Active faulting and continental slope instability in the Gulf of Patti (NE Sicily, Italy): a field, marine and seismological joint analysis

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Abstract

The Gulf of Patti and its onshore sector represents one of the most seismically active region of the Italian Peninsula. Over the period 1984–2014, about 1800 earthquakes with small-to-moderate magnitude and a maximum hypocentral depth of 40 km occurred in this area. Historical catalogues reveal that the same area was affected by several strong earthquakes such as the Mw=6.1 event in April 1978 and the Mw=6.2 one in March 1786 which have caused severe damages in the surrounding localities. The main seismo-tectonic feature affecting this area is represented by a NNW–SSE trending right-lateral strike-slip fault system called "Aeolian-Tindari-Letojanni" (ATLFS) which has been interpreted as a lithospheric transfer zone extending from the Aeolian Islands to the Ionian coast of Sicily. Although the large-scale role of the ATLFS is widely accepted, several issues about its structural architecture (i.e., distribution, attitude, and slip of fault segments) and the active deformation pattern are poorly constrained, particularly in the offshore.

An integrated analysis of field structural geology with marine geophysical and seismological data, has allowed to better understand the structural fabric of the ATLFS which, in the study area, is expressed by two major NW-SE trending, en-echelon arranged fault segments. Minor NNE-SSW oriented extensional structures mainly occur in the overlap region between major faults, forming a dilatational stepover. Most faults display evidence of active deformation and appear to control the main morpho-bathymetric features. This aspect, together with diffused continental slope instability, must be considered for the revaluation of the seismic and geomorphological hazard of this sector of southern Tyrrhenian Sea.

1. Introduction

The Gulf of Patti, in the Tyrrhenian side of NE Sicily (southern Italy, Fig. 1A), is a densely populated area that hosts several villages, a number of strategic industrial sites and seabed infrastructures (e.g. electric power and telecommunications cables). As documented by seismological data, this area has been struck in historical times by a number of M ~ 6 earthquakes which caused severe damages in the whole coastal area and surrounding region (Gasparini et al., 1982, 1985; Rovida et al., 2011). A high-rate seismicity (more than 2000 events in the last 30 years) is currently registered in the Gulf of Patti and the distribution of events forms a roughly NNW-SSE trending seismic belt (Fig. 1B). The latter has been interpreted as related to the activity of a major fault system running across NE Sicily and known as the Aeolian–Tindari–Letojanni Fault System (ATLFS in Fig. 1C, see Ghisetti, 1979; Locardi and Nappi, 1979; Lanzafame and Bousquet, 1997, Palano et al., 2012). This fault system is a major tectonic boundary separating the western Calabria-Peloritani extensional belt, to the east, from the north Sicily continental collision zone to the west (see inset in Fig. 1C) (e.g. Lanzafame and Bousquet, 1997, Nicolich et al., 2000; Doglioni et al., 2001; Faccenna et al., 2004; Chiarabba et al., 2008, Goes et al., 2004; Neri et al., 2004; Pepe et al., 2000; Pepe et al., 2005; Billi et al., 2006; Palano et al., 2012; Barreca et al., 2014). Notwithstanding its geodynamic role, the northern part of the ATLFS, which runs across the Gulf of Patti, poses a significant seismic hazard in the region. Furthermore, new high resolution swath bathymetry and seismic data, just to the east of the investigated area (Rovere et al., 2014), revealed an highly unstable continental slope with the occurrence of large submarine slides, capable of mobilizing huge volumes of material. The overall regional instability is increased by the over-steepening caused by the high rate (1-2 mm/yr) uplift that affects the coastal areas, as confirmed by raised Pleistocene and Holocene paleo-shorelines (Ferranti et al., 2006; Scicchitano et al., 2011). The coupling of intense seismo-tectonic deformation and critical morpho-dynamic conditions in the offshore makes the studied region one of the most critical area of southern Italy in terms of geo-hazard.

In this paper we present the results of integrated onshore/offshore analyses focused on the characterization of active faults and stability of submarine slopes. The study is based on seismological, field structural and marine geophysical data (seismic reflection and swath bathymetry), to provide a comprehensive assessment of the potential hazards affecting the area.

2. Tectonic framework

2.1. General outlines

North-eastern Sicily is a crucial tectonic domain within the central Mediterranean orogeny (Fig. 1A), which ensues from the Neogene-Quaternary convergence between the European and African plates (Barberi et al., 1974; Patacca et al., 1990; Faccenna et al., 2001). The ~N-S trending tectonic shortening has progressively involved a laterally variable pre-orogenic domain, characterized by the Hyblean continental block (HB in Fig. 1A) and the adjacent Ionian oceanic lithosphere on the African side, which subducted beneath Europe. In north-eastern Sicily the resulting contractional belt is formed by two major superposed structural levels, the Calabro-

Peloritani terrane and the underlying Sicilian fold and thrust belt, deriving from the detachment and overthrusting of portions of the North African paleomargin.

The Calabro-Peloritani terrane (CPT in Fig. 1C) is largely exposed in north-eastern Sicily where it forms the backbone of the Peloritani mountains. The thrust stack consists of imbricate sheets of Hercynian metamorphic rocks and associated Meso-Cenozoic sedimentary covers (Ogniben, 1969). The Africa-derived units occupy the central and western portion of Sicily (SFTB in Fig. 1C) and involves thrust sheets represented by Meso–Cenozoic shallow marine to open shelf sedimentary rocks. During the convergence, the subduction and rollback of the Ionian oceanic lithosphere (Barberi et al., 1974; Malinverno and Ryan, 1986; Scarascia et al., 1994; Gueguen et al., 1998; Gvirtzman and Nur, 1999; Doglioni et al., 2001; Faccenna et al., 2001, 2004) favored lithospheric thinning and formation of the Tyrrhenian Basin in the back-arc region (Fig. 1A).

The articulated morphology of the North African paleomargin strongly influenced the migration pattern and rate of the upper plate of the subduction system (Faccenna et al., 2004). Indeed, while the orogenic belt migrated at a rate of 1–2 cm/yr during the last 5–6 Myr in northern Sicily and in the Southern Apennines (Ferranti and Oldow, 2005), north-eastern Sicily and Calabria experienced a more rapid (5–6 cm/yr) E to SE motion (Goes et.al., 2004). The relatively lower rate of migration of the orogenic belt is explained by the involvement in the collision zone of the Pelagian and Apulian continental blocks alongside the subducting and retreating Ionian oceanic slab beneath northeastern Sicily and Calabria. The different rates of motion above the continental vs. oceanic segments of the African-Adriatic margin caused the curved shape of the accretionary wedge, lithospheric wrenching at slab edges (Wortel and Spakman, 2000; Govers and Wortel., 2005; Gutscher et al., 2015; Barreca et al., 2016; Polonia et al., 2016) and strong back-arc extension in the central part of the Tyrrhenian basin (Gueguen et al., 1998; Faccenna et al., 2004; Rosenbaum and Lister, 2004).

2.2. Current kinematics and Seismotectonics

The current kinematics of north-eastern Sicily and southern Calabria is dominated by the subduction and roll-back of the Ionian slab (Faccenna et al., 2001). A ~70° Benioff-Wadati zone dipping towards the NW, beneath the southern portion of the Tyrrhenian Basin, has been documented since the early 1970s (Chiarabba et al., 2005 and reference therein) by sub-crustal earthquakes occurring down to a depth of 600 km (Frepoli et al., 1996) and by a body of high-velocity anomaly within the upper mantle (Selvaggi and Chiarabba, 1995; Faccenna et al., 2004; Neri et al., 2012). The different rate of motion between north-eastern Sicily and Calabria and the adjacent colliding domains results in wrenching at the edges of the migrating upper plate block and tearing at depth (Govers and Wortel., 2005; Gutscher et al., 2015; Barreca et al., 2016; Polonia et al., 2016), where the slab is thought to detach from adjacent continental sectors, a process known as "Subduction Transfer Edge Propagator" (STEP) faulting (Govers and Wortel., 2005). Govers and Wortel (2005) have proposed the ATLFS as the surface expression of such STEP fault zone (see also Gallais et al., 2013).

The northern part of the ATLFS consists of a swarm of NNW–SSE trending transtensional faults which extends from the Aeolian Islands to the Tyrrhenian coast of Sicily between Capo Milazzo and Capo Tindari. Dextral transtension along this belt is confirmed by GPS estimation of ~3.6 mm/yr of extension along the N126E direction (Palano et al., 2012). This regional discontinuity is regarded to have a primary role in the seismo-tectonics of this sector since it is currently marked by intense seismicity and it is spatially related to strong historical earthquakes (Fig. 1C). A major historical event associated with the activity of the ATLFS occurred on March 10, 1786 (MCS maximum intensity of IX with an estimated magnitude of 6.2, see e.g., http://emidius.mi.ingv.it/CPTI by Rovida et al. 2011) causing the destruction of several villages facing the Gulf of Patti. In addition, a Mw= 6.1 earthquake occurred in the Gulf of Patti on April 15, 1978, about 10 km west of Capo Milazzo (Gasparini et al., 1982, 1985, Rovida et al. 2011). The earthquake hit primarily the Tyrrhenian side of northeastern Sicily but was also felt over a large part of Sicily and Calabria. Significant damages and collapses occurred in about 100 sites along the Gulf of Patti coast and also in the Aeolian Islands (Barbano et al., 1979). More recently (in August 2010), the area was affected by significant seismic energy released by a M=4.8 event located 9 km SW of the Vulcano island. The seismic event was widely felt in northeastern Sicily and caused some damage on a number of masonry buildings (see Azzaro et al., 2014).

