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CONTINENTAL SLOPE GEOMORPHOLOGY: LANDSLIDES AND POCKFORMS OF SOUTHERN SARDINIAN MARGIN (ITALY)

Abstract: Deiana G., Meleddu A., Paliaga E.M., Todde S. & Orrù P.E. *Continental Slope Geomorphology: Landslides and Pockforms of Southern Sardinian Margin (Italy)*. (IT ISSN 0391-9839, 2016)

The southern Sardinia continental margin is characterized by a submarine depositional system divided by Pliocene tectonics into several marginal basins in which arrives sedimentary contributions from various segments of the Continental Shelf of two deformational regimes. The oldest corresponding to a compressive phase of crustal thickening during the Oligocene Miocene, contemporary to the rotation of the Sardo-Corso block and the opening of the Algero-Provençal basin.

Based on multibeam data collected during MAGIC (Marine Geohazard along Italian Coasts) surveys, integrating with seismic data acquired during of previous research projects (Progetti Finalizzati CNR, CARG, PRIN and others), have been studied the main gravitational processes in the continental slope of south Sardinia. South western Sardinia continental margin includes the distal shelf and upper slope in front of San Pietro and Sant'Antioco islands, the Gulf of Palmas and Teulada Cape.

Instability areas are represented by canyons headscarps in retrogressive erosion, particularly active are the Toro Canyon heads and the Teulada canyon system which shows evidences of tectonic control. In this area, particularly significant is the complex landslide off the Toro Island which affects a volume of loose sediments of about 7 km³; two low-angle landslides that develop off the coast of Cape Teulada affects a volume of 2 km³. Areas characterized by fluids emission are home of large pockforms (d > 500 m) concentrated in the summit area of the most active headscarps, while large fields of pockmarks and mud volcanoes were found on the right side of Teulada Canyon.

Sardinian southern margin includes distal shelf and upper slope of the Gulf of Cagliari and the northernmost part of Ichnusa seamount. Gravitational instability processes are represented by two major landslides located 10 Nm off the city of Cagliari, the landslide body is affected by processes of base scouring due to the migration of the meanders of the Pula Canyon. 10 nautical miles off Punta Zavorra, on an isolated strip of continental shelf were recognized block landslides evolved along the main tectonic features (NW-SE) that give rise to a debris avalanche deposit; gravitational instability occurs at the summit area of the left side of Sant'Elia Canyon, where significant creep waves affects surface sediments.

Keywords: Southern Sardinia Continental Margin, Submarine Landslides, Pockforms, Pockmarks.

Riassunto: Deiana G., Meleddu A., Paliaga E.M., Todde S. & Orrù P.E. *Geomorfologia della scarpata Continentale: frane e Pockforms del Margine Meridionale Sardo (Italia)*. (IT ISSN 0391-9839, 2016)

Il margine continentale della Sardegna meridionale è caratterizzato da un sistema deposizionale sottomarino controllato dalla tettonica pliocenica suddiviso in diversi bacini marginali, nei quali pervengono i contributi sedimentari dei vari segmenti di piattaforma continentale di due regimi deformativi. Il più antico corrispondente ad una fase compressiva di ispessimento crostale durante l'Oligocene – Miocene, contemporaneamente alla rotazione del blocco Sardo – Corso ed all'apertura del bacino Algero – Provenzale.

Sono stati studiati i principali processi gravitazionali nella scarpata continentale della Sardegna meridionale attraverso i dati multibeam acquisiti durante le indagini MAGIC (Marine Geohazard along Italian Coasts) e l'integrazione con dati sismici acquisiti nel corso di precedenti progetti di ricerca (Progetti Finalizzati CNR, CARG, PRIN e altri).

Il margine continentale della Sardegna occidentale meridionale include la piattaforma distale e la scarpata superiore antistante le Isole di San Pietro e Sant'Antioco, il Golfo di Palmas e Capo Teulada.

Le aree di instabilità sono rappresentate dalle testate dei canyon in evoluzione retrogressiva; particolarmente attive sono le testate del Canyon Toro e il sistema canyon Teulada che mostra evidenze di controllo tettonico. In quest'area, particolarmente significativa è la frana complessa che si sviluppa a largo dell'Isola del Toro il quale interessa un volume di sedimenti sciolti di circa 7 km³; due frane a basso angolo presenti a largo di Capo Teulada interessano un volume di 2 km³. Le aree interessate dall'emissione di fluidi sono sede di grandi pockform (d > 500 m) e sono concentrate nella zona sommitale delle testate più attive, mentre i grandi campi di pockmark e vulcanetti di fango sono stati riscontrati sul lato destro del Canyon Teulada.

