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SCIENCE

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Geohazard features of the Southern Sardinia

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ABSTRACT

The Maps of Geohazard features of Southern Sardinia produced in the framework of the Magic project (MArine Geohazard along Italian Coasts) are here presented. The MaGIC project (Marine Geohazard along the Italian Coasts) had the aim of mapping the geohazard in the Italian seas. The features were derived from the digital elevation model interpretation of the seafloor morphology and shallow sub-surface. From the marine geo-hazards point of view, the main critical elements are represented by gravitational mass processes in the canyon heads, some of which, as in the Toro Canyon, are exposed to seismic triggering. In other cases, we observed that gravitational dynamics connected to fluid leakage processes (pockforms). Large landslides and debris avalanches have been detected in Cagliari Gulf, whereas in eastern upper slope, crescent bedforms, occurring in the eastern sector of the upper slope testify to the upward migration of hyperpycnal erosional structures linked to flows from nearby river inputs.

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KEYWORDS
Magic project; geohazard; seafloor mapping; submarine geomorphology; submarine landslide; submarine Canyon

1. Introduction

The article illustrates the Maps of Geohazard features of Southern Sardinia (Main Map) produced in the framework of the Magic project (MArine Geohazard along Italian Coasts), a large coordinated initiative that involved the whole marine geological research community in Italy in 2007–2013. The features were derived from the interpretation of the digital elevation model (DEM) of the morphological expression of the seafloor and shallow sub-surface.

Two levels of interpretation are presented: the map of the Physiographic Domain at a scale of 1:250.000 and the map of the Morphological Units and Morpho-bathymetric Elements (areas and vectors respectively) at 1:100.000 scale.

2. Study area: the Southern Sardinia

The southern Sardinia continental margin can be divided into three sectors with different physiographic and structural characteristics. The south-western sector is 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 a narrow shelf and a steep slope limited offshore by the Ichnusa Seamount. The Sardinian south-western margin has been investigated through geophysical surveys and deep drills, to know the rank and the geometry of the depositional sequences (Fanucci et al., 1976; Casula et al., 2001; Lecca, 2000; Finetti et al., 2005; Figure 1). High-angle faults characterize the tectonic setting of the western Sardinia margin. This tectonic phase, which occurred between the Middle-Upper Oligocene and the Miocene, is associated with the intra-back arc of the Apennine-Maghrebian Chain, an extensive rifting system (Casula et al., 2001; Cherchi & Montadert, 1982; Faccenna et al., 2002; Sowebutts, 2000). Based on the ECORS-CROP profiles, the genesis of the continental margin could be identified in the local extensional tectonic context of a compressive structure system of a western branch of the Pyrenean Chain (Fanucci & Morelli, 1997). The Sardinian Rift fault zones followed different pre-existing structural discontinuities within the Paleozoic basement (Lecca, 2000). Kinematic studies of the central Mediterranean evidence that the Sardinia-Corsica Block has been stable in the last 7 million years. However, the INGV earthquake catalogue (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 Island-Quirino Seamount, and two of magnitude 4.5 in March 2006, in correspondence of the extension at sea of the NW-SE fault which delimits westerly the Campidano rift valley

