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CONTINENTAL SHELF AND SLOPE GEOMORPHOLOGY: MARINE SLUMPING AND HYPERPYCNAL FLOWS (SARDINIAN SOUTHERN CONTINENTAL MARGIN, ITALY)

Abstract: Meleddu A., Deiana G., Paliaga E.M, Todde Samuele & Orrù P.E., *Continental shelf and slope geomorphology: marine slumping and hyperpycnal flows (Sardinian southern continental margin, Italy).* (IT ISSN 0391-9839, 2016)

The study area is located in southern Sardinian continental margin, morphostructural characters that control the southern Campidano affect the structure of the continental shelf in front.

The southern part of the Sardinian rift, with the superimposed Campidano Graben structure, continues within the sea in the Cagliari Gulf, both at the continental shelf level and in the upper slope regions. In this area the morphology shows important tectonic features that follow the main regional tectonic. In particular the western shelf edge is oriented parallel to an important tectonic feature N. 130°, resulting in a steep (> 40°) fault wall exposure. The continental shelf reaches a maximum width of about 2 Km and is characterized by sub planar morphology with a slightly steep ground (about 3-4%).

Along the eastern edge, an area characterized by the short distance between the shelf edge and the coastline (d < 1000 m) has been studied. In case of an important phenomena of mud-flow and debris-flow onshore, the turbidity can get to the shelf edge and trigger gravity flows to overload, putting, as a consequence, the coastal environment life at risk of abnormal waves back. Here, there is the Rio Geremeas, characterized by a steep river equilibrium profile (L = 15 km, H 900 m) that, in the event of extreme rainfall could generate to mud flows / debris flow resulting hyperpycnal flows at sea.

The geomorphology of the slope is characterized by submarine canyon and several tributary channels, inside of them are landslides.

Inside Foxi Canyon heads a retrogressive evolution have been detected bedforms 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, this bedforms are called "crescent-shaped bedforms". These forms could be generated by the erosion and deposition repetition due to the load of gravity sedimentary flows (Casalbore & *alii* 2013).

Key words: Geohazard, Submarine canyon, Hyperpycnal flows, Sardinia (Italy).

Riassunto: Meleddu A., Deiana G., Paliaga E.M, Todde Samuele & Orrù P.E., *Geomorfologia della piattaforma e scarpata continentale: frane sottomarine e flussi iperpicnali (Margine continentale meridionale sardo, Italy).* (IT ISSN 0391-9839, 2016)

L'area di studio si trova nel margine continentale meridionale sardo, i caratteri morfostrutturali che controllano il Campidano meridionale condizionano l'assetto della piattaforma continentale antistante .

Il settore meridionale del Rift sardo, con la struttura del Graben del Campidano, prosegue in mare nel Golfo di Cagliari, sia sulla piattaforma continentale che nelle zone a maggiore pendenza. In questa area la morfologia mostra lineamenti tettonici importanti che seguono la tettonica regionale. In particolare il ciglio della piattaforma è orientato parallelamente ad un'importante lineamento tettonico disposto a N. 130°, questo porta all'esposizione di un versante di faglia ben definito (> 40°). La piattaforma continentale raggiunge una larghezza massima di circa 2 Km ed è caratterizzata da una morfologia subplanare a debole pendenza (circa 3-4%).

Lungo il bordo orientale, è stata studiata una zona caratterizzata da una breve distanza tra la costa e il ciglio della piattaforma (d <1000 m). Nel caso di un importante evento di colata rapida (debris flow e mud flow), la torbida può raggiungere il ciglio della piattaforma continentale e innescare flussi gravitativi da sovraccarico, mettendo, di conseguenza, l'ambito costiero a rischio di onde anomale di ritorno. Qui, è presente il bacino idrografico del Rio Geremeas, caratterizzato da un ripido profilo di equilibrio (L = 15 km, H 900 m) che, in caso di precipitazioni estreme potrebbero generare mud flows e debris flow con conseguenti flussi iperpicnali in mare.

La geomorfologia della scarpata continentale è caratterizzata da canyon sottomarini e diversi canali tributari, all'interno dei quali sono presenti frane sottomarine.

All'interno della testata del Canyon Foxi in evoluzione retrogressiva, sono state riscontrate forme di fondo caratterizzate da una lunghezza d'onda di decine di metri e un'altezza di diversi metri, con le creste disposte approssimativamente perpendicolari alla massima pendenza, queste forme di fondo vengono chiamate "crescent-shaped bedforms". Tali forme possono essere generate dalla ripetizione di fenomeni di erosione e deposizione dovuti al carico sedimentario dei flussi gravitativi (Casalbore & *alii* 2013).

Termini Chiave: Pericolosità geo-ambientali, Canyon sottomarino, Flussi iperpicnali, Sardegna (Italia).

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INTRODUCTION

The definition of natural hazards in the deep sea (submarine landslides, volcanic eruptions, fluid escape, earthquakes, retrogressive erosion of submarine canyons heads, bedforms migration, etc.) is realized by high-resolution mapping of hazard features.

To define the type of event, the causative factors and the effects are necessary extensive research and advanced technologies. Technological development is offering marine geology powerful seafloor mapping tools, multibeam bathymetry above all; they are essential for geohazard characterization and through repetitive surveys, monitoring and understanding of ongoing geological processes (Chiocci & *alii*, 2011).