Il margine meridionale sardo include la piattaforma distale e la scarpata superiore del Golfo di Cagliari e la parte settentrionale del seamount Ichnusa. Processi di instabilità gravitativa sono rappresentati da due maggiori frane sottomarine localizzate a 10 Nm a largo della città di Cagliari, il corpo di frana è interessato da processi di scaldamento alla base legati alla migrazione dei meandri del Canyon Pula. 10 miglia

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nautiche a largo di Punta Zavorra, su un lembo residuale di piattaforma continentale sono state riconosciute frane a blocchi che si sono evolute lungo i principali lineamenti tettonici (NW-SE) che danno origine a un deposito di debris avalanche; l'instabilità gravitativa si verifica nella zona sommitale sul lato sinistro del Canyon Sant'Elia dove importanti onde a creep interessano i sedimenti superficiali.

Termini chiave: Margine Continentale della Sardegna meridionale, Frane sottomarine, Pockforms, Pockmarks.

GEOLOGICAL AND GEOMORPHOLOGICAL SETTINGS

The Sardinian southern margin was explored by geophysical surveys and deep drilling from the late sixties and early seventies, (Finetti & Morelli, 1973; Ryan & Hsu, 1973). The first investigations on continental shelf have been performed by the University of Trieste (1970) and Genova (1974-75) (Fanucci & *alii*, 1976). Subsequent seismic reflection data were detected during P. F. Oceanography and Marine Fund (Sparker-Uniboom 0.5-1 kJ, Resp. Scient. A. Ulzega (Carta & *alii*, 1986), on the occasion of a collaboration University of Paris-University of Cagliari (Thomas & *alii*, 1988) and, finally, during different seismic campaigns (1983-1991, Sparker 1-3.5 kJ).

An analysis of existing studies, shows that the first setting the high-angle fault zones system and tectonic blocks which later formed the continental margin of western Sardinia can be traced all'Oligo-Miocene, when, in the intra-arc back on the Maghrebic-Apennines, it produced a wide rift system (fig. 1) (Cherchi & Mantadert, 1982; Lecca & *alii*, 1997; Sowerbutts A., 2000; Casula & *alii*, 2001; Facenna & *alii*, 2002). The rifting system is clearly a consequence of the convergence Africa-Europe and could also be considered as impactogen (Sengör, 1995). With different arguments, Carmignani & *alii* (1994) offering membership Sardinian rift to Northern Apennines system, with associated transgressions and transtension upper Oligocene-early Miocene and distension in the lower-middle Miocene. According to data from ECORS-CROP seismic profiles, the genesis of the margin could be identified in the reverse extensional tectonics of a compressional structures system of a western branch of the Pyrenean chain (Fanucci & Morelli, 1997). Whatever the genetic model, the Sardinian rift constitutes an extensional system associated with the Apennine-Maghrebic convergence with location, in one case, high-angle with respect to the Maghrebic Range, and in the other parallel to the northern Apennines segment.

Therefore the margin, which was a western branch of the rift system, it later assumed the structural and evolutionary characteristics of divergent margin relating to an extensional basin associated with an area of convergence (Lecca, 2000).

The fault zones Sardinian rifts have used various types of structural pre-existing discontinuities within the Palaeozoic basement; similarly, it is estimated that this has also occurred in the continental margin (Lecca, 2000). Thomas & *alii* (1988) correlate sedimentary units Sar-

dinian rift with those seismic stratigraphic present in the margin basins.

However, this correlation must be understood in a broad sense, because we have data to suggest that at least in some parts of the margin is recognizable latest developments, as already identified in the southwestern Sulcis (Lecca & *alii*, 1986).

This heterochrony the extensional process in the western edge find similarities and correspondences both with two rifting stages of the Asinara Gulf (Genneseux & Thomas, 1986), both with the recognition and a late jump of volcanism in southwestern Sulcis (Cherchi & Mantadert, 1982). In relation to the area studied, the infrastructure of the upper margin consists of large tectonic blocks in lithologies Palaeozoic, spread by direct faults high-angle (fig. 1) (Finetti & *alii*, 2005); the relative movement of these blocks has produced a series of basins, located either in the current continental shelf and in the slope, probably evolved during the Lower-Middle Miocene, whose filling is characterized by terrigenous-carbonate sequence of the Mesozoic-Tertiary and the volcano-sedimentary sequence Oligo-Miocene syn-rift.

The same structural motif is also detectable in the outer shelf where the acoustic basement, represented by Oligo-Miocene volcanics and locally by Mesozoic limestones, is covered by sedimentary prism Plio-Quaternary to a depth of -180 meters (Ulzega & *alii*, 1980).