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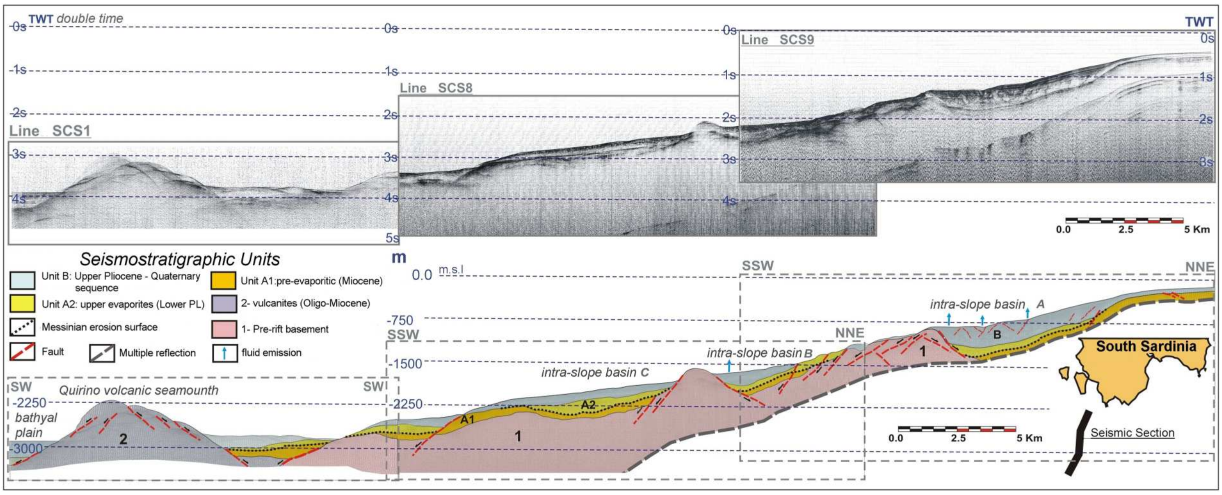

Figure 1. Multichannel seismic profile of the southwestern Sardinia in the top. While in down the interpreted seismic profile with the seismostratigraphic units.

(Figure 2). 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 (Marcella well-1). The filling of the lowering tectonic trench is characterized by fluvial sediments (Ussana Formation), followed by marine marly arenaceous and carbonate Lower Miocenic sequences.

3. Methods and software

As the maps were produced using the same interpretative and carthographic standards, the procedure is described in detail in Ridente and Chiocci (this volume). The legend of the Physiographic Domain map is present on the map, while the legend of the Morphological Units and Morpho-bathymetric Elements map is present as a separate table.

4. Morphological units and morpho-bathymetric elements sheets

4.1. Capo Carbonara (Sheet 59)

The Sheet 59 ‘Carbonara’ includes the part of the sea off the homonymous cape that extends from Marina di Capitana in the Cagliari Gulf to the North of Serpentara Island on Sardinia’s eastern coast.

The western sector may relate to the evolution of the southern Sardinian continental margin, which is characterized by a submarine depositional system controlled by tectonics. It is divided into several marginal basins, which receive 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 entire 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 submarine blocks (Fanucci et al., 1976).

The North-East area can be correlated with the evolution of the Sardinian eastern 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.

The eastern continental shelf shows a wider extension than the western sector of the sheet, reaching an average width of 4 miles; it has regular or weakly bumpy morphology with an average slope of 2%.

The main geomorphological features that can be observed in the sheet N°59 Capo Carbonara are the Sant’Elia canyon headscarp, where gravitative movements and crescentic bedforms (Casalbore et al., 2013) occur followed downwards by channelsized features of downflows (Meleddu et al., 2016). A NW-SE oriented fault scarp is set in the continental shelf, along the continuation of the Campidano graben eastern fault. The Carbonara and Simius canyon headscarps with widespread gravitational instability areas (Figure 2(a); (e)).

4.2. Cagliari (Sheet 60)

The sheet 60 ‘Cagliari’ includes a part of the continental margin of southern Sardinia; this sector is characterized by a submarine depositional system controlled by Pliocene tectonics, divided into several marginal basins in which sedimentary contributions from various segments of the continental shelf arrive (Lecca et al., 1998).

The structure of the margin is characterized by the succession of two deformational regimes. The oldest