In 2007, the Italian project MaGIC (Marine Geohazards along the Italian Coasts) was born, it is a 5-year project (December 2007 - December 2012) funded by the Italian Civil Protection Department as a national-scale effort aimed at investigating geohazards on the Italian continental margins (Chiocci & Ridente, 2011).

The geomorphological study of the upper slope in the Sardinian southern margin, shown in this manuscript, was carried through the analysis and interpretation of geophysical data acquired during two oceanographic cruises (Canale di Sardegna 2009 – Canale di Sardegna 2010) by Universitatis R/V (CoNISMA) under the project Magic. In the eastern sector, the substantial mass movements mapped along the continental slope and within the main canyon, whose heads due to retrogressive trend approach the coastline, represent extremely interesting geo environmental emergencies for local and regional assessments of geo-hazard.

GEOMORPHOLOGY AND STRUCTURAL GEOLOGY

The continental margin of Southern Sardinia is characterized by a submarine depositional system, controlled by Pliocene distensive tectonics. It is divided into several marginal basins (Wezel & *alii*, 1981), in which the sedimentary contributions of the various segments of the continental shelf arrive (Lecca & *alii*, 1998).

The structure of the southern Sardinian continental margin, highlighted in numerous seismic profiles acquired from the 70s (Morelli & Nicolich, 1990; Blundell & *alii*, 1992; Egger, 1992; Giese & *alii*, 1992; Torelli & *alii*, 1992; Tricart & Torelli, 1994), is characterized by the succession of two deformational regimes. The oldest corresponds to a compressive phase of crustal thickening occurred during the Oligocene – Miocene, contemporary to the Sardinia – Corsica microplate rotation and opening of Alghero - Provencal basin (Mascle & *alii*, 2001). The most recent is associated with the phase of rifting of the Tyrrhenian Sea, during which there was a tectonics that has led to a slight

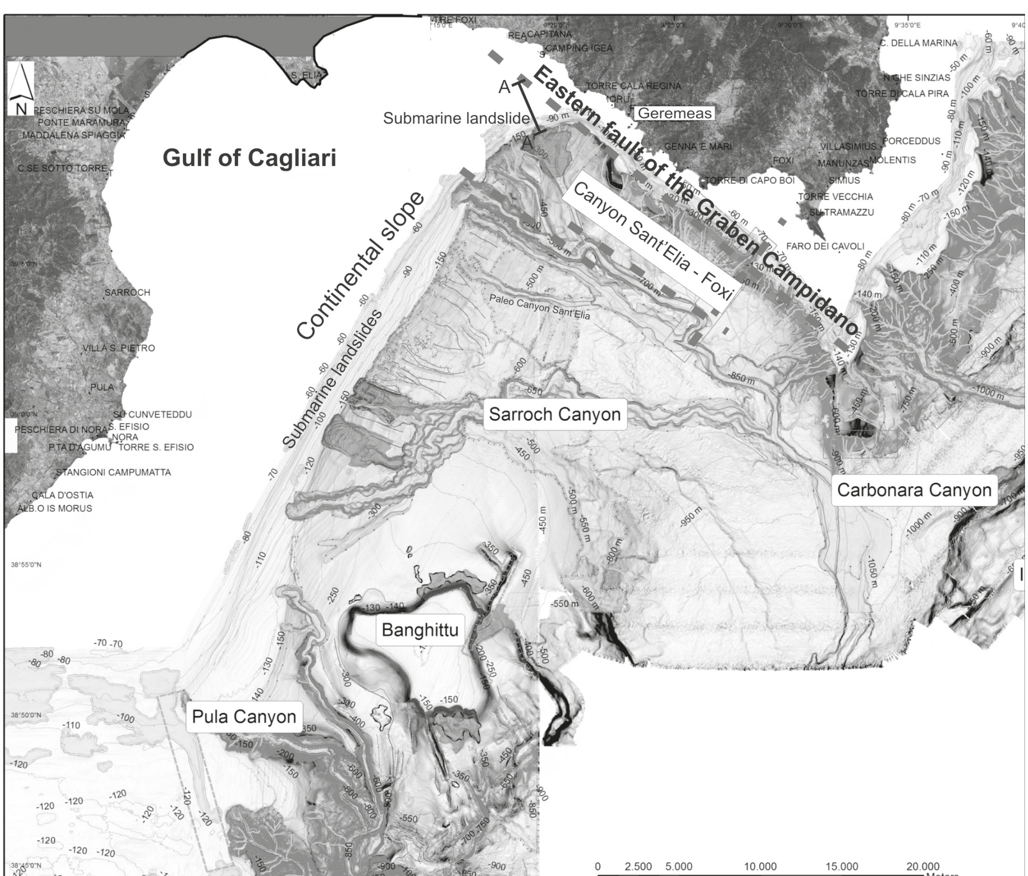

FIG. 1 - DTM (Digital Terrain Model) of the continental shelf and slope of the Cagliari Gulf. In the eastern sector, the continental shelf break is located at the depth of about -120m, presents evident tectonic control, and its direction follows on the shelf the trend of the Campidano Graben eastern side fault exposing a really steep fault wallaffected by diffused and channelized erosion.
A-A' is the location of the seismic profile present in figure 5.

thinning of the Earth's crust, which occurred before the Messinian crisis.