In internal continental shelf, the most significant morphological high, are represented by Toro Islands and Vacca Island, the Secca of Toro and Banco Pomata at north-west of the island of Toro.

DTM analysis of the Continental Margin of Southwest Sardinia made it possible to define main morpho-bathymetric elements that characterize this field margin.

The area to the west of the escarpment, dominated by the presence of Toro Canyon and S. Antioco canyon affects the continental shelf in which are present large areas to rocky outcrops correlated with volcanic systems oligo-Miocene (Toro Island and Secca 103).

The head of the Toro Canyon is indented into the edge of the continental shelf for about 7 Km, along the western fault of Palmas Gulf. To the south east of the Toro Island were as paleo submerged shore lines on beachrock facies related to the Last Glacial Maximum (LGM), while near the head an extended mega dune field documents the activity of important bottom tractive current.

On the edge, at the heads of the Canyon S. Antioco are present some closed depressions correlated to the fluid release processes. In intermediate slope it can detect an important complex landslide which affects the covers in quaternary loose sediments, the total area affected by the landslide complex reaches about 73.5 km².

The high structure of the Toro's horst defines the southern limit of the western sector. To the east the continental slope is incised by the Canyon of Teulada and the Canyon of Spartivento.

The Spartivento Canyon belongs to a major canyon system which affects the western southern slope of Sardinia. The geomorphological structure of the individual tested, characterized by clear asymmetry between the sides of

