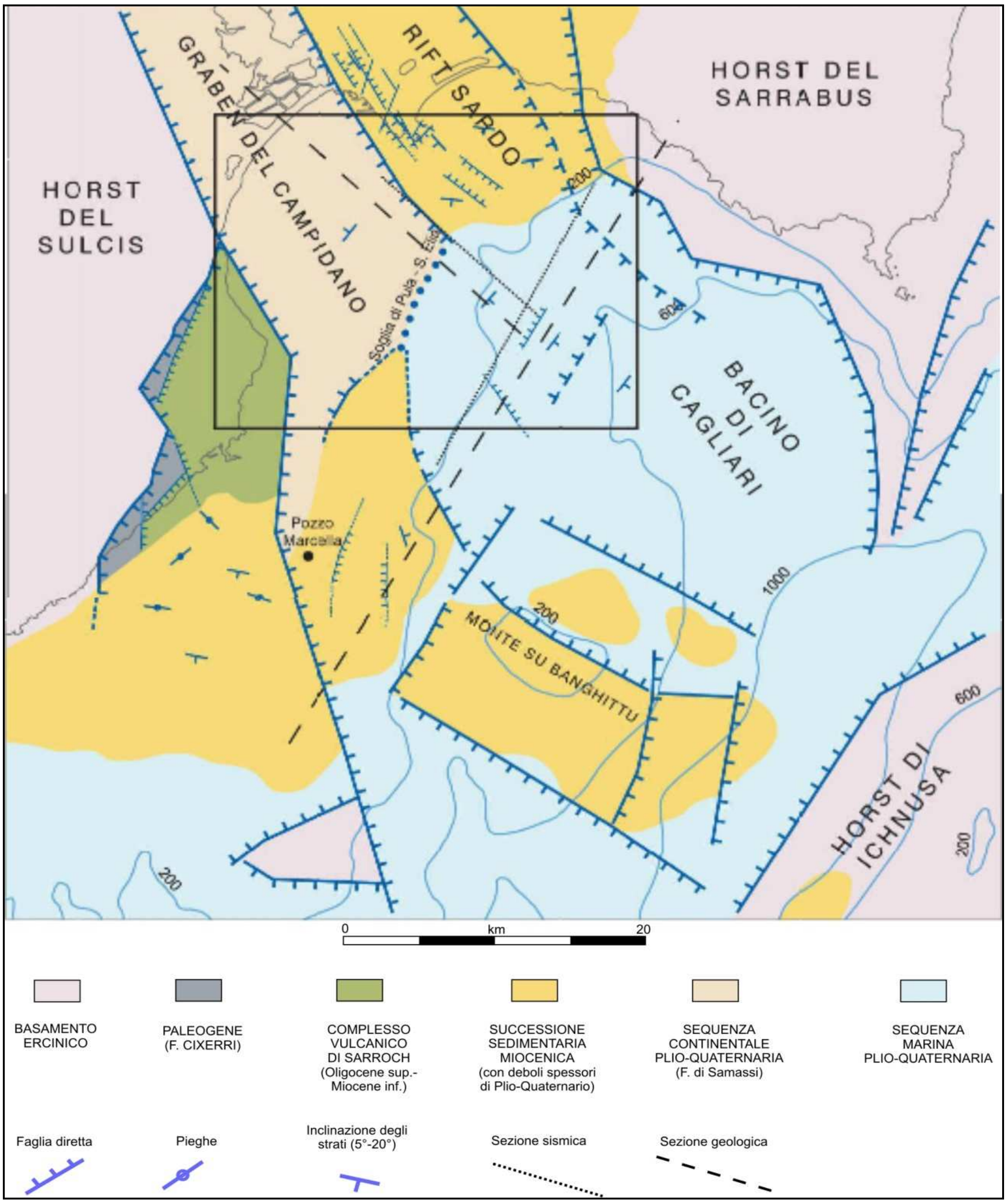


Fig. 58– Cagliari gulf geologic sketch from the CARG project sheet 566 – PULA, can be clearly noted how morphologies are controlled by tectonics, in particular can be observed how upper Oligocene tectonic lineaments, later reactivated, controls both the emerged and submerged main structures as the Campidano Graben retracing the Rift Sardo main lineation. Sulcis, Sarrabus and Ichnusa Horsts are clearly by a direct faults system mainly NW-SE and NE-SW oriented following regional trends.

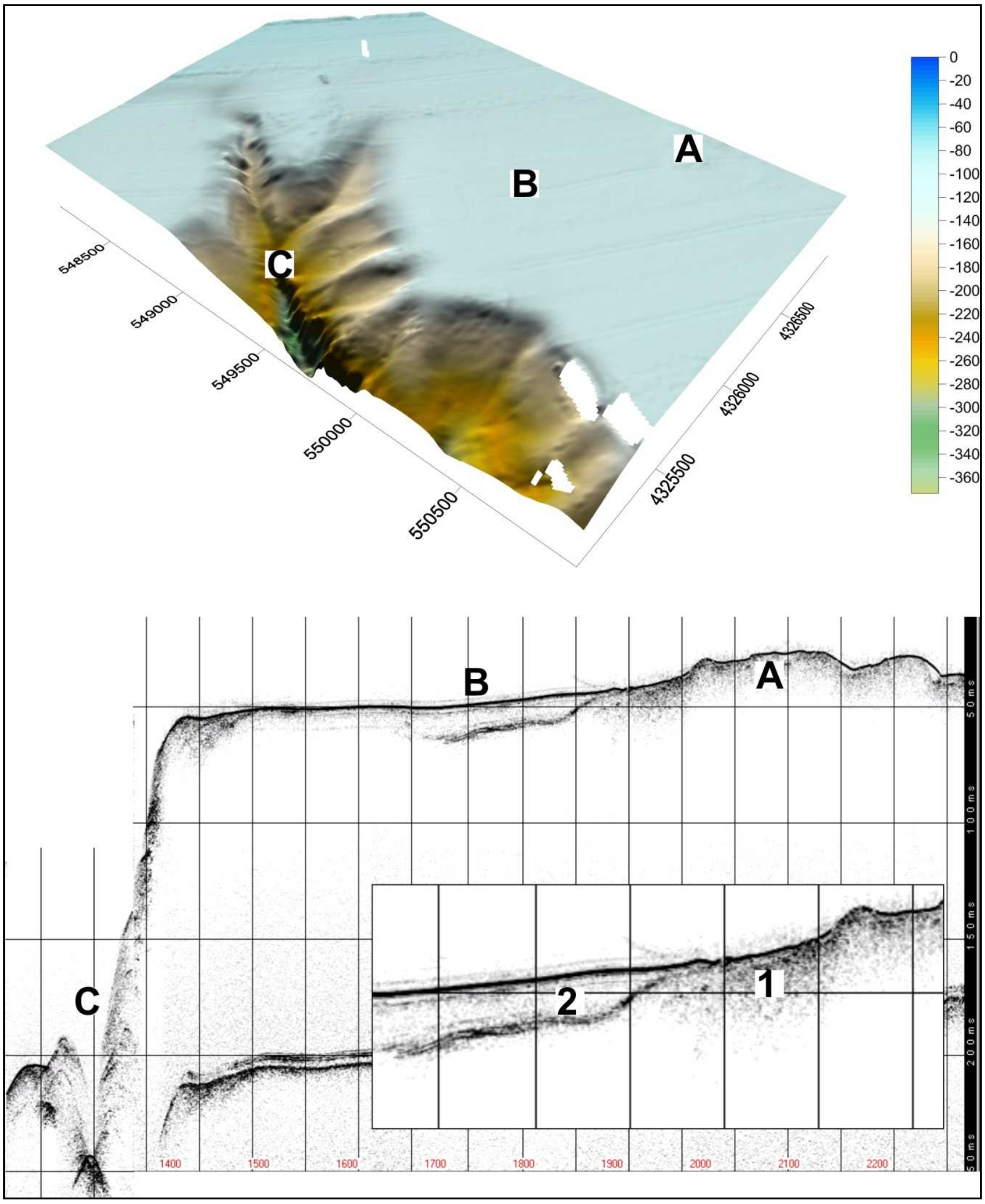


Fig. 59 - DTM and SBP 3,5 kHz echographic profile acquired on east Sardinia continental shelf 4 Km east of Cape Carbonara showing; A:Acoustic basement correlated with Palaeozoic granitic lithologies; B: Plio-Quaternary outer shelf fine and slimy sands; C:Cavoli Canyon talweg; 1: Detail of the rocky substrate formed by granitic Varisican basement; 2: Detail of the transparent response of the Plio-Quaternary sediments composed by outer shelf loose fine and slimy sands.

STRUCTURAL GEOMORPHOLOGY

Sardinian southern continental margin can be divided into three sectors with different physiographic and structural characteristics.

The south-western sector, characterized by normal faults defining intra-platform and intra-slope basins; the Cagliari Gulf, extension at sea of the Campidano rift valley; and the eastern sector, with shortly extended continental shelf and very steep slope limited offshore by the Ichnusa seamount. Sardinian south-western margin have been explored by geophysical surveys and deep drills which hallowed to define the order and the geometry of the depositional sequences (Finetti & Morelli, 1973; Fanucci et al., 1976; Lecca 2000; Finetti et al., 2005).(Fig. 60). High-angle faults system characterize the first setting of the tectonic blocks that constituted western Sardinia continental margin between middle-upper Oligocene and Miocene when, in the intra-back arc area of the Apennine-Maghrebian chain, an extensive system of rifting settled (Cherchi & Montadert, 1982; Lecca et al., 1997; Sowerbutts A., 2000; Casula G. et al., 2001; Faccenna C. et al., 2002). Based on the data from the ECORS-CROP profiles, the genesis of the margin could be identified in the extensional tectonic inversion of a compressive structure system of a western branch of the Pyrenean chain (Fanucci & Morelli, 1997). The Sardinian Rift is an extensional system associated with the Apennine-Maghrebian convergence, the margin was a western branch of the rift system and has later assumed the structural and evolutionary characteristics of a divergent margin, relative to an extensional basin associated with an area of convergence (Lecca, 2000).

The Sardinian Rift fault zones follow various pre-existing structural discontinuities within the Paleozoic basement; similarly, this occurred even in the continental margin (Lecca, 2000). Kinematics of the central Mediterranean, show that the Sardinia-Corsica block is stable in the last 7 million years. However, the INGV earthquake catalog (seismicity of the last 25 years) shows three main events in southern Sardinia, one of magnitude 5.5 in August 1988 along the active fault S.Antioco, Toro Is.-Quirino Seamount, and two 4.5 in

March 2006, at the extension to the sea of a major NW-SE Campidano border fault that marks the western edge of the rift valley. (Fig. 61).

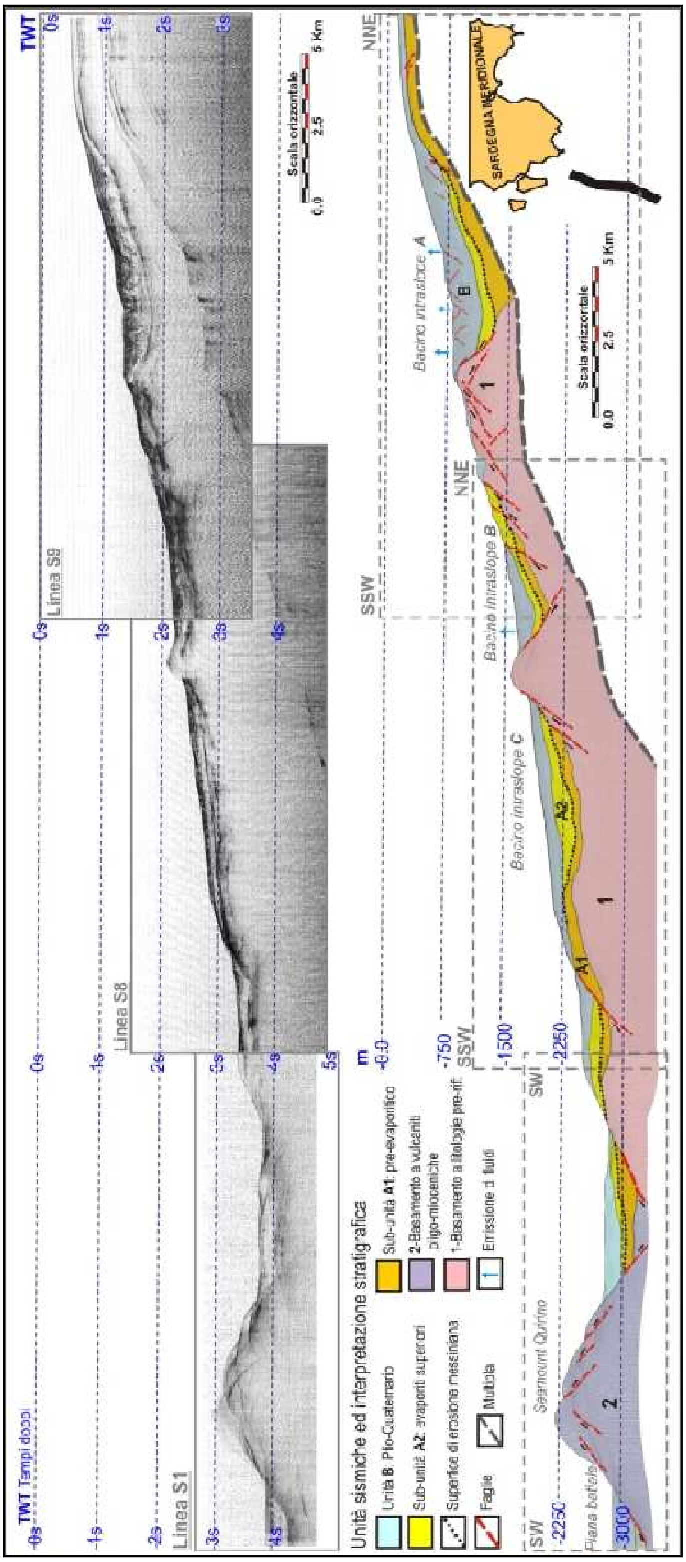


Fig. 60 – South western Sardinian continental margin structural setting,

Units preceding the Oligo-Miocene rifting phase are represented by the Paleozoic basement and by marine Eocene covers, fluvial sandstones and claystones of the Cixerri Formation (Upper Eocene-lower Oligocene), while the beginning of the oligo-Miocene rifting is accompanied by andesitic volcanism (upper Oligocene-Aquitanian) of the Sulcis block (Pozzo Marcella-1). The filling of the lowering tectonic trench is characterized by fluvial sediments (Ussana form.), followed by marine marly arenaceous and carbonate Lower Miocenic sequences.

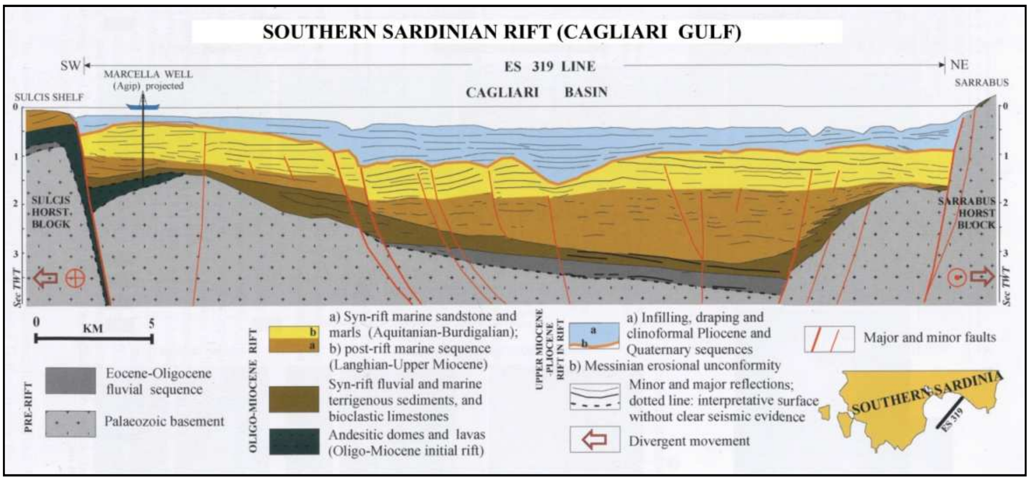


Fig. 61 – Continental margin structural setting in the Cagliari gulf area. (Finetti, 2005)

San Pietro Island Area

The continental shelf within the San Pietro and S.Antioco islands is characterized by an irregular morphology dominated by outcrops of volcanic substrate. Differential erosion highlights many volcanic morphologies as neck-shaped emission centers, craters buildings and calderas. A system of mega-dikes, also highlighted by differential erosion, affects the entire emission centers zone, following a tangential trend that sometimes continues for more than 5 km seamless. The emplacement of this grand display of mega dikes, within the Tertiary rifting geodynamics, presents analogies with similar incidents, at least in dimensional characters, as noticed in active rifting areas (Wright et al., 2006; Ayele et. al., 2009).

The seaward limit of the volcanic outcrops is represented by a palaeo-cliff line with foot at the average depth of -140 m, are distinguished both rotational landslide niches than mega-blocks collapse at the basis. Hypothesis that the gravitational and erosive morphologies observed may be related to the last phase of low sea-level standing Last Glacial Maximum (MIS 2) was confirmed by sampling of a littoral thanatocoenosis (Orrù et al., 2012).

The volcanic structures

The inner shelf is characterized by extensive outcrops of the volcanic substrate. Can be distinguished the northern sector, home of an extended lava spread, where lava flows shaped four lobes about 1.5 km wide and about 4 - 5 km long NW – SE oriented. On the top surface of the volcanic flow can be recognized the undulations showing flow direction. Emission center had to be near the Corno island, which would be the southern portion of the volcano, while the northern portion appears collapsed. To the same emission center can be attributed the lava flows that from Capo Sandalo and Punta Borrona shows flow direction from the sea to the island inland. The most important emission center was found five miles off Golfo di Mezzaluna, a massive neck, (Aranda-Gómez, JJ et al 2010) characterized by sub-circular and tabular morphology with a diameter of about 1 km, the base is located at - 100 m and the top at - 82

m. The system counts eight emission centers, with neck shape, distributed for 5nm towards S-SE from the main edifice. Six miles off Punta Geniò a caldera edifice was detected, only his eastern half rim is preserved, it rises from -100m to -84m, the morphology shows analogies with volcanic morphologies present on the sea bottom near Campi Flegrei (Di Vito et al., 1999) which suggest cineritic rock types (Putignano & Orrù 2010).

A kilometer east of the main emission center there is a sub circular depression with a diameter of 1200m, which starting from a depth of -105m reaches a depth of - 135 m, this morphology can be classified as a caldera latu sensu (Karatson et al, 1999) while not allowing a clear genetic interpretation. A system of dykes, put in relief by differential erosion for more than 10 meters of height from the sea bottom, affects the entire area of the emission centers (Tibaldi 2003; Acocella et al., 2006) following tangentially. The dikes have a slightly sinuous development that sometimes exceeds 6km seamlessy, following orientation ranging N/NW to N/NE. The only exception is represented by a dike of considerable thickness, radiating from the main emission center and oriented NW-SE, this appears to be subsequent to the emplacement of the dykes system trending NS. On the intermediate and internal shelf prevails erosive trend for Quaternary age, with evidences of the last regression (20-18 Ky) which consist of a progradation on the front of the outer shelf, and erosive bed forms alignments correlated with palaeo-cliffs and terraces in intermediate and inner shelf (Lecca et al 1983; Carboni & Lecca, 1992). The volcanic outcrops played a role in conditioning the evolution of palaeo environments that followed the last sea level rise (Milia 1998) that has left evidence of articulated palaeo shorelines as palaeo cliffs, palaeo valleys, palaeo lagoons and beach-rocks on the continental shelf. Ten miles off Capo Sandalo the limit between inner and outer shelf end is represented by an array of walls in the volcanic substrate. The palaeo cliffs alignment shows several morphologies related to gravitational processes setback for undermining the base, their foot lies at the average depth of - 140 meters and the top at the average depth of -90 meters, these cliffs are controlled by tectonic lineation trending NNW-SSE and NE-SW. On rock walls are recognized rotational landslide niches and large collapsed blocks. The lithologic character of these cliffs assumes long evolutionary times and a polycyclic processing which has probably began as early in the middle Miocene and followed during the various Pliocene-Pleistocene transgressive phases. However the erosive morphologies now observable are mainly due to the last phase of stationary low sea level (MIS 2); in this phase, processes of physical alteration of the rocky surfaces had played important role due to the Periglacial climatic conditions. The same tectonic lineation that controls the orientation of the rocky frames have probably triggered rotational landslides of which can be recognized both the detachment niches that the landslide bodies. At the foot of the rocky frames extends large abrasion platforms, masked by the draping of the Holocene sediments. Ignimbrite lavas which are often based on tuffs and volcanoclastites levels, leading to differential erosion that, together with the intense fracturation, have led to the evolution of collapse gravitational movements and decametric blocks tipping.

Outer Continental Shelf

Off the palaeo cliffs array, about eight miles from San Pietro Island coasts, morphologies became smooth and regularized by the Holocene silty drape, few outcrops of the Miocene sedimentary sequence are noticeable in the intermediate shelf region and only one large Miocene sequence outcrop lies close to the shelf break 12 miles NW of Capo Sandalo. The Pliocene sequence is recognized from seismic data between the upper slope and the intermediate shelf, over which is founded the sedimentary prograding prism, consisting of several system tracts characterized by various types of pattern. For limited groups of sections is possible to side correlate up to four falling-low stand system tract related to as many glacial-eustatic fluctuations. The age of these oscillations, can only be generically identified as middle-upper Pleistocene (Lecca, 2000). Sparker profiles analysis allowed to distinguish seismic facies in two main types: bedrock and layered acoustic facies. The basement is defined by intensely reflective acoustic facies, with disorganized response with numerous small hyperbole, sometimes chaotic, until they merge with the background noise. These facies can be attributed to well lithified bodies and limited upwards by non-planar surfaces (pre-rift Paleozoic lithologies basement sometimes with Mesozoic and Paleocene covers; Oligo-Miocene volcanics; other lithologies as Quaternary limestone and sandstone) (Lecca, 2000). Opaque reflectors are elements that for their good degree of lithification and / or for their surface irregularities reflect and refract large part of the seismic energy, giving rise to seismic facies similar to those produced by a geological basement. These kind of behaviors are associated with groups of thick and well lithified layers of the Miocene sequence (volcanoclastites and limestone), to the erosive surface and units laid during the Messinian regression, Quaternary erosive surfaces, littoral-continental deposits and calcareous assemblages (Lecca, 2000). The presence of layered sedimentary unit is clearly defined by reflections showing lateral continuity, the various layered facies are representative of different types of stratification characters (layers frequency, thickness, texture and consistency. These characters are identifiable within the Miocene marine sequences that fill the basins of the lower and middle Miocene, and in the sedimentary Pliocene-Quaternary margin growth, mainly at the level of the outer continental shelf and in its transition to the continental slope (Lecca, 2000). The units more easily crossed by the seismic signal, sometimes also with seismically transparent layers, can be formed by marine sediments of various nature and be in incoherent conditions (hydro plastic conditions or sands with water in the inter granular porosity) or semi-coherent conditions due to the water expulsion by lithostatic load, these are the conditions in which usually is the Pliocene-Quaternary sequence (Lecca, 2000).