Cagliari basin is the innermost part of the sedimentary system of the entire margin, delimited and controlled by tectonic blocks of southern Sardinian continental margin, in particular by the movements of Mount Ichnusa and Su Banghittu submarines blocks (Fanucci & *alii*, 1976).

The morphostructural characters shown in figure 1 control the southern Campidano and affect the appearance of the continental shelf and slope (Fanucci & *alii*, 1976) in the Gulf of Cagliari, in fact it is possible to recognize the continuation of the Campidano Graben in the submerged area.

The western continental shelf break is oriented parallel to an important tectonic features disposed to N130°, resulting in a steep (> 40°) fault wall exposure well defined. The continental shelf is characterized by sub planar morphology with a slope of about 3-4%.

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 gravity flows involving the bedrock; the resulting deposit mainly consists of blocks of considerable size (up to 250 m) (Deiana & *alii*, 2012) (fig. 1).

The continental slope is incised by extensive canyon systems and numerous tributary channels, (fig. 1) and the continental shelf break is at the average depth of -120 m, to arrive to lower altitudes in correspondence of the retreat for regressive erosion of canyon heads (Ulzega & *alii*, 1986).

ONSHORE GEOMORPHOLOGY

In the area of interest, the catchment area is represented by the Rio Geremeas that develops in the southeastern area of the Gulf of Cagliari, south of the Sette Fratelli and interestes a mountain system predominantly granitic, characterized by peaks and plateaus and that extends to the coast of alluvial cover.

The river originates and flows on a granite basement draining the waters of the southern part of the massif of Sarrabus, develops in the N-S direction perpendicular to the coastline, and flows in the vicinity of the residential-tourist Geremeas, between Torre delle Stelle and Capitana. The main river channel of the Rio Geremeas has an extension greater than 60 kmq and a development of nearly 20 km before flowing into the sea, presents a sub-straight monocursale type watercourse that develops within a broad alluvial valley closed between the rocky hills.

Onshore, in case of extreme rainfall event (rainfall > 200 mm/h), the hazard levels of the Rio Geremeas basin would be affected by the high slope of the equilibrium profile and by the presence of vast source areas in hyper fractured granites, together with the significant longitudinal development, 15 km, which corresponds to a strong altitudinal gradient from 0 to 900 meters. The hypothetical debris flow would start from a source area on the side of the "Sette Fratelli", would travel a high slope transfer area, would reach the coastal plain and then inserted at sea, this hypothetical path is shown in Figure 2.

In October 2008, in Capoterra, on the western edge of the Gulf of Cagliari, following an extreme rainfall event on the Rio San Girolamo basin approximately 400mm in two hours, there was a debris and mud flow event to be dispersed in the proximal continental shelf without risk of submarine landslide. Here the edge of the continental slope is located at 19 Km from the coast, while in the eastern sector, object of study, the shelf break is about 900 m from the coast.

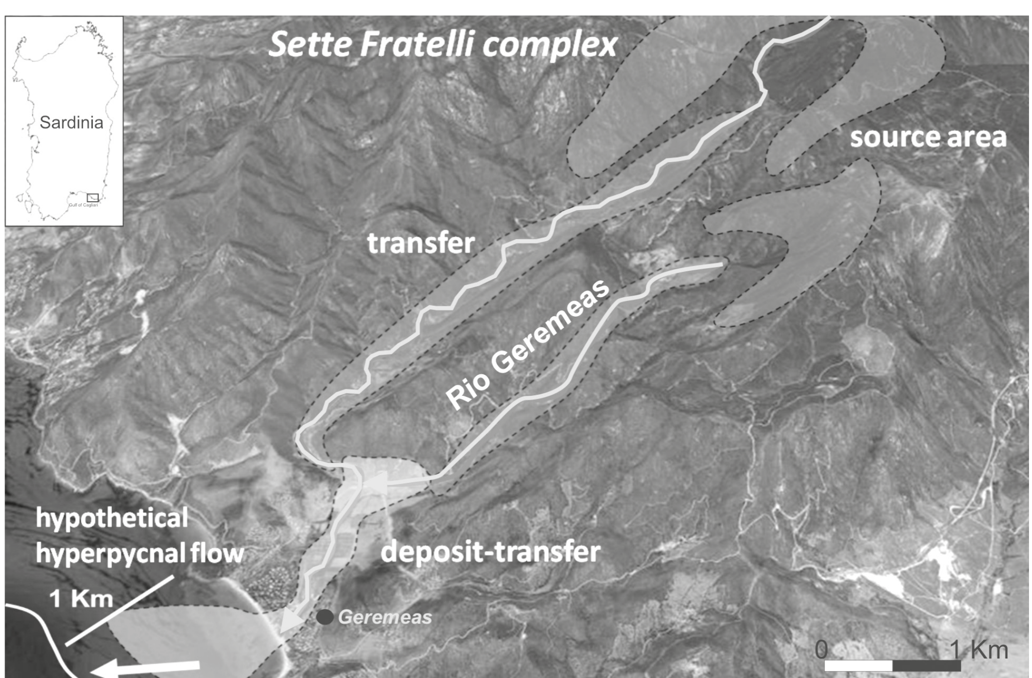

FIG. 2 - Hypothetical path of debris and mud flow that would start from a source area on the side of the "Sette Fratelli" in hyper fractured granites, would travel a high slope transfer area and would reach the coastal plain then inserted at sea. The shelf break interested by Foxi Canyon head is about 900 m from the coast.