3. Field data

A detailed morpho-structural analysis has been performed in the on-land sector, where meso-faults and fractures attitudes were collected at 40 key sites (see crossed hammers in Fig. 2A and cumulative plots). Slip vectors on fault planes were obtained when steps, or more rarely, slickensides and Riedel fractures, were present.

The Gulf of Patti is a fault-controlled morphological depression (Billi et al., 2006), also extending on-land (Fig. 2A), and it is filled by Plio-Quaternary marine to continental deposits (Di Stefano and Lentini, 1995). Structural measurements highlight that tectonic deformation of the area is expressed by two main fault populations characterized by different trends and kinematics. As already evidenced by previous studies (e.g. Billi et al., 2006 among many others), the main set is represented by a NW-SE to NNW-SSE trending oblique (transtensional) faults system which develops from Capo Tindari to the village of Novara (Fig. 2A). Faults related to this system are well exposed along the ~200 m high cliff of the Tindari promontory (Fig. 2B). N150-160E trending, 65-80° dipping fault surfaces sometime exhibit a double generation of slickenlines, the younger of which plunging at ~ 60° towards N130E (Fig. 2C). To the south, between Belvedere and Novara villages, the fault array is oriented ~N150E and fault planes dip towards the NE at about 70°. Kinematic indicators on mesofaults associated to a well-developed cataclastic zone suggest extensional and strike-slip sense of motion (see stereoplot 1 in Fig. 2A).

A second faults system, NNE-SSW oriented, is developed on the eastern part of the on-land basin where it displaces middle Pleistocene deposits (Fig. 2D). It is mainly composed of steeply-dipping (70-80°), N5-25E oriented faults with pure (~90° pitch) normal sense of motion (Fig. 2E and stereoplot 2 in Fig. 2A).

As a whole, measured faults pattern depicts a triangular-shaped deformation zone with a major NNW-SSE trending bounding transtensional fault system (the Tindari-Novara segment) to the west, and a secondary NNE-SSW extensional faults array to the east. Our data are in good agreement with previous works in the area (Billi et al.,2006; De Guidi et al., 2013).

The recent and current activity of the described faults systems is not precisely constrained on-land because of the lack of Holocene sediments. However, several morphological clues, such us straight fault scarps and fresh triangular facets (see De Guidi et al., 2013), suggest a recent activity for both fault systems.

4. Offshore data

In order to map the offshore prosecution of the two fault systems detected on-land and to constrain their possible recent activity, we used a grid of very-high-resolution (sub-bottom chirp) and (Sparker) single-channel reflection seismic data acquired in the continental shelf and in the upper slope of the Gulf of Patti, coupled with swath bathymetry. The lines run mainly in the NE-SW direction and are tied by lines acquired in NW-SE direction (see Fig. A1 for location). On the whole, the reflection seismics provide an integrated image at different resolution/penetration of the uppermost Quaternary succession in the Gulf of Patti and farther to the north. A brief description of equipment used for data acquisition as well as detail on data processing is reported in Appendix.

4.1 Swath bathymetry

Bathymetric data were acquired using an EM710 Simrad (Kongsberg©inc) echo-sounder, which emits more than 400 beams included in a 140° swath coverage for each ping. This equipment allow to collect soundings until 2800 m below the sea-floor (bsf). All pings were processed by hand to remove data outliers using Fledermaus 3D software. The processed depth measurements were then organized in 20X20 m regularly spaced matrix called Digital Terrain Model (DTM, Fig. 3A). The final DTM covers about 1100 km² of seafloor surface in the -1276/-22 m b.s.l. elevation range and include a partial view of the Patti and Milazzo shelves, the slope area comprised between the northern Sicily coast and a partial view of the distal, SE sector of the Vulcano island.

Seafloor morphology data revealed the occurrence of a poorly-developed continental shelf which extends discontinuously from north of Capo Tindari to the westernmost sector of Capo Milazzo, where it appears almost completely obliterated by retrogressive erosion sparked by the presence of two canyon branches, that we named Colantoni, the easternmost, and Fanucci, the westernmost (Paolo Colantoni and Francesco Fanucci were emeritus professors of marine geology for several Italian universities and research centers. They passed away in 2015 and 2014, respectively). The overall shape of the continental shelf reflects the general trend of the coastline in map view. In detail, it dips to the north and exhibits a marked shelf break with a step of about 5 m along the -150 m isobaths. The most relevant morpho-bathymetric features in this sector are the large submarine canyons, that have deeply incised the continental slope. The most prominent undersea relief is the Patti Ridge (Fig. 3A) which extends for about 15 km from the Tyrrhenian coastline, in the SE, to the southern flank of the Vulcano island, in the NW. Particularly, the ridge is represented by an asymmetric culmination which rises up to -450 m b.s.l. and it is characterized by a gently sloping SW flank, incised by the Patti Valley, and a steeper NE slope (see bathymetric profile A-A' in Fig. 3A) which in turn represents the SW flank of the adjacent Milazzo Canyon. This last is the most impressive submarine incision occurring in the eastern part of the investigated sector (see Fig. 3A), just to the east of the Patti Ridge. It is expressed by a NW-SE trending ~15 km long and more than 300 m deep (see bathymetric profile B-B' in Fig. 3A) submarine incision. The canyon has a sinuous path and a flat thalweg that upstream bifurcates in two minor incisions, i.e. Colantoni and Fanucci branches (see above). The headwalls of the upstream incisions roughly corresponds to the coastline, thus testifying the active retrogressive erosion in the area.

The high-resolution multibeam data allowed for the mapping of several submarine slides (white polygons and/or yellow jagged lines in Fig. 3A) that are mainly distributed along the steepest flanks of the major canyons. These zones of slope instability were identified by morphological inspection of DTM, thanks to some peculiar tracts (depressed sectors that often exhibit a wide spectrum of seabed morphologies spanning from undulated to heavily rugged). These morphological characters are typical of sediment gravity flow processes (e.g., debris flows). However, evidence of deep-seated gravitational slope deformation has been found ca. 5 km off the coastline along the western flank of the Fanucci branch. Here, gravitational deformation is expressed by a wide (~ 5.5 km^2) collapsed area that underlies to a ~75-m-high amphitheater-shaped headwall (Fig. 3B). As also suggested by sub-seafloor data (see next section 4.2), this structure may be interpreted as the seafloor expression of a large slip surface involving the western flank of the Fanucci branch.

4.2 Seismic reflections profiles

4.2.1 Seismic stratigraphy

A number of depositional sequences bounded by unconformities or correlative para-conformities were recognized on Sparker profiles in the first 200-300 m below the sea-floor (bsf). The most recent sequence overlays a widespread erosional surface that ostensibly formed during the sea level stillstand of the Last Glacial Maximum (LGM, see Sparker profile SP 13 in Fig. 4), whereas a stack of depositional sequences, which are interpreted as representing the falling and low-stand systems tracts, record older Middle-Late Pleistocene eustatic cycles. In high-resolution seismic profiles the most recent sequence is expressed by well-stratified, laterally continuous, high-amplitude reflectors with typical thickness of 30-40 m. This stacking pattern is typically observed in the central Mediterranean shelf and upper slope affected by vertical tectonic movements (Chiocci et al., 1997; Ridente and Trincardi, 2002; Pepe et al., 2003, 2014; Kuhlamann et al., 2015).

4.2.2 Fault pattern

A variety of structural discontinuities is observed across the Gulf of Patti and farther to the north. Although they rarely show displacements larger than a few tens of meters, they document tectonic regimes active in the region through time. Fault systems probably associated with negative flower structures are observed at shots 2700–3700 (see Sparker profile SP 19 in Fig. 5A). They consist of NNE-SSW to ~ N-S trending (the strike was derived by correlation with adjacent lines) steeply-dipping extensional structures forming narrow (1-2 km wide) horst and graben associations (Fig. 5B). Faults exhibit small displacements (3-20 m) and some of them also deform the seafloor producing 15-20 m-high and straight scarps. Wipe-out zones are often observed near faults traces, suggesting the presence of trapped fluids that ascend through fault zones (Fig. 5B). Some faults are sealed by Upper Quaternary sediments but small-scale active faults can be clearly observed. Particularly, the Chirp profile CHP 43 (Fig. 5C) shows a SW-dipping active normal (or transtensional) fault that deforms the seafloor of about 3 m (zoom in Fig. 5D). The whole seismic dataset and the bathymetric map suggest that this fault segment is at least 5.8 km-long and it belongs to a larger NW-SE oriented fault zone developed along the Patti Valley.

Similar to those observed on-land, fault systems are arranged into two azimuthal domains, NNE-SSW and NW-SE trending. NW-SE striking structures have been detected in the central (i.e. along the Patti Valley) and NE portion (i.e. along the NE flank of the Patti Ridge) of the investigated sector and mainly consist of normal (or transtensional) faults. These tectonic features form a large fault zone, running from the SW of Capo Milazzo to the SE flank of the Vulcano Island, which roughly follows the trend of the Milazzo canyon and of the adjacent Patti Ridge (see above). The latter appears as a fault-bounded bathymetric culmination (Fig.5E). NNE-SSW trending extensional faults occur only in the central sector of the Gulf of Patti where they form horst and graben associations (Fig. 5B). Based on the integration of the new structural data coupled with data available in literature (e.g. Gabbianelli et al, 1996; Cuppari et al., 1999; Colantoni et al., 2001; Argnani et al., 2007) a simplified structural map of the Gulf of Patti and its northern prolongation (Fig. 6) is here proposed.