Sedimentary bodies geometry

In reference to the seismic / stratigraphic interpretation, Lecca (2000), stands out for the outer continental shelf of the Sulcis, the following seismic-stratigraphic units:

The geological basement: extrapolating on the continental shelf the formations outcropping in coastal areas, where the acoustic basement is detected below the layered units, it is attributable to many formation (Varisican basement, various Mesozoic and / or Paleocene covers) (Lecca, 2000). Generally, the appearance of the acoustic basement indicate its rise with reduced Miocene and or

Quaternary carbonate covers. In addition, in conjunction with magnetic anomalies, locally the acoustic basement could be Oligo-Miocene andesites (Lecca, 1982). In these instances the proofing attempts were always vain, due to the low success of substrate sampling due to the quaternary organogenic limestone crusts. The presence of ignimbrite sequences, which is known to be widespread in the emerged rift, in the upper parts of the tectonic blocks can be deduced by morphological evidences, and for coastal outcrops vicinity (Lecca, 2000).

The Miocene sequence in the high resolution seismic lines is detected only in its upper part, failing to reach the underlying basement unless when this rises back laterally. In rare cases can be observed onlap interpreted as coastal standing on slightly inclined basement surfaces, and as marine onlap on the steepest (Lecca, 2000). The Miocene sequence is distinguishable in at least two parts. The upper, more easily crossed by the seismic signal, with little spaced clinoform reflectors, laterally correlatable with the Sinis pre-evaporitic Tortonian and Messinian marls described by (Cherchi et al.,1978). The lower part, from which the clinoform reflections arrives broadly spaced and for which Burdigalian age can be assumed (Lecca, 2000).

The Messinian erosive surface: the Messinian eustatic fall, recognized in Sardinia only in Sinis (Cherchi et al, 1978), has left evidence in outer continental shelf Lecca (2000). In many seismic sections of the Sulcis outer shelf, can be identified the erosion surface developed at the expense of the Miocene marine sequence. Its presence is highlighted by the overlying lower Pliocene wavy parallel distal fine sediments stratification. This level was also recognized on the sparker seismic acquired during the "Sardinia Channel 2009" campaign. On the profiles could be identified at a polycyclic evolution palaeo riverbed carved on undifferentiated volcanic substrate affected by surface erosion irregular evolving polycyclic with ultimate definition likely attributable to MIS2. Above the erosive surface opaque seismic facies was observed and interpreted as silt-sandy sediments filling related to the closing stages of Versilian transgression, MIS 1, covered by closing transgressive cycle marine sedimentation and *Posidonia oceanica* bioconstructions.

The Pliocene-Quaternary sequence that in the rest of the margin and in the bathyal plain shows a depositional continuity, in the upper slope and the shelf areas consists of several sub-units probably due both to Pliocene tectonic control both for influence of high frequency quaternary eustatic oscillations (Lecca, 2000). The entire sequence can be easily recognized thanks to the presence of Messinian erosive surface which constitutes a sequence boundary type 1 sensu Van Wagoner et al (1987). To Pliocene is attributed the part before inclined layers, parallel or tangential (down laps) correlated with the first regressive event (falling-low stand systems tract) of the outer shelf prograding prism (Lecca, 2000). Except for deposits that fill large Messinian incisions, the lower part is characterized by a wavy parallel pattern with concordance relationship sensu (Mitchum et al., 1997) with the Messinian erosive surface (Lecca, 2000). Its areal distribution generally follows the relative tectonic lows of outer shelf areas, while in inner shelf was mostly eroded (Lecca, 2000). In the lower part there are no littoral depositional units, it is produced instead a distal sediments condensed section, probably due to the fast rise of the sea level compared to the response capacity of the sedimentary system (Lecca, 2000). Furthermore, the available volumes of sediments were limitated because during the Messinian this part of the margin, being well above foothills systems, has undergone a major clastic denudation (Lecca, 2000). During this time the continental shelf, probably had a reduced wideness and was presumably located several tens of meters above the current sea level (Lecca, 2000) as documented by the presence of Pliocene shoreline and outer shelf facies below Sinis basalts (Pecorini, 1972), all the above prograding complex is attributable Quaternary. Above the Pliocene sequence, between the upper slope and the intermediate shelf, lies the sedimentary prograding prism consisting of several systems tracts characterized by various types of cliniform pattern (Lecca, 2000).

San Pietro island area submerged shorelines

The palaeo-environments evolution which occurred in this continental shelf area since the last sea level rise, have been strongly influenced by extensive volcanic outcrops (Milia, 1998) and left evidence of highly articulated palaeo shorelines such as palaeo valleys, palaeo cliffs, palaeo lagoons and palaeo beaches in beach rock facies. Messinian eustatic fall, known in Sardinia only in the Sinis region (Cherchi et al, 1978), has left evidence in several seismic sections of the outer shelf in front of the Sulcis region, can be identified the erosive surface developed at the expense of the Miocene marine sequence. Its presence is indicated by the overlying deposition of undulated parallel fine and distal Pliocene sediments (Lecca, 2000). Inside Cala Fico ria which have been recognized on the seismic Air Gun tracks acquired during the oceanographical campaign "Sardinia Channel 2009", a 50 meter wide channel can be followed for about three miles out to sea, limited by high rock terraces, seismic surveys proved to be the culmination of a fossil palaeo-valley engraved both on the acid volcanics than on the middle-upper Miocene layered sequence. The erosive surface reaches the depth of -200 meters, this fact, together with the analysis of seismic facies allows to establish a relation with the Messinian continental phase. (Cherchi & Montadert, 1982), on this surface lean in unconformity a prograding wavy reflectors sequence, attributable to Plio-Pleistocene sedimentation. The last phase of fluvial erosion has affected the existing deposits during MIS 2 up to -123 m (LGM). The subsequent filling of the palaeo-valley (upper Pleistocene - Holocene) is distinguishable in a lower unit with weakly inclined and wavy well marked reflectors interpreted as alternation of medium and coarse littoral and delta sands; and the summit unit characterized by a semitransparent seismic facies with piano-parallel reflectors, correlatable with medium-fine sediments of littoral and lagoon environment.

The limit of the inner shelf is defined, off Cape Sandal, by an alignment of walls engraved in the volcanic substrate with the foot located at the average depth of - 140 meters and the top at the average depth of -90 meters, these are large structures controlled by tectonic trends NNW-SSE and NE-SW oriented which evolved in cliff environment.

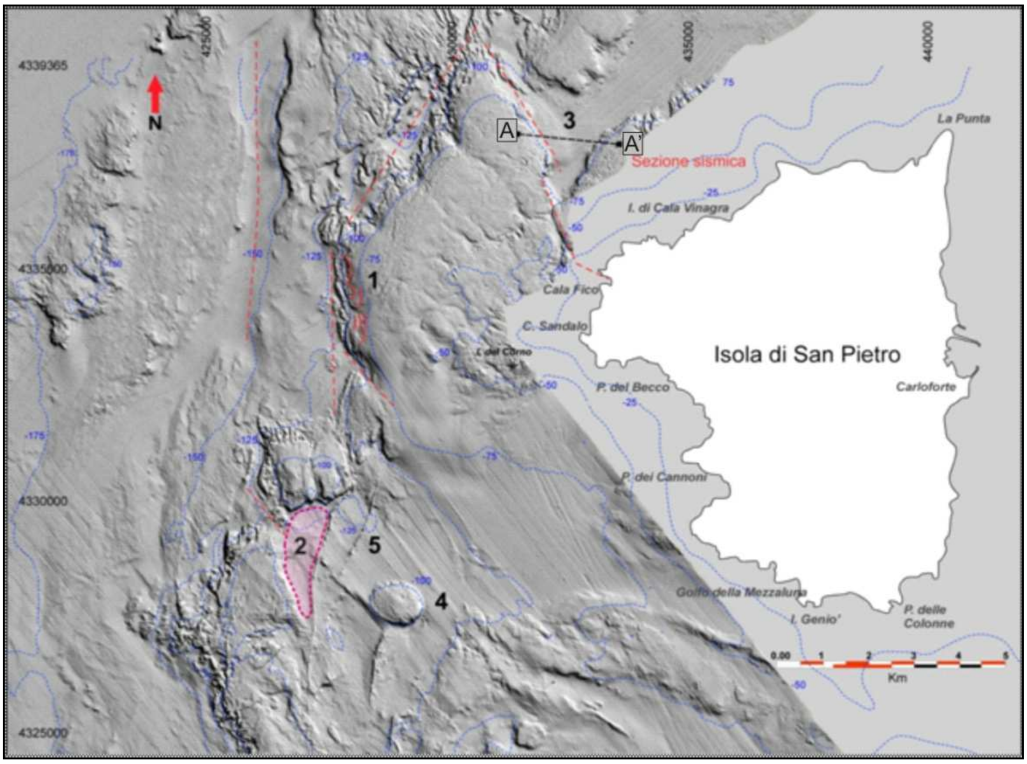


Fig. 62 - San Pietro Island sea bottoms DTM showing:-1) Palaeo cliffs array structurally controlled where rotational landslide niches have been recognized; 2) Palaeo lagoon set on a structural-volcanic depression, from which was dredged at - 125 m below actual sea level a thanatocoenosis testifying the sea level stationing during the last glacial maximum (LGM - MIS 2); 3) Messinian setting palaeo valley, re-engraved during MIS 2, Sparker profile track; 4) main emission center with sub circular neck morphology basal diameter of approximately 1 km; 5) parade of sub parallel dykes trending NS and N 10 ° E.

The lithologic character of these cliffs assume long evolutionary times and polycyclic processing probably began from the middle Miocene and followed during the various Pliocene-Pleistocene transgressive phases. The lavas are often based on ignimbrite tuffs and volcanoclastites levels, this has led to differential erosion that, together with the intense fracturation, have led to the evolution of gravitational movements of collapse and decametric blocks tipping, however landforms that now we can observe are mainly due to the last phase of low sea level standing (MIS 2); in this phase important role have been played by physical alteration processes of the rock surfaces due to Periglacial climatic conditions. At the foot of the frames extends large fossil abrasion platforms, masked by the draping of the Holocene sediments.

Conglomeratic sandstone Beachrocks constituted two extensive outcrops in the northern part of the island of San Pietro, about half a mile off Cala Vinagra and

Punta delle Oche, at a depth of - 45 m; testifying the more southern border of a palaeo shoreline that can be followed, with some discontinuity both off Capo Altano that off Funtanamare beach. The overall appearance of the beachrock bodies is characterized by clear erosive forms on the top surface and on the edges, the arrangement in “banks” slightly tilted towards the sea, typical of these outcrops, resumes the beaches sedimentary body arrangement characters; the sedimentary structures represented are typical of coastal environment (such as plane parallel lamination, wedge-shaped, sigmoid and inclined); these sedimentary structures are typically truncated by interlayer erosion surfaces. Layer surfaces are truncated by a summit erosional surface with erosive channels and mufflers caused by witnessing to the partial removal of the upper part of the original sedimentary record. Erosive processes along the edges follow different ways: the structure arrangement exposes layer heads to recession along the inner boundary, while along the outer limit base undermining phenomena cause fractures, settling differential failures and block tilting (Orrù & Ulzega, 1986). Most of the beachrocks found along the Sardinian shelf, characterized by thickness ranging between 4 and 5 meters (Ulzega et al, 1984), have developed within micro tidal environment during the Holocene transgression and have been subjected to sin-sedimentary cementation processes (DeMuro & Orrù, 1998). Based on the depth at which are found, these beachrocks can be attributed to Younger Dryas, a negative pulsation within the more general Holocene marine transgression (Orrù et al., 2004). In the Capo Sandalo area, on the seabed DTM has been recognized a palaeo shoreline, between -120m and -130m, linked to the MIS 2 where has been rd a palaeo-ria breaking the continuity of the rock frames, the bottom of the bay instead of closing as can be seen in the actual rias (Cala Fico) opens up like an amphitheater rising up to -120 m; the depressed area is filled by fine sediments and may have hosted during the MIS 2 low standing, a palaeo-lagoon, it is unclear whether this morphology is the product of erosion or as including part of a caldera or crater, like others in the vicinity. Dredging sampling returned a sandy silt containing a blackish gray thanatocoenosis rich in shellfish from intertidal lagoon and infra-littoral environment and some open shelf species.

Cagliari gulf area

The Cagliari gulf continental margin setting is to be put in relation with southern Sardinian continental margin evolution, characterized by a submarine depositional system controlled by extensional Pliocene tectonics and divided into several marginal basins, which receives sedimentary contributions from the various segments of the continental shelf (Lecca et al., 1998). Cagliari basin is the innermost part of the sedimentary system of the whole margin, defined and controlled by the tectonic blocks of the continental margin of southern Sardinia, in particular by the movements of the Ichnusa seamount and Su Banghittu blocks (Fanucci et al., 1976).

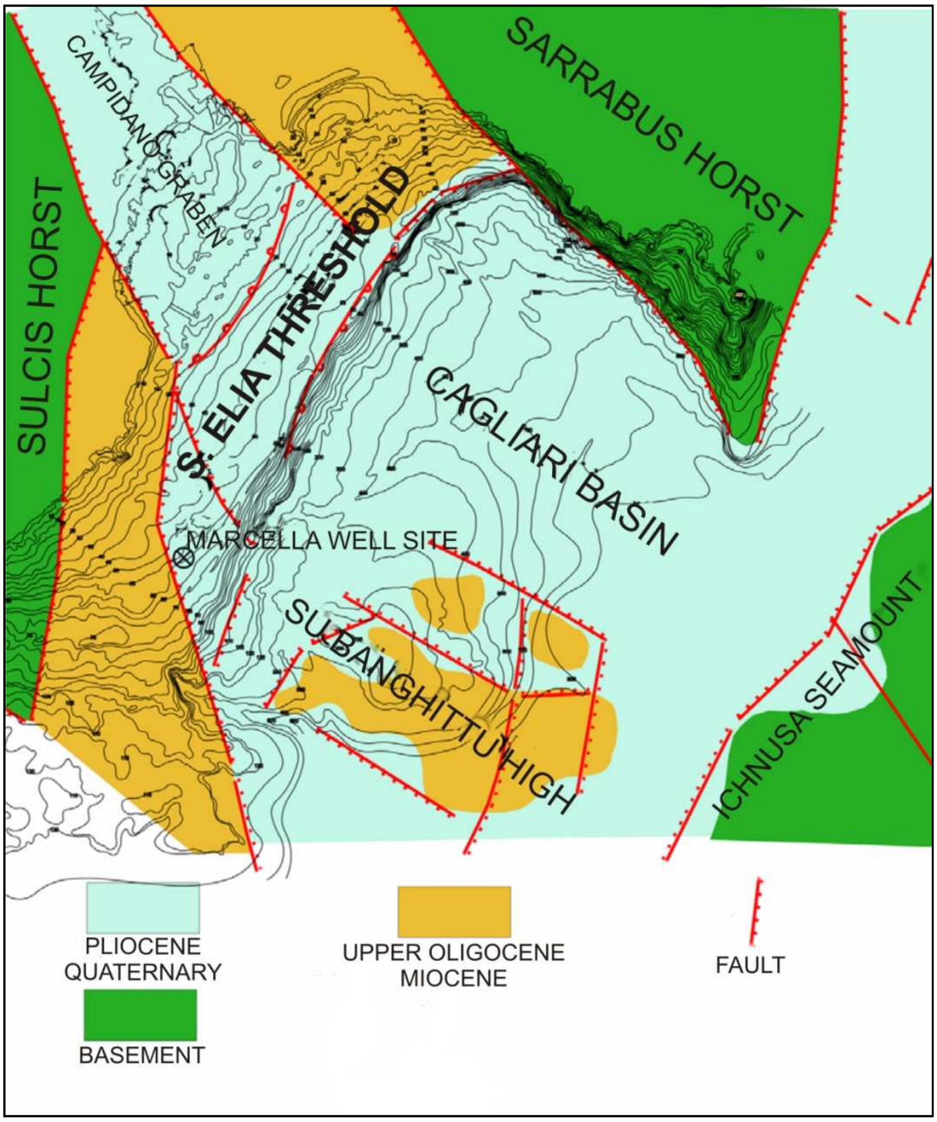


Fig. 63 – Cagliari gulf tectonic sketch from Cossellu 2007 modified.

The north-east area can be correlated with the evolution of Sardinian oriental continental margin; a passive margin which defines to the west the Tyrrhenian basin and extends from Ichnusa Seamount at 39° N to the Etruscans Seamount at 41° 30' N.

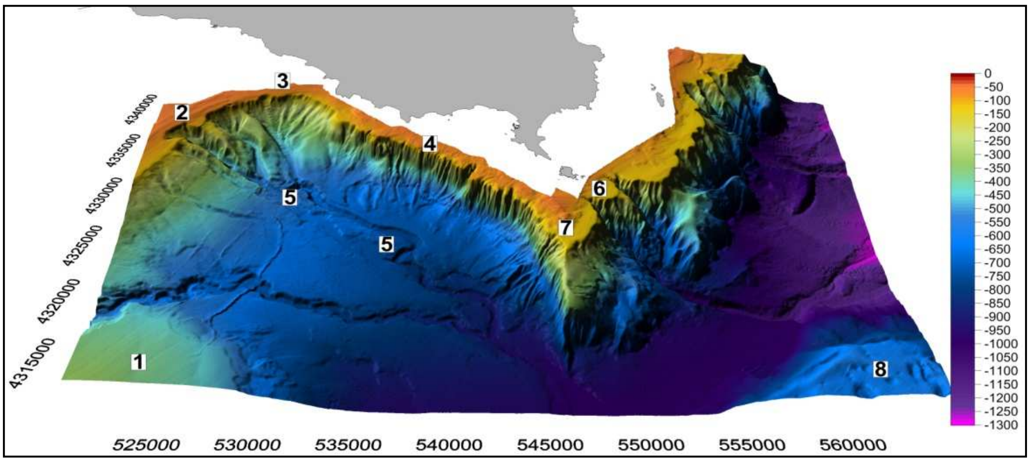


Fig. 64 - The main geomorphological features that can be observed in the Cagliari gulf area are: 1)Banchittu's residual strip of continental shelf; 2) Sant'Elia canyon headscarp, indented to the continental shelf for about 900m, reaches the depth of -80m, showing inside a creeping surface; 3) Foxi canyon headscarp were can be observed gravitative movements and "crescent-shaped bedforms"; 4) The fault wall, set above the continuation on the continental shelf of a Campidano graben's eastern side fault, is affected by diffused erosive processes on the edge; 5) Carbonara canyon's meandering bed; 6) Simius canyon headscarp; 7) The continental shelf edge lies at the average depth of -120m; 8) The Ichnusa Seamount.

The eastern continental shelf shows wider extension than the western sector, reaching an average width of 4 miles, has regular morphology or weakly bumpy and is characterized by an articulated morphological arrangement with an average 2% slope. The geomorphology of the slope is characterized by submarine canyon and several tributary channels, inside of them are localized various kinds of landslides.

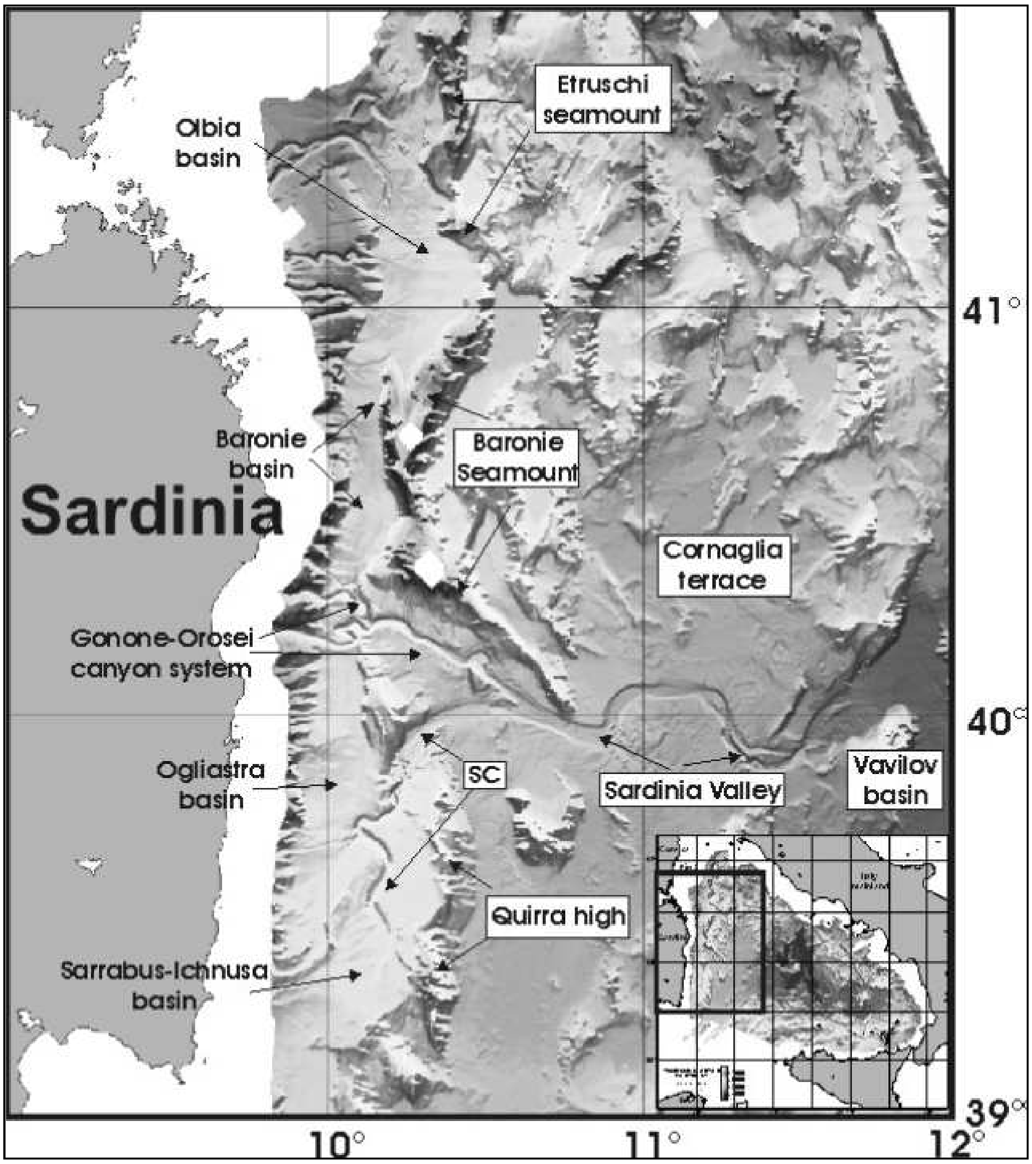


Fig. 65 – Shaded model of Thyrrenian basin to which south-eastern Sardinian continental margin belong.