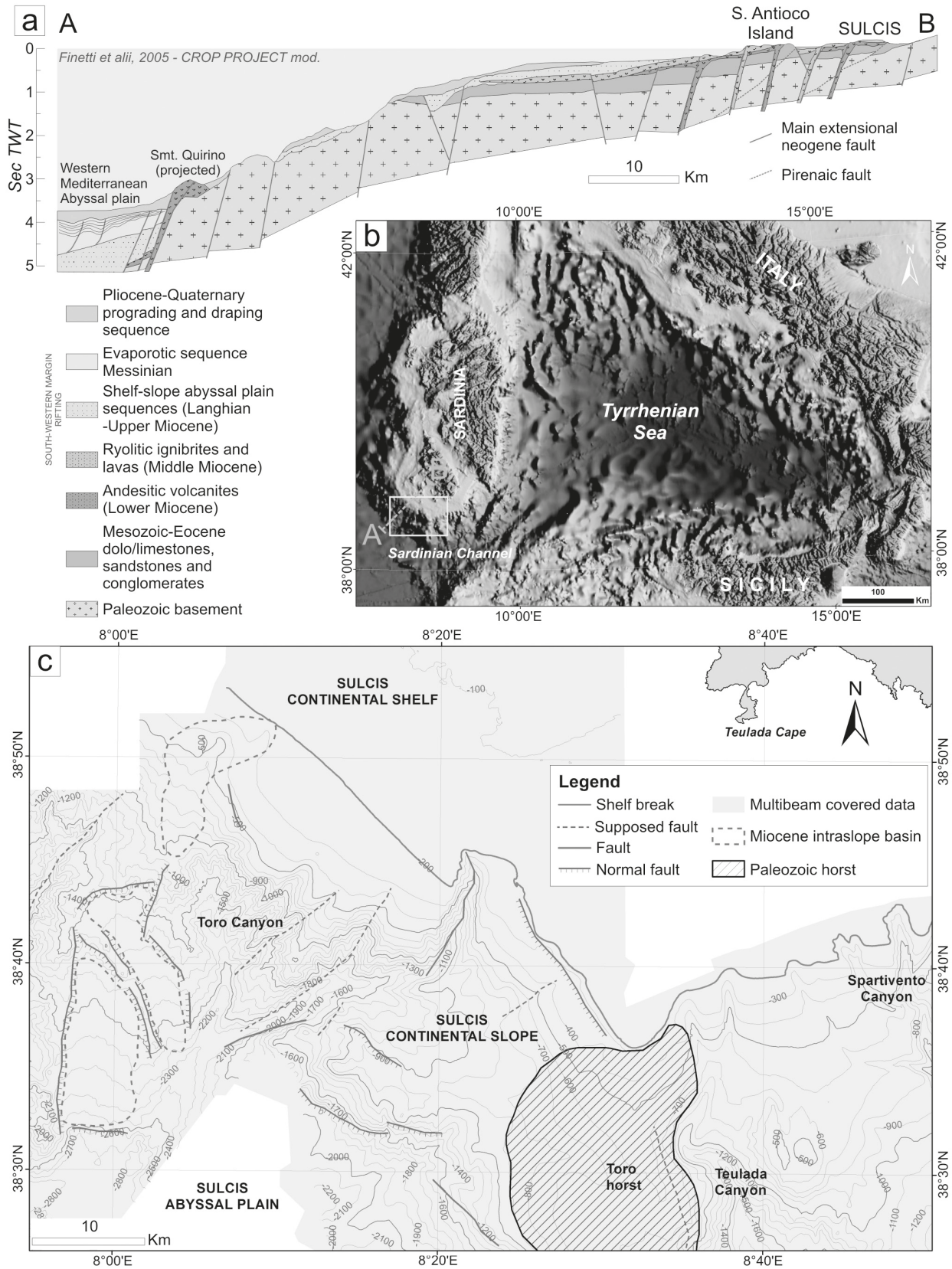


FIG. 1 - a) Schematic section of the south-west continental margin of Sardinia (from Finetti & alii, 2005 CROP PROJECT mod.); b) Study area; c) structural map of the continental margin south-western Sardinia.

the thalweg, seems to be correlated with the tectonic lineaments oriented approximately north-south to strike slip component.

The Canyon of Teulada is defined by the presence of three main channels ribbon affecting the Pliocene-Quaternary sequence up to affect the edge of the continental shelf at a depth of -150 meters.

Slope areas morphology is affected by the presence of two significant landslides affecting the shell to incoherent sediments of quaternary age; their detachment niches are defined by high net frames up to 30 meters.

In this sector is detectable an extended area characterized by the presence of pockmarks.

MATERIALS AND METHODS

The data discussed in this paper were acquired during two different oceanographic cruises carried out with the R / V *Universitatis* under MAGIC Project (Marine Geohazards Along The Italian Coasts) funded by the Department of Civil Protection.

In particular we have acquired multibeam data with total coverage and seismic data at very high GeoChirp resolution.

During the campaigns the acquired data have been properly corrected through the motion sensor and gyro, while the correct positioning has been guaranteed by the GPS (Satellite Differential GPS); all data have been acquired according to the reference system UTM WGS84 - time 32N.

1. The Reson Seabat 8160 MBES operates at a frequency of 50 kHz. One hundred and twenty-six beams are transmitted from the transducers within a fan of 1501 opening angle. Return values provide bathymetric depth information at angular increments of 1.21 with a vertical resolution of 1.4 cm and 20 m of footprint at 750 m water depth. MBES data were neatly recorded using the PDS2000 software at 5 Kn along closely spaced line with track offsets of 500–1500 m, providing complete coverage of the southern Sardinian margin, ranging from 250 to 1300 m water depth.
2. The GEOACOUSTICS GeoChirp IISBP system (4x4 transducer array) uses advanced frequency modulation (FM) and digital signal processing (DSP) techniques giving rise to optimized seabed penetration and record resolution over the 1–12 kHz frequency range. At the surface the GeoChirp Transceiver is used to control output power levels (up to 10 kW), repetition rate and output wave form (high resolution or high penetration). The data obtained from this device were systematically recorded during all expeditions at sea using the Delph Seismic Plus software, in high-resolution mode.

DISCUSSION AND CONCLUSION

Until now, morphologies type pockmarks have never been documented in the continental margin south-western Sardinia; during the MAGIC campaigns, different sectors

of the upper escarpment, dominated by the presence of these morphologies have been identified.

The detected pockmarks can be grouped into three different families according to the morphology that characterizes them: elongated (sub-circular), irregular and circular (fig. 2). This classification is based on the terminology already used by Judd and Hovland (2007). The elongated pockmarks present plan “elliptic” with the major axis orientation approximately NW-SE.

The maximum size for the most significant elongated pockmarks are about 2.8 km (major axis) to 0.8 km (minor axis); the depth of the elongated pockmarks reaches about 50 meters.

They show in cross-section profile V mostly symmetrical with morphology of irregular bottom; In fact, sometimes, pockmarks affects the entire thickness of the Plio-Quaternary to expose the underlying bedrock (fig. 2).

Pockmarks with this morphology are detectable only in the upper slope of the north-west area of the margin (fig. 3).

The irregular pockmarks have size in subcircular plant, probably originated from the coalescence between two or more adjacent smaller pockmarks and feature typical irregular perimeter; in cross-section show profiles of major depression is asymmetrical V that U.

The average size for the most significant pockmarks reach diameters of about 1.5 km and a maximum depth of about 60 meters (fig. 2).

Most of these pockmarks were detected in the north-west area of the study area, in correspondence of the main heads of the S. Antioco Canyon; however some isolated cases are detectable in peripheral areas in this area (fig. 3).