Seismic profiles also document widespread non-tectonic deformation (see section 4.1). Indeed, a landslide-related slip surface can be observed in the Sparker profile SP 10, which crosses the continental shelf between Capo Tindari and Capo Milazzo in SW-NE direction (Fig. 7A and inset 1 for location). The slip surface has developed on the western flank of the Fanucci branch and it dips toward the east, coherently with the downslope direction. The detachment at the base of the submarine slide displays an average inclination of about 75° and progressively becomes horizontal at depth. Upslope, it displaces the seabed and creates a ~75 m-high, circular-shaped scarp (see inset 2 in Fig. 7A and section 4.1). Elsewhere, along a NNW-SSE section across the continental slope, the Sparker profile SP 13 also provides morphological evidences of concave-upward sliding surfaces that involve and displace finely-laminated sediments that, on the whole, testify slope instability processes (i.e. slumping, Fig. 7B, see inset for location). These features occur over a 4 km-long area and include a series of undulations of the seafloor, suggesting this is an ongoing process.

5. Seismological data

The analysis of the seismic activity has been carried out referring to national and local catalogues (see: http://csi.rm.ingv.it/; http://www.ct.ingv.it/ufs/analisti/catalogolist.php) which include earthquakes hypocentral parameters. The selected events have been properly filtered to consider only well located earthquakes (i.e. maximum azimuthal gap of 240°, root mean square (rms) residuals < 0.3 sec and standard location errors (Erh and Erz) < 3.0 km and a maximum hypocentral depth of 40 km). Over the period 1984–2014, about 1800 seismic events with $1.0 \leq ML \leq 4.8$ occurred in the area between the Vulcano island and the mainland of the Gulf of Patti (Fig.

8A). In general, the map distribution of events depicts a ~ 10-15 Km wide and NW-SE trending seismic belt that, at a more detailed scale, is composed of several NE-SW oriented clusters which can be observed in the offshore just west of Capo Milazzo. On-land, where many earthquakes occurred as swarms (see Scarfì et al., 2005; Giammanco et al., 2008), preferential events distribution is more difficult to observe. The typical seismogenic depth is between 5 and 15 km while deeper (~ 40 km) seismicity was detected only SW of Capo Calavà (see sections in the right panel of Fig. 8A).

In order to obtain information on seismic faulting, fault plane solutions of earthquakes with M > 2.7 were selected from the RCMT and the "Sicily and Calabria focal mechanism database" (http://www.bo.ingv.it/RCMT; http://sismoweb.ct.ingv.it/focal/; see Pondrelli et al., 2006; Scarfì et al., 2013). As a whole, focal solutions suggest that seismogenic faulting occurs both on NW-SE and on NE-SW trends according with two preferential and contrasting mechanisms (Fig. 8B). The NW-SE nodal planes characterize events with dextral strike–slip or oblique movements mainly located SW and S of the Vulcano Island. Instead, normal mechanism on NE-SW and NNE-SSW oriented dislocation planes are dominant in the near-offshore and mainland roughly between Capo Milazzo and Capo Tindari. A GIS-derived earthquake density map (Fig. 8C) estimated from the considered time interval (1984–2014) was built up by using Kernel density algorithm (Silverman, 1986). The map displays that the highest concentration of events takes place mainly in the mainland within the Tindari-Barcellona tectonic depression (see section 3) and west of Capo Milazzo roughly along the Patti ridge (see Fig. 3A for location).

6. Kinematic reconstruction

The integration of onshore and offshore datasets provides new insights into the structural pattern and fault kinematic in an area of north-east Sicily and its offshore prolongation characterized by frequent seismicity. Field analysis revealed that tectonic deformation is mainly expressed by a major transtensional NW-SE trending tectonic boundary, the Tindari-Rocca Novara fault zone, and subordinately by an array of NNE-SSW striking minor extensional faults, in agreement with previous studies (e.g. Billi et al., 2006; De Guidi et al 2013). A first relevant observation is that the Tindari-Rocca Novara fault segment could not be followed in the offshore as expected, since it appears to terminate just off the coastline (see also Argnani et al., 2007). At the same time, another major NW-SE trending fault zone has been found to the east, between the SE flank of the Vulcano island and Capo Milazzo. This fault zone, here indicated as "Vulcano-Milazzo fault zone", is composed by a swarm of transtensional fault segments which appear to control the main morpho-bathymetric features, i.e. the Patti Ridge and the Milazzo canyon (Fig. 6). West of this tectonic alignment, an array of NNE-SSW oriented minor extensional faults occur, very similar in trend and kinematics to those observed on-land. The general pattern of these minor extensional faults, obtained by merging offshore and on-land data, depicts a lozenge-shaped tectonic depression between two major bounding fault systems, the Tindari-Rocca Novara fault zone on-land and the Vulcano-Milazzo fault zone offshore. Taking into account the right-lateral offset of the Tindari-Rocca Novara Fault (see section 3 and Fig. 2 C) and inferring a similar movement for the Vulcano-Milazzo Fault, based on the focal mechanism of the 1978 earthquake, the Gulf of Patti can be tectonically interpreted as a dilatational stepover area developed between two major right-stepping, right-lateral bounding fault systems (Fig. 9).

Even though a straightforward correlation between shallow faulting and the recorded seismicity (mainly from 5 to 15 km depth, see Fig. 8A) cannot be directly inferred because of the relatively low penetration of our seismic dataset, the indications provided by the focal plane solutions (see section 5), within their intrinsic uncertainty, appear to support this interpretation. The high-rate earthquake density also supports the proposed kinematic reconstruction since relay zones are commonly regarded as sites of earthquake rupture nucleation (foreshock and/or aftershock events, see also Barka and Kadinsky-Cade, 1988; Kadinsky-Cade and Barka, 1989).

7. Discussion and Conclusions

An integrated analysis of field, seismological and marine geophysical data in the Gulf of Patti (Tyrrhenian side of NE Sicily) allowed to provide new constraints on active faulting and on the submarine morphological setting of this hazardous area. Particularly, the correlation between field data with the offshore seismic investigation and morpho-bathymetry allowed to better understand the structural pattern and fault kinematics of this sector of the NE-Sicily continental margin. The major structural discontinuities recognized in the area consist of two right-lateral, NW-SE trending transtensional fault zones, namely the Tindari-Rocca Novara, on-land, and the Vulcano-Milazzo, offshore. In addition, NNE-SSW to and N-S striking extensional faults occur mainly along the sector where the two larger fault zones overlap. Accordingly, the central portion of the Gulf of Patti and its southward prolongation (i.e. the Tindari-Barcellona tectonic depression, see Billi et al., 2006) is interpreted as releasing stepover (Fig. 9) resulting from a local stress perturbation between two right-stepping, right lateral en-echelon arranged fault systems. We exclude a releasing bend configuration since continuity between master faults have not been clearly observed in the seismic profiles. Current and historical seismicity suggests that moderate earthquakes ($1<M<4.6$) mainly occur within the releasing zone whereas major events (e.g. the 1786, Mw=6.2; 1978, Mw=6,1, Rovida et al., 2011) are roughly aligned with the larger bounding faults (see also Barka and Kadinsky-Cade, 1988; Kadinsky-Cade and Barka, 1989).

Although it was not possible to identify first order crustal faults in the Gulf of Patti due to the shallow penetration of our geophysical dataset, and hence the possible sources of the largest earthquakes of the area went undetected, most of the faults mapped offshore show evidence of active deformation as they offset Holocene deposits and locally also deform the seafloor. These faults may be hence interpreted as secondary shallow structures linked to the deep, unidentified seismogenic faults. The interpretation of morpho-bathymetric data has shown that the Gulf of Patti offshore is characterized by a complex system of deeply-incised canyons and channels, extending from the shelf margins down to deeper sectors. The over-steepening caused by the uplift of the Capo Milazzo area induce both the emplacement of canyons and a diffuse slope instability in the Gulf of Patti. The spatial distribution of both shallow and deep-seated slides reveals that slope instability is mainly concentrated along the steep, fault-controlled, flanks of the major incisions, thus allowing to hypothesize that the canyons should be still active morphological features. The result of retrogressive erosional processes at the canyon head, which is documented by the intense headward erosion, suggests a possible progressive approach and a potential erosional risk for the present-day coastline (e.g. Colantoni branch), that may induce severe damage to the buildings and artifacts in the next future.

In conclusion, our data indicate that the Gulf of Patti is a highly-critical region of the south-eastern Tyrrhenian Sea, since it is currently affected by intense seismicity and submarine gravity flows. Taking into account that the area hosts several villages as well as relevant infrastructures (industrial sites, submarine gas pipelines, electric power and telecommunications cables) it represents a vulnerable district in terms of geo-hazard.

Appendix

A grid of very high-resolution seismic reflection profiles was recorded along the continental shelf and the slope of the Gulf of Patti, on board the R/V Urania, during January 2014. The lines run mainly in the NE-SW direction and are tied by lines acquired in NW-SE direction (see Fig. A1 for location). The acoustic source used during seismic prospecting was a 1 kJ Sparker power supply with a multi-tips Sparker array, which avoids ringing and has a base frequency of about 800 Hz, fired at a time interval of 2 s. Data was recorded using a single-channel streamer with an active section of 2.8 m, containing seven high-resolution hydrophones, for 1.5 s two way time (t.w.t.) at a 10 kHz (0.1 ms) sampling rate. Positioning was ensured by a Differential Global Positioning System (DGPS).