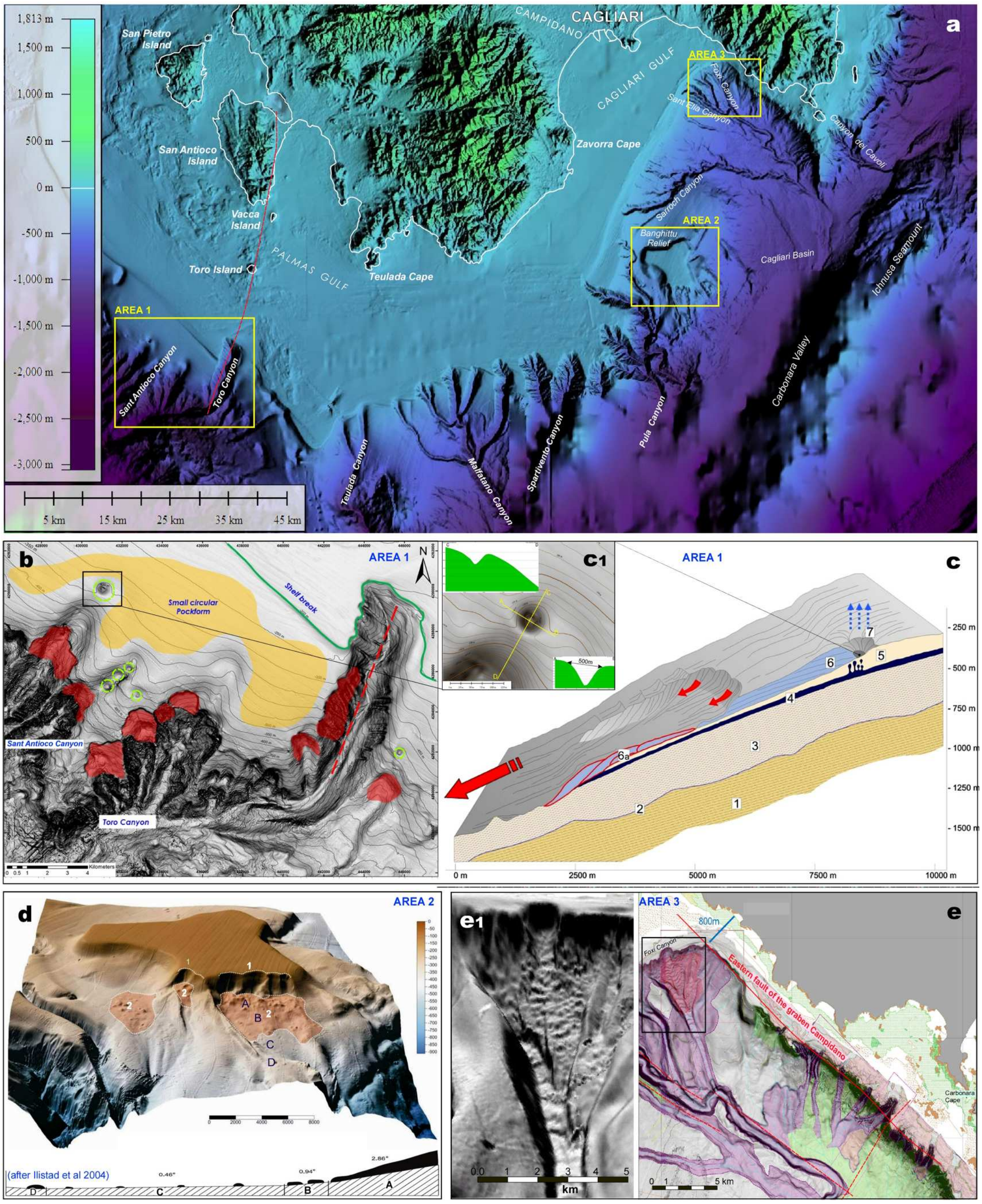

Figure 2. – (a) DTM from MBES data showing landforms in South Sardinian Continental Margin with location of key areas: 1 Area – Toro Canyon heads with fluids emission and complex landslide; 2 Area – Banghittu tabular relief affected by block landslides and debris avalanches; 3 Area – Foxi Canyon heads with retrogressive evolution and 'crescent-shaped' bedforms. (b) – DEM of the main morpho-bathymetric elements of the Toro and S. Antioco canyon systems (AREA 1). The Toro Canyon headscarp incidents on the edge of the continental shelf along the western fault of Palmas Gulf. Warheads in retrogressive erosion and mass movements (red areas) and fluids emission morphologies with pockmarks (green circle). (c) – Sectioned block diagram of the main channel of the Sant'Antioco Canyon (AREA1), the release of fluids triggering gravitational processes. 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 process; 6° – landslide surface deposit; 7 – fluid release depression. (c1) Particular of the pockmark depression, at the head of the Canyon of Sant 'Antioco. With a maximum width of 900 m and a depth of – 85 m. (d) 'Banghittu' is a residual part of the continental shelf of the Gulf of Cagliari. The edge of the relief is affected by gravitational movements involving the bedrock (1), mainly shaped by detached block-like features and failure-related bedforms (block sizes > 250 m). The landslide deposits (2) are divided into four distinct areas, to the main part of the deposit to the base of the slope (A) follows a zone characterized by the presence of scattered blocks (B), from which branch paths of translation (C) of the main shifted blocks (D) (Ilstad et al., 2004). (e) – DTM (Digital Terrain Model) of the eastern sector of Cagliari Gulf, the continental shelf break presents evident tectonic control, with fault exposing a teep wall affected by diffused and channelized erosion; (e1) – Foxi Canyon head, crescent-bedforms generated by the erosion and deposition repetition due sedimentary channeled flows (Casalbore et al., 2013).

corresponds 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-Provencal Basin (Mascle et al., 2001). Cagliari's lagoon barrier system evolves during MIS 5 (Orrù, Antonioli et al., 2011).