In the Cagliari gulf area, inside Foxi canyon's head scarp, a retrogressive evolution have been detected bed forms characterized by a wave length of dozen of meters and a height of several meters, with the ridge lines arranged approximately perpendicular to maximum slope line, this bed forms are called "crescent-shaped bedforms". These are generated by the erosion and deposition repetition due to the load of gravitative sedimentary flows.

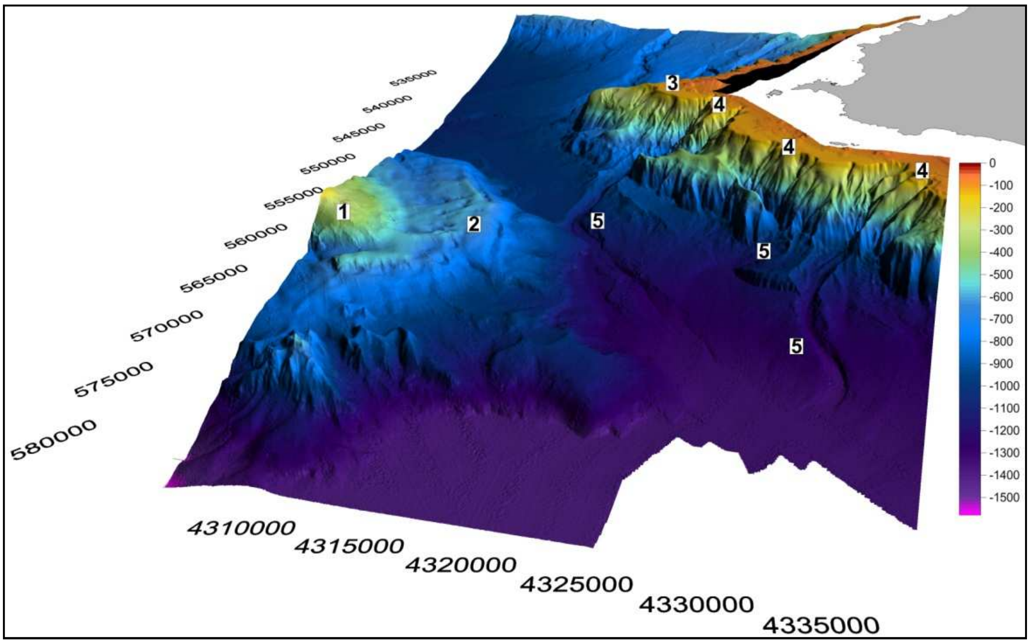


Fig. 66 - On the east side of the continental shelf in the Cagliari gulf area can be observed: 1)The Ichnusa seamount whose slopes have their origin at -1000 meters and the summit reaches -140 meters; 2) Depressions of unknown origin, with a maximum diameter of 700 meters and deep up to 60 meters, which are comparable to "mega pockmark" structures detected in the summit area of the Ichnusa seamount; 3) The edge of the continental shelf lies around -130 m and reaches the depth of -80m at canyon heads; 4) Canyon heads assume predominantly a converging hydrographical pattern, the Simius canyon, whose head scarp is located at a depth of -80 m, reaches 17 km in length and the depth of -1400m in lower slope areas, along its course the canyon engraves the Ichnusa seamount foot causing several landslides. Main channels in the upper slope area have erosive V-shape profiles with steep slopes in which are detected evidences of active gravitative processes; 5)The main channels, in intermediate slope areas assume flat-bottom morphology, filled by intra-canal deposits.

Structural Geomorphology

The southern part of the Sardinian rift, with the superimposed Campidano Graben structure continues at sea within the Cagliari gulf, both at the continental shelf level than in the upper slope regions. In the Capo Carbonara area the morphologies show important tectonic features that follow the main regional tectonic, the continental shelf reaches a maximum width of about 2.3 nm and is characterized by sub planar morphology with a slightly steep sea bottom (3-4 %). More in detail, the western shelf edge is oriented parallel to an important tectonic feature N130°, resulting in a steep (>40°) fault wall exposure. Carbonara canyon, reaching a length of about 22 km starting from the head scarp at a depth of -90 meters reaches -1090 meters pointing out as one of the main morphological units of the area. The canyon has a meandering trend and evidence of NE – SW oriented tectonic control are clearly identifiable. The main tributary channels of Carbonara Canyon, and their ten secondary heads scarps that are set in this area cause the edge withdrawal, which was usually located at an average depth of -120 meters in these sectors moves back down to -90 meters due to retrogressive evolution at the continental shelf expenses. On the continental shelf large areas shows outcropping or sub-outcropping Palaeozoic crystalline basement, in such areas are observed several isolated pinnacles, erosion furrows, and erosion escarpments reaching maximum heights up to 20 meters. The upper continental slope is affected by large areas of widespread erosion (approximately 33 km^2), within which is possible to observe important landslides and channelled flows. In this same area there are also relevant gravitative instability deposits, related to the detachment niches inside the Carbonara canyon head. All along the fault wall tracing the shelf edge in this area, another widespread erosion area have been recognized, covering approximately 28 km^2 where the main erosion processes are gravitational movements, channelled flows and cliffs as high as 75 meters, directly engraved in the Palaeozoic bedrock.

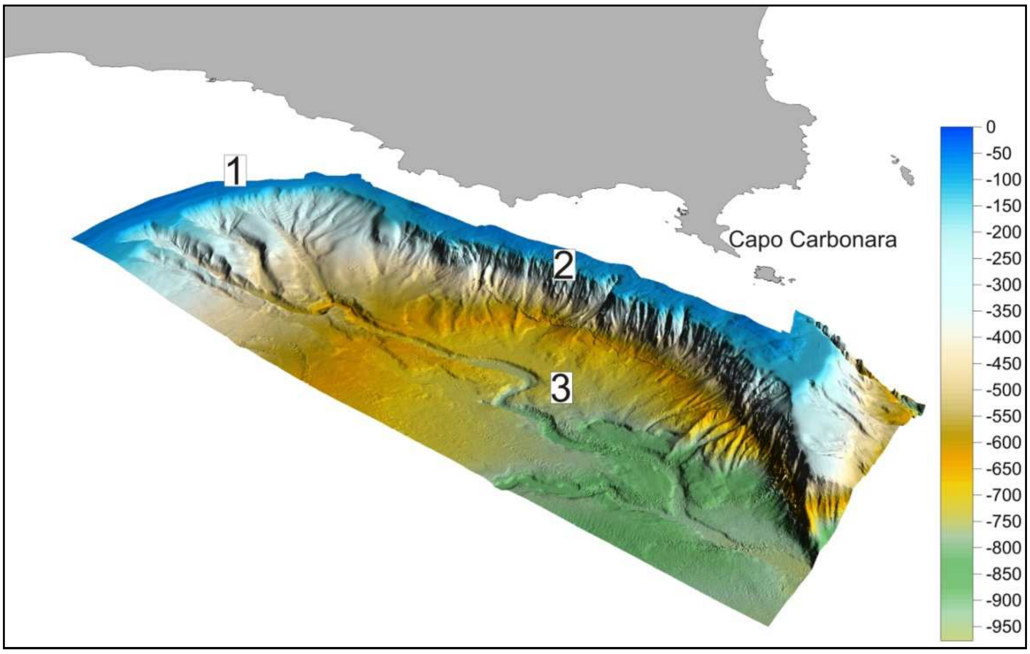


Fig. 67 - On the western continental shelf of the Capo Carbonara area can be recognized: 1) The Foxi/Carbonara canyon heads, house of significant sedimentary transportation, testified by the presence of characteristic bed forms, the head scarp region also hosts relevant gravitative deposits, mainly in runaway condition if triggered; 2) The continental shelf edge, which direction follows on the shelf the trend of the Campidano graben eastern side fault exposing a really steep fault wall affected by diffused and channelized erosion capable to expose the underlying Paleozoic crystalline basement; 3) The Carbonara canyon which also follows the main tectonic trend from the shelf edge down to the slope regions, secondary tectonic lineaments NE-SW oriented with evidences both on the shelf than in upper slope where dislocated the canyon's bed.

Cagliari gulf area submerged shorelines

On the Cagliari gulf area outer continental shelf are exposed relic coastal depositional systems related to the stage 1 of the Versilian transgression (Chappel & Shackleton, 1986), with sandstone-conglomerate beach-rock facies, interpretable as submerged shorelines (Segre, 1968), and with associated backshore depressions filled by fine sediments, which can be interpreted as a palaeo-lagoon (Gandin, 1970; Pittau Demelia & Loi, 1982; Ulzega et al, 1986). The most intact outcrops are found at a depth of -45 m, while fragmented strips remain at -60, -30, -15 and -1.5 m. The arrangement in "banks" slightly inclined towards the sea, typical of these outcrops, follows the arrangement characters of beach sedimentary body (Orrù et al., 2004).

These sedimentary structures are typically truncated by interlayer erosional surfaces; beachrock's forms of erosion agree with the submersion and conservation model for beach ridges on the continental shelf in accordance with the *trangressive submergence* process (Penland et al, 1988). This mechanism provides the submarine re-elaboration of the littoral sedimentary body, in the absence of cementation, to make shifting the palaeo beach towards the shore. Beachrock cementation is carbonate and has two precipitation generations, the first calcite-magnesium of littoral marine environment, and the second micritic calcite precipitated in sub aerial environment in the phreatic groundwater oscillation band. Similar deposits have been dated, basing on isotope analyzes (14^{C}) in north-eastern and south-eastern Sardinia (Ozer et al, 1984). The main beach-rock (-45 m) shows age of between 9.5 and 9.9 ky BP, while the shallow beachrocks (-1 / 1.5 m), closing the Versilian transgressive cycle show isotopic age ranging between 4.5 and 6 ky BP (Demuro & Orru, 1998).

In proximal shelf are recognizable several generations of submerged delta sedimentary bodies related to the transgressive Versilian cycle, stage 1. In fact, in the eastern Gulf of Cagliari, the shallow beachrock (-1.5 m) rests on an alluvial deposit weakly cemented and partly buried by the sub-actual Rio Foxi delta gravels (Orru, 1991).

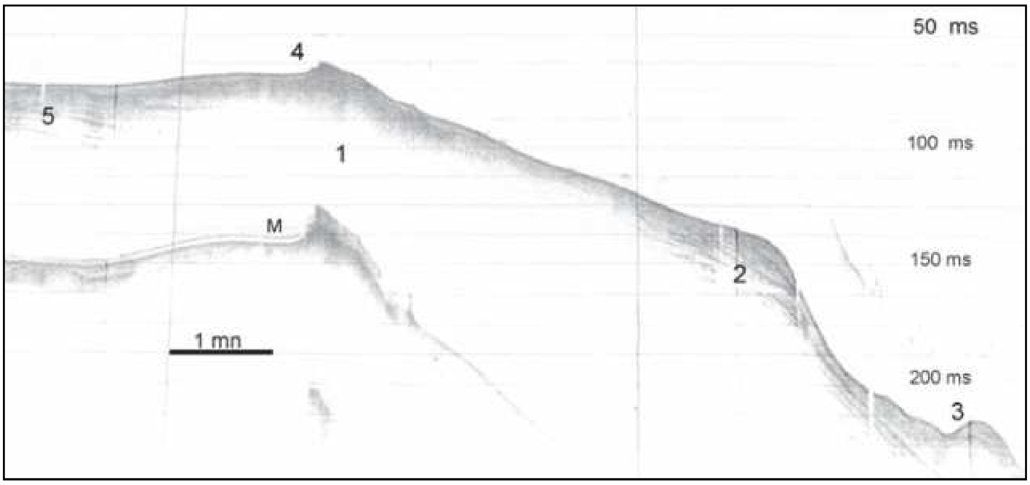


Fig. 68 - Sub Bottom Profiler 3.5 kHz seismic record- Section in the shelf edge area 6 nm off Capo Sant'Elia SE - NW (outer gulf of Cagliari): 1) deaf substrate, upper Miocene biogenic limestone; 2) submerged depositional terrace with sub-parallel and prograding convex geometry reflectors; 3) basal accumulations derived by gravitational sliding; 4) outcrops of the main -50m beachrock, MIS 1; 5) depression filled by parallel lamination fine sediments, palaeo-lagoon; M) multiple.

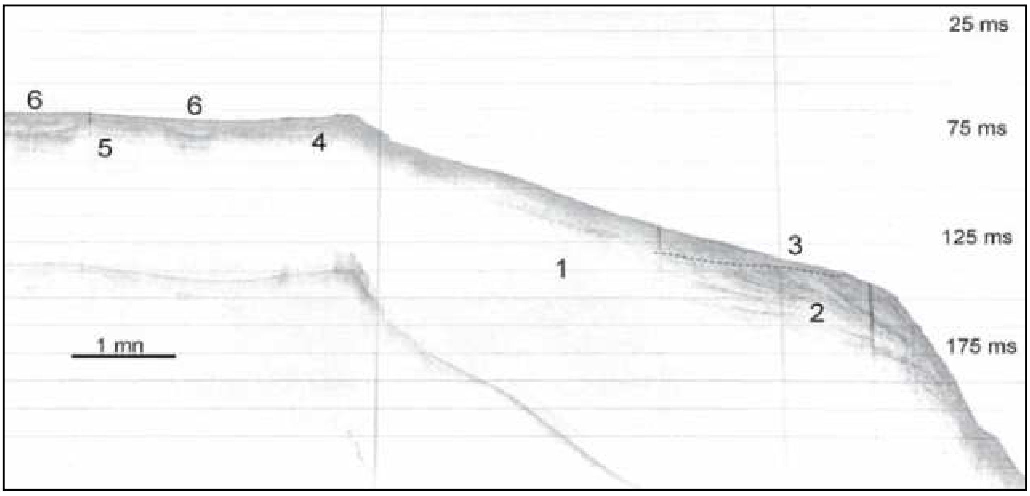


Fig. 69 - Sub Bottom Profiler 3.5 kHz seismic record - Section NNW-SSE on the shelf edge 6 nm off Capo Sant'Elia (outer gulf of Cagliari): 1) deaf seismic facies of the tertiary substrate and absence of sedimentary geometries, upper Miocene biogenic limestone; 2) Pliocene-Quaternary prograding prism, opaque seismic facies, with rare inclined reflectors; the sedimentary geometries are represented by pinch-out towards the shore and foreset inclined towards the sea; 3) erosion surface truncates the inclined reflectors, Würmian low standing terrace, MIS 2;4) outcrops of the main beachrock at -50 m, MIS 1; 5)buried littoral sandbar;6) depression filled by fine sediments, palaeo-lagoon.

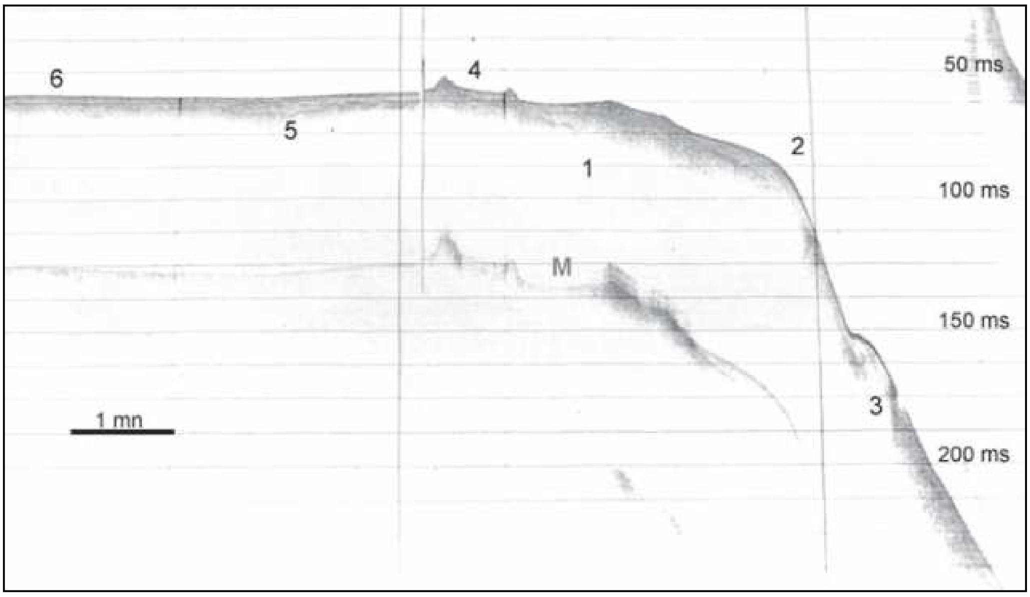


Fig. 70 - Sub Bottom Profiler 3.5 kHz seismic record - Section WNW-ESE on the shelf edge 6 nm off Capo Sant'Elia (outer gulf of Cagliari): 1) seismically deaf substrate, biogenic limestone of the Upper Miocene; 2) residual submerged low standing depositional terrace, MIS 2; 3) accumulation by gravitational sliding in upper slope; 4) outcrops of rock beach organized into two banks, -45 and -55 m, MIS 1; 5) palaeo-lagoon filling; 6) marine bioclastic sedimentation; M) multiple.

Sedimentary bodies geometry

A series of deep canyons, E-W oriented, cut both the slope and the continental shelf, coming sometimes near the coast. The edge develops at the constant depth of more or less -125m and it rises to lower depths in correspondence of the canyons' head withdrawing, which is caused by regressive erosion (Orrù & Ulzega, 1988). Due to the considerable Plio-Quaternary sediment cover, which characterizes the continental shelf, its morphology is generally regular and steady inclined from the coastline to the edge, where a noticeable break of the slope occurres. It is made up by thick prograding (Lecca et al., 1979; Ulzega A., 1988) In this area have been studied submerged depositional terraces, which refer to the sea level low-standing, and situated in the continental shelf of southern Sardinia. The structural structure affecting the southern part of the Campidano plain, also conditions the frame of the ahead continental shelf (Fanucci et al., 1976). Morphological characteristic recognisable in the emerged land are also visible on the continental shelf, which regularly develops in the area of the Gulf of Quartu with wide and weakly inclined surface. The shelf ends with a marked edge in correspondence of the -110m isobath; its width all along the coast between the Gulf of Quartu and Capo Carbonara, is reduced to 1-2 miles. To the eastern area of the Gulf of Cagliari s.s., the extent of continental shelf is of about 6 miles; its marked edge is recognisable until the depth of -75m and it is interrupted eastward by the head canyon of Foxi and in its middle side by the canyon of S.Elia. The heads of S.Elia canyon shows active withdrawing, clean and directly cut in the basement. Towards west, the edge, less sharp and deeper, appears at a depth of 120m and it is characterised by prograding fine sediments (Ulzega et al., 1980b; Ulzega et al., 1986).

The main structural elements derived by seismic profile analysis, is the faults continuity of Campidano plain, in the inner area of the Gulf of Cagliari. The noticeable asymmetry on the emerged land, is also particularly evident. This asymmetry is represented by limit surfaces at the lower limit of both Pliocene and Quaternary, and by a series of structural highs oriented NW-SE towards the andesitic relief of Sarroch (Fanucci et al., 1976; Lecca et al., 1986). It is even possible to observe an area of recent subsidence, which includes the internal part of the platform and probably the flat land part of Campidano, now occupied by the wide marsh of S.Gilla, which receives the terrigenous contribution from two important rivers, Rio Mannu and Cixerri. The structural condition of the depression limit might be now defined, even if it appears possible, that exists a prolongation of the depression toward sea, before the Plio-Quaternary levelling (Fanucci et al., 1976). The Plio-Quaternary sedimentation shows a continuity, which records the more thickness, close to the inner zone of the platform. Besides, while the Pliocene deposits drape the basement, the Quaternary deposits show prograding geometry. In those deposit it is possible to find traces of shorelines, related to the Late-Quaternary glacio-eustatic phases (Ulzega et al., 1980b; Ulzega et al., 1986). Due to the erosive effects of the regression during the last glacial period, the present morphology of the shelf is regular, with the exception of the least extended Holocene deposits. During the recent Quaternary the subsidence on the continental shelf has been extremely limited therefore the deepest limit of the regression is at about -110m.

The continental shelf shows the typical characters of the Sardinian eastern margin with an extension limited to a few miles and deeply cut by active canyons. The shelf edge, generally over 100m, presents a clean break of declivity with extremely limited prograding areas; due to the regressive erosion correspondingly to the heads of the canyons, the bedrock outcrops locally.

DISCUSSION

This work started within the Marine Strategy project carried out by the Geology and Biology operative units of the Cagliari University, focused on the Coralligenous Habitat mapping on Sardinia’s continental margins. Aim of this work is to produce the most detailed as possible predictive habitat mapping, starting from a detailed geomorphologic study successively integrated with biological and oceanographic data coming both from direct investigations than from bibliographic data. This goal has been recognized as highly ambitious, and for this reason the work have been focused on target biocoenosis **A4.26 – “Mediterranean coralligenous communities moderately exposed to hydrodynamic action”** and **A4.713 – “Caves and overhangs with Corallium rubrum”**, as defined by EUNIS classification (European Nature Information System), subsequently reunite under the name of Coralligenous biocoenosis for the mapping of which has been reached a high level of confidence.

First phase consisted in the recognition of continental shelf and upper slope main Physiographic domains, mainly done starting from morphobathymetric dataset, have been recognized the continental shelf areas, upper slope, canyon and seamounts.