The circular pockmarks have very variable sizes: smaller, detectable only in the outer continental shelf and at its edge (the north-western sector of the area studied), have a diameter of about 8 to 10 meters and a depth of about 2 ÷ 3 meters; the pockmarks with larger have a diameter which reaches 900 meters to a depth of up to 95 meters. The transverse profile is typically symmetrical V and U; only rare exceptions are asymmetrical profile (fig. 2).

The circular pockmarks are those that crop up most extensively in the study area: in particular, the bulk density of these forms is detectable in the Toro Spur, where in an area of about 50 km² were detected 25 pockmarks, sometimes according to well defined alignments (fig. 3).

Some circular pockmarks aligned were also detected within one of the tributary channels of S. Antioco Canyon.

The single-channel seismic profiles to very high resolution show the geometry of the reflectors within pockmarks. In particular the analysis of the seismic recordings highlights the following observations:

1. The symmetry of the flanks of pockmarks, whether it is of V which U-shaped transverse profile, is also conserved in the geometry of the seismic reflectors;
2. In some pockmarks there were no discontinuities in the geometry of the seismic reflectors;
3. In some pockmarks it is possible to detect the discontinuity and truncation in seismic reflectors.

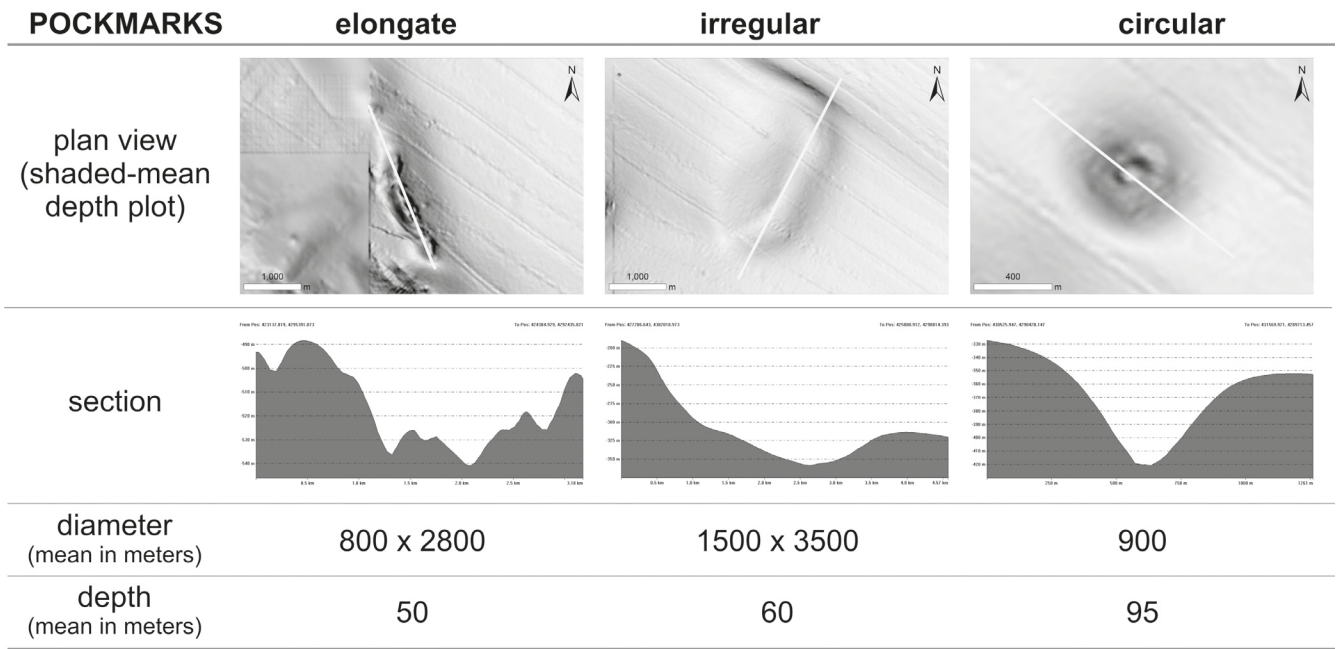


FIG. 2 - Compilation of morphologic characteristics of pockmark-like seabed features (pockforms). Plan views show details of multibeam records (cf. locations in Fig. 3). The locations of sections are indicated on the plan views. The diameters and depth are average values calculated from all features of each type.