On the edge of the continental shelf, sedimentary bodies, interpreted as submerged depositional terraces, were detected in continuity (Ulzega et al., 1986), referring to the last sea level low stand at 120 m water depth, MIS 2 (Chappell & Shackleton, 1986). The main terrace extends for about 8 miles, while its extension perpendicular to the coast reduces to only 200–300 m in correspondence with the active heads of the S. Elia Canyon On the outer continental shelf, due to the Versilian transgression, MIS 1 (Chappell & Shackleton, 1986), relic littoral depositional systems are exposed in beach-rock sandstone-conglomerate facies, interpreted as submerged shorelines (Segre, 1968). The 'banks' arrangement is slightly inclined towards the open sea, which is typical of these outcrops. The sedimentary structures shown are those typical of coastal environments (such as plane-parallel lamination, wedge-shaped, sigmoidal and inclined).

In the upper continental slope, there are large gravitational phenomena, in particular landslides involving large sediment volumes, in order of tens of millions of m^3 each. These landforms show deposits characterized by a gibbous surface and scarps overflowing at the foot of the landslide.

On the west side of Cagliari Gulf is he residual strip of continental shelf named 'Banghittu', the morphology of the relief is influenced by tectonic features, an N136-oriented fault system. The edges of the tabular relief are affected by gravitational movements involving the bedrock; the most significant movements affect block sizes up to 250 meters in length that migrate from the detachment point up to several kilometers away on a weakly inclined plane, according to the Debris Avalanche dynamics (Deiana et al., 2012; Ilstad et al., 2004; Meleddu et al., 2016).

4.3. Teulada (Sheet 61)

The structure of the margin of Sheet 61 'Teulada' highlighted in numerous seismic profiles acquired from the 1970s (Blundell et al., 1992; Egger, 1992; Giese et al., 1992; Lecca et al., 1998; Morelli & Nicolich, 1990; Torelli et al., 1992 Tricart & Torelli, 1994; Wezel et al., 1981;), is characterized by the overlap of two successive regimes of deformation. The oldest corresponds to a compression phase of crustal thickening during the Oligocene-Miocene, which coincided with the rotation of the Sardo-Corso block and the opening of the Algero-Provencal Basin (Mascle et al., 2001). The most recent deformation phase is associated with the Tyrrhenian rifting phase, during which a distensive tectonic phase which occurred before the Messinian crisis (Bouillin et al., 1998).