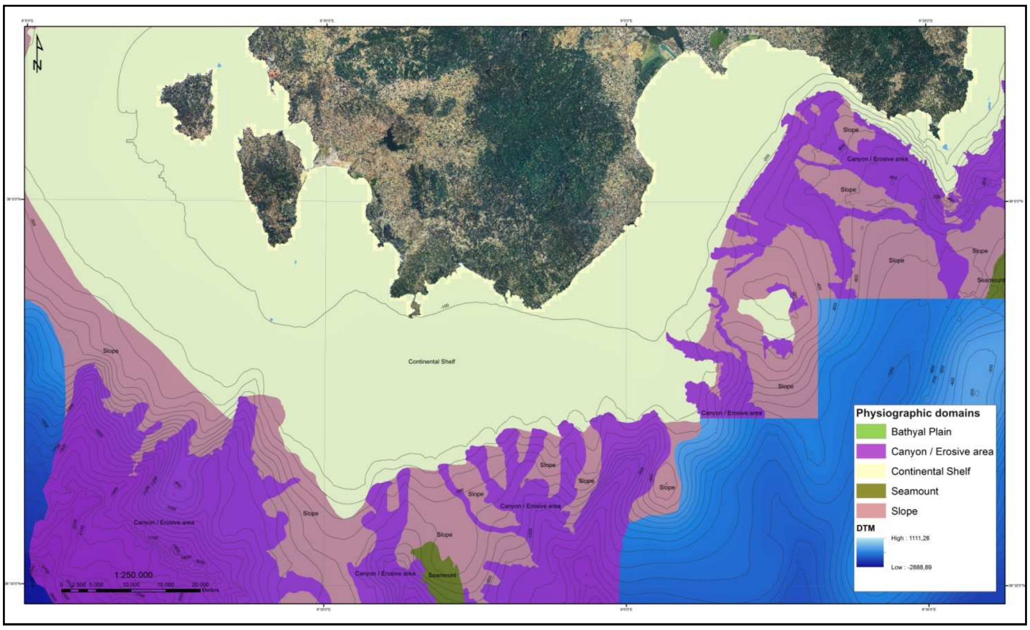


Fig. 71 – Chart of physiographic domains of Sardinian southern continental margin.

For the morphobathymetric (geomorphologic) elements mapping the work started from high resolution DTMs, with a fine scale interpretation which can grant the recognition of every small element, up to metric resolution. Have been recognized elements related to sedimentary dynamics, such as bed forms and depositional terraces; erosive features, fine to broad scale, from scar, scours to channel and canyons systems and various types of landslides, moreover of course tectonic and structural features have been recognized, studied and mapped.

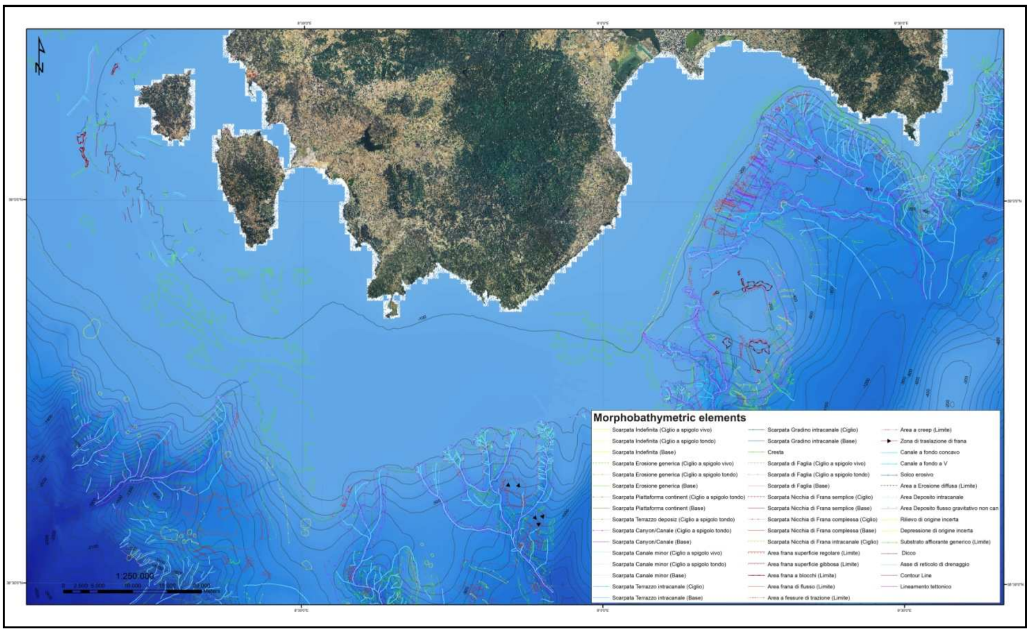


Fig. 72 - Chart of main morphobathymetric elements of Sardinian southern continental margin.

Seabed classification maps have been obtained by the integration of original and bibliographic data, starting from backscatter coverage obtained from the MaGIC project dataset which cover the major part of study area, shallow areas (from -60/-50m up to the shore) have been integrated thanks to SSS full coverage achieved during the oceanographic campaign “Mappatura delle praterie a Posidonia oceanica lungo le coste della Sardegna”, carried out between june 2000 and february 2001 founded by the Environment ministry of Italy. The big gap left by MaGIC project between Palmas gulf and Capo Spartivento has been filled with EMODnet seabed nature dataset.

Coralligenous Habitat

Coralligenous Habitats develop on both hard and soft bottoms, in 4 to 160 m of water depth (Ballesteros, 2006) and adapt to low levels of nutrients and temperature from 10 to 23°C in waters with moderate hydro - dynamics (Ballesteros, 2006). The extreme variability of their bathymetrical distribution is partially governed by the light-dependency of participating benthic organisms (Ballesteros, 1992), a finding particularly true for macro algae, adapted to grow at dim-light conditions. Architecture and morphology are primarily controlled by biological carbonate productivity that responds to climate, oceanography, physiography, changes in accommodation space and terrigenous supply. Modern Mediterranean coralligenous build-ups are characterized by large structures that may be up to 4 m high and greater than 50 m in lateral continuity. Coralligenous build-ups vary in shape and dimension: nevertheless, their geomorphologic expression have not been exhaustively categorized. Various definitions for characterizing CHs structures, reflecting different constructional morphologies, have been reported in the scientific literature. For examples, CHs have been identified as coralligenous de plateau (Bosence, 1985), columnar crustose coralline algal build-ups (Di Geronimo Et Alii, 2001), and algal reefs (Bosence, 1985) or banks (Ballesteros, 2006). Definitions are generally based on scuba divers visual observations or direct sampling. From a geomorphologic point of view, the following main morphologies have been distinguished: 1) banks-flat frameworks with thickness ranging from 0.5 to 4 m mainly built over more or less horizontal substrata, and 2) rims-structures on submarine vertical cliffs or surrounding the opening of submarine caves, generally located in shallower waters than banks (Pérès & Picard, 1964; Laborel, 1987; Ballesteros, 2006). If rims develop on a hard original substrate, banks are generally reported as a consequence of the coalescence of rhodoliths, indicated as a coralligenous de plateau (Pérès & Picard, 1964).

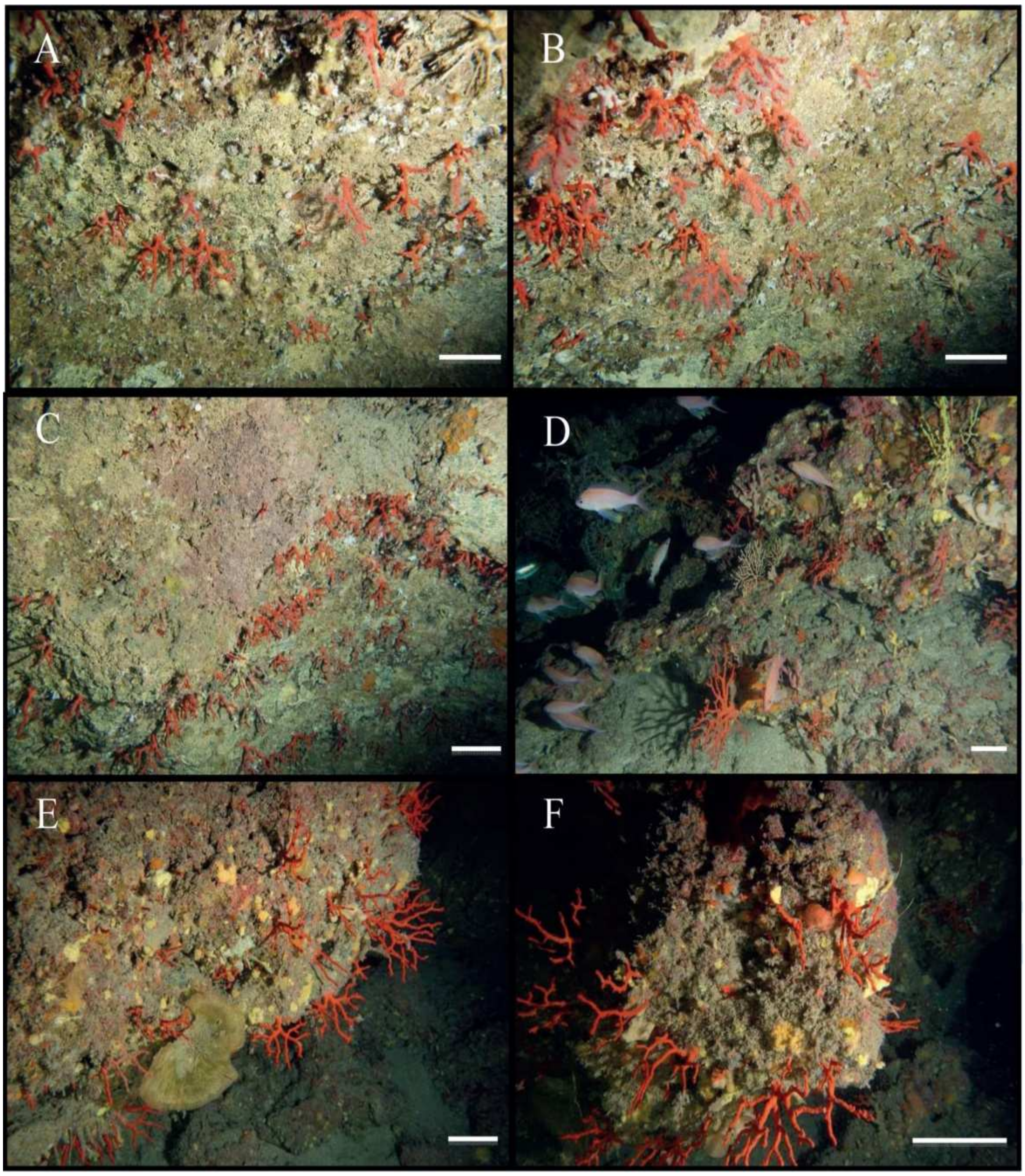


Fig. 73 - Red coral colonies of the studied sites: A, B, C) High density patches of C.rubrum with colonies oriented 145°, along highly sloping walls in CCc; D, E, F) Vertical, 90° and 145° oriented colonies in red coral patches in SPi, where colonies occurred mostly along ridges of small steps that characterized this site. Scale Bar: 10 cm.

Mediterranean Sea coral communities have been widely investigated in the last several decades, and information about their biology and distribution in the photic zone of the Mediterranean basin has progressively accumulated, underlining the paramount ecological role of these communities in benthic food webs (Tsounis et al. 2006b; Linares et al. 2008; Cerrano et al. 2010).

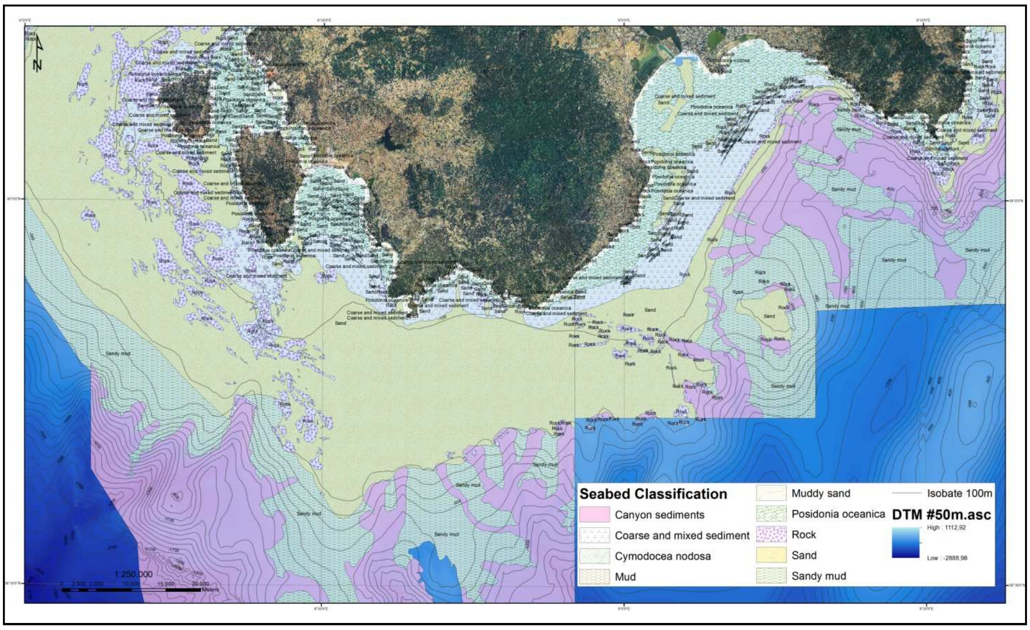


Fig. 74 – Chart of seabed classification of Sardinian southern continental margin.

Coralligenous communities are, in the Mediterranean Sea, among the most complex and diversified assemblages living on hard bottoms. In the last 10.000 years, they have contributed to creating significant organogenic reef-like bioconstructions (Laborel 1987; Sartoretto et al., 1996). These structures result from a multi-stratified accretion, made of a macro algae and invertebrates complex, in dynamic equilibrium due to the simultaneous activities of builders (coralline rhodophythes, scleractinians, bryozoans, serpulids) and different disruptive agents, of which clionids and allied sponges are the most important ones. Whenever either of these actions prevails, it favors the accretion or the erosion of these bio-constructions (Cerrano et al., 2001). Coralligenous biocoenosis have high biodiversity. The richness and diversity of species in coralligenous biocoenosis are partially due to their evident substrate heterogeneity, which has 3-dimensional features. Hong (1982) underlined the abundance of crevices and micro cavities which, depending on their size and exposure, host large kinds of organisms, distributed according to light irradiance and water movement. Moreover, these cavities are subject to different rates of organic and inorganic sedimentation, including a strong microhabitat differentiation. According to Picard (1985), this is a common feature in what he called "complex climatic mesoecosystems", formed by a polybiocenotic species assemblage (Cerrano et al., 2001).

Radiocarbon dating has allowed to determine the age of these bioconstructions: the deeper ones date back to the early Holocene or to the late Pleistocene, during the last great transgression, caused by the general increase in temperature at the end of the Würm period. Sartoretto et al., (1996), dated the oldest Mediterranean reefs at around 8500 B.C., suggesting they had formed at a depth not greater than 10-15m. The coralligenous buildings growing on soft bottoms along the Apulian coasts are constituted by mounds of calcareous sub-fossil algae (*neogoniolithon mamillosum*), developed probably 10,000 years ago in the littoral zone (Cerrano et al., 2001).

Coralligenous build-ups vary in shape and dimension: nevertheless, their geomorphologic expression have not been exhaustively categorized. Various definitions for characterizing CHs structures, reflecting different constructional morphologies, have been reported in the scientific literature. For examples, CHs have been identified as coralligenous de plateau (Bosence, 1985), columnar crustose coralline algal build-ups (Di Geronimo et alii, 2001a,b, 2002), and algal reefs (Bosence, 1983) or banks (Ballesteros, 2006). Definitions are generally based on scuba divers visual observations or direct s*ampling.* From a geomorphologic point of view, the main morphologies that have been distinguished are: 1) flat-banks frameworks with thickness ranging from 0.5 to 4 m mainly built over more or less horizontal substrata, and 2) rims-structures on submarine vertical cliffs or surrounding the opening of submarine caves, generally located in shallower waters than banks (Pérès & Picard, 1964; Laborel, 1987; Ballesteros, 2006). If rims develop on a hard original substrate, banks are generally reported as a consequence o*f the coalescence of rhodoliths,* indicated as a coralligenous de plateau (Pérès & Picard, 1964). Once CHs has been identified on the DTM, SBP seismic records have been studied in order to cross-check interpretational hypothesis

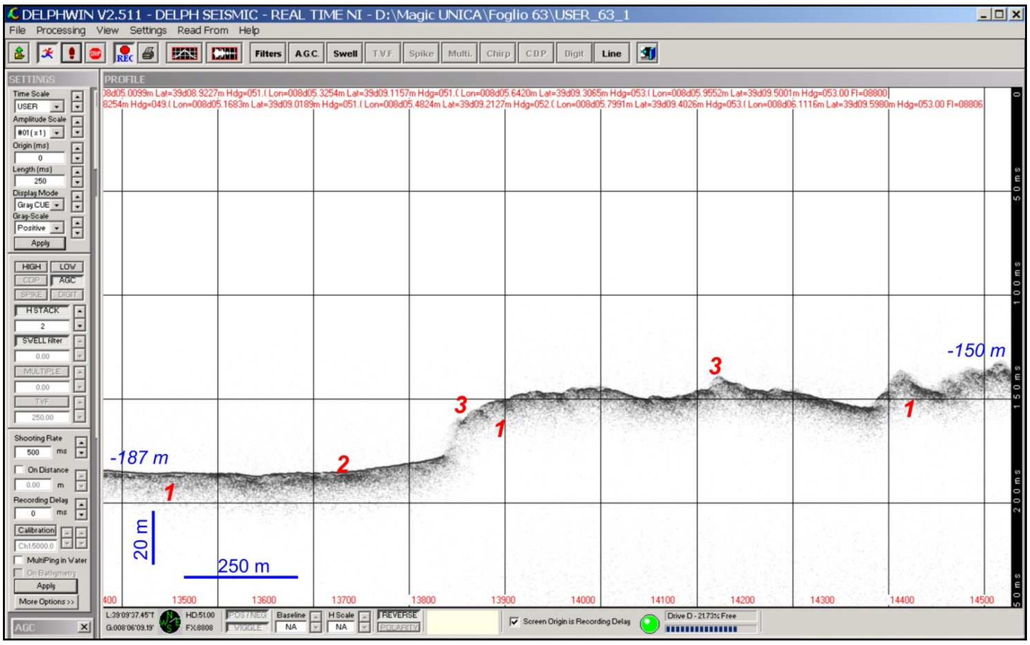


Fig. 75 - High resolution seismic record - GeoAcoustics Chirp II Sub-Bottom Profiler - A1_SBP_6 San Pietro Is. : 1 acoustic basement correlated with the Sulcis Oligo-Miocene volcano-sedimentary series. 2 - outer shelf loose silty sands sediments (Holocene); 3a - Thick coralligenous assemblages (1 to 2 meters) on residual pinnacles; 3b - Thick coralligenous assemblages (1 to 2 meters) on a palaeocliff.

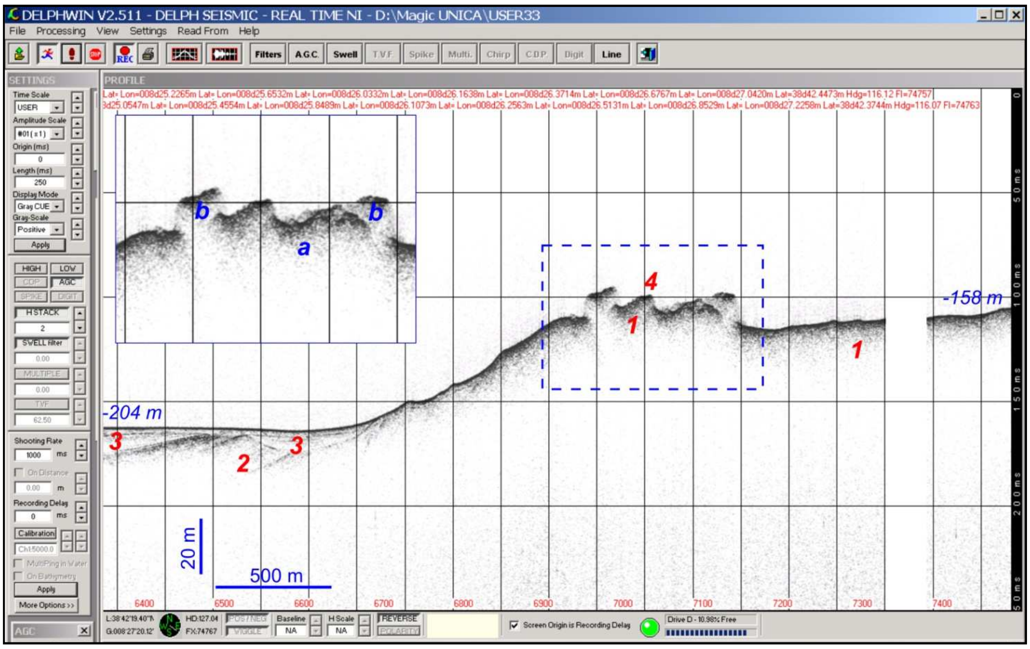
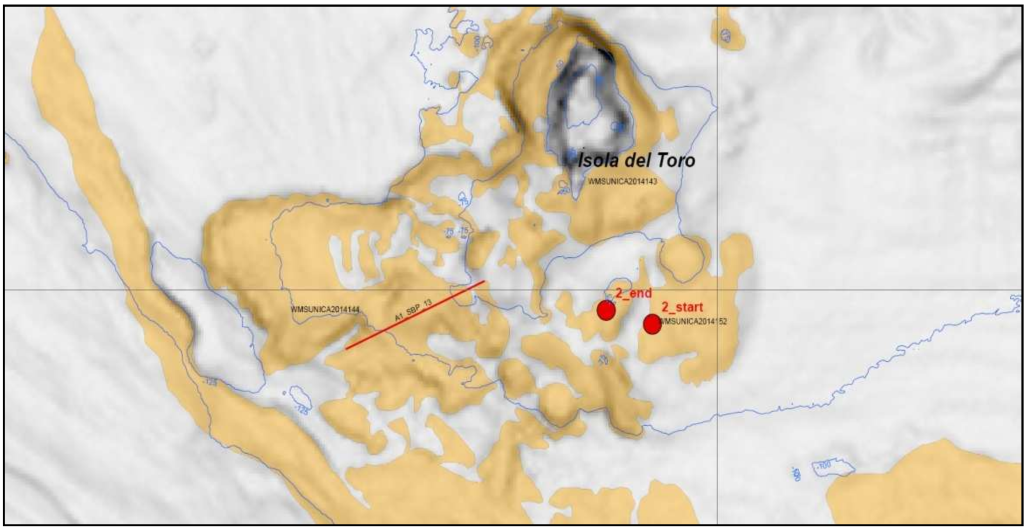
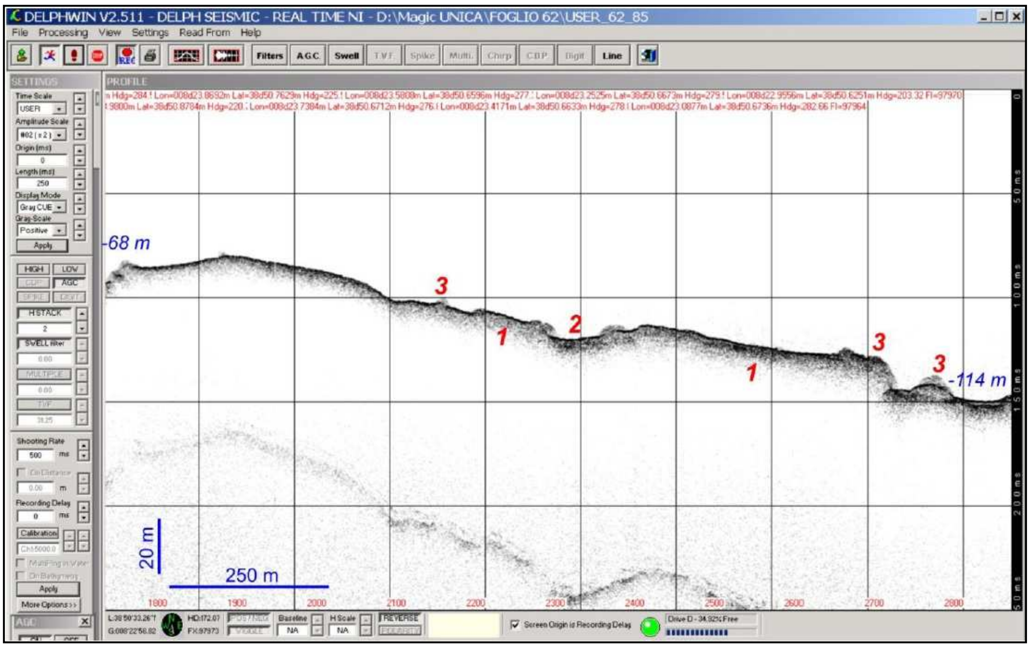


Fig. 76 - High resolution seismic record - GeoAcoustics Chirp II Sub-Bottom Profiler - Profilo A1_SBP_15 Toro Canyon area: 1 acoustic basement correlated with the Sulcis Oligo-Miocene volcano-sedimentary series. 2 –Pliocene sediments; 3 – outer shelf loose silty sands sediments (Holocene) – 4 – Thin Coralligenous assemblages(<1m) on rocky substrate. a – Volcanites rocky substrare; b – Coralligenous assemblages on rocky substrate.