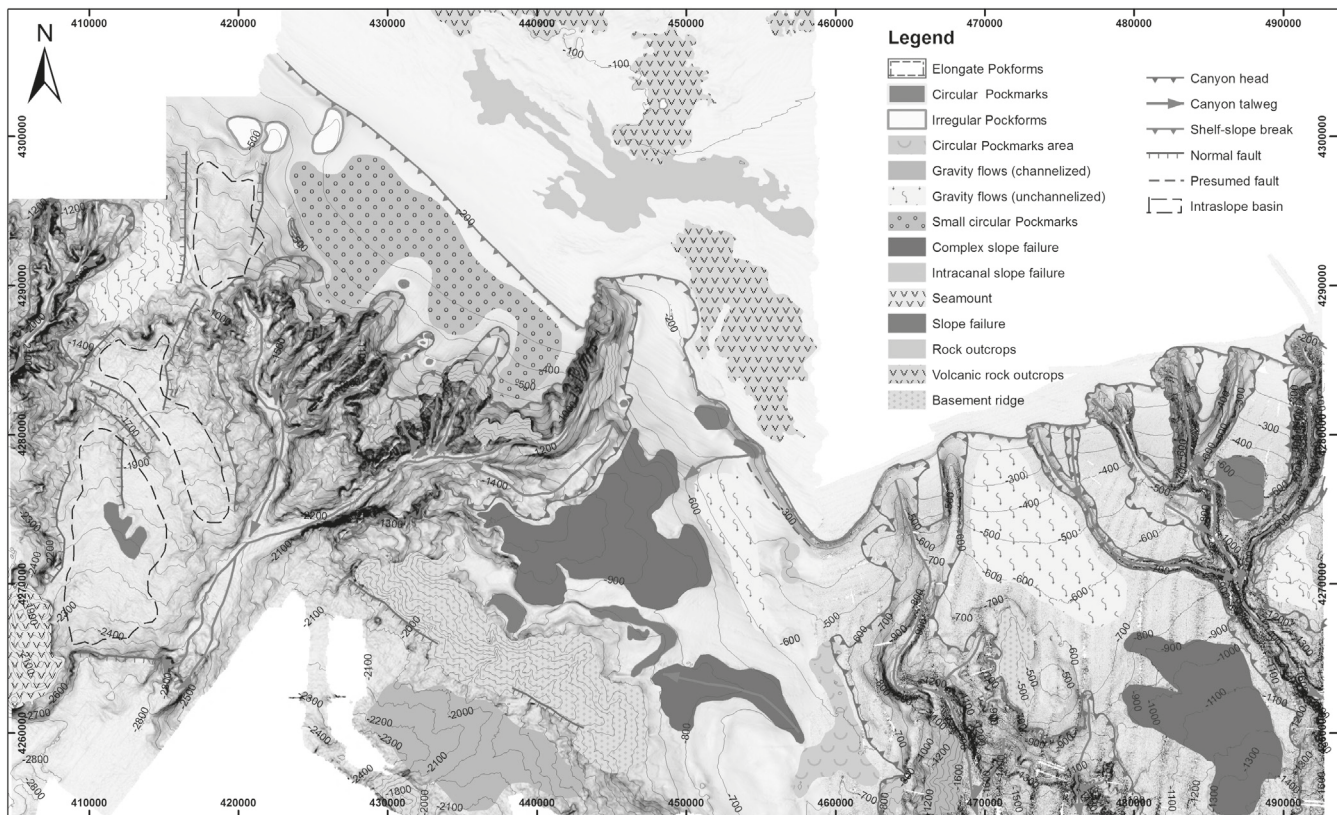


FIG. 3 - Geomorphic map. Main and most representative morpho-bathymetric elements of south Sardinian continental margin.