Data processing include: spherical divergence correction, de-ghosting, band-pass (300-2000 Hz) filter, swell filter, trace mixing, time variant gain, and mute of water column. Signal penetration was found to exceed 500 ms t.w.t. The vertical resolution is ~1 m near the seafloor.

A set of ultra-high resolution reflection seismic data was also recorded by using the Chirp II (Benthos©inc) Chirp sub-bottom profiler, operating with 16 transducer in a wide frequency band (2–7 kHz) with a long pulse (20–30 ms). The lines have been acquired along the same directions of the very high-resolution seismic reflection profiles.

Data processing include: a) true amplitude recovery using a T^2 spherical divergence correction; b) time variant gain to boost amplitudes of deeper arrivals and c) mutes to eliminate the signal noise on the water column. Signal penetration was found to exceed 90 ms two-way time (t.w.t.). Vertical resolution is up to 5 cm near the seafloor.

All seismic lines were depth-converted. An average value of 1515 m/s for the sound velocity was derived by the sound velocity profiles recorded during the multibeam data acquisition. Since information was available on velocities of seismic units, we have adopted an average value of 1750 m/s for the sedimentary deposits. The adopted seismic velocities were based on sonic log data for coeval sedimentary units drilled offshore Southern and Western Sicily (Pepe et al., 2010). However, the inherent uncertainty of our approach does not influence the general frame of the structural interpretation presented in this study.

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References

Argnani, A., E. Serpelloni, and C. Bonazzi (2007), Pattern of deformation around the central Aeolian Islands: Evidence from multichannel seismics and GPS data, Terra Nova, 19, 317–323, doi:10.1111/j.1365-3121. 2007.00753.x.

Azzaro R., D'Amico S., Mostaccio A., Scarfì L., (2002). Terremoti con effetti macrosismici in Sicilia orientale nel periodo Gennaio 1999 - Dicembre 2001. QUADERNI DI GEOFISICA, 27.

Azzaro R., D'Amico S., Mostaccio A., Scarfì L., Tuve' T., Manni M., (2014). Terremoti con effetti macrosismici in Sicilia orientale nel periodo Gennaio 2009 - Dicembre 2013. QUADERNI DI GEOFISICA, 120.

Barbano M.S., Bottari A., Carveni P., Cosentino M., Federico B., Fonte G., Lo Giudice E., Lombardo G. e Patané G. (1979). Macroseismic study of the gulf of Patti earthquake in the geostructural frame of North-Eastern Sicily. Bollettino della Società Geologica Italiana, vol. 98, pp.155-174.

Barka, A. A. and Kadinsky-Cade, K. (1988). Strike-slip fault geometry in Turkey and its influence on earthquake activity. Tectonics. 7, 663-684.

Barreca, G., V. Bruno, F. Cultrera, M. Mattia, C. Monaco and L. Scarfì (2014). New insights in the geodynamics of the Lipari-Vulcano area (Aeolian Archipelago, southern Italy) from geological, geodetic and seismological data, Journal of Geodynamics, 82, 150-167; http://dx.doi.org/10.1016/j.jog.2014.07.003.

Barreca, G., L. Scarfì, F. Cannavò, I. Koulakov and C. Monaco (2016). New structural and seismological evidence and interpretation of a lithospheric-scale shear zone at the southern edge of the Ionian subduction system (central-eastern Sicily, Italy). Tectonics, 35, doi:10.1002/2015TC004057.

Billi A., Barberi G., Faccenna C., Neri G., Pepe F. & Sulli F. (2006) - Tectonics and seismicity of the Tindari Fault System, southern Italy: Crustal deformations at the transition between ongoing contractional and extensional domains located above the edge of a subducting slab. Tectonics, 25, TC2006, doi:10.1029/2004TC001763.

Chiarabba C., De Gori P., Speranza F. (2008) - The southern Tyrrhenian subduction zone. Deep geometry, magmatism and Plio-Pleistocene evolution. Earth Planet. Sci. Lett., 268, 408-423, doi:10.1016/j.epsl.2008.01.036.

Chiarabba, C., Jovane, L., Di Stefano, R.,(2005). A new view of Italian seismicity using 20 years of instrumental recordings. Tectonophysics 395 (34), 251–268.

Chiocci, F.L., Ercilla, G., Torres, J., (1997). Stratal architecture of western Mediterranenan margins as the result of the stacking of Quaternary lowstand deposits below 'glacio-eustatic fluctuation base-level'. Sedimentary Geology 112, 195-217.

Colantoni P., Cuppari A., Gabbianelli G., Morelli D., (2001). The Milazzo Canyon and its mid-slop depositional wedge on the Northern Sicilian Continental margin (Tyrrhenian Sea). GeoActa, v. 2001-2002, pp 15-26. Bologna.

Cuppari, A., Colantoni, P., Gabbianelli, G., Morelli, D., Alparone, R., (1999). Assetto ed evoluzione morfo-strutturale dell'area marina compresa tra il margine della Sicilia settentrionale e le Isole Eolie (Golfo di Patti). Atti AIOL XIII,137–149.

De Guidi G., Lanzafame G., Palano M., Puglisi G., Scaltrito A., Scarfì L. (2013) - Multidisciplinary study of the Tindari Fault (Sicily, Italy) separating ongoing contractional and extensional compartments along the active Africa–Eurasia convergent boundary. Tectonophysics, in print.

Di Stefano, A., and R. Lentini (1995), Ricostruzione stratigrafica e significato paleotettonico dei depositi plio-pleistocenici del margine tirrenico tra Villafranca Tirrena e Faro (Sicilia nord-orientale), Studi Geol. Camerti, 1995(2), 219 – 237.

Doglioni C., Innocenti F. & Mariotti G. (2001) - Why Mt Etna? Terra Nova, 13: 25-31.

Faccenna, C., Becker T.W., Lucente F.P., Jolivet L., Rossetti F. (2001) - History of subduction and back-arc extension in the central Mediterranean. Geophys. J. Int., 145, 809–820, doi:10.1046/j.0956-540x.2001.01435.x.

Faccenna C., Piromallo C., Crespo-Blanc A., Jolivet L., Rossetti F. (2004) - Lateral slab deformation and the origin of western Mediterranean arcs. Tectonics, 23, TC1012, doi: 10.1029/2002TC001488.

Ferranti, L., and J. S. Oldow (2005), Latest Miocene to Quaternary horizontal and vertical displacement rates during simultaneous contraction and extension in the Southern Apennines orogen, Italy, Terra Nova, 17, 209–214.

Ferranti L., Antonioli F., Mauz B., Amorosi A., Dai Pra G., Mastronuzzi G., Monaco C., Orru' P., Pappalardo M., Radtke U., Renda P., Romano P., Sanso' P., & Verrubbi V. (2006) - The last glacial sea-level high stand along the coast of Italy. Tectonic implication. Contribution from the 32nd IGC, Editorial Quat. Internat.145-146, 30-54.

Frepoli A., Selvaggi G., Chiarabba C., Amato A. (1996) - State of stress in the Southern Tyrrhenian Subduction Zone from fault-plane solutions. Geophys. J. Int., 125, 879-891, doi: 10.1111/j.1365-246X.1996.tb06031.x.

Gabbianelli G., Tramontana M, Colantoni P. Fanucci F., (1996) - Lineamenti morfostrutturali e sismostratigrafici del Golfo di Patti (margine nord siciliano). In: F.M. Faranda & P. Povero (Eds.): "Data Report". Eocumm95, Conisma, pp. 443-453.

Gallais, F.,Graindorge, D.,Gutscher, M.A., Klaeschen,D., (2013). Propagation of a lithospheric tear fault (STEP) through the western boundary of the Calabrian accretionary wedge offshore eastern Sicily (Southern Italy). Tectonophysics 602, 141–152. http://dx.doi.org/10.1016/j.tecto.2012.12.026.

Gasparini, C., Iannacone, G., Scandone, P., Scarpa, R., (1982). Seismotectonics of the Calabrian Arc. Tectonophysics 82, 267–286.

Gasparini, C., Iannaccone, G., Scarpa, R., (1985). Fault-plane solutions and seismicity of the Italian peninsula. Tectonophysics 117, 59–78.

Ghisetti F. (1979) - Evoluzione neotettonica dei principali sistemi di faglie della Calabria centrale. Bollettino Società Geologica Italiana, 98, 387-430.

Giammanco, S., Palano, M., Scaltrito, A., Scarfì, L., Sortino, F., (2008). Possible role of fluid overpressure in the generation of earthquake swarms in active tectonic areas: the case of the Peloritani Mts. (Sicily, Italy). Journal of Volcanology and Geothermal Research 178, 795–806. http://dx.doi.org/10.1016/j.jvolgeores.2008.09.005.

Goes S., Giardini D. Jenny S., Hollenstein C., Kahle H.G. & Geiger, A. (2004) - A recent tectonic reorganization in the south-central Mediterranean. Earth Planet. Sci. Lett., 226, 335-345.

Govers, R., Wortel, M.J.R., (2005). Lithosphere tearing at STEP faults: response to edges of subduction zones. Earth Planet. Sci. Lett. 236, 505–523.