Biocoenosis distribution and conditions

ROV surveys were focused on locating and quantifying occurrence, size structure, and density of red coral in southern coasts of Sardinia (central western Mediterranean Sea). The main objective was to compile an extensive set of data through non-destructive methods (without causing any destruction to the colonies), in contrast with fishery dependant data gathered in the majority of past studies on *Corallium rubrum*. For each site the following parameters have been retrieved and measured: 1) Abundance: *i*) number of patches in 100 linear meters; the total distance covered by the survey was obtained from ROV track positioning and *ii*) number of colonies per USU as per GORI *et alii*, 2010. 2) Density, estimated per each site as the mean number of colonies within patches per square meter (i.e. mean of densities within USU). 3) Basal diameter and colony height (from the basis of the colony to the farthest tip, following Follesa *et alii*, 2013), in order to determine the proportion of colonies with a diameter of more than 8 mm (Sardinian legal size limit for harvesting, Follesa *et alii*, 2013), and the portion of colonies that reached the maximum reproductive output. Red coral colonies were measured only if well positioned with respect to the picture perspective, while dead colonies were counted but had not been measured. 4) From size/frequency distribution, the population structure of sites was investigated through descriptive statistics including skewness, kurtosis and associated *p*-values. Significance for skewness and kurtosis was calculated using small sample skewness and kurtosis test implemented in the “Skewness and Kurtosis-Free statistics Software”. 5) Site complexity was evaluated through slope (expressed as “low”, <25°, “medium”, from 25° to 45°, or “high”, >45°), and profile curvature (high or low alternation of concavity and convexities) as parameters, at different scales, from small scale DTM and from ROV videos. 6) Number and percentage of non-ramified, ramified, dead and alive colonies, and orientation of colonies (0°, 45°, 90°, 135°, 180°), as in Rossi *et alii* (2008): 0° orientation is perpendicular to the horizontal sea floor, facing straight up, while 180° facing straight down. 7) Colony age was determined following growing rates, estimated for Sardinian populations. Determination of growth rate was made by “thin section-organic matrix staining datation method” according to Marschal *et alii* (2004).




DELPHWIN V2.511 - DELPH SEISMIC - REAL TIME NI - D:\Magic UNICA\FOGLIO 62\USER_62_85

```
n Hdg=284.! Lon=008d23.8692m Lat=38d50.7629m Hdg=225.! Lon=008d23.5808m Lat=38d50.6596m Hdg=277.: Lon=008d23.2525m Lat=38d50.6673m Hdg=279.! Lon=008d22.9556m Lat=38d50.6251m Hdg=203.32 FI=97970
! 9800m Lat=38d50.8784m Hdg=220.: Lon=008d23.7384m Lat=38d50.6712m Hdg=276.! Lon=008d23.4171m Lat=38d50.6633m Hdg=278.! Lon=008d23.0877m Lat=38d50.6736m Hdg=282.66 FI=97964
```

Fig. 77 – Toro Island area, SW Sardinian continental shelf, map of Coralligenous habitat distribution produced after morphobathymetric and seismic data interpretation, the red line indicates the SBP profile localization, red dots indicates start and finish of ROV transect for interpretative hypothesis verification, below the high resolution seismic record - GeoAcoustics Chirp II Sub-Bottom Profiler - Profile A1_SBP_13 Toro Island area: 1 acoustic basement correlated with the Sulcis Oligo-Miocene volcano-sedimentary series. 2 – depressions filled by outer shelf loose silty sands (Holocene) 3 - Thin Coralligenous assemblages(<1m) on rocky substrate. Interpretative hypotheses have been partially verified and corrections will be applied on definitive maps.

Two pilot sites have been identified for this study, the first located on the top surface of a lava flow in the San Pietro Island area, Southwestern Sardinia continental margin, while the second, is located in a canyon head scarp notch engraved at the expense of the Paleozoic crystalline basement in the Capo Carbonara area, Southeastern Sardinia continental margin.

Two ROV dives (1 per site) of about 2 hours each (4 hours of filming in total) at an average speed of 0.34 knots were conducted, resulting in a total distance of 2.74 nautical miles (5.07 km). The useful sampling distance (i.e. rocky bottoms, discarding soft bottoms and non-clearly visible images) covered by the ROV was 1.15 out of 1.22 nautical miles in SPi and 1.20 nautical miles out of 1.52 in CCc. A total of 178 high definition frames were used for the image analysis. In detail, 66 SPi during a 2.13 km long transect and 112 in CCc (within a 2.22 km useful transect). By summing all the USU, a surface of 16.5 m2 was investigated in SPi and 28 m2 in CCc. The minimum number of USU proposed by Kipson et alii, 2011 for describing species diversity and patterns within coralligenous assemblages was considered a proper reference for the description of red coral patches in each site (i.e. minimum of 4000 cm2 per site, using 20×20 cm squares). Red coral colonies were found in both sites, in different scenarios: along rocky ridges of carbonatic outcrops and boulders in SPi and over steep walls in CCc. Among all frames investigated, a total of 1801 colonies were counted (330 and 1471 in SPi and CCc, respectively). Moreover, a total of 448 colonies were measured (having the proper position with respect of the laser beams): 81 colonies in SPi and 367 in CCc.

SAN PIETRO ISLAND SITE

The survey was carried out at depths ranging between 80 and 85 m, with an average depth of 82 m. As shown in Fig. 79, the site is the top surface of a lava flow attributed to the Miocene volcanic sequence. At a small scale it did not show a particular roughness, while a larger scale analysis underlined an irregular surface, although overall complexity remains low.

Fig. 78 – Pilot areas localization.

The site is characterized by small steps (i.e., 1-meter tall steps) with sparse small boulders, slope values ranged between 1° and 5° (low) on the surface of the lava flow, with high values (45° to 90°) along steps ridges. A total of 13 patches of red coral were found along the transect, 0.61 patches per 100 m, the mean density in examined patches was 12.88±16.18 colonies/m2, while within USU (50×50 cm squares) a maximum of 49 and a minimum of 2 colonies were found. Red coral occurred along steps ridges, with colonies oriented 45°, 90° and 135°(respectively 32.6%, 34.8%, and 17.4% of the total measured colonies. While no overhanging colony was found, 15.2% of colonies were oriented in vertical position on the top surface of boulders (i.e. 0°, facing straight up). In detail within used frames, 5 colonies were dead (2.51% out of the total counted colonies), while 78 were non-ramified (39.20%) and 116 were ramified colonies (58.29%).

Analyzing the frequency distribution, the modal class in basal diameter was that of 6 mm, which was dominant in terms of number of colonies compared to other classes (kurtosis 9.42, *p*-value=0), while in height the modal class was the 6-8 cm. The mean value for basal diameter and height of colonies were 7.9±4.9 and 6.96±4.05 respectively. The positive value of skewness in the size/class distribution indicates a predominance of small sized colonies within the population; this data is confirmed by the fact that 57.8% of the measured colonies had a basal diameter lower than 8 mm, which is the actual limit in force in Sardinian waters. Regarding the age structure of this population, the mean age among measured colonies was 25.4, and the modal class was 20 years old. The youngest colony was estimated to be 10 years old, and the oldest 94 years old.

CAPO CARBONARA CANYON

The survey was performed at depths ranging from 88 to 115 m. The dive site is located in the shelf edge area on a NW-SE oriented regional fault wall, in the top of a deep and steep V-shaped channel indented into the continental shelf for 900 m. This canyon is controlled by a secondary tectonic feature oriented NE-SW. The CCc site shows high roughness both at small and large scale; the DTM analysis underlines an irregular surface and the overall complexity is high. The small-scale analysis describes an area characterized by a 50 meter high rocky wall overlooking the channel head; slope values ranges between 13° and 29° (medium) on the flatter parts, with high values (45° to 68°) along the rocky wall. Through a larger scale view, the site shows a high turnover of concavity and convexity throughout vertical walls with high values of slope, where red coral occurred. A total of 16 patches of red coral were found (0.72 patches per 100m on average) along the track, over steep walls concavities and on crust ridges. In all patches, the majority of colonies were oriented 90° (20.6%) and 135° (60.2%), with a minority oriented 45° (5.1%). In detail, out of a total of 1471 colonies, 454 colonies were non ramified, 573 were ramified and 444 were dead (respectively 30.8%, 39.1% and 30.1%). The mean density for this site was 54.14±32.36 colonies/m2, while a maximum of 97 and a minimum of 2 colonies were found within USU. The modal size class in basal diameter was that of 6 mm. The size/class frequency distribution emphasizes the predominance of small size colonies (skewness 1.26, *p*-value=0) and few size/classes compared to the total (i.e. positive kurtosis: 2.77, *p*-value=0).

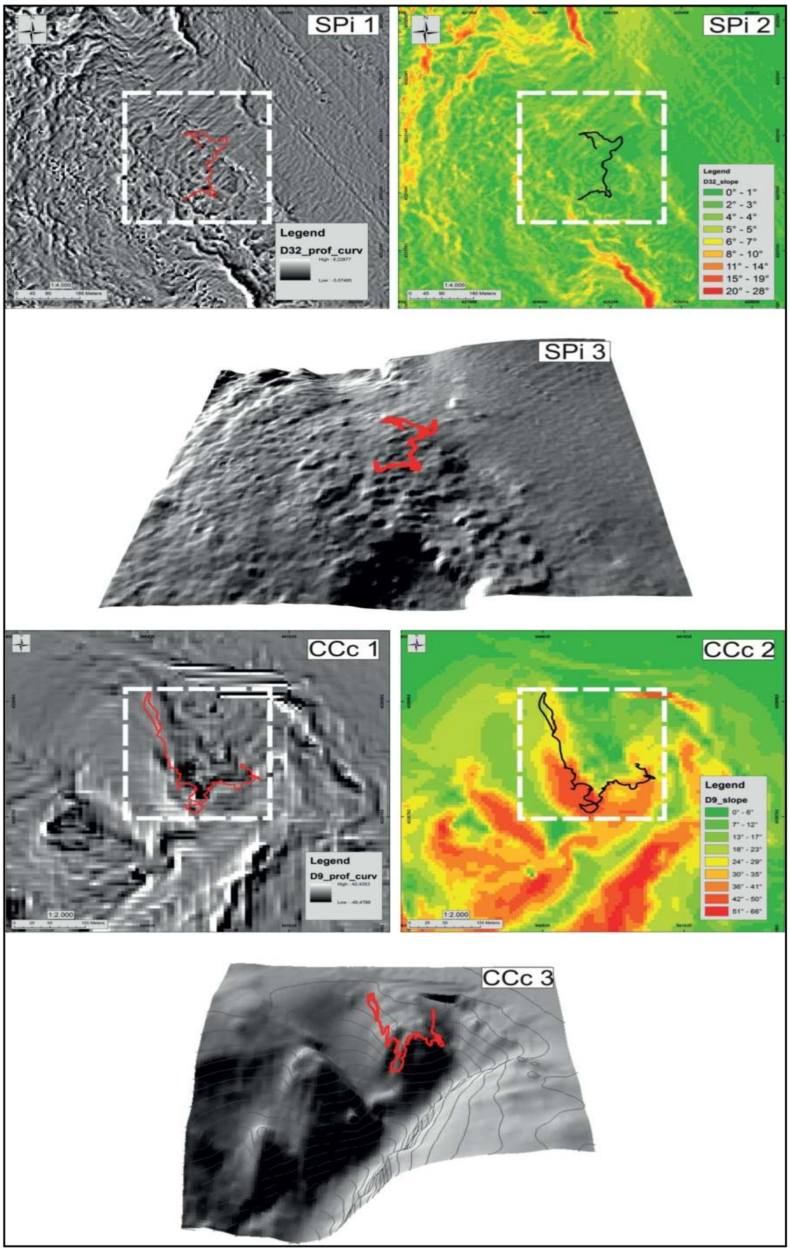


Fig. 79 – Preliminary approach to sea bottom analysis from Cau Paliaga et al., (2015); SPi 1) Profile curvature; SPi 2) slope and SPi; 3) 3D view maps of SPi (vertical exageration 1.5×). The survey was conducted on the top surface of a lava flow; despite localized excerptions, overall complexity of the site is low. CCc 1) Profile curvature, CCc 2) slope map and CCc 3) 3D view of CCc (vertical exageration 1.5×), conducted on the head of a V-Shaped, strongly deepened, erosive channel. Overall complexity of the site is high.

Furthermore, the 26.1% of measured colonies has a basal diameter larger than 8 mm while the modal size/age class was 20 years old. The mean age for this population was 19.8 and the oldest colony was estimated to be 60 years old, while the youngest 7.3.

Through DTM analysis sites with different geomorphologic setting were described, showing how these sites host red coral patches with different population structures and densities. SPi, which is the shallower site, showed low level of geomorphologic complexity together with a lower mean density compared to CCc (12.88 vs 54.14 col/m2). Conversely, CCc showed higher complexity with steep rocky walls where red coral occurs with perpendicular and overhanging position (Fig. 73 - Red coral colonies of the studied sites: A, B, C) High density patches of C.rubrum with colonies oriented 145°, along highly sloping walls in CCc; D, E, F) Vertical, 90° and 145° oriented colonies in red coral patches in SPi, where colonies occurred mostly along ridges of small steps that characterized this site. Scale Bar: 10 cm.). Although direct measures of current and sedimentation rates were not taken in the investigated sites, differences in the current intensity were easily deducted from the accumulation of silt. In particular, the accumulation was almost absent in SPi, while was on the gently sloping surfaces of the canyon in CCc. This observation is confirmed by a higher frequency of vertically growing colonies in SPi, that are actually absent in CCc, possibly because of the accumulation of sediment does not make the substrate suitable for settling of *C. rubrum*. The canyon shape described in CCc probably provides more vertical rocky walls, where the accumulation of silt cannot occur and the currents provide good organic matter availability (Tsounis et alii, 2005). In addition, smaller colonies are present in higher density in CCc, compared to SPi where the suitable surface for red coral is larger. Concerning size structure of investigated populations, results indicate that a large portion of colonies do not reach the minimum commercial size of 8 mm (43.2% of SPi and 26.1% of CCc colonies are above this limit). Moreover, mean value for colony height is very low in CCc (3.87±2.30 cm), which is over 2 cm lower than 6 cm, the size proposed by Tsounis et alii, 2006 as the measure at which deep colonies reach the 100% of fertility and can ensure the maximum reproductive output. On the other hand the mean height for SPi is almost 1 cm higher than the previously cited limit. The two populations were significantly different, showing a significant positive skewness values in the size frequency distribution (2.74 in SPi and 1.26 in CCc) which underlines that both populations are composed mainly by small and consequently young colonies. In detail, the higher skewness revealed in SPi is justified by the presence of large sized colonies that are absent in CCc, which influence the overall size class distribution. A higher occurrence of young colonies was found in CCc, along with elevated densities, and a considerable number of dead colonies (more than 30%).

The two populations of *Corallium rubrum* found at different depths showed different pattern of density and population structure with respect to what is known from literature (Rossi et alii, 2008; Follesa et alii, 2013). The shallower site, SPi, showed lower densities and larger colonies than those found in the deeper site, CCc. These results demonstrates that it is not possible to define a general pattern using depth as a single factor influencing red coral distribution. In the two investigated sites, geomorphologic complexity seems to be the most important factor influencing hydrodynamic and, in turn, the presence and density of red coral colonies.

Gorgonians & Black Coral (Deepwater corals)

The knowledge on the ecology of hard bottom gorgonians and black corals dwelling in the mesophotic zone of temperate areas (50–200 m depth in the western Mediterranean basin) is still limited due to the practical difficulties of investigations in deep waters. Nevertheless, the awareness of their ecological relevance is progressively increasing (Cerrano et al. 2010; Bo et al. 2015). Because of the disappearance of algal and seagrass “forests” with increasing depth as a result of light attenuation, in the twilight zone benthic sessile organisms become progressively more important contributors to the three dimensional complexity of mesophotic ecosystems, finally building up the so-called animal forests (Rossi et al. 2012; Rossi 2013). Indeed, just like terrestrial forests, these habitats create hot spots of biodiversity within their extension: They provide refuges for numerous species, host nursery areas for several commercial fish and play also key site and species-specific roles on the early-stage recruitment of other epibenthic. Deepwater corals are long-lived species that play an important role in the pelagic–benthic transfer of energy (Cerrano et al. 2010); besides this, they also amplify the ecosystem’s overall complexity along continental margins by providing new colonizable surface for the benthos (Gili and Coma 1998; Cerrano et al. 2010). In the deepest part of the circa-littoral zone, hard bottom coral assemblages dwell also on isolated rocky pinnacles commonly included among the so-called roche du large ecosystems (Peres and Picard 1964). These rocky pinnacles represent one of the less known ecosystems within Mediterranean mesophotic environments (Bo et al. 2012). Large anthozoans, such as gorgonians and black corals, represent the most frequently observed coral taxa in these ecosystems. Distribution of coral communities along these geomorphologic features may be determined by the combination of both biological and environmental factors that can synergistically affect spawn, larval development and settling, growth, and death rates of individuals. In particular, it has been recently postulated that the geomorphologic and mineralogical characteristics of settlement substrates could be important factors structuring benthic biodiversity, by affecting sediment accumulation rates, bottom currents and, ultimately, the rates of food supply (Wilson et al. 2007; Davis 2009). Recent studies, in fact, invoked geological features of the substrate along with interactions among corals (or generally other benthic organisms) as one main factors shaping coral communities dwelling in Mediterranean coralligenous habitats, which show very high variability within the smallest spatial scale (replicate or even from patch to patch. Furthermore, mesophotic coral habitats, host some commercially relevant species, they are becoming increasingly subjected to fishing activities that directly damage these fragile communities (Bo et al. 2014).

The high resolution morpho-bathymetric map (Fig. 80) was obtained by using a hull mounted MultiBeam echosounder, the EM 2040 Kongsberg operating with 300 KHz of frequency. Data were acquired with 40% lateral overlap and processed to remove spikes due to navigation system problems and/or to the acquisition system. Acquisition and processing of data were performed using the CARIS packet (CARIS HIPS and SIPS 8.1.2, Canada). The final data were organized in a grid with cell size of 1 m using the geographic system WGS84 UTM32 N. Video and photo footage was gathered by a ROV “Pollux” during two surveys conducted in October 2011 and September 2013 on board of the Research Vessel Astrea exploring the Carloforte Shoal in a depth range comprehended between 186 and 210 m depth. ROV was equipped with a digital camera (Nikon D80, 10 megapixel), a strobe (Nikon SB 400), a high definition video camera (Sony HDR-HC7), a navigation camera (1/3-inch SONY CCD, focal length 4–9 mm), and 3 jaw grabbers. The ROV hosted also a depth sensor, a compass, and three laser beams providing a 10-cm scale for the measurement of the frames area and size of organisms. The ROV was equipped with an underwater acoustic tracking position system (Tracklink 1500 MA, LinkQuest Inc.) providing detailed records of the tracks along the seabed. Four video transects were carried out on the Carloforte Shoal in three distinct habitats: 1) mud (transect T1, 650 m long), 2) bench terraces (transects T2 and T3, 380 and 520 m long, respectively), and 3) plateau (transect T4, 460 m long) (Fig. 80). Seven hundred and twenty-seven frames (166, 451, and 110 frames for the three habitats, respectively) were randomly extrapolated from the video footage with the software DVDVideoSoft for a total of about 2110 m2 of explored area (frames on average 3 m2). Each frame was then elaborated with the software ImageJ (Rasband W., Research Services Branch, Maryland, USA) in order to calculate the density of each target species (N° colonies m-2 ± Standard Error). Target species were considered as all the arborescent, habitat-forming anthozoans including scleractinians, alcyonaceans, antipatharians and zoanthids. ROV-Imaging technique was employed also to define the morphometric characteristics of the black coral colonies (basal diameter, height and width) in order study the population structure of L. glaberrima. Measures of height and width were gathered also for Isidella elongata. Other information, such as associated fauna and the in vivo aspect of the black coral colonies, has been registered. Finally, the fishing impact, based on the number of frames showing lost gears (N° impacted frames) and their direct damages on the colonies (N° of entangled colonies), has been quantitatively estimated (Bo et al., 2015)

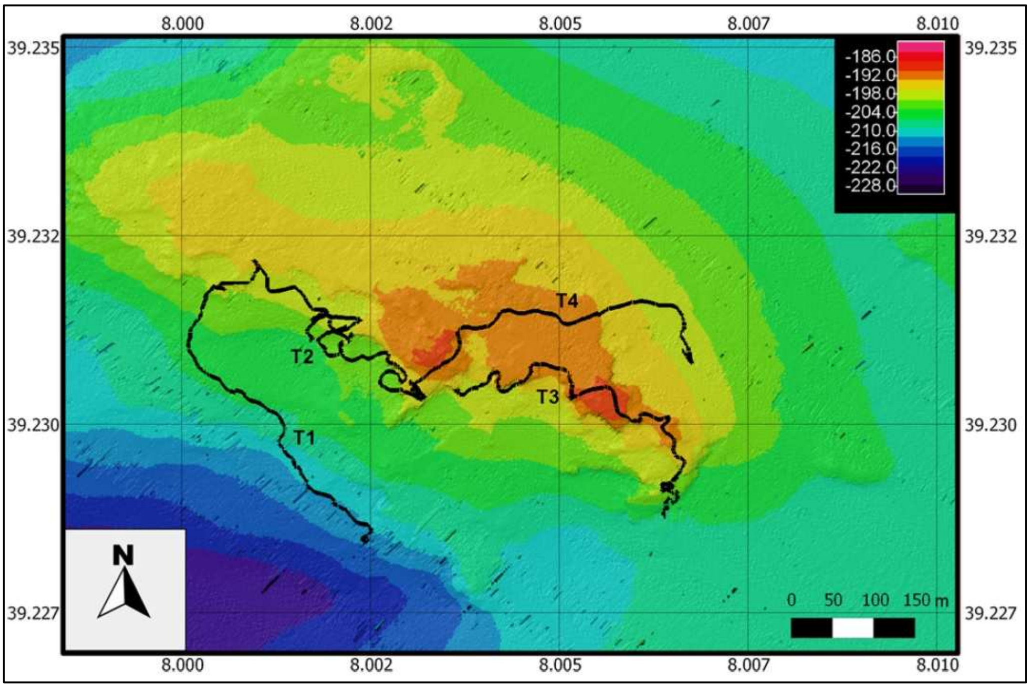


Fig. 80 - High-resolution bottom topography. Multibeam maps of one the San Pietro area studied shoal. Four ROV transects are represented in the map (T1, 650 m long,muddy area; T2, 380 m long and T3, 520 m long, bench terraces area, T4, 460 m long, plateau area).