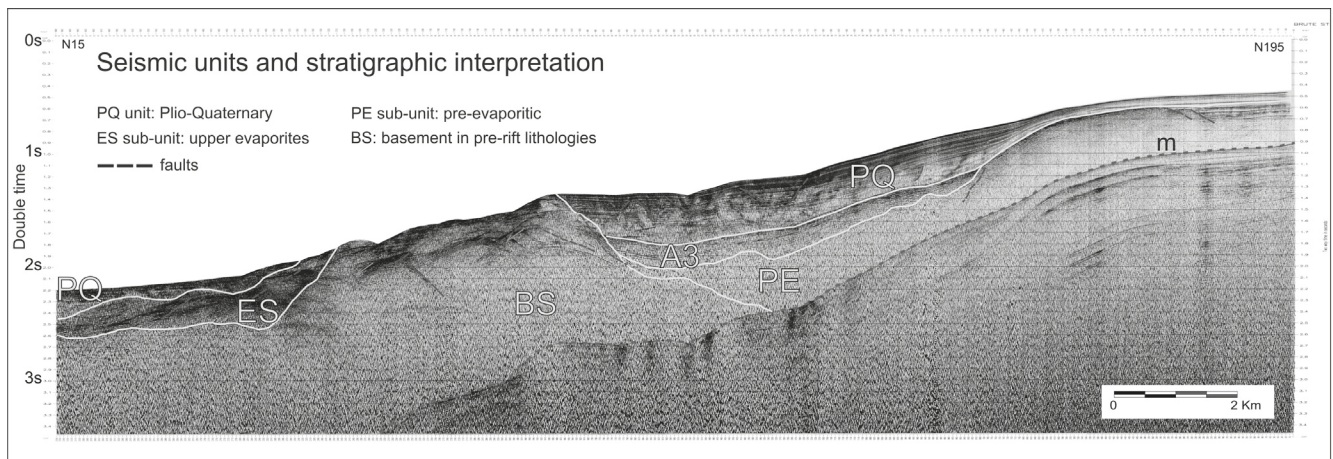


FIG. 4 - Multichannel seismic section acquired in the Continental Margin of the south-western Sardinia. BS - Seismic Facies correlated with the acoustic basement, pre-rift lithologies (Paleozoic); PE - Reflectors facies with onlap type terminations interpreted as coastal on slightly inclined basement and as marine onlap for steeper facies affected by normal faults; Pre- evaporitic (Upper Aquitanian -Tortonian). ES - Seismic facies reflectors with sub-parallel to wavy type terminations onlap on the basement; (Messinian); PQ - Seismic facies reflectors with low amplitude and high lateral continuity with internal cliniform geometry near to shelf edge and parallel in the intermediate sector; this seismic unit is correlated with Plio-Quaternary.

The first observation implies that the genesis of these forms could be linked with continuous and steady processes that have always interested the same seabed sector for very long periods of time. It also implies that the origin of these morphologies is not to be put in relation with erosive processes. The second observation could be explained by two hypotheses: a) It is pockmarks currently showing evidence of inactivity and are interpreted as relict landforms, to be linked with ancient processes of formation.

In this case it is assumed that whether the sedimentary contributions of the upper escarpment have not been sufficient to fully fill the depressions, it is that the genesis of pockmarks can be correlated with slow and continuous processes that have allowed the preservation of the original morphology. These depressions are to be linked with very slow deformation processes that affect very porous sediments, in hydroplastics conditions, therefore able to absorb the deformation preserving the continuity in the geometry of the seismic reflectors.

The last observation implies instead, that it is currently active morphologies. The pockmarks in which it is possible to detect breakdown in the seismic reflectors emerge only in the high structure of the Taurus Spur, in the south-eastern sector of the area studied.

To understand the genesis and distribution of pockmarks the southern continental margin of Sardinia must contextualize in the geological and stratigraphic framework that characterizes the study area.

The geological and stratigraphy structure of the area has been defined through a number of studies based on acquisition campaigns of seismic data both single-channel high-resolution, both multi-channel.

In particular, the multi-channel seismic sections acquired along the entire margin have identified (fig. 4):

- a lower seismic facies correlated with the acoustic basement in pre-rift lithologies (Paleozoic);

- a facies in spotlight with type onlap endings interpreted as coastal on slightly inclined surfaces of the base and how marine onlap on steeper affected by normal faults;
- Pre- evaporitic (Aquitanian sup.-Tortonian);
- ES - Facies seismic reflectors from sub-parallel to rolling with onlap type terminals on the base; upper evaporites (Messinian);
- PQ - seismic facies with low amplitude reflectors and excellent lateral continuity with internal geometry cliniforme near the platform edge and parallel to the intermediate sector; This seismic unit is correlated with Plio-Quaternary deposits.

The stratigraphy's examination of detail of pockmarks detected was carried out on the basis of very high resolution seismic records GeoChirp acquired as part of MAGIC campaigns (fig. 5).

The seismic records, together with the data acquired from Lecca & alii (1988) during some dredging in this area of margin, indicate that pockmarks affect only the Plio-Quaternary *Orbulina Universa* mud. It is known that the great part of pockmarks detectable in continental shelf and continental slope environment is associated with the ascent processes of fluids through preferential migration routes (Judd & Hovland, 2007; Fernández-Puga & alii, 2007, among others). This model of evolution is also confirmed in the upper continental slope of Sulcis where the highest concentration of pockform is detected in areas where the Pliocene-Quaternary reach the greater thicknesses.

Seismic facies Pliocene-Quaternary is distinguishable in a basal subunit characterized by a transparent facies, correlated with sediments rich in organic fraction and saturated water, and an upper subunit in which the seismic reflectors are interrupted by the presence of discontinuities correlated with the migration routes of the fluids upwards.