In figure 3 is shown as the Rio Geremeas hydrographic basin, characterized by steep slope, has a longitudinal profile similar to that event of Rio San Girolamo in the 2008, albeit with higher altitudinal gradient.

Than, the waterways in the area of study, if affected by rainfall events characterized by parameters above the average, might be able to generate debris and mud flow phenomena, putting at risk the coastal area (Paliaga & *alii*, 2014).

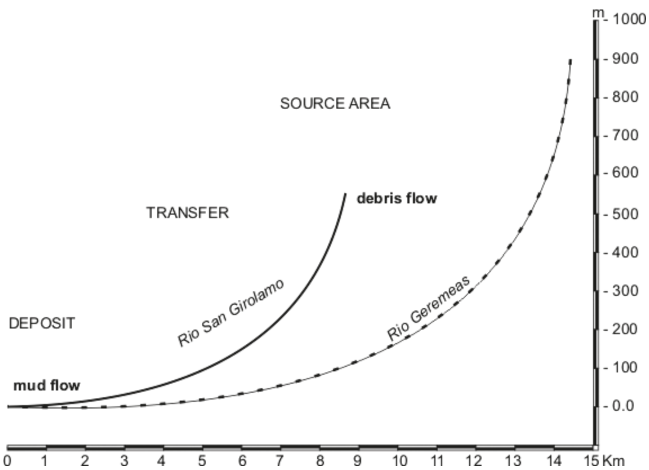

FIG. 3 - Profile of equilibrium between Rio San Girolamo (flash flood 22 ottobre 2008, Capoterra) e Rio Geremeas. Rio Geremeas hydrographic basin is characterized by steep slope and has a longitudinal profile similar to that event of Rio San Girolamo in the 2008, albeit with higher altitudinal gradient. Rio Geremeas is characterised by a significant longitudinal development and a strong altitudinal gradient from 0 to 900 meters.In case of extreme rainfall event (rainfall > 200 mm/h), a debris and mud flow event may occur such as that has interested Rio Geremeas in Capoterra.

MATERIALS AND METHODS

The data discussed in this paper were acquired during two different oceanographic cruises, "Canale di Sardegna 2009"and "Canale di Sardegna 2010" both carried out with the R / V Universitatis under the "MaGIC" Project (Marine Geohazards Along The Italian Coasts). In particular, multibeam data and seismic data have been acquired with total coverage 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 –fuse 32N.

The Reson Seabat 8160 MBES operates at a frequency of 50 kHz. The Multibeam echosounders (MBES) collect bathymetric soundings in a swath perpendicular to the ship track. This is done by electronically forming a series of transmit and receive beams in the transducer hardware which measure the depth to the seafloor in discrete angular increments or sectors across the swath (Hughes & *alii*, 1996).

It has allowed a complete coverage of the southern Sardinian continental margin, ranging from 60 m to 3000 m water depth, in the study area the range is between - 60 m and – 1000 m as shown in the bathymetric map, in figure 4.

Subsequently, the data acquired have been subjected to manual editing and the application of additional filters for the elimination of errors.

The geoacoustics GeoChirp II SBP 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.

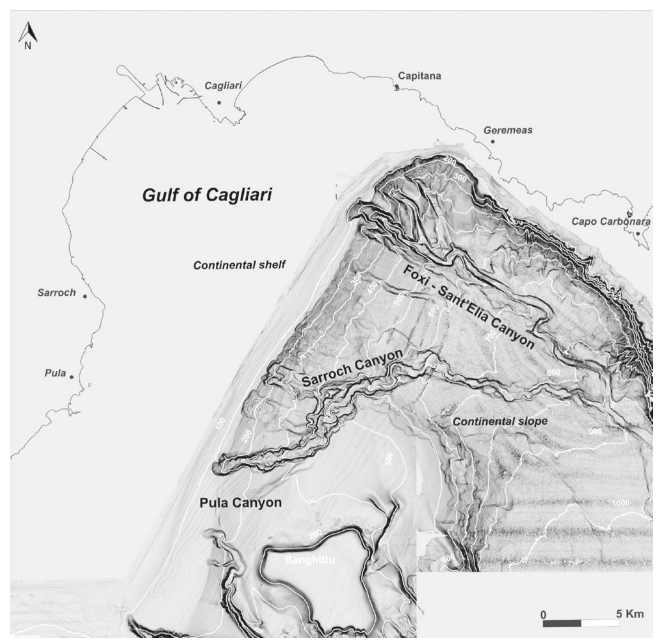

FIG. 4 - Bathymetric map of the continental slope of the eastern sector of the sardinian southern continental margin, represented with depth contours every 100m

In addition to chirp data sparker data were acquired.

A seismic section showing the continental shelf break in correspondence of the Foxi canyon head is shown in figure 5. The interpretation of the seismic section has identified biogenic limestone of the Upper Miocene, submerged depositional terrace with sub-parallel and prograding convex geometry reflectors, basal accumulations derived by gravitational sliding, outcrops of the beach rock at -50m, depression filled by parallel lamination fine sediments (paleo-lagoon) and the multiple.