Until a few decades ago, quantitative and qualitative information on sessile mesophotic fauna were hard to obtain because of the poor reliability and spatial resolution of traditional destructive benthic sampling techniques (e.g., trawls and dredges), in addition to their unknown capture capabilities. The recent and fast development of underwater remotely operated vehicles (ROV), coupled with multibeam echo-sounder (MBES), enabled to perform controlled sampling and detailed observation of specific mesophotic habitats with noninvasive protocols, which are particularly relevant for habitats of conservation interest.

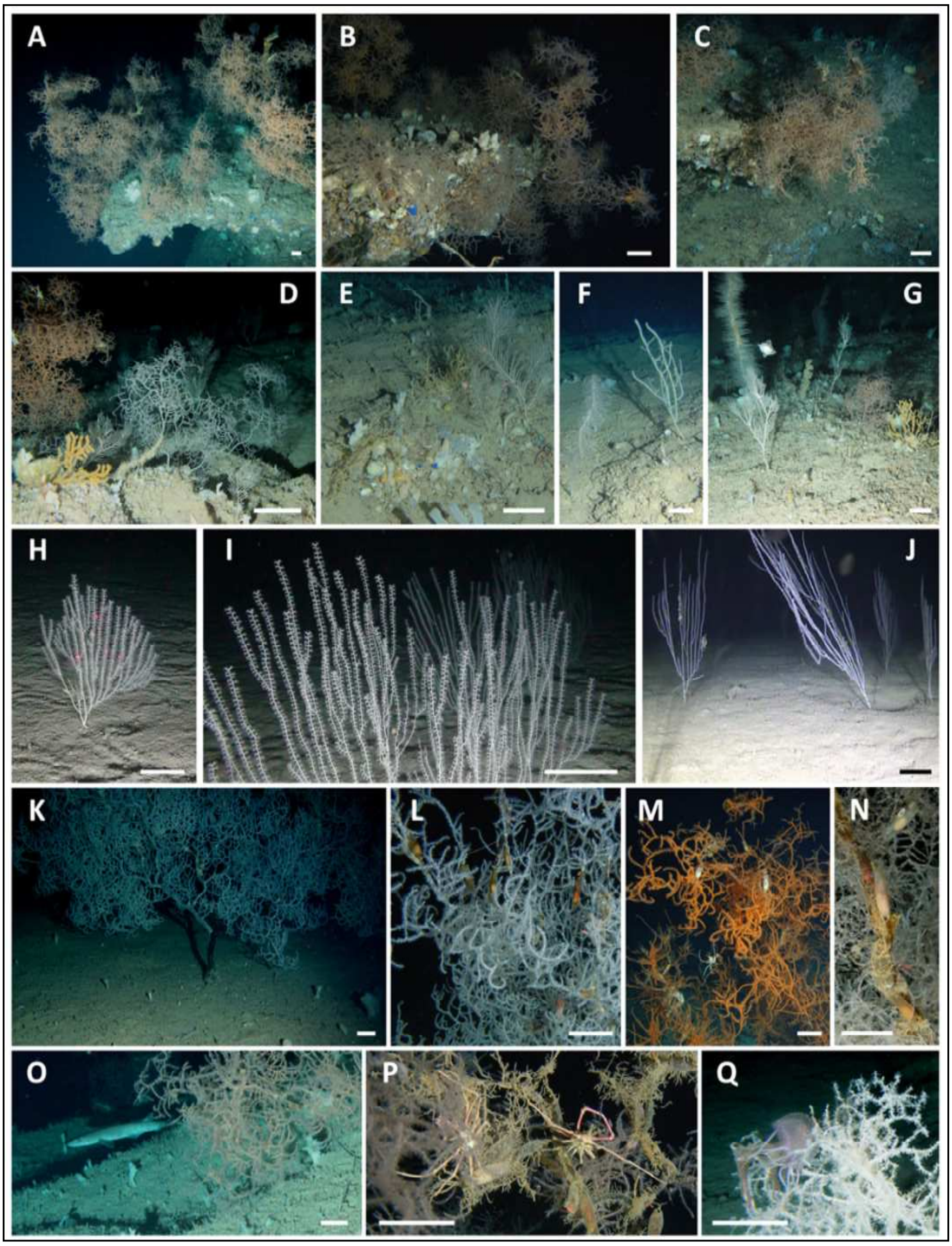


Fig. 81 - ROV images of the coral community of the Carloforte Shoal mod. From Bo et al., 2015.

A-C. Arborescent colonies of Leiopathes glaberrima densely arranged on the rocky bench terraces. D. Coral assemblage of a rocky emergence of the plateau. E. Colonies of Callogorgia verticillata surrounded by Bebryce mollis on the plateau. F. The black corals Parantipathes larix and Antipathes dichotoma on the silted bottom of the plateau. G. Mixed assemblage of black corals and alcyonaceans on the plateau. H-J. Colonies of Isidella elongata on the soft bottom around the rocky areas. K. Giant specimen of L. glaberrima anchored on a flat, silted rocky bottom. L-N. Catshark's eggs hanging from the ramifications of L. glaberrima. N. Specimen of Scyliorhinus canicula moving among the coral colonies. P. A pair of the crab Anamathia rissoana living on a coral colony. Q. Entrapped specimen of Pelagia noctiluca on a coral colony. Scale Bar: 10 cm.

Along the Sardinian continental shelf (central-western Mediterranean), investigations on coral assemblages are limited to the target species *Corallium rubrum* (Cannas et al. 2011; Follesa et al. 2013; Cau et al. 2015; Bo et al. 2015), whereas the status of communities of large anthozoans such as gorgonians and black corals are mostly unknown. The only relevant piece of information refers the description of the coral garden located in the Carloforte shoal (southwestern Sardinia), characterized by a dense and pristine forest of the black coral *Leiopathes glaberrima* and a large meadow of *I. elongata* (Bo et al. 2015). Nevertheless, information about levels of deepwater coral species turnover (i.e., beta diversity) among different rocky pinnacles is very scarce. Up to date, published studies have been mostly focused on community description and/or determining whether communities dwelling in different locations and/or habitats differ from each other at different spatial scales, coping with the renewed need of censuring presence and distribution of these species of the twilight zone of the Mediterranean basin (Cerrano et al. 2010).

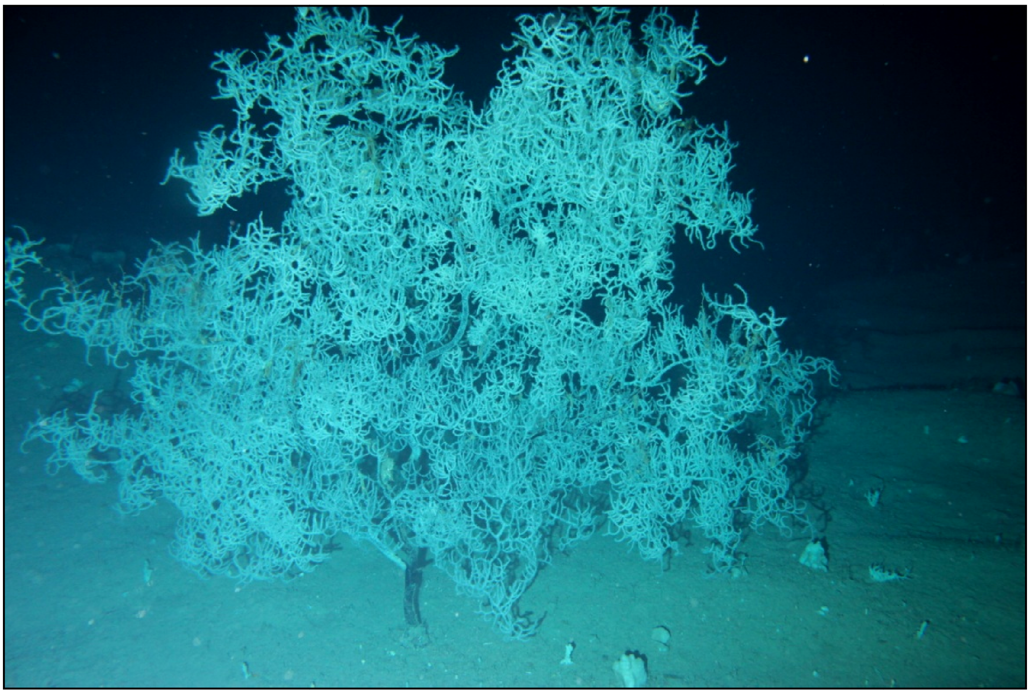


Fig. 82 – Leiopates Glaberrina colony founded in the "coral garden" area located in the San Pietro Island shoal (SW Sardinia continental shelf).

Works produced with the research group of marine biology at the University of Cagliari aims to improve the actual knowledge of deep coral forests, quantifying both fine-scale occurrence and abundance along different geomorphologic features, but also focusing on the possible role of substrate features in supporting their distribution and shaping communities composition. To do so, using combination of ROV footage and multi-beam echo-sounder inspections, we tested the null hypothesis of no differences in the total coral abundance and species turnover encountered on five rocky pinnacles, dwelling between 120 and 170 m depth along the south Sardinia continental margin, characterized by different regional geomorphologic features (i.e., habitat heterogeneity, average slope of the substrate and sediment coverage). Finally, biologists carried out the visual census of allochthonous debris deposited on the five rocky pinnacles in order to identify the possible anthropogenic factors of disturbance of the communities under scrutiny. The bathyal plan biocoenosis hosts relevant demersal resources as *Aristeus Antennatus* (Risso, 1816) and *Aristaeomorpha Foliacea* (Risso, 1827), in the Sardinian Seas the blue and red and the giant red shrimp represent the most important demersal resources for the trawling fleet. In general, before the 1960s few low tonnage wooden boats operated almost exclusively on the middle slope (max 400 m depth) and only with really good sea conditions. In the early 1990s, the Sardinian fishing fleet was renewed as a consequence of government policy (DM 26/07/1995) with the aims of reducing the fishing effort in shallower waters (GFCM-SACS, 2004). The main change involved the replacement of old, low tonnage wooden boats with large steel boats suitable for operate on deeper fishing grounds. In Sardinian seas the red shrimps are actively exploited by Sardinian fleets and occasionally by Sicilian, Tuscanian and Spanish trawl fleets. Nowadays about 300 tons of both shrimps are landed each year with seasonal variation and annual fluctuations (IREPA, 2010) (Fig. 83). The deep water red shrimps represent one of the most important deep-water fishing resources in Sardinia (up to 15–20%, as biomass; IREPA, 2003–2010) which correspond to a high economic income (Palmas F., 2014, Sabatini et al., 2013).

The regulation of fisheries has so far been based on limitations of fishing capacity (licenses), minimum landing sizes, net mesh sizes and temporary fishing closures (45 days during the fall), but the establishment of no-fishing zones has been increasingly advocated as a further component of the fishery management strategy (European Council Regulation n. 1967/2006).

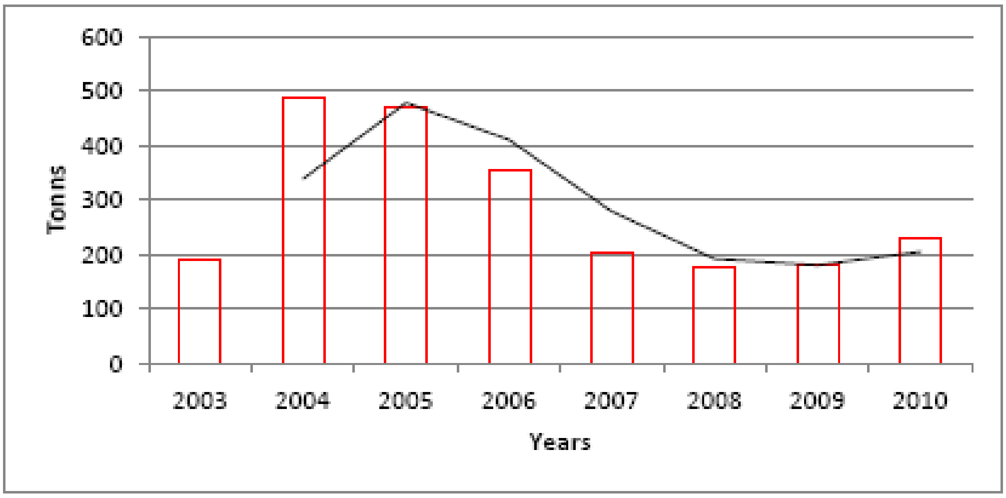


Fig. 83 - Bars denoted annual landings for both Aristeid in Sardinian Seas (2003-2010) (IREPA, 2010) and line black denotes moving everage. From Palmas F. PhD Thesis 2014.

The Aristeid fishing grounds are characterized by sandy muds (until 400 m) and deep muds (>500 m depth), situated near to submarine trenches, canyon and seamounts (Cau et al., 2002; Sabatini et. 2011) (Fig. 84). The main fishing grounds are located in the southern part of Sardinia (Sardinia Channel) and they are mainly exploited by several trawlers of Cagliari and Sant'Antioco which operate two days fishing trips (Fig. 85 - Aristeid fishing grounds in the Sardinian Seas.From Palmas F. PhD Thesis 2014.). Other important fishing grounds are located in the western coast between Sant'Antioco and Alghero. In the northern Sardinia they are mainly located in front of Porto Torres near the Tramontana canyon. The usual fishing grounds of the eastern areas are situated between the Corsica border, and the Quirra canyon, at south. In this area most of the boats fished on the Baronie Seamount (also called by fishermen "K bank") and in the several bathyal canyons of the east coast (Palmas F., 2014).

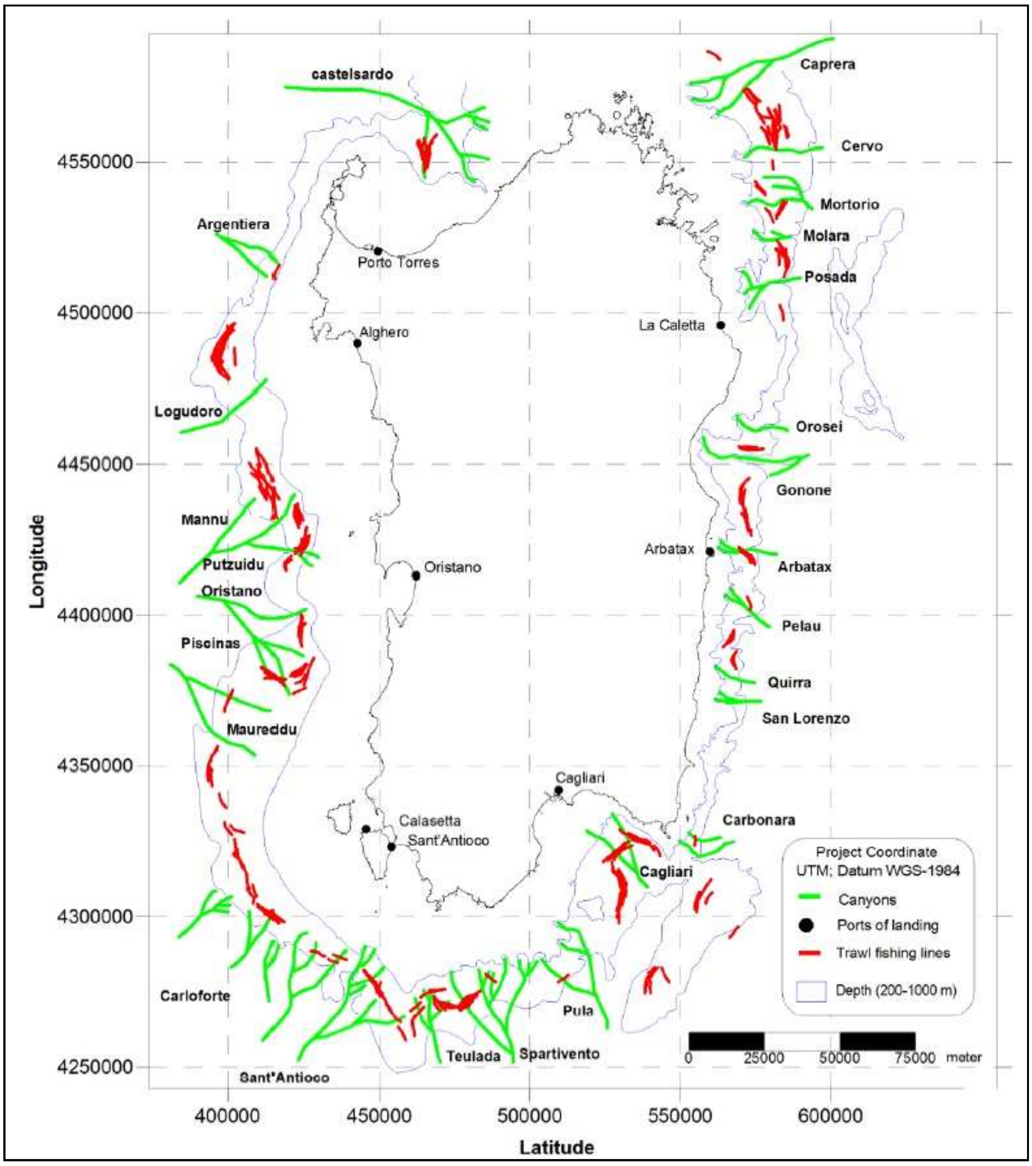


Fig. 84 - Distribution of trawl fishing lanes in relation to the presence of submarine canyons. From Palmas F. PhD Thesis 2014.

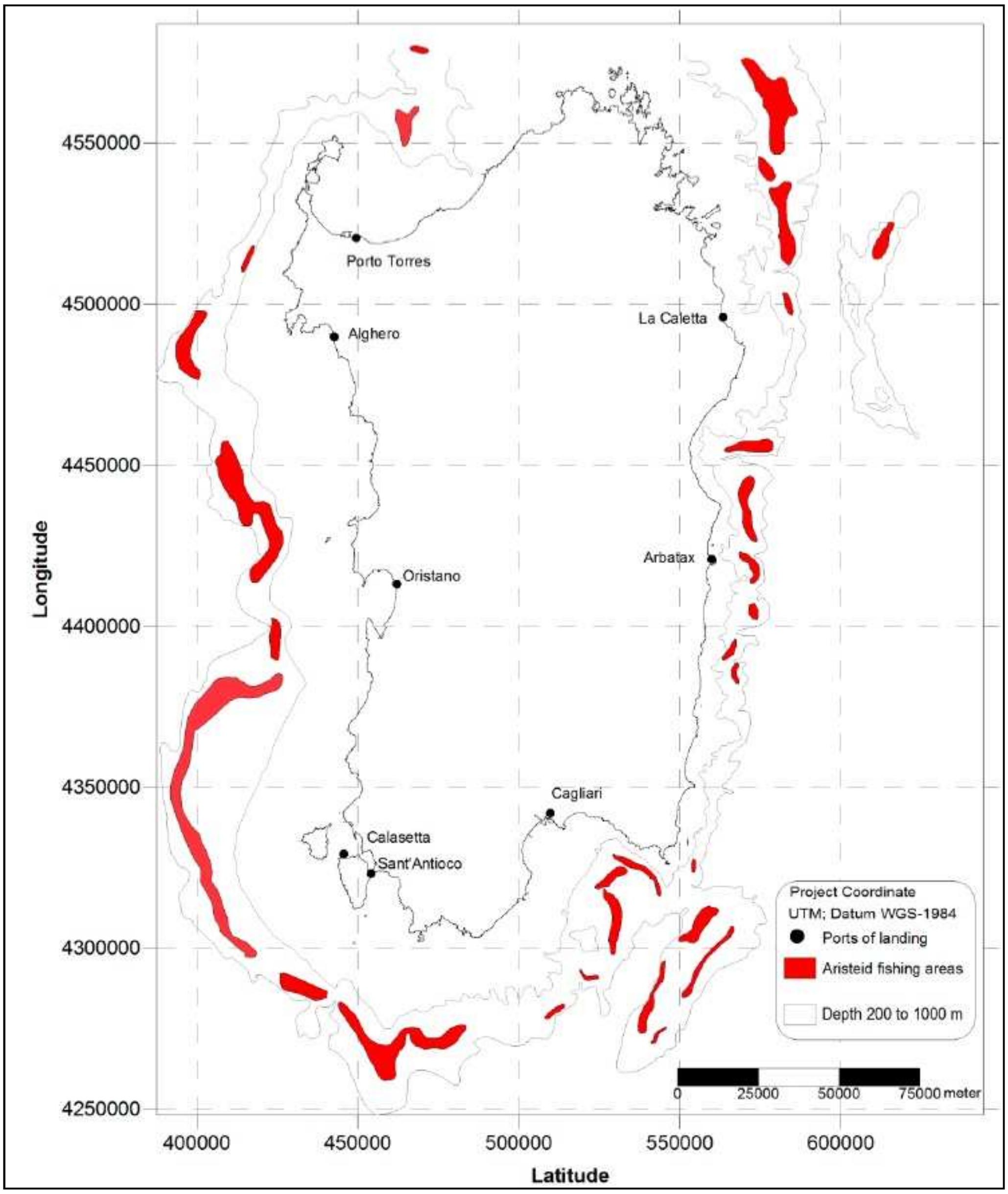


Fig. 85 - Aristeid fishing grounds in the Sardinian Seas.From Palmas F. PhD Thesis 2014.