Guegen, E., Doglioni, C., Fernandez, M., (1998). On the post 25 Ma geodynamic evolution of the western Mediterranean. Tectonophysics 298, 259–269.

Gutscher, M.-A., S. Dominguez, B. Mercier de Lepinay, L. Pinheiro, N. Babonneau, A. Cattaneo, Y. Le Faou, G. Barreca, A. Micallef, and M. Rovere (2015), Tectonic expression of an active slab-tear from high-resolution seismic and bathymetric data offshore Sicily (Ionian Sea), Tectonics, 34, 39–54, doi:10.1002/2015TC003898.

Gvirtzman, Z., Nur, A., (1999). Formation of Mount Etna as a consequence of slabrollback. Nature 401, 782–785.

Kadinsky-Cade, K., and A. Aykut Barka, (1989). Effects of restraining bends on the rupture of strike-slip earthquakes, U.S. Geol. Surv. Open-File Rep. 89-315, 181-192.

Kuhlmann, J., Asioli, A., Trincardi, F., Klügel, A., Huhn, K., (2015). Sedimentary response to Milankovitch-type climatic oscillations and formation of sediment undulations: evidence from a shallow-shelf setting at Gela Basin on the Sicilian continental margin. Quaternary Science Reviews 108, 76-94

Lanzafame G. & Bousquet J.C. (1997) - The Maltese escarpment and its extension from Mt. Etna to the Aeolian Islands (Sicily): importance and evolution of a lithosphere discontinuity. Acta Vulcanologica, 9: 113-120.

Locardi, E., Nappi, G., (1979). Tettonica e vulcanismo recente nell'isola di Lipari (implicazioni geodinamiche). Boll. Soc. Geol. It. 98, 447–456

Malinverno, A., Ryan W. B. F., (1986). Extension in the Tyrrhenian Sea and shortening in the Apennines as result of arc migration driven by sinking of the lithosphere, Tectonics, 5(2), 227–245, doi:10.1029/TC005i002p00227.

Neri, G., A. M. Marotta, B. Orecchio, D. Presti, C. Totaro, R. Barzaghi, Borghi A. (2012), How lithospheric subduction changes along the Calabrian Arc in southern Italy: Geophysical evidences, Int. J. Earth Sci., doi:10.1007/s00531-012-0762-7.

Neri, G., Barberi, G., Oliva, G., Orecchio, B., (2004). Tectonic stress and seismogenic faulting in the area of the 1908 Messina earthquake, south Italy. Geophys. Res. Lett. 31, 10 (doi: 10.1029/2004GL019742).

Nicolich R., Laigle M., Hirn A., Cernobori L., & Gallart J. (2000) - Crustal structure of the Ionian margin of Sicily: Etna volcano in the frame of regional evolution. Tectonophysics, 329, 121 – 139.

Ogniben L. (1969) - Schema introduttivo alla geologia del Confine calabro-lucano. Mem. Soc. Geol. It., 8: 453-763.

Palano M., Ferranti L., Monaco C., Mattia M., Aloisi M., Bruno V., Cannavò F., Siligato G. (2012) – GPS velocity and strain fields in Sicily and southern Calabria, Italy: Updated geodetic constraints on tectonic block interaction in the central Mediterranean. Journal of Geophysical Research, vol. 117, b07401, doi:10.1029/2012jb009254.

Patacca E., Sartori R., Scandone P. (1990) - Tyrrhenian basin and Apenninic arcs: Kinematic relations since late Tortonian times. Mem. Soc. Geol. Ital., 45, 425-451.

Pepe, F., G. Bertotti, F. Cella, and E. Marsella (2000), Rifted margin formation in the south Tyrrhenian Sea: High resolution seismic profile across the north Sicily passive continental margin, Tectonics, 19, 241 – 257.

Pepe, F., A. Sulli, M. Agate, D. Di Maio, A. Kok, C. Lo Iacono, and R. Catalano (2003). Plio-Pleistocene geological evolution of the northern Sicily continental margin (southern Tyrrhenian Sea): New insights from high-resolution, multi-electrode sparker profiles, Geo Mar. Lett., 23 (1), 53–63.

Pepe, F., A. Sulli, G. Bertotti, and R. Catalano (2005), Structural highs formation and their relationship to sedimentary basins in the north Sicily continental margin (southern Tyrrhenian Sea): Implication for the Drepano Thrust Front, Tectonophysics, 409, 1–18.

Pepe, F., Bertotti, G., Ferranti, L., Sacchi, M., Collura, A.M., Passaro, S., Sulli, A., (2014). Pattern and rate of post-20 ka vertical tectonic motion around the Capo Vaticano Promontory (W Calabria, Italy) based on offshore geomorphological indicators, Quat. Int., 30 (1), e14.

Polonia A., Torelli L., Artoni A., Carlini M., Faccenna C., Ferranti L., Gasperini L., Govers R., Klaeschen D., Monaco C., Neri G., Nijholt N., Orecchio B., Wortel R. M. (2016) – The Ionian and Alfeo-Etna fault zones: New segments of an evolving plate boundary in the central Mediterranean Sea? Tectonophysics, Doi: 10.1016/j.tecto.2016.03.016.

Pondrelli, S., S. Salimbeni, G. Ekström, A. Morelli, P. Gasperini, and G. Vannucci (2006), The Italian CMT dataset from 1977 to the present, Phys. Earth Planet. Inter., http://dx.doi.org/10.1016/j.pepi.2006.07.008, 159/3-4, 286–303.

Ridente, D., Trincardi, F., (2002). Eustatic and tectonic control on deposition and lateral variability of Quaternary regressive sequences in the Adriatic basin. Mar. Geol. 184 (3e4), 273-293.

Rosenbaum, G., Lister, G.S., (2004). Neogene and Quaternary rollback evolution of the Tyrrhenian Sea, the Apennines, and the Sicilian Maghrebides. Tectonics 23, TC1013. doi:10.1029/2003TC001518.

Rovere M., Gamberi F., Mercorella A., Leidi E., (2014). Geomorphometry of a submarine mass-transport complex and relationships with active faults in a rapidly uplifting margin (Gioia Basin, NE Sicily margin). Marine Geology, 356, 31–43.

Rovida, A., Camassi, R., Gasperini, P., Stucchi, M., (2011): CPTI11, the 2011 version of the Parametric Catalogue of Italian Earthquakes. INGV, Milano, Bologna, http://emidius.mi.ingv.it/CPTI, DOI:10.6092/INGV. IT-CPTI11.

Scarascia, S., A. Lozej, and R. Cassinis (1994), Crustal structures of the Ligurian, Tyrrhenian and Ionian Sea and adjacent onshore areas interpreted from wide-angle seismic profile, Boll. Geofis. Teor. Appl., 36, 5 – 19.

Scarfì L., Barberi G., Musumeci C., Patanè D., (2014). Crustal structure and fault kinematics between the Aeolian Arc and the Ionian Sea offshore as revealed by earthquake tomography and focal mechanisms stress inversion, Rendiconti Online della Società Geologica Italiana, 31, doi: 10.3301/ROL.2014.140.

Scarfì, L., A. Messina, and C. Cassisi (2013), Sicily and Southern Calabria focal mechanism database: a valuable tool for the local and regional stress field determination, Ann. Geophys., 56, 1, D0109, doi:10.4401/ag-6109.

Scarfì, L., Langer, H., Scaltrito, A., (2005). Relocation of microearthquake swarms in the Peloritani mountains—implications on the interpretation of seismotectonic patterns in NE Sicily, Italy. Geophysical Journal International 163, 225–237. http://dx.doi.org/10.1111/j.1365-246X.2005.02720.x.

Scicchitano G., Spampinato C., Ferranti L., Antonioli F., Monaco C., Capano M., Lubritto C. (2011) – Uplifted Holocene shorelines at Capo Milazzo (NE Sicily, Italy): evidence of coseismic and steady-state deformation. Quaternary International, 232, 201-213, doi: 10.1016/j-quaint.2010.06.028.

Selvaggi, G., and C. Chiarabba (1995), Seismicity and P-wave velocity image of the Southern Tyrrhenian subduction zone, Geophys. J. Int., 121, 818– 826.

Silverman, B.W., 1986. Density Estimation for Statistics and Data Analysis. Chapman and Hall, New York.