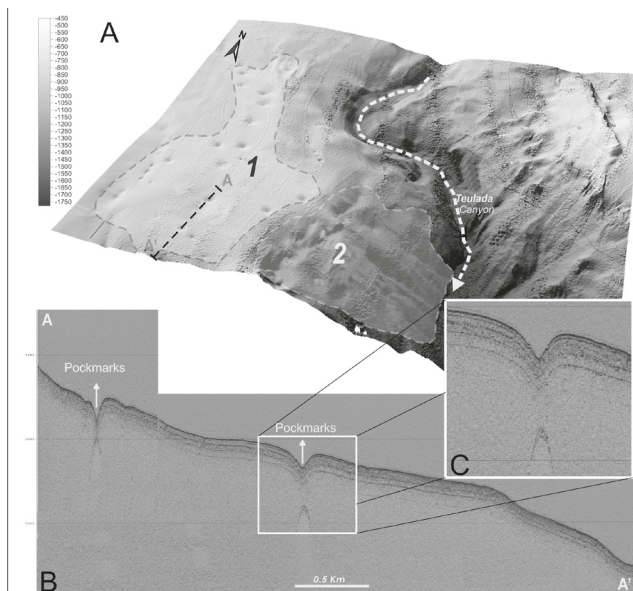


FIG. 5 - A - 3D model of the upper southern Sulcis continental margin. 1 - to Pockmarks area associated with fluid escape processes; 2 - Left side of the Canyon Teulada talweg affected by landslides. Predisposing factor is the fall of geomechanical sediments properties as a result of the fluid escape process. B - GeoChirp recording: two pockmarks; C) seismic reflectors are interrupted and below the closed depression is detectable response to a transparent seismic signal correlated with the presence of fluids escape. The seismic record showing current state of activity of these morphologies.

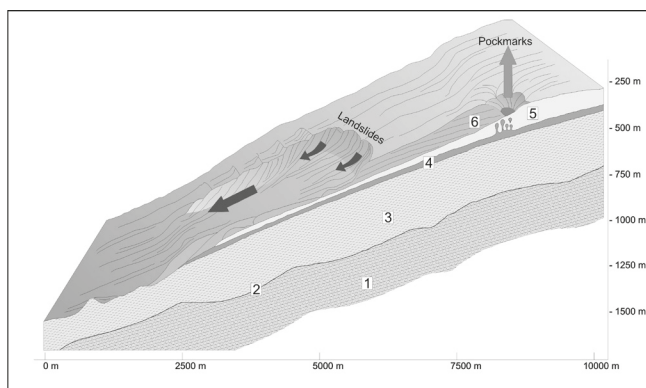


FIG. 6 - Sectioned block diagram of the main channel of the Sant'Antioco Canyon. 1 - Miocene sequence; 2 - Messinian erosion surface; 3 - Pliocene sedimentary sequence; 4 - Level saturated in fluids with a high content in organic matter; 5 - Holocene sedimentary cover; 6 - Deposits interested by landslide processes.

The data in this study suggest a possible link between the processes of fluid escape and the presence of some gravitational processes.

The pockmarks are in fact located in the upper slope areas, in areas characterized by the presence of gravitational processes. The evolutionary model for these gravitational processes provides (fig. 6):

1. the presence of a basal facies (transparent to the seismic signal) correlated with saturated sediments and fluids rich in organic matter that acts as a reservoir.

2. presence of discontinuity within the sequence Plio-Quaternary correlated with preferential ways of fluid migration (such discontinuities were also recognized in seismic recordings at very high resolution GeoChirp).
3. A layer in fine sediments of Pleistocene saturated in fluids but not affected by gravitational processes;
4. A layer to Holocene sediments affected by gravitational processes due to a fall in the geomechanical properties of the sediments correlated with fluid migration processes.

The migration of fluids in fact would be responsible for the reduction of the shear strength of the upper slope sediments. For the first time, as a result of oceanographic campaigns carried out under the MAGIC project, were identified several areas of continental slope dominated by the presence of pockmarks.

One of the prerequisites for the formation of pockmarks is the presence of fluid migration processes (liquid and / or gas) through the shell to inconsistent sediments.

In the upper slope of the Sulcis, not being known evidence of the presence of gas, the processes of formation of pockmarks appear to be related to release of water from the Pliocene-Quaternary sediments.

For some sectors it is proposed the generic term "pockforms" to describe these morphologies and differentiate them from real "pockmarks" whose genesis is to be put in relation with erosive processes from fluid leakage.

The spatial distribution of gravitational processes can be controlled by the presence of pockmarks; has been suggested a possible link between the fluid escape processes and the presence of some important gravitational processes that characterize the upper slope.

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