RESULTS

Starting from a detailed geomorphologic analysis of the continental shelf and upper slope regions of Sardinian Southern Continental Margin, purpose of this work was to produce the first broad scale habitat mapping charts for this area through a multidisciplinary approach.

Regarding methodological results:

- Have been integrated bibliographic and new original oceanographic data regarding Sardinian southern continental margin.
- Both bibliographic and original data have been integrated in GIS environment in order to easily manage and allow subsequent data integration.
- Geologic, Geomorphologic and Biologic data of this area have been integrated for the first time.

Regarding cognitive results, the study has been mainly based on the data acquired in the MAGIC project cruises framework (2009 & 2010) which consists in High Resolution bathymetric and seismic records:

- Analysis of MBES derived high resolution DTM (5*5m bin size) allowed the individuation, reconnaissance and study of the main geomorphologic elements in the continental shelf and upper slope area of the whole Sardinia southern continental margin thus completing existing knowledge of those areas.
- In the San Pietro Island area an important volcanic district has been deeply studied and mapped, individuating relevant features such as lava flows top surfaces, large necks, calderas and an important mega-dykes system whose emplacement, in the geodynamic context of the Tertiary rifting, has similarities with areas of active rifting, at least as regards the characteristics of size.
- In the San Pietro Island area, the reconnaissance of the palaeo shoreline related to the LGM (MIS 2) on the DTM, gave us the opportunity to deepen its study by identifying, along the same, a palaeo cliffs alignment and inside an interruption in the cliffs, we found what

was supposed to be a palaeo lagoon, hypothesis confirmed by a littoral thanatocoenosis sampling.

- In the Toro Canyon area previous knowledge has been deepened by mapping in detail the particular features in this continental shelf and upper slope area such as volcanic outcrops, gravitative processes and different kinds of pockforms and the Toro Canyon head scarp.
- Inside Cagliari's gulf Su Banghittu flanks have been studied, recognising from SBP records confirmation of tectonic control of the slopes and subsequent debris avalanche phenomena.
- In the Cagliari gulf area have been studied Sant'Elia Canyon head scarp (as part of the main Carbonara Canyon) with its relevant gravitative processes really close to the coast line and the fault wall which follows at sea regional tectonics from the eastern side of the Campidano Graben, giving rise to an impressive 25km long tectonically controlled fault wall rising from -650 up to -80m with the shelf edge at the average depth of -100m.
- The union of the MAGIC project derived datasets allowed the creation of a merged thematic cartography for the whole southern margin, a Physiographic domain and Morphobathymetric elements charts have been created in GIS environment.

Regarding Habitat Mapping and biocoenosis distribution knowledge results:

- For the very first time on Sardinian southern margin a multidisciplinary approach has been used to study the relationship between biotic and abiotic components of marine habitats and how seabed morphologic features influences different Coralligenous assemblages development styles.
- In two pilot sites, located respectively on the SW and SE ends of the margin, has been possible locating, quantifying occurrence, size, structure and density of coral colonies through non-destructive methods by R.O.V. surveys.

- Isolated shoals, (also called pinnacles) have been recognised as hot spots of biodiversity within their extension, providing refuges for numerous species, host nursery areas for several commercial fish and play also key site and species-specific roles on the early-stage recruitment of other epibenthic. Distribution of coral communities along these geomorphologic features may be determined by the combination of both biological and environmental factors that can synergistically affect spawn, larval development and settling, growth, and death rates of individuals. In particular, geomorphologic and mineralogical characteristics of settlement substrates have been recognized as important factors structuring benthic biodiversity, by affecting sediment accumulation rates, bottom currents and, ultimately, the rates of food supply.

- Underwater remotely operated vehicles (ROV), coupled with multibeam echo-sounder (MBES), enabled to perform controlled sampling and detailed observation of specific mesophotic habitats with noninvasive protocols, which are particularly relevant for habitats of conservation interest. Along the Sardinian continental shelf investigations on coral assemblages were limited to the target species *Corallium rubrum*, whereas the status of communities of large anthozoans such as gorgonians and black corals was mostly unknown.

- The study of seabed features characterizing Coralligenous assemblages distribution allowed to create predictive maps of Coralligenous biocoenosis distribution which have been later validated by ROV surveys.

- From the overlay of the information gathered by ROV surveys on the previously created predictive maps based on acquired bathymetric data, a detailed (1:25.000) Coralligenous biocoenosis distribution cartography have been constructed and validated.

REGIONE AUTONOMA DELLA SARDEGNA

POR SARDEGNA

UNIONE EUROPEA
Fondo sociale europeo

Enrico M. Paliaga gratefully acknowledges Sardinia Regional Government for the financial support of his PhD scholarship (P.O.R. Sardegna F.S.E. Operational Programme of the Autonomous Region of Sardinia, European Social Fund 2007–2013—Axis IV Human Resources, Objective l.3, Line of Activity l.3.1.)

REFERENCES

- Aigner, T., 1985. Storm Depositional Systems. Lecture Notes in Earth Sciences, 3. Springer-Verlag, Berlin, 174 pp.
- Alessio M., Antonioli F., Belluomini G., Improta S., Manfra L. & Preite Martinez M. (1994) – La curva di risalita del Mare Tirreno negli ultimi 40 ka ottenuta mediante datazione di speleotemi sommersi e dati archeologici. Mem. Descr. Carta Geol. D'It., 52, 261-276.
- Alvarez W. (1972) Rotation of the Corsica-Sardinia microplate. Nature Physics Science, 235, 103-105, New York.
- Antonioli F. & Ferranti L. (1992) Geomorfologia costiera e subacquea e considerazioni paleoclimatiche sul settore compreso tra S.M. in Navarrese e Punta Goloritzè (Golfo di Orosei, Sardegna). Il Giornale di Geologia, 54, 2, 65-89.
- Antonioli F., Anzidei M., Lambeck K., Auriemma R., Gaddi D., Furlani S., Orru` P., Solinas E., Gaspari A., Karinja S., Kovacˇic´ V., Surace L., (2007). Sea level change during Holocene from Sardinia and northeastern Adriatic (Central Mediterranean sea) from archaeological and geomorphological data. Quaternary ScienceReviews 26, 2463–2486.
- Anzidei M., Lambeck K.,Antonioli F. , Furlani S., Mastronuzzi G. , Serpelloni E. and Vannucci G. (2014). Coastal structure, sea-level changes and vertical motion of the land in the Mediterranean (eds. Sedimentaty coastal zones from high to low latitudes; similarities and differences) Special Publication - Geological Society of London(June 2014), 388(1):453-479
- Arthaud F. & Matte P. (1966) Contribution à l'étude de tectoniques superposées dans la chaine hercynienne: étude microtectonique des séries metamorphiques du Massif des Maures (Var.). C. R. Acad. Sci. (Paris), 262, 436-439, Paris.
- Arthaud F. & Matte P. (1977) Late Paleozoic strike-slip faulting in southern Europe and northern Africa: Result of a right-lateral shear zone between the Appalachians and the Urals. Bull. geol. Soc. Amer., 88, 1305-1320, Boulder.
- Auzende, J.M., Bonnin, J., Olivet, J.L., 1973. The origin of the western Mediterranean basin. Journal of the Geological Society of London 129, 607–620.
- Auzende, J.M., Olive& J.L. and Bonnin, J., 1974. Le Detroit Ssrdano-Tunisien et la zone de fracture Nord-Tunisienne. Tectonophysics, 21: 357-374.
- Ayele, A., D. Keir, C. Ebinger, T. J. Wright, G. W. Stuart, W. R. Buck, E. Jacques, G. Ogubazghi, and J. Sholan (2009), September 2005 mega-dike emplacement in the Manda-Harraro nascent oceanic rift (Afar depression), Geophys. Res. Lett., 36, L20306, doi:10.1029/2009GL039605.
- Ballesteros E, Avançats E, Csic DB (2006) Mediterranean coralligenous assemblages: a synthesis of present knowledge. Oceanogr. Mar Biol An Ann Rev 44:123–195
- Ballesteros E. 1992 Els vegetals i la zonació litoral: espècies, comunitats i factors que influeixen en la seva distribució. Barcelona: Arxius Secció Ciències IEC 101: 1–616
- Barberi, F.; Cherchi, A., Evolution du Mesozoique-Cenozoique de la Sardaigne, Cagliari. C.I.E.S.M.',XXVIII Congr. Ass.,Cagliari, 1981
- Barca S. & Costamagna L.G. – (1997) – Compressive "Alpine" Tectonics in Western Sardinia: Geodynamic Consequences. C.R. Acad. Sci. Paris, 325, 791-797.

- Barca S. & Olivieri R. (1991) Age and source of calcareous blocks resedimented into Hercynian flysch type sediments of Sarrabus (southeastern Sardinia). in: (Eds) Geologia del Basamento Italiano. Siena, 21-22 Marzo 1991.

- Barca S. & Costamagna L.G. (2005) – Stratigrafia ed analisi di facies dei depositi permiani del Lago Mulargia (Sardegna sud-orientale): primi risultati. Geol. Rom., 38, 11-17

- Bard, E., Hamelin, B., Fairbanks, R.G., 1990. U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130000 years. Nature 346, 456–458.

- Beccaluva, L., Bonatti, E., Dupuy, C., et al., 1990. Geochemistry and mineralogy of volcanic rocks from the ODP Sites 650, 651, 655 and 654 in the Tyrrhenian Sea. Proceedings of the Ocean Drilling Program — Scientific Results 107, 49–74.

- Belluomini G., Iuzzolini P., Manfra L., Mortari R. & Zalaffi M. (1986) – Evoluzione recente del delta del Tevere. Geologica Romana, 25, 213-234.

- Bernard-Griffith J. & Cornichet J. (1985) Origin of eclogites from South Brittany (France): a Sm-Nd isotopic and REE study. Chem. Geol., 52, 185-201.

- Bo M, Bavestrello G, Angiolillo M, Calcagnile L, Canese S, Cannas R, et al. (2015) Persistence of Pristine Deep-Sea Coral Gardens in the Mediterranean Sea (SW Sardinia). PLoS ONE 10(3): e0119393. doi:10.1371/journal.pone.0119393.
- Worm B., (2006) Impacts of Biodiversity Loss on Ocean Ecosystem Services DOI: 10.1126/science.1132294 Science 314, 787 (2006);

- Bosence DWJ. 1985. The morphology and ecology of a mound-building coralline alga (Neogoniolithon strictum) from the Florida Keys. Palaeontology 28: 189–206.

- Brown, C.J., Todd, B., Kostylev, J., Pickrill, R.A., V.E., 2011. Image-based classification of multibeam sonar backscatter data for objective surficial sediment mapping of Georges Bank, Canada. Continental Shelf Research 31, S110–S119

- Burg J.P. & Matte P. (1978) A cross section through the french Massif central and the of its variscan evolution. Z. dtsch. geol. Ges., 129, 429-440, Berlin.

- Burg J.P., Delor C. P., Leyreloup A. F. & Romney F. (1989) Inverted metamorphic zonation and Variscan thrust tectonics in the Rouergue area (Massif Central, France): P-T-t record from mineral to regional scale. In: (Eds) Daly J. S., Cliff R. A. & Yardley B.W.D.: «Evolution of Metamorphic Belts», Geol. Soc. London Spec. Publ., 423-439, London.
- Cameron, A. and Askew, N. (eds.). 2011. EUSeaMap Preparatory Action for development and assessment of a European broad-scale seabed habitat map final report. Available at http://jncc.defra.gov.uk/euseamap

- Cappelli B., Carmignani L., Castorina F., Di Pisa A., Oggiano G. & Petrini R. (1992) A Hercynian suture zone in Sardinia: geological and geochemical evidence. Geodinamica Acta, 5 (1-2), 101-118, Paris.

- Carmignani L., Carosi R., Di Pisa A., Gattiglio M., Musumeci G., Oggiano G. & Pertusati P.C. (1994b) The hercynian chain in Sardinia (Italy). Geodinamica Acta, 7, 31-47.

- Carmignani L., Franceschelli M., Pertusati P. C. & Ricci C. A. (1979) Evoluzione tettonico-metamorfica del basamento ercinico della Nurra (Sardegna NW). Mem. Soc. Geol. Ital., 20, 57-84, Roma.

- Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C. A. (1982b) Guida alla Geologia del Paleozoico Sardo. Guide Geologiche Regionali, 215 pp., Soc. Geol. Ital., Cagliari.

- Carmignani L., Cocozza T., Ghezzo C., Pertusati P.C. & Ricci C.A. (1987) Structural Model of the Hercynian Basement of Sardinia. Stabilimento L. Salomone, Roma.

- Carminati, E., Wortel, M.J.R., Spakman, W., Sabadini, R., 1998a. The role of slab detach- ment processes in the opening of the western-central Mediterranean basins: some geological and geophysical evidence. Earth and Planetary Science Letters 160, 651–665.

- Carminati, E., Wortel, M.J.R., Meijer, P.Th., Sabadini, R., 1998b. The two stage opening of the western-central Mediterranean basins: a forward modelling test to a new evolutionary model. Earth and Planetary Science Letters 160, 667–679. Carminati,

- Carminati, E., Lustrino, M., Cuffaro,M., Doglioni, C., 2010. Tectonics,magmatismand geody- namics of Italy: what we know and what we imagine. ISSN 1441–8142 In: Beltrando, M., Peccerillo, A., Mattei, M., Conticelli, S., Doglioni, C. (Eds.), Electronic Edition. TheGeology of Italy, Journal of the Virtual Explorer, 36. doi:10.3809/jvirtex.2010.00226. paper 8.

- Carminati, E., et al., Geodynamic evolution of the central and western Mediterranean: Tectonics vs. igneous petrology constraints, Tectonophysics (2012), doi:10.1016/j.tecto.2012.01.026

- Carobene, L. and Pasini, G., 1982. Contributo alla conoscenza del Pleistocene superiore e dell’Olocene del Golfo di Orosei) Sardegna orientale. Bollettino Societa Adriatica di Scienze, 64(1980), Suppl., Trieste, 5–36.

- Carosi R. & Oggiano G. (2002) Transpressional deformation in northwestern Sardinia (Italy): insights on the tectonic evolution of the Variscan Belt. Comptes Rendus Geosciences, 334 (4), 287-294, Paris.

- Carosi R., Palmeri R., 2002. Orogen-parallel tectonic transport in the Variscan belt of northeastern Sardinia (Italy): implications for the exhumation of medium-pressure metamorphic rocks. Geological Magazine 139 (5): 497-511.

- Casini L., Funedda A. & Oggiano G. (2010) A balanced foreland-hinterland deformation model for the Southern Variscan belt of Sardinia, Italy. Geol. J., 45: 634–649. doi: 10.1002/gj.1208.

- Cassinis G., Cortesogno L., Gaggero L., Pittau P., Ronchi A. & Sarria E. (1999) Late Paleozoic continental basins of Sardinia. In: (Eds) Cassinis G. «The Continental Permian of the Southern Alps and Sardinia (Italy). Regional reports and general correlations-», Intern. Field Conf. Field-trip Guide-book, 116, Brescia.

- Casula G., Cherchi A., Montadert L., Murru M. & Sarria E. (2001) The Cenozoic graben system of Sardinia (Italy) : geodynamic evolution from new seismic and field data. Marine and Petroleum Geology, 18: 863-888, Oxford.

- Cau A. , Paliaga E.M. , Cannas R., Deiana G, Follesa M. C., Sacco F., Todde S. , Orrù P. E., 2015 Preliminary data on habitat characterization relevance for red coral conservation and management Ital. J. Geosci., Vol. 134, No. 1 (2015), pp. 60-68, 7 figs., 2 tabs. doi: 10.3301/IJG.2014.40

- Cau A. , Follesa M. C., Moccia D., Alvito A., Bo M., Angiolillo M., Canese S. , Paliaga E. M., Orrù P. E, Sacco F. , Cannas R. (2015) Deepwater corals biodiversity along roche du large ecosystems with different habitat complexity along the south Sardinia continental margin (CW Mediterranean Sea) Marine Biology DOI 10.1007/s00227-015-2718-5

- Preliminary data on habitat characterization relevance for red coral conservation and management. Ital. J. Geosci., Vol. 134, No. 1 (2015), pp. 60-68, 7 figs., 2 tabs. (doi: 10.3301/IJG.2014.40)

- Cerrano C, Danovaro R, Gambi C et al (2010) Gold coral (Savalia savaglia) and gorgonian forests enhance benthic biodiversity and ecosystem functioning in the mesophotic zone. Biodivers. Conserv. 19:153–167. doi:10.1007/s10531-009-9712-5

- Cerrano C., Bavestrello G., Bianchi C.N., Calcinai B., Cattaneo-Vietti R., Morri C., Sarà M. (2001) The role of sponge bioerosion in the Mediterranean coralligenous accretion. In: Faranda F.M., Guglielmo L. & Spezie G. (Eds). Mediterranean Ecosystems: Structures and Processes. Springer-Verlag, Milan: 235–240.

- Chappell, J., and N.J. Shackelton. 1986 Oxygen Isotopes and Sea Level, Nature. Vol. 324, no. 6093, 137-140.

- Cherchi A. & Montadert L. (1982) Oligo-Miocene rift of Sardinia and the early history of the Western Mediterranean Basin. Nature, 298 (5876), 736-739, London.

- Cherchi A., Marini A., Murru M. & Ulzega A. (1978c) Movimenti neotettonici nella Sardegna meridionale. Mem. Soc. Geol. It., 19: 581-587, Roma.

- Cocherie A. (1978) Géochimique des terres rares dans les granodiorites. Thèse 3.me cycle. Univ. Rennes.

- Cocherie A. (1985) Interaction manteau-croûte: son rôlè dans la genèse d’associations plutoniques calcoalcalines, costraintes geochimiques (elements en traces et isotopes du strontium et de l’oxygene). Doc. B.R.G.M., 246 pp., Orleans.

- Cocozza T. (1967) Il Permo-Carbonifero del Bacino di San Giorgio (Iglesiente, Sardegna Sud Occidentale). Mem. Soc. Geol.Ital., 6, 607-642, Roma.

- Cortesogno L., Cassinis G., Dallagiovanna G., Gaggero L., Oggiano G., Ronchi A., Seno S. & Vanossi M. (1998) The Variscan post-collisional volcanism in Late Carboniferous-Permian sequences of Ligurian Alps, Southern Alps and Sardinia (Italy): a synthesis. Lithos, 45 (1), 305-328.

- Cortesogno L., Gaggero L., Oggiano G. & Paquette J. L. (2004) Different tectono-thermal evolutionary paths in eclogitic rocks from the axial zone of the Variscan chain in Sardinia (Italy) compared with the Ligurian Alps. Ofioliti, 29, 125-144.

- Corti, G., Cuffaro, M., Doglioni, C., Innocenti, F., Manetti, P., 2006. Coexisting geody- namic processes in the Sicily Channel. In: Dilek, Y., Pavlides, S. (Eds.), Tectonics and magmatism in the Mediterranean region and Asia: Geological Society of Amer- ica Special, 409, 83–96.

- G.R. Cutter Jr.*, Y. Rzhanov, L.A. Mayer. Automated segmentation of seafloor bathymetry from multibeam echosounder data using local Fourier histogram texture features Journal of Experimental Marine Biology and Ecology 285 – 286 (2003) 355 – 370

- Social Vulnerability to Environmental Hazards Social Science Quarterly 1540-6237 http://dx.doi.org/10.1111/1540-6237.8402002

- Sea-floor images and data from multibeam surveys in San Francisco Bay, Southern California, Hawaii, the Gulf of Mexico, and Lake Tahoe, California-Nevada. USGS Data Series DD-55.

- Introduction to the Special Issue: Marine and Coastal GIS for Geomorphology, Habitat Mapping, and Marine Reserves. Marine Geodesy, 31: 1–8, 2008 Copyright © Taylor & Francis Group, LLC ISSN: 0149-0419 print / 1521-060X online DOI: 10.1080/01490410802466397

- De Muro S. & Orrù P. (1998) “Il contributo delle beach-rock nello studio della risalita del mare olocenico. le beach-rock post-glaciali della Sardegna Nord-Orientale” – Il Quaternario, Italian Journal of Quaternary Sciences Vol.11(1), 19-39

- Morfologia e dinamica delle frane sottomarine potenzialmente tzunamogeniche del margine meridionale sardo (Progetto MAGIC) G. DEIANA , P.E. ORRÙ, E. PALIAGA, S. TODDE; Rend. Online Soc. Geol. It., Vol. 21 (2012), pp. 484-486, 2 figs., Roma 2012

- Deiana G.*, Lecca L., Paliaga E., Todde S. & Orrù P.E., (2014) Landslides induced by fluid release Sardinian southern margin. Rend. Online Soc. Geol. It., Suppl. n. 1 al Vol. 31 pp 524.

- Landslides and pockforms of southern Sardinian margin. Deiana, Giacomo; Meleddu, Antonietta; Paliaga, Enrico; Todde, Samuele; Orrù, Paolo E. (2015) Geomorphology for Society

- Del Moro A., Di Simplicio C. & Rita F. (1972) Lineamenti geopetrologici del cristallino sardo. Età radiometrica delle plutoniti del settore Ogliastra-Gallura. Min. et Petr. Acta, 18, 245-254.

- Del Moro A., Di Simplicio P., Ghezzo C., Guasparri G., Rita F. & Sabatini G. (1975) Radiometric data and intrusive sequence in the Sardinian Batholith. N. Jb. Mineral., Abh, 126 (1), 28-44, Stuttgart.

- Del Moro A., Di Pisa A., Oggiano G. & Villa I. M. (1991) Isotopic ages of two contrasting tectonomorphic episodes in the Variscan chain in N Sardinia. In: (Eds) Geologia del basamento italiano. Siena.

- Del Rio M. (1973) Palinologia di un livello «Permo-Carbonifero» del bacino di San Giorgio (Iglesiente, Sardegna sud-occidentale). Boll. Soc. Geol. Ital., 92, 485-494, Roma.

- Di Pisa A. & Oggiano G. (1987) Low-pressure and high temperature metamorphic rocks in Anglona region (Northern Sardinia). In: Rend. Soc. Ital. Mineral. Petr., Special issue on “Granites and their surroundings”, 89-90

- Di Simplicio P., Ferrara G., Ghezzo C., Guasparri G., Pellizzer R., Ricci C. A., Rita F. & Sabatini G. (1974) Il metamorfismo e il magmatismo paleozoico nella Sardegna. Rend. Soc. Ital. Mineral. Petrol., 30 (2), 979-1068, Milano.