Wortel M.J.R. & Spakman W. (2000) - Subduction and slab detachment in the Mediterranean-Carpathian region. Science, 290, 1910-1917

Figure captions

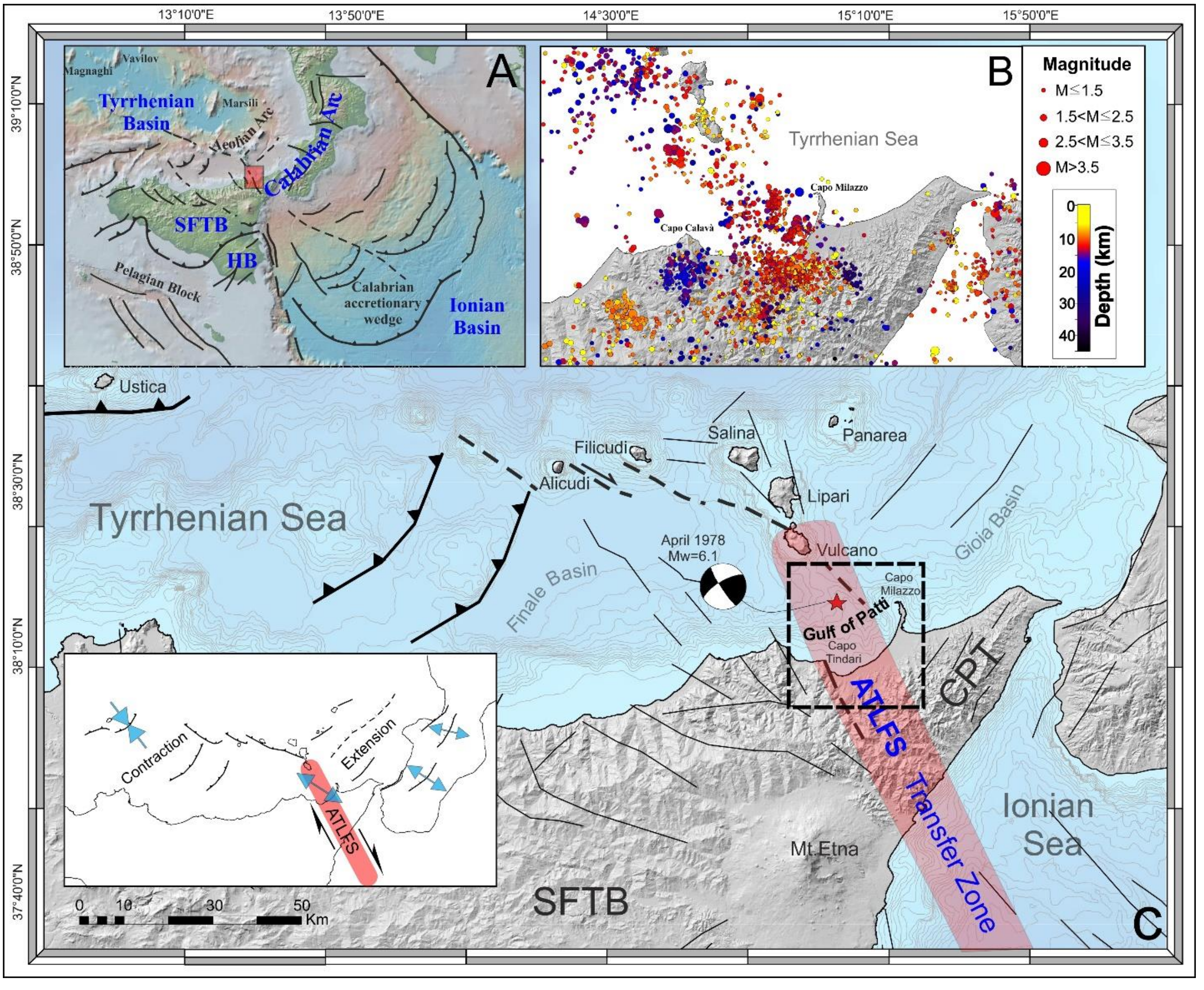
Fig. 1 - A) Tectonic sketch map of the Calabrian Arc area and relative off-shore; the red rectangle represents the investigated area (SFTB, Sicilian fold and thrust belt; HB, Hyblean block). B) Map view of the earthquakes with a maximum hypocentral depth of 40 km occurred in the study area from 1984 to 2014. C) Simplified structural map of the SE sector of the Tyrrhenian Basin (CPT, Calabro-Peloritani terrane). The NNW–SSE striking Aeolian–Tindari–Letojanni Fault System (ATLFS) represents an incipient transfer zone (Billi et al., 2006; Barreca et al., 2014) separating a contractional domain, to the west, from an extensional one to the north-east (see inset in Fig 1 C). Focal mechanism of April 15, 1978 earthquake (Mw=6.1, see Gasparini et al., 1982) is also reported.

Fig. 2 - A) Structural map of the onshore sector of the Aeolian-Tindari-Letojanni Fault System and most representative stereoplots (red, fault plane and slip vectors; dashed black lines indicate fractures). The inset shows the cumulative plots of the detected faults (fault planes and slip vectors, at the top) and fractures (rose diagram, at the bottom). B) NW-SE trending oblique (transtensional) fault segment singled out along the Capo Tindari cliff. C) NW-SE trending striated fault plane with slickenlines plunging at ~ 60° towards N130E. D) NNE-SSW trending extensional fault segment detected within the Tindari-Barcellona tectonic depression where it displaces middle Pleistocene deposits. This fault set is mainly composed by steeply-dipping structures with pure (~90° pitch) normal sense of motion (E).

Fig. 3 – A) Morpho-bathymetric map of the Gulf of Patti as derived by the analysis of a 20x20 m resolution DTM (in the background). B) 3D view of a deep-seated gravitational deformation affecting the Fanucci branch of the Milazzo canyon.

Fig. 4 – Sparker profile SP 13 (see inset for location) showing the most recent sequence which overlays a widespread erosional surface that ostensibly formed during the sea level stillstand of the Last Glacial Maximum (LGM). Vertical exaggeration = 4:1 (4X).

Fig. 5 – Interpretation of the depth converted single channel seismic profiles acquired in the Gulf of Patti (see inset in the bottom right corner for location). A) Sparker profile SP 19 showing horst and graben structures (B) locally involving Holocene deposits. Bounding faults sometimes produce straight, 15-20 m high fault scarps. C) Chirp profile CHP 43 showing a NNW-SSE oriented extensional (or transtensional) fault segment (D) dislocating Holocene deposits of about 3 m. E)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13°50'0"E
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15°10'0"E
15°50'0"E
39°10'0"N
38°50'0"N
38°30'0"N
38°10'0"N
37°40'0"N
A
Tyrrhenian Basin
Aeolian Arc
Calabrian Arc
SFTB
HB
Pelagian Block
Calabrian accretionary wedge
Ionian Basin
B
Magnitude
M≤1.5
1.5<M≤2.5
2.5<M≤3.5
M>3.5
Depth (km)
Tyrrhenian Sea
Capo Milazzo
Capo Calavà
Ustica
Filicudi
Salina
Panarea
Alicudi
Lipari
Vulcano
Tyrrhenian Sea
April 1978
Mw=6.1
Finale Basin
Gioia Basin
Capo Milazzo
Gulf of Patti
Capo Tindari
CPT
ATLFS
Transfer Zone
Ionian Sea
Mt.Etna
SFTB
Contraction
Extension
ATLFS
Km
C

Figure 1

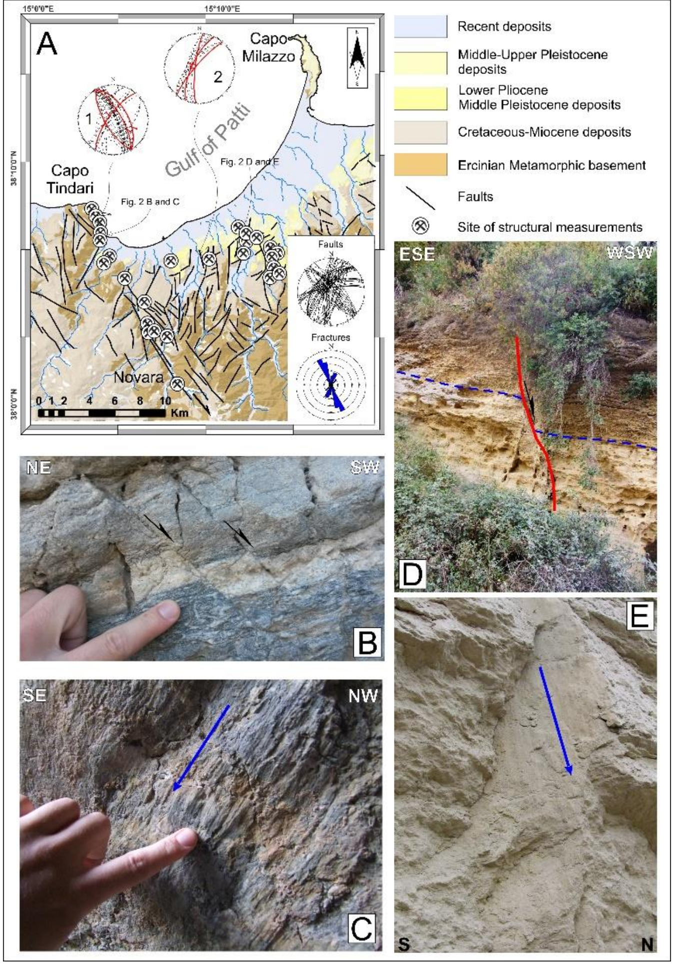


Figure 2

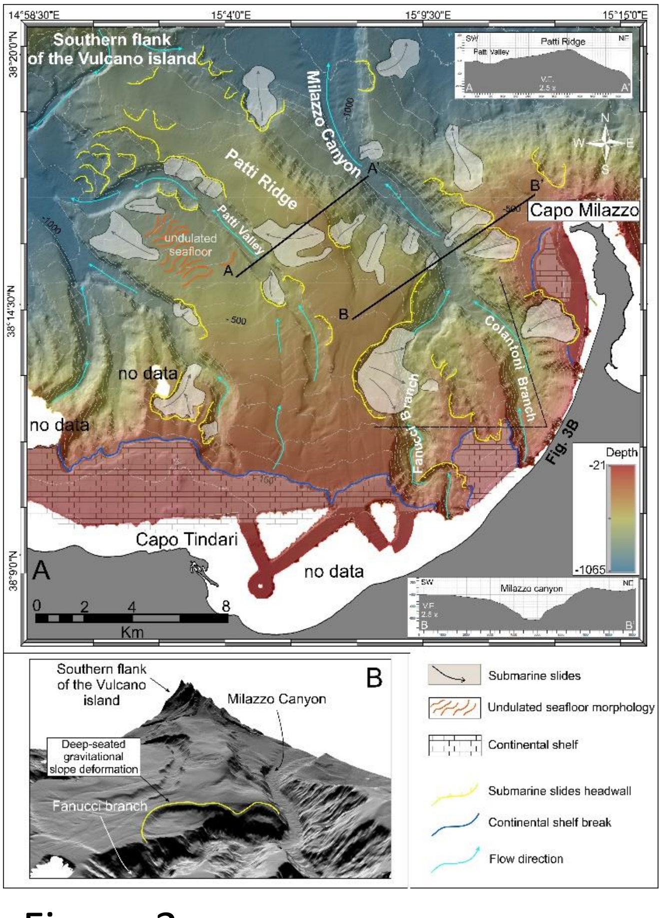
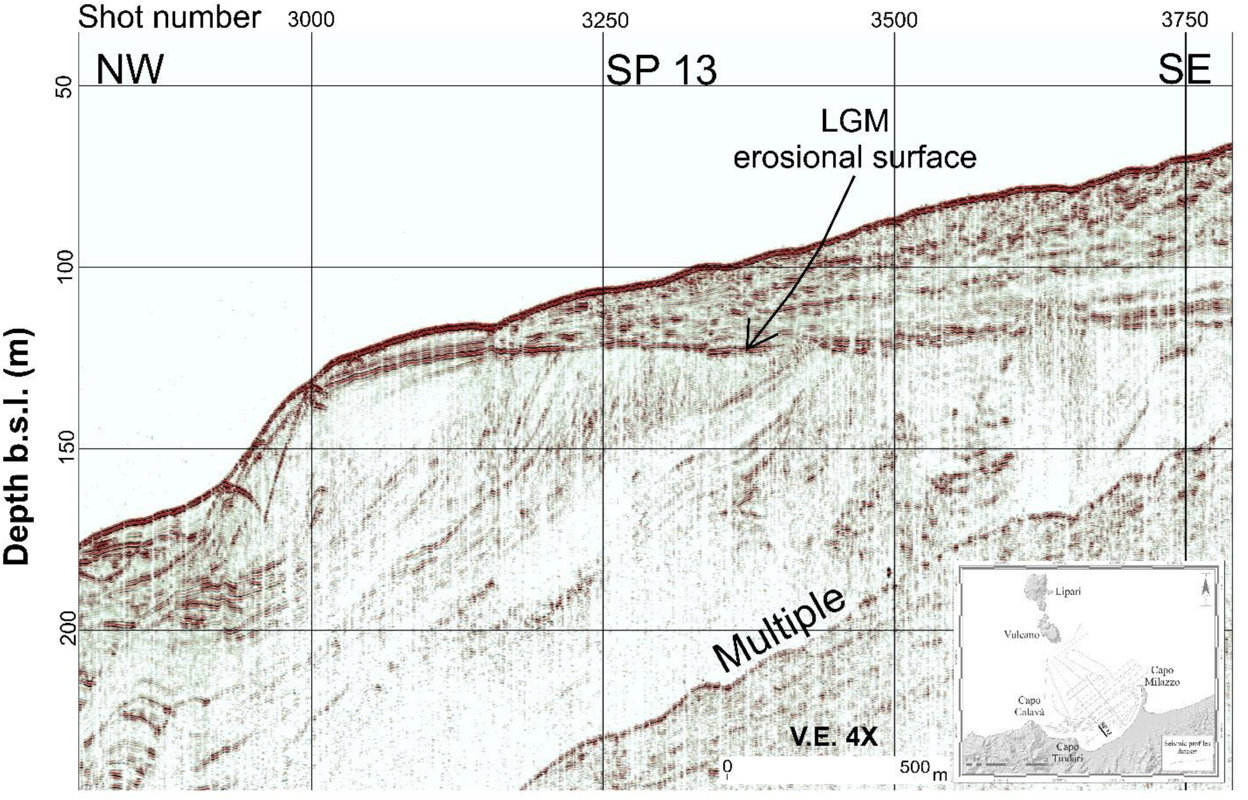


Figure 3



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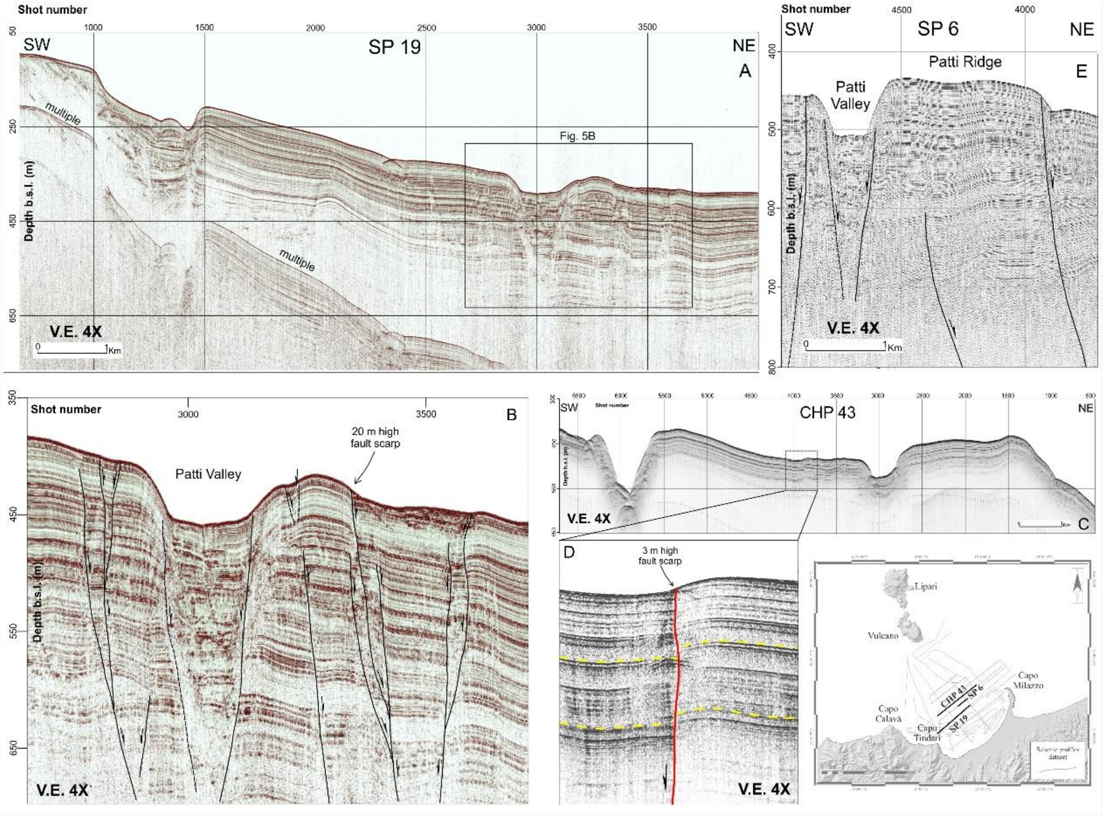


Figure 5

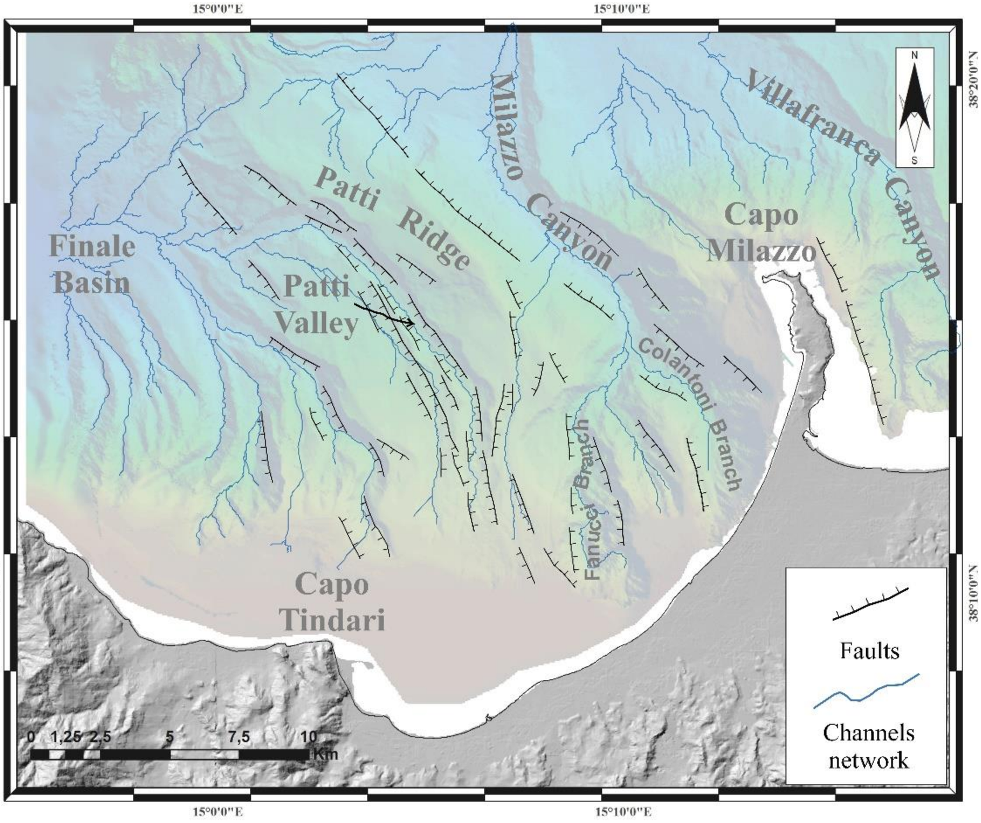


Figure 6

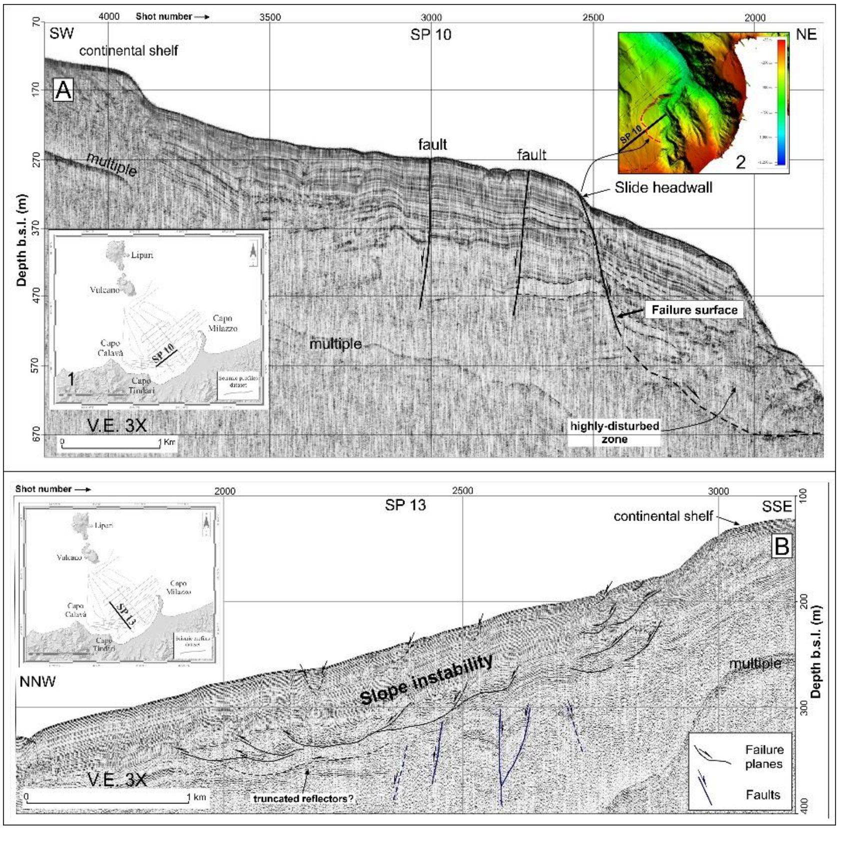


Figure 7

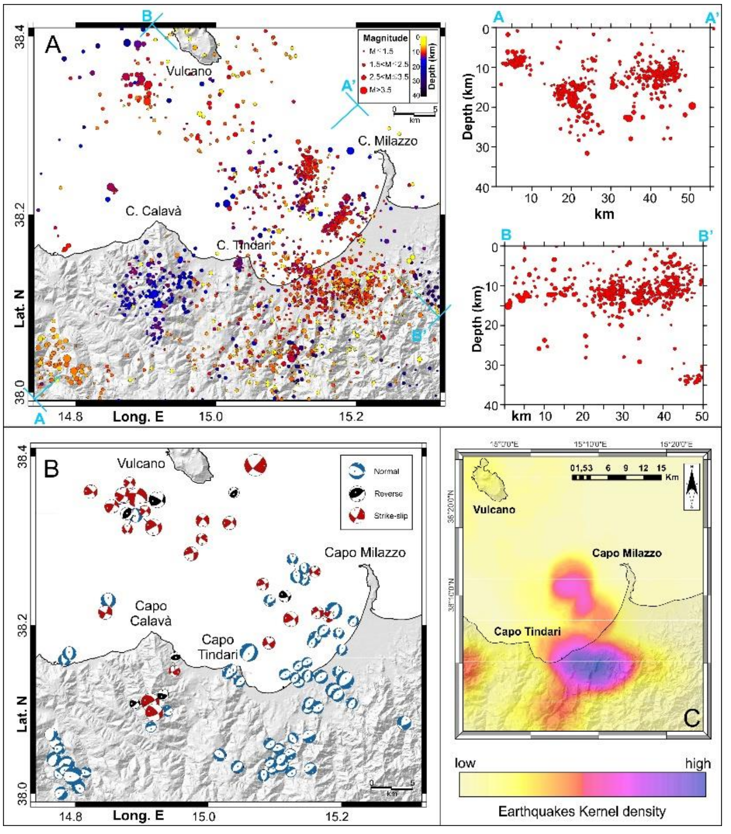


Figure 8

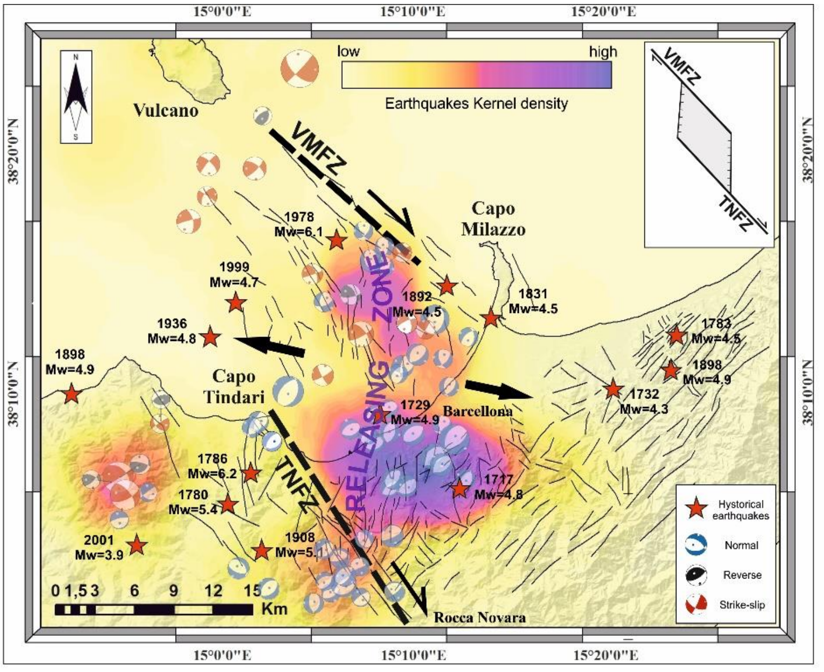
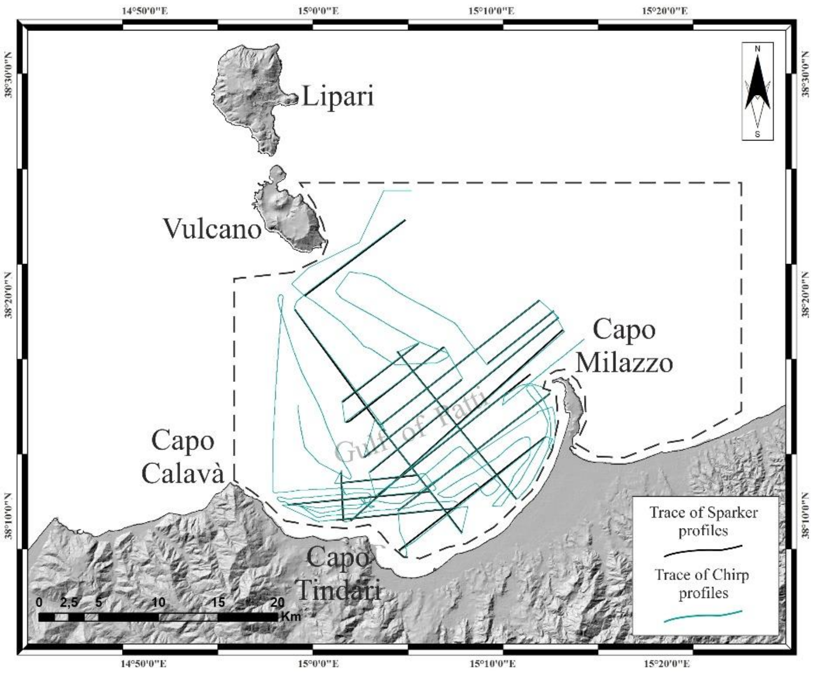


Figure 9



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N
S
Lipari
Vulcano
Capo
Milazzo
Gulf of Patti
Capo
Calavà
Capo
Tindari
Trace of Sparker
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Trace of Chirp
profiles
0 2,5 5 10 15 20
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Figure A1

Sparker profile SP 6 showing the extensional (or transtensional) fault segments affecting the Patti Ridge. Vertical exaggeration = 4:1 (4X).   .

Fig. 6 - Structural map of the Gulf of Patti obtained by picking fault segments on the whole seismic dataset. Detected faults mainly consist of extensional (or transtensional) structures arranged into two azimuthal (NW-SE and ~N-S trending) domains. Faults associated with a clear gravitational deformation have not been reported in the structural map.

Fig. 7 - A) Sparker profile SP 10 (see inset 1 for location) showing two extensional (or transtensional) fault segments, in the western part of the section, and a deep-seated gravitational slope deformation in the eastern one (see shaded relief in inset 2 for slide headwall location). B