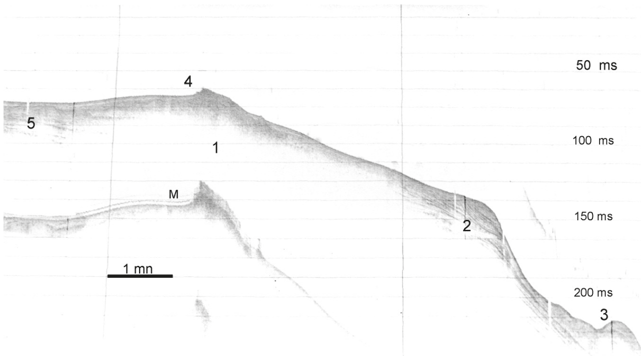

FIG. 5 - Sparker 3,5 Khz profiles: location in fig. 1 - section in correspondence of Foxi Canyon head, 10 km off Capo S. Elia SE – NW (outern Gulf of Cagliari): 1) deaf substrate, upper Miocene biogenic limestone; 2) submerged depositional terrace with sub-parallel and prograding convex geometry reflectors (LGM); 3) basal accumulations derived by gravitational sliding; 4) outcrops of the main -50m beachrock, (10,83±170 cal BP); 5) depression filled by parallel lamination fine sediments, palaeo-lagoon; M) multiple.

GEOMORPHOLOGY OF THE UPPER SLOPE

The area of interest includes the shelf and continental slope of the Sardinian southern margin in front of the Gulf of Cagliari, in which gravity movements and sedimentary flows channeled were detected.

In the geomorphological map (fig. 6) the main morphologies that affect the study area are shown. In the north-eastern sector of the Gulf of Cagliari there are three main canyon: Pula Canyon, Sarroch Canyon and Foxi Canyon.

In the upper continental slope sector there are significant size gravity flow phenomena, in particular two main systems were found, generated by various events which affect not only the upper slope but also the shelf edge area. These landslides interest large volumes of sediments, in order of tens of millions of m^3 each, showing deposits characterized by gibbous surface and creep, which spills over the landslide foot, inside an erosive meandering canyon system.

In the upper area of the continental slope in the Gulf of Cagliari, have been recognized two landslides that indent the continental shelf break. The first landslide grows at depths of 105 m and 380 m. The detachment area is characterized by the presence of a sector with obvious creep deformation correlated with the slow evolution of the gravitational process. There is a dual destabilizing mechanism, in the continental shelf break is present the gravitational collapse and, at the base, the deposit is affected by erosion by Sarroch Canyon. Overall, the landslide affecting a sediment volume of about 50 million m^3. The sediment affected by the gravitational event shows bedforms that are the result between the movement of the fluid and of the particles.

The second landslide is located at a depth of -110 m to -420 m, is characterized by the presence of two specific niches of detachment that indicate the presence of more events and affects approximately 80 million m^3.

The Foxi Canyon is characterized by a retrogressive evolution head and the morphology observed attests more evolutionary phases with the presence of a paleoriver.

A landslide of high dimension that interested an important sector of the Foxi Canyon head evolves between a minimum depth of -140m and a maximum-380m and is affected by the channelized flows, that cause erosion at the top and then carry eroded material according to preferential directions.

The upper portion of the landslide shown in figure 7 is characterized by the presence of numerous bedforms in the shape of a half moon characterized by a wavelength variable from tens to hundreds meters and heights of several meters with the ridge lines arranged approximately perpendiculars to the maximum slope, called "crescent shaped bedform".

These forms could be generated by the repetition of erosion and deposition due to the sedimentary load of the gravitational flows (Casalbore & *alii*, 2013) and indicate the mobility of the sediment at a different time scale. Similar wave-shaped features have been observed in the axes of submarine channels and canyons (e.g., Prior & *alii*, 1986; Piper & *alii*, 1985; Wynn & *alii*, 2002; Green & Uken, 2008).

These bedforms have a predictable internal layering and are usually interpreted as being produced by the combination of erosion and deposition caused by tractive forces.

SHELF BREAK HYPERPYCNAL FLOWS AND GRAVITATIONAL PROCESSES

The Foxi Canyon head affected by the landslides with the "crescent shaped bedforms" is localized along the southern edge of Sardinia, in the eastern sector. In this sector, there is an area in which the extension of the continental shelf is minimal, infact, in front of Geremeas the shelf break is from the coast less than a kilometer. It is assumed that the bedforms situated at higher altitudes can be active, with evolutionary dynamics and upward migration of the ridge lines to relate with the influence of hyperpycnal flows in this portion of the margin.

The speed of the hypothetical mud / debris flow onshore would suffer friction of the ground decelerating but reached the sea, the mixing of terrestrial sediments with water, would allows the formation of hyperpycnal flows. Given the reduced distance between the edge of the slope and the coast line (<1000m), the hyperpycnal flows may be able to cross the continental shelf and get to greater depths.

The hypothetical path that would do the hyperpycnal flow along the continental shelf and the dynamics which would generate in the shelf break and in the Foxi canyon head are represented in figure 8.