The Cagliari Basin is the innermost part of the sedimentary system of the entire margin, defined and controlled by the tectonic blocks of the continental margin of southern Sardinia, and in particular by the movements of the submarine blocks of Ichnusa Seamount and Su Banghittu (Fanucci et al., 1976). These marginal basins close to the South of the Oligo-Miocene rift (Cherchi & Montadert, 1982) in southern Sardinia, which reactivated during the Plio-Quaternary extensional movements associated with the opening of the southern Tyrrhenian Sea (Casula et al., 2001; Orrù et al., 2014). The continental shelf is very wide and is distinguishable in two areas: the inner shelf, dominated by the presence of Paleozoic, Mesozoic and Tertiary rock types, and the outer shelf, morphologically regular and characterized by prograding Plio-Quaternary sediments on the edge; the edge of the continental shelf is detectable between 120 and 180 m depth (East and West sector of the sheet, respectively).

The upper slope of Sheet 61 'Teulada' is characterized by two major canyon systems, the Teulada Canyon is the westernmost portion of a major canyon system that affects the southern Sardinia escarpment. The Spartivento Canyon, characterized by apparent asymmetry, seems to be correlated with pre-existing tectonic lineaments. The slope morphology is articulated by the presence of two significant landslides and a large area with pockform. (Figure 2(a))

4.4. Toro-Vacca (Sheet 62)

The Sheet 62 'Toro-Vacca' is located in the southern sector of the western continental margin of Sardinia.

Several studies show that the first setting of the system of high-angle fault zones and tectonic blocks, which later formed the continental margin of western Sardinia, can be traced back to the Oligo-Miocene, when, in the area of intra-back arc on the Apennine-Maghrebian Chain, an extensive rifting system formed (Cherchi & Montadert, 1982; Faccenna et al., 2002; Sowebutts, 2000). The rifting system is a consequence of the Africa-Europe convergence (Sengor, 1995). On the basis of data from the ECORS-CROP profiles, the genesis of the margin could be identified as an extensional tectonics inversion of a compressional system of structures belonging to a western branch of the Pyrenean Chain (Fanucci & Morelli, 1997). In Sheet 62 'Toro-Vacca', the basement of the top margin consists of large tectonic blocks of Paleozoic lithologies, displaced by high-angle normal faults (Finetti et al., 2005); the relative movement of these blocks has produced a series of basins located in both actual shelf and in the continental slope, which probably evolved during the Lower-Middle Miocene, whose filling is characterized by the terrigenous-carbonatic sequence of Mesozoic-Tertiary and by the volcano-sedimentary Oligo-Miocene sin-rift sequence. The same structural motif is also seen in the outer continental shelf, where the acoustic basement, represented by the Oligo-Miocene volcanic and locally by Mesozoic limestone, is covered by the Plio-Quaternary sedimentary prism down to 180 water depth (Ulzega et al., 1980). In the inner continental shelf, the most significant morphological highs are represented by Toro and Vacca islands, and by Toro and Banco Pomata shoals, located NorthWest of Vacca Island. (Figure 2(b))

The Continental Margin of the Sheet 62 'Toro-Vacca' is dominated by rocky outcrops related to the Oligo- Miocene volcanic system. In the distal sector of the continental shelf, an extended field of mega-dunes documents the activity of important bottom currents (De Falco et al., 2015; Deiana et al., 2022). The Toro Canyon headscarp, indents on the edge of the continental shelf for about 7 km along the western fault of Palmas Gulf, clearly shows tectonic control by a seismogenic fault. Near the head of the Canyon of Toro was detected closed depressions (diameter = 900 m, deep = 85 m) correlated to fluids release processes (pockform) which corresponded downward large complex landslides (Figure 2(c)) (Deiana et al., 2016).

4.5. Sant'Antioco (Sheet 63)

The continental shelf within Sheet 63 'Sant'Antioco' is characterized by an irregular morphology dominated by outcrops of volcanic substrate, with Coralligenous assemblage (Orrù, Solinas et al., 2011; Piazzi et al., 2022). Differential erosion highlights many volcanic morphologies as neck-shaped emission centers, craters and calderas (Conforti et al., 2016; Deiana et al., 2021). 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 seamlessly. The emplacement of this grand display of mega dikes, within the Tertiary rifting geodynamics, presents analogies with East African active rifting areas (Ayele et al., 2006; Wright, 1977). The seaward limit of the volcanic outcrops is represented by a paleo-cliff line with a foot at 140 m depth; deep-seated gravitational rotational landslides niches are distinguished (Deiana et al., 2021; Demurtas et al., 2021a, 2021b, 2022), together with collapse mega-blocks at the basis. The hypothesis that the gravitational and erosive morphologies may be related to the last phase of low sea-level, standing Last Glacial Maximum (MIS 2), was confirmed by a recent sampling of a littoral thanatocoenosis (Deiana et al., 2021; Orrù et al., 2012).