- Di Vincenzo G., Carosi R. & Palmeri R. (2004) The Relationship between Tectono-metamorphic Evolution and Argon Isotope Records in White Mica: Constraints from in situ 40Ar/39Ar Laser Analysis of the Variscan Basement of Sardinia. J. Petrol., 45 (5), 1013–1043.

- Di Vito MA, Isaia R, Orsi G, Southon J, de Vita S, D’Antonio M, Pappalardo L, Piochi M (1999) Volcanic and deformational history of the Campi Flegrei caldera in the past 12 ka. J Volcanol Geotherm Res 91: 221-246

- Di Geronimo I., Di Geronimo R., Improta S., Rosso A., Sanfilippo R. (2001) Preliminary observations on a columnar coralline build-up from off SE Sicily. Biol. Mar. Medit., 8 (1): 229-237.

- Edel J. B., Montigny R. & Thuizat R. (1981) Late paleozoic rotations of Corsica and Sardinia: new evidence from Paleomagnetic and K-Ar studies. Tectonophysics, 79, 201-233, Amsterdam.

- Ehrhold A., Hamon D., Guillaumont B. The REBENT monitoring network, a spatially integrated, acoustic approach to surveying nearshore macrobenthic habitats: application to the Bay of Concarneau (South Brittany, France). ICES Journal of Marine Science 2006;63:1604-1615.

- Elter F. M., Musumeci G. & Pertusati P. C. (1990) Late Hercynian shear zones in Sardinia. Tectonophysics, 176, 387-404, Amsterdam.

- Faccenna C., Speranza F., D’Ajello Caracciolo F., Mattei M., Oggiano, G., (2002) Extensional tectonics on Sardinia (Italy): insights into the arc–back-arc transitional regime, Tectonophysics 356 213– 232.

- Fanucci, F. et al., (1976). The continental shelf of Sardinia: structure and sedimentary characteristics Roma Società geologica italiana.

- Fanucci F., Fierro G., Ulzega A., Gennesseaux M., Rehault J.P. & Viaris De Lesegno L. (1976) – The continental shelf of Sardinia: Structure and sedimentary characteristics. Boll. Soc. Geol. It., 95: 1201-1217, Roma.

- Ferranti, L., Antonioli, F., Mauz, B., Amorosi, A., Dai Pra, G., Mastronuzzi, G., et al. (2006). Markers of the last interglacial sea level high stand along the coast of Italy: tectonic implications. Quaternary International, 145-146, 30-54.

- Ferrara G., Ricci C. A. & Rita F. (1978) Isotopic ages and tectono-metamorphic history of the metamorphic basement of northeastern Sardinia. Contr. Mineral. Petrol., 68, 99-106, Berlin.

- Terrazzi deposizionali sommersi della piattaforma continentale della Sardegna orientale e meridionale. Mem. Descr. Carta Geol. d’It. LVIII (2004), pp. 27-36

- Ferraro F., Orrù P. & Ulzega A. (1998) Terrazzi deposizionali sommersi della piattaforma continentale della Sardegna orientale e meridionale. Mem. Descr. Carta Geologica d’Italia, LIV Servizio Geologico Nazionale, Roma.

- Analisi vettoriale di minerali pesanti dei sedimenti di piattaforma continentale e scarpata / (Sardegna orientale e meridionale) / Giuliano Fierro, Angelica Morozzo Della Rocca, Giovanni Battista Piacentino.

- Finetti, I., and Morelli, C, 1973a. Geophysical exploration of the Mediterranean sea. Boll. Geofis. Teor. Appl., 15:263-344

- Fondi R. (1979) Orme di Microsauri nel Carbonifero superiore della Sardegna. Mem. Soc. Geol. Ital., 20, 347-356, Roma.

- Franceschelli M., Memmi I. & Ricci C. A. (1982) Zoneografia metamorfica della Sardegna settentrionale. In: (Eds) Carmignani L., Cocozza T., Ghezzo C., Pertusati P. C. & Ricci C. A., «Guida alla Geologia del Paleozoico Sardo». Soc. Geol. Ital., Guide Geologiche Regionali, 137-149

- Franceschelli M., Puxeddu M., Cruciani G. & Utzeri D. (2007) Metabasites with eclogite facies relicts from Variscides in Sardinia, Italy: a review. Int. J. Earth Sci., 96 (5), 795-815. doi: 10.1007/s00531-006-0145-z.

- Franke W. (2000) The mid-European segment of the Variscides: tectonostratigraphic units, terrane boundaries and plate tectonic evolution. In: (Eds) Franke W., Haak V., Oncken O. & Tanner D., «Orogenic Processes: Quantification and Modelling in the Variscan Belt». Geological Society, 179, 35-61, London.

- Gattacceca J., Deino A., Rizzo R., Jones D. S., Henry B., Beaudoin B. & Vadeboin F. (2007) Miocene rotation of Sardinia: New paleomagnetic and geochronological constraints and geodynamic implications. Earth and planet. Sci. Lett., 258 (3-4), 359-377.

- Ghezzo C. & Orsini J. B. (1982) Lineamenti strutturali e composizionali del batolite ercinico Sardo-Corso in Sardegna. In: (Eds) Carmignani L., Cocozza T., Ghezzo C., Pertusati P. C. & Ricci C. A., «Guida alla Geologia del Paleozoico sardo.» Società Geologica Italiana. Guide Geologiche Regionali, 165-182, Cagliari.

- Howell, K. L., 2010. A benthic classification system to aid in the implementation of marine protected area networks in the deep/high seas of the NE Atlantic. Biological Conservation, 143, 1041 – 1056.

- Issel A., 1914 Lembi fossiliferi quaternari e recenti osservati nella Sardegna meridionale dal Prof. D. Lovisato. Atti Acc. Lincei Rend. Fis., s 5., v 23: 759-770.

- James H. Brown et al., (2011) Energetic Limits to Economic Growth BioScience 61(1):19-26. 2011 doi: http://dx.doi.org/10.1525/bio.2011.61.1.7

- Kevin E. Kohler , Shaun M. Gill, 2006 Coral Point Count with Excel extensions (CPCe): A Visual Basic program for the determination of coral and substrate coverage using random point count methodology. Computers & Geosciences 32 (2006) 1259–1269

- Kindler P., Davaud E. & Strasser A. (1997) Tyrrhenian coastal deposits from Sardinia (Italy): a petrographic record of high sea levels and shifting climate belts during the last interglacial (isotopic substage 5 e). Paleogeography, Paleoclimatology, Paleoecology, 133, 1-25

- Laborel J. (1987) Marine Biogenic construction in the Mediterranean. Sci. Rep. Port-Cros. natl., 13: 97-126

- Lambeck K., Antonioli F., Anzidei M., Ferranti L., Leoni G., Scicchitano G., Silenzi S. (2011) Sea level change along the Italian coast during the Holocene and projections for the future. Quaternary International, 232, 250-257.

- K. Lambeck, F. Antonioli, A. Purcell, S. Silenzi. Sea level change along the Italian coast for the past 10,000 years, Quat. Sci. Rev. 23 (2004) 1567 – 1598.

- Lecca L., Lonis R., Luxoro S., Melis E., Secchi F. & Brotzu P. (1997) Oligo-Miocene volcanic sequences and rifting stages in Sardinia: a review. Per. Miner., 66, 7-61, Roma.

- Lecca L., Panizza V., Pisano S. (1998), The sedimentary framework of Cagliari basin: a Plio-Quaternary rift basin in the southern Sardinia margin, Il Quaternario, 11(2), 301 – 318

- Lecca L. (2000), La piattaforma continentale miocenico-quaternaria del margine occidentale sardo: blocco diagramma sezionato, Rendiconti Seminario Facoltà Scienze Università di Cagliari, 70, Fasc. 1.

- Linares C, Coma R, Garrabou J et al (2008) Size distribution, density and disturbance in two Mediterranean gorgonians: Paramuricea clavata and Eunicella singularis. J Appl Eco 45:688–699. doi:10.1111/j.1365-2664.2007.0

- Lustrino, M., Morra, V., Fedele, L., Franciosi, L., 2009. The beginning of the Apennine subduction system in central-western Mediterranean: constraints from Cenozoic "orogenic" magmatic rocks of Sardinia (Italy). Tectonics 28. doi:10.1029/ 2008TC002419.

- Follesa M.C, Cannas R., Cau A., Pedoni C., Pesci P. and Cau A., 2013 Deep-water red coral from the island of SardiniaMarine and Freshwater Researchhttp://dx.doi.org/10.1071/MF12235

- Marini A. & Murru M. (1981) Sull'età della formazione di Nuraghe Casteddu (Dorgali, Sardegna orientale). Rend. Soc. Geol. Ital., 4 (7), 11-12.

- Matte P. (1986) Tectonics and plate tectonics model for the Variscan belt of Europe. Tectonophysics, 126, 329-374, Amsterdam.

- Matte P. (1991) Accretionary history and crustal evolution of the Variscan belt in Western Europe. Tectonophysics, 196, 309-337, Amsterdam.

- Matte P. (2001) The Variscan collage and orogeny (480-290 Ma) and the tectonic definition of the Armorica microplate: a review. Terra Nova, 13 (2), 122-128.

- C. Maxia, G. Pecorini Il Quaternario della Sardegna Atti del X Congresso Internazionale di Studi Sardi. Cagliari (1968), pp. 57–84

- Maxia M. (1983) Segnalazioni di potenti successioni carbonifere marine nella Sardegna meridionale. Rend. Soc. Geol. Ital., 6, 21-24, Roma.

- Mohn C. et al. (2002) Numerical studies on flow amplification at an isolated shelfbreak bank, with application to Porcupine Bank. Continental shelf research 22 (9), 1325-1338

- Montigny, R., Edel, J.B., Thuizat, R., 1981. Oligo-Miocene rotation of Sardinia: K–Ar ages and paleomagnetic data of Tertiary volcanics. Earth and Planetary Science Letters 54, 261–271.

- Musumeci G. (1991) Displacement calculation in a ductile shear zone: Monte Grighini shear zone (Central-Western Sardinia). Boll. Soc. Geol. It., 110, 777, Roma.

- Oggiano G. & Di Pisa A. (1992) Geologia della catena ercinica in Sardegna-Zona assiale. In: (Eds) Carmignani L., Pertusati P. C., Barca S., Carosi R., Di Pisa A., Gattiglio M., Musumeci G. & Oggiano G., «Struttura della Catena Ercinica in Sardegna. Guida all'Escursione», Gruppo Informale di Geologia Strutturale, 147-167, Siena.

- Oggiano G., Cherchi G. P., Aversano A. & Di Pisa A. (2005) Note illustrative F° 428 "Arzachena" della Carta Geologica d'Italia alla scala 1:50.000, Servizio Geologico d'Italia, 144.

- Olita A, Ribotti A, Fazioli L et al (2013) Surface circulation and upwelling in the Sardinia Sea: a numerical study. Cont Shelf Res. 71:95–108. doi:10.1016/j.csr.2013.10.011

- Olivieri R. (1969) Conodonti e zonatura del Devoniano superiore e riconoscimento di Carbonifero inferiore nei calcari di Corona Mizziu (Gerrei-Sardegna). Boll. Soc. Paleont. Ital., 8 (2), 63-152, Modena.

- Orrù P. E., Ulzega A. (1989) Carta geomorfologia della piattaforma continentale e delle coste del Sulcis Sardegna sud occidentale, Scala 1:100.000, STEF, Cagliari.

- Orrù P. E, F. Antonioli, K. Lambeck, V. Verrubbi (2004) Holocene sea-level change in the Cagliari coastal Plain (Southern Sardinia, Italy) Quaternaria Nova, VIII (2004), pp. 193–212

- Orrù P. E., Antonioli F., Paul J. Hearty, Ulrich Radtke (2011) Quaternary International Volume 232, Issues 1–2, 15 February 2011, Pages 169–178 Tectonic Contribution to Relative Sea Level Change

- Orrù P. & Ulzega A. (1990), Carta geomorfologica della piattaforma continentale e delle coste del Sulcis – Sardegna sud occidentale. Scala 1:000.000, STEF , Cagliari.
- Orrù P.E., Mastronuzzi G., Deiana G., Pignatelli C., Piscitelli A., Solinas E., Spanu P.G., Zucca R. (2014). Sea level changes and geoarchaeology between Malfatano Bay and Piscinnì Bay (SW Sardinia) in the last 4 ky. Quaternary International, 336, 180-189.

- Orsini JB (1980) Le batholite corso-sarde: un exemple de batholite hercynien (structure, composition, organisation d'ensemble). Sa place dans la chaîne varisque de l'Europe moyenne. Thèse Doc Sci, Aix-Marseille III, 390 pp

- Ulzega, A., Oser, A. 1982. Comptes-rendus de l'Excursion- Table ronde Tyrrhénien de Sardaigne: 110 p. INQUA, Univ. Cagliari, April 1980.

- Ulzega, A., Oser, A., Lecca, L., Leone, F., Pecorini, G., Spano, C., Cordy, J.M. 1980. Excursion – Table ronde Tyrrhénien de Sardaigne. Guidebook: 88 pp. INQUA, Univ. Cagliari.

- Paliaga E.M., Deiana G., Todde S. & Orrù P.E., (2014) Geological seabed and habitat mapping on SW Sardinia continental shelf. Rend. Online Soc. Geol. It., Suppl. n. 1 al Vol. 31 pp 667.

- Paliaga E.M., Deiana G., Meleddu A., Todde S. & Orrù P.E., (2014) Marine slumping risk induced by hyperpycnal flows Sardinian southern continental margin. Rend. Online Soc. Geol. It., Suppl. n. 1 al Vol. 31 pp 534.

- Palmas F., Gastoni A., Pendugiu A.A., Pesci P., Sabatini A. (2011). Preliminary data on demersal assemblages in Spartivento Canyon (South Sardinia). Biol. Mar. Medit.18: 358-359

- Palmas F., Olita A., Pendugiu A.A., Brambilla W., Sabatini A. (2011). A method for collecting oceanographic data during the bottom trawling. Biol. Mar. Medit. 18:360-361

- Palmas F. (2014) Ph.D Thesis. Environmental influences on the spatio-temporal distribution of *aristeus antennatus* (risso, 1816) and *aristaeomorpha foliacea* (risso, 1827) in the central-western mediterranean. Università degli studi di Cagliari, 183 pp.

- Palmeri R., Fanning M., Franceschelli M., Memmi I. & Ricci C. A. (2004) SHRIMP dating of zircons in eclogite from the Variscan basement in north-eastern Sardinia (Italy). Neues Jahrbuch fur Mineralogie Monatshefte, 6, 275-288.

- Paquette J. L., Peucat J. J., Bernard-Griffiths J. & Marchand J. (1985) Evidence for old Precambrian relics shown by U-Pb zircon dating of eclogites and associates rocks in the Hercynian belt of South Brittany, France. Chem. Geol., 52, 213-216.

- Nouveau manuel de bionomie benthique de la Mer Méditerranée. Rec Trav Stn Mar Endoume 31:1–137

- Perroud H. & Bonhommet (1981) Paleomagnetism of the Ibero-Armorican arc and the Hercynian orogeny in Western Europe. Nature, 292, 445-447.

- Pittau P., Del Rio M. & Funedda A. (2008) Relationships between plant communities characterization and Basin formation in the Carboniferous-Permian of Sardinia. Boll. Soc. Geol. It., 127 (3).

- Putignano M.L., Orrù P.E., Schiattarella M. (2014) Holocene coastline evolution of Procida Island, Bay of Naples, Italy. Quaternary International, 332, 115-125.

- Ricci C. A. & Sabatini G. (1978) Petrogenetic affinity and geodynamic significance of metabasic rocks from Sardinia, Corsica and Provence. N. Jb. Geol. Paläont., Mh., 1978, 23-38.

- Riley, S. J. Et al. (1999) A terrain ruggedness index that quantifies topographic heterogeneity, Intermountain Journal of Sciences, vol. 5, No. 1-4,1999.

- Rossi P., Oggiano G. & Cocherie A. (2009) A restored section of the “southern Variscan realm” across the Corsica-Sardinia microcontinent. Comptes Rendus Geosciences, 341 (2-3), 224-238.

- Sartori, R., Carrara, G., Torelli, L., Zitellini, N., 2001. Neogene evolution of the southwestern Tyrrhenian Sea (Sardinia Basin and western Bathyal Plain). Marine Geology 175, 47–66.

- A. Sau, L. Lecca, R. Lonis, F. Secchi, M.L. Fercia La seconda fase del Rift-Sardo: volcanismo ed evoluzione dei sub-bacini di Ardara-Chilivani e Bonorva (Sardegna settentrionale) Bollettino della Società Geologica Italiana, 124 (2005), pp. 3–20

- Serri, G., Innocenti, F., Manetti, P., 2001. Magmatism from Mesozoic to Present: petrogenesis, time–space distribution and geodynamic implications. In: Vai, G.B., Martini, I.P. (Eds.), Anatomy of an Orogen: the Apennines and Adjacent Mediterra- nean basins. Kluwer Acad. Publ, 77–104.

- Shackleton, N.J., Imbrie, J. and Hall, M.A. (19831. Oxygen and carbon isotope record of East Pacific core V19-3(1: implications for the formation of deep water in the late Pleistocene North Atlantic Earth and Planetary Science Letters, 65, 233-244.

- Shackleton, N.J. and Opdyke, N.D. (1973). Oxygen isotope and palaeomagnetic stratigraphy of equatorial Pacific core V28-238: oxygen isotope temperatures and ice volumes on a 10 ~ year and a 10 ~' year scale. Quaternary Research, 3, 39-55.

- Sowerbutts, A., 2000. Sedimentation and volcanism linked to multiphase rifting in an Oligo-Miocene intra-arc basin, Anglona, Sardinia. Geological Magazine, 137: 395-418.

- Spalletta C. (1982) Brecce e conglomerati a liditi come indicatori paleogeografici del Carbonifero inferiore. In: (Eds) Carmignani L., Cocozza T., Ghezzo C., Pertusati P. C. & Ricci C. A., «Guida alla Geologia del Paleozoico Sardo», Soc. Geol. Ital., Guide Geologiche Regionali, 197-201.

- Speranza, F., Villa, I.M., Sagnotti, L., Florindo, F., Cosentino, D., Cipollari, P., Mattei, M., 2002. Age of the Corsica-Sardinia rotation and Liguro-Provençal Basin spreading: new paleomagnetic and Ar/Ar evidence. Tectonophysics 347, 231–251.

- Thomas B. & Gennesseaux M. (1986) A two stage rifting in the basin of the Corsica-Sardinia strait. Marine Geol., 72, 225-239.

- Trincardi, F., Zitellini, N., 1987. Therifting in theTyrrhenianbasin.Geo-Marine Letters 7,1–6.

- Tsounis G, Rossi S, Aranguren M et al (2006a) Effects of spatial variability and colony size on the reproductive output and gonadal development cycle of the Mediterranean red coral (Corallium rubrum L.). Mar Biol 148:513–527. doi:10.1007/ s00227-005-0100-8

- Tsounis G, Rossi S, Gili J-M, Arntz W (2006b) Population structure of an exploited benthic cnidarian: the case study of red coral (Corallium rubrum L.). Mar Biol 149:1059–1070. doi:10.1007/ s00227-006-0302-8

- Ulzega, A. & Hearty, P.J. 1986. Geomorphology, stratigraphy and geochronology of Late Quaternary marine deposits in Sardinia. Z. Geomorphol. N.F., Suppl. Bd. 62: 119-129.

- Antonio Ulzega, Silvana Fais Indagini geologiche sulla piattaforma continentale sarda per la ricerca di placers. Trieste : [s.n.], 1980. P. 11-26 : ill. ; 24 cm. ((Estr. da: Atti del Convegno scientifico nazionale sui placers marini, Trieste, 25-26 giugno 1980.

- Ulzega A., Carboni S., Coppa De Castro M.G., Cristini A., Fais S., Ferrara C., Lecca L., Leone F. (1980), Indagini geologiche sulla piattaforma continentale, Conv. Scient. Naz. sui Placers marini, Atti, Trieste.

- Carboni S., Lecca L., Leone F. & Ulzega A. (1979) La piattaforma continentale della Sardegna sud-occidentale (Saggio di cartografia dei fondi marini). Istituto di Geologia e Paleontologia, Università di Cagliari, Pubblicazione n.303, 1-13. STEF, Cagliari, 1979.

- Vai G.B. & Cocozza T. (1986) Tentative schematic zonation of the Hercynian chain in Italy. Bull. Soc. géol. France, 8, 95-114, Paris.

- Vardabasso S. (1962) Questioni paleogeografiche relative al Terziario antico della Sardegna. Mem. Soc. Geol. Ital., 3, 655-673, Roma.

- Vigliotti L. & Langenheim V. E. (1995) When did Sardinia stop rotating? New paleomagnetic results. Terra Nova, 7, 424-435.

- Vladimir E. Kostylev (2005) Characterization of Benthic Habitat on NortheasternGeorges Bank. American Fisheries Society Symposium 41:141–152, 2005

- von Raumer J. F., Stampfli G. M. & Bussy F. (2003) Gondwana-derived microcontinents the constituents of the Variscan and Alpine collisional orogens. Tectonophysics Collisional Orogenesis in the Geological Record and Modern Analogues, 365 (1-4), 7-22.

- Westphal M., Orsini J. B. & Vellutini P. (1976) Le micro-continent corso-sarde, sa position initiale: données paléomagnétiques et raccords géologiques. Tectonophysics, 30, 141-157.

- Wezel F.C., Savelli D., Beccaluva M., Tramontana M., Bartole R. (1981) Plio-Quaternary depositional style of sedimentary basins along insular Tyrrhenian margins, Sedimentary basins of Mediterranean margins, CNR, 239-269.

- Wilson et al., (2007) Multiscale Terrain Analysis of Multibeam Bathymetry Data for Habitat Mapping on the Continental Slope. Marine Geodesy, 30: 3–35, 2007 Copyright © Taylor & Francis Group, LLC ISSN: 0149-0419 print / 1521-060X online DOI: 10.1080/01490410701295962

- Wright TJ, Ebinger C, Biggs J, Ayele A, Yirgu G, Keir D, Stork A (2006) Magma-maintained rift segmentation at continental rupture in the 2005 Afar dyking episode. Nature 442:291–294. doi:10.1038/nature04978

- Würtz M. et al. (2012). Mediterranean Submarine Canyons: Ecology and Governance. Gland, Switzerland and Málaga, Spain: IUCN. 192 pages.

- Zito, G., Mongelli, F., De Lorenzo, S., Doglioni, C., 2003. Heat flow and geodynamics in the Tyrrhenian Sea. Terra Nova 15, 425–432.