The sediment carried by hyperpycnal flow along the shelf and deposited on the edge of the slope, could generate instability and overload condition on the underlying sediments which may lead to subsidence. On the edge, breaking the equilibrium conditions of loose and saturated sediments, can give rise to gravitational processes able to generate turbid flows, in which the energy of motion is provided by a difference in density between the suspension

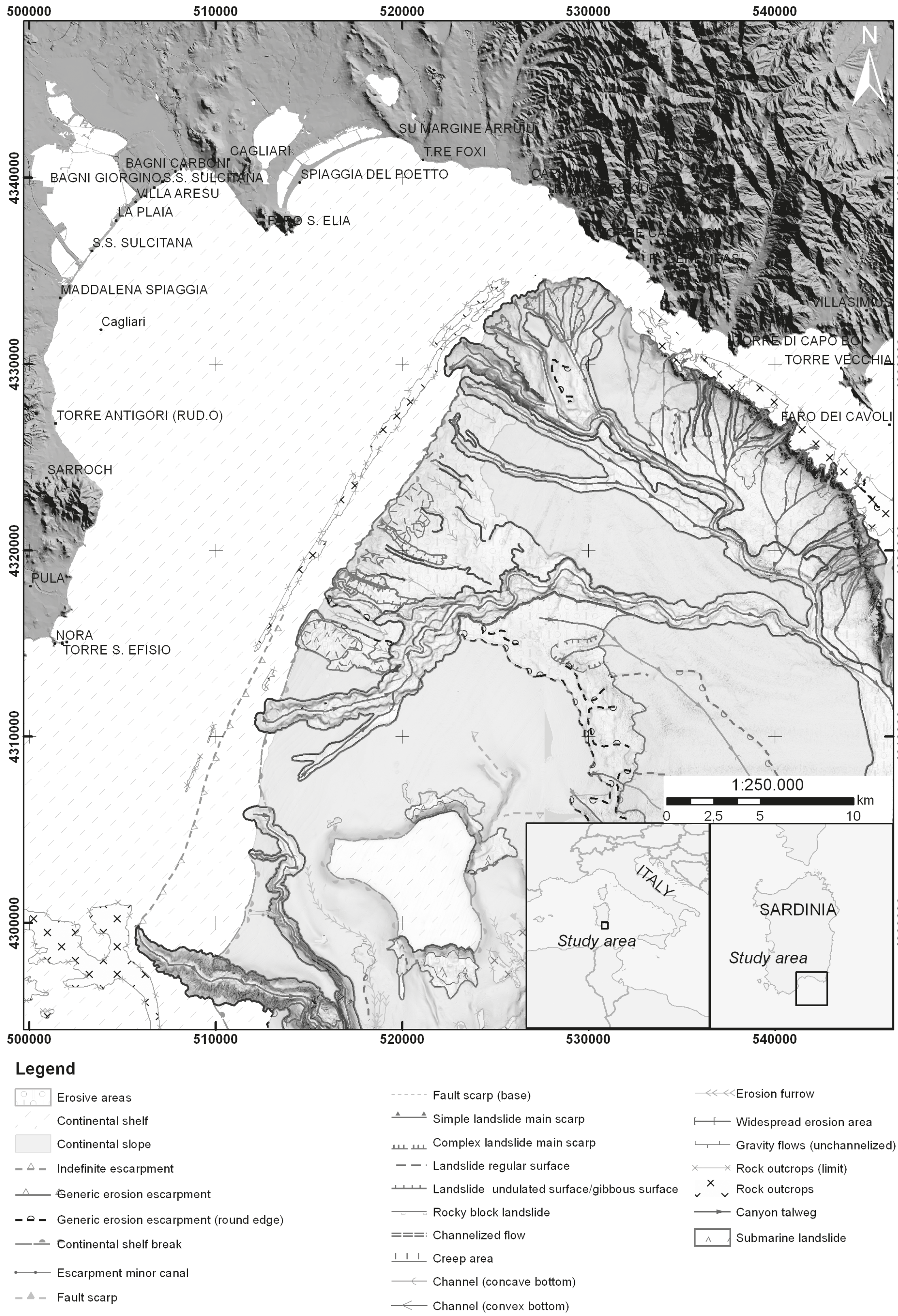

FIG. 6 - Geomorphological map in which are represented the major morphologies affecting the eastern sector of the Sardinian southern continental margin. These are represented by landslides, canyons and areas to widespread erosion.

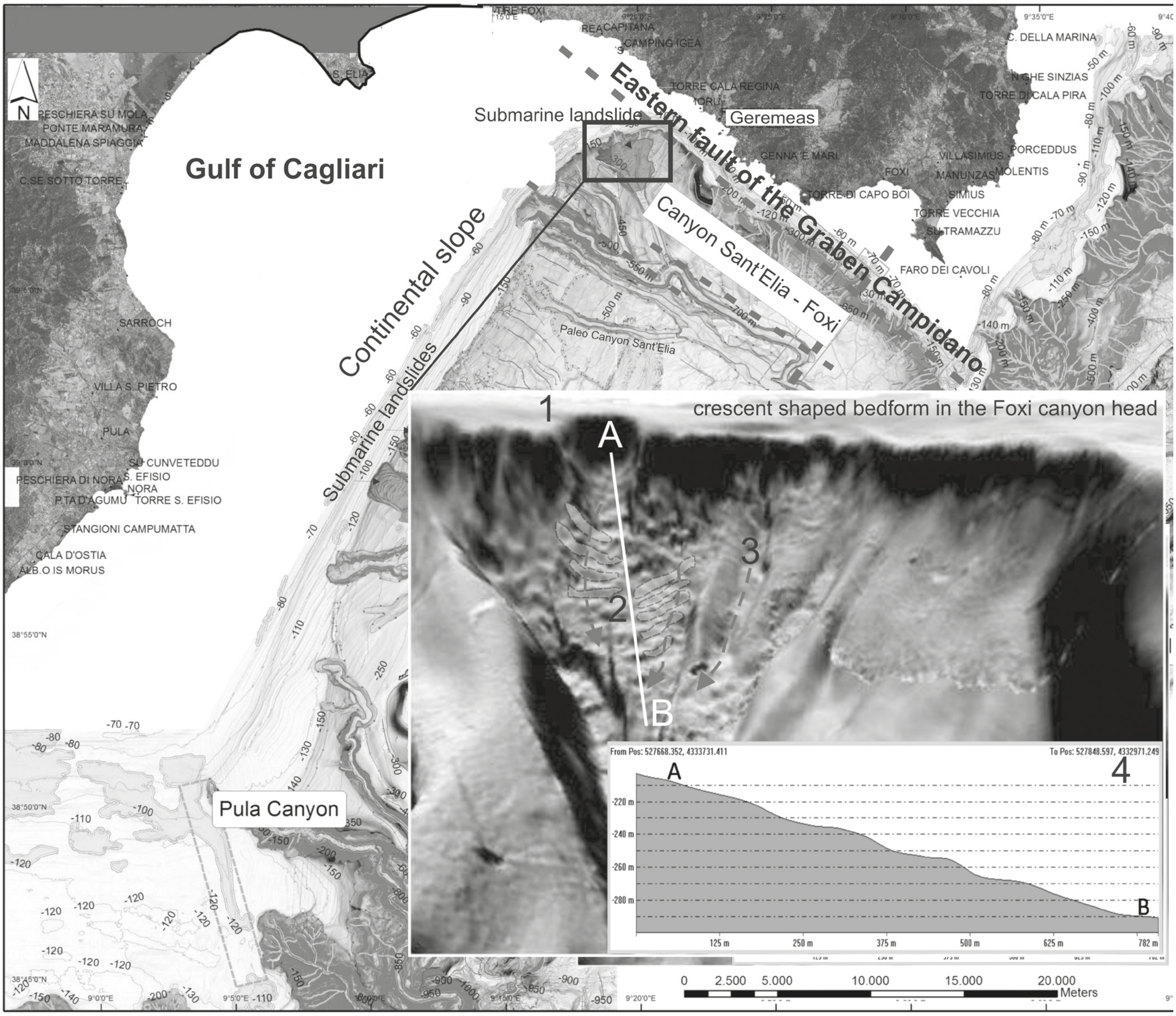

FIG. 7 - Foxi Canyon head: 1)shelf break 2)bedforms characterized by a wave length of dozen of meters and a height of several meters, with the ridge lines arranged approximately perpendicular to maximum slope, this bedforms are called "crescent-shaped bedforms". These forms could be generated by the erosion and deposition repetition due to the load of gravitative sedimentary flows (Casalbore et al., 2013); 3) channeled flows 4) longitudinal morphological profile that highlights thebed forms.

of the sediment and the surrounding fluid. The generated underwater landslide could put in motion a considerable mass of loose sediments, which enriched in water, would acquires fluidity and under the action of the force of gravity, begins a fast motion with high transport capacity and a strong erosive action on the seabed.

In the world, other cases have been analyzed, they refer to the relationship between the dynamic on the ground and in the sea who study the dynamics of transport and sedimentation of hyperpycnal flows in the upper slope, for example the studies carried out in the Var Canyon, located in the western sector of the Bay of Angels, SE France. Here the material from the field emerged was transported by hyperpycnal flows, directly on the head of the canyon to the limited extent of the continental shelf, and has generated gravitational phenomena on the edge of it and triggered turbid currents. (Mulder & *alii*, 1998).

On October 1, 2009, the area between Scaletta Zanclea and Giampilieri villages was struck by heavy rainfall that generated mud and debris flows that caused 37 victim and severe damage to the local settlements along the coast (Ortolani, 2009). The availability of multi-temporal bathymetric surveys in the area in front of Scaletta Zanclea and Giampilieri, before and after the event, allowed to define the morphological changes produced by this catastrophic event on the seabed.

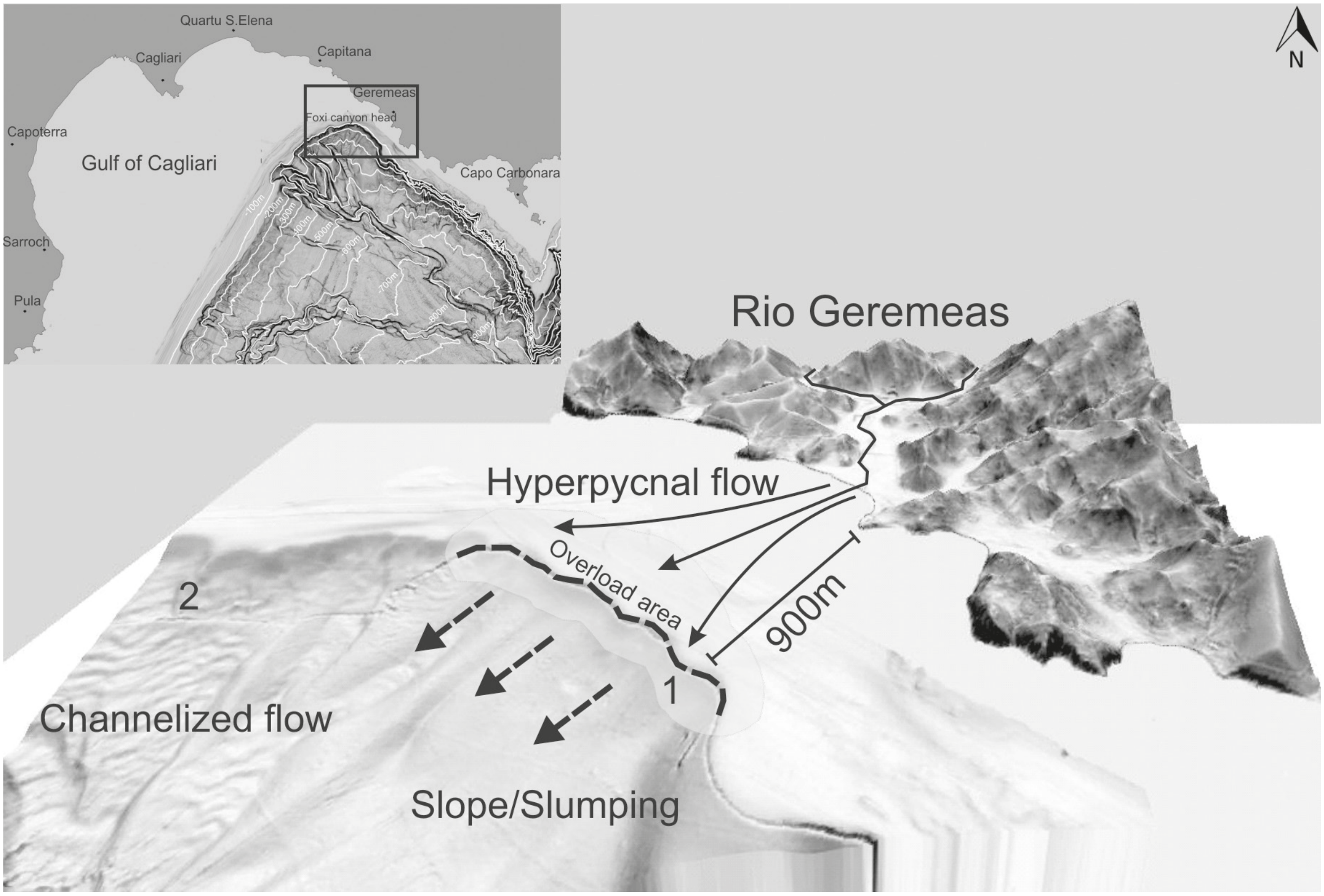

FIG. 8 -3d model of the north-eastern sector of the Gulf of Cagliari; 1) Areas susceptibles to the potential triggering of quick gravitative movements in upper slope. Watercourses present onshore may be capable of giving rise to important important phenomena of mud flow and debris flow, by putting the coastal environment life at risk of abnormal waves back because of the short distance between the shelf edge and the coastline (d < 1000m); 2) Foxi canyon head characterized by the presence of bed forms related to gravitational flows.

DISCUSSION AND CONCLUSION

In the Sardinian southern sector, the geological hazard is mainly linked to the submarine canyon dynamic and potentially tzunamigenic landslides. In fact, in the Sardinian margin the presence of submarine landslides, could aggravate the instability of the area.

The main gravitational processes on the upper slope of the Sardinian southern edge, have been analyzed for the assessment of marine geohazard. Also, the relationship between erosive-depositional processes acting on the inside slope of submarine canyons has been analized, are debris that move according to the direction of maximum slope causing erosion near the shelf break, as evidenced by the detachment crowns inside the head of the Canyon Foxi.

The retreat of Canyon Foxi head in the Gulf of Cagliari, is an element of risk because the shelf break would arrive up to shallow depths. The sedimentary dynamics present in the canyons could represent one of the triggering factors of gravitational instability, the risk is mainly related to the possibility that within the channels could occur a landslide.

Inspired by the debris flow processes (onshore) - hyperpycnal flow (shelf/ slope) occurred as a result of an extreme event (Scaletta Zanclea November 1, 2009), the possible connections between the gravitational processes at high speeds (debris flow and mud flow)in the area on the ground with the trigger of gravitational processes in the slope have been analyzed.

Then, the possible relationship land / sea and the possible evolution of hyperpycnal flows in the continental slope have been analyzed, through the study of the Geremeas river basin (south-eastern Sardinia). They are developing morphometric measurements of the hydrografic basin and sediment transport monitoring, forecasting models inherent full of debris flow and models on the simulation of submarine landslides and height release wave.

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