4.6. Southern Sardinia submarine geohazard

Sardinian continental margin presents hazards mainly associated with gravitational instability which gives rise to different types of processes.

In particular, in the distal continental shelf off the San Pietro island coast, extensive paleo-cliffs are preserved, controlled by NE-SW tectonic features. Paleo-cliffs show deep-seated gravitational slope deformations evidenced by rotational kinematics (Demurtas et al., 2021a) and block-slides involving acid volcanic rocks whose evolution can be correlated with the LGM paleo coastline cliff environment (Deiana et al., 2021; Orrù et al., 2012). On the upper continental slope in front of the San Pietro and Sant'Antioco islands, the Gulf of Palmas and Capo Teulada. the instability areas are represented by the canyon heads in retrogressive erosion where intra-channel and head landslides are distinguished (Figure 2(b)). The heads of the Toro Canyon are particularly active, showing evident tectonic control. The trigger of the gravitational movements appears to be linked to the emission of fluids highlighted by pockforms (Figure 2(c)) concentrated in the summit area of the most active canyon heads (Deiana et al., 2016). In the Gulf of Cagliari, off Punta Zavorra, along the edges of the isolated relief of 'Banghittu' evolved block slides were detected along the main tectonic lines (NW-SE) which gave rise to a debris-avalanche deposit (Figure 2(d)).

10 miles off the Cagliari city, along the continental shelf edge, two important landslides are detected with the landslide body affected by basal undermining processes due to the migration of the Pula Canyon meanders (Meleddu et al., 2016).

In the upper continental slope of the eastern sector of Cagliari Gulf, due to the high slope, erosion and retreat processes dominate which have led to the exhumation of the 'Campidano di Cagliari' graben border fault. In this area, the continental shelf is very small and the head of the Foxi Canyon (Figure 2(c)) is very close to the coastline, so the hyperpicnal flows can reach the edge and give rise to flows channeled into the slope (Meleddu et al., 2016).

Geo-risks in southern Sardinia are linked to the presence of potentially tsunamogenic landslides, both in a quiescent state and in a reactivated state. Exposed elements are represented by the waterfront of the city of Cagliari, various coastal towns, numerous tourist settlements and important port and industrial structures.

5. Conclusions

The southern Sardinian margin is characterized by a system of intra-platform and intraslope basins related to the tertiary rifting phase and to the reactivation of transtensional lineaments with a prevalent NW-SE trend, to which the greater evidence of gravitational instability is connected; in particular, on the sides of the Toro Canyon, tectonically controlled, a high concentration of large submarine landslides has been detected, evolved with great probability following seismic triggering.

In the same area and along the upper slope of Teulada, the gravitational instability seems to be related to extensive pockmarks fields, from fluid leakage.

On the western side of the Cagliari Gulf, off of Punta Zavorra, also the evolution of mega-blocks landslides that slide on low-angle subaqueous slopes, up to about ten kilometers from the detachment zones, seems to be somehow connected with the active tectonic.

On the eastern edge of the Cagliari Gulf, near the steep escarpment that corresponds to the eastern border fault of the Campidano, gravitational movements both mass and channeled are detected. Along the Foxi Canyon head, on the eastern upper slope of the Cagliari Gulf, crescent-shaped bedforms highlight the upward migration of hyperpycnal flows linked to nearby river inputs.

Software

As the maps were produced using the same interpretative and cartographic standards, the procedure is described in detail in Ridente and Chiocci (this volume). To interpret and edit Maps *Global Mapper – Blue Marble Geographics* and *ESRI ArcGIS* software were utilized.

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Data availability statement

Data are available upon reasonable request by contacting the first authors at the mail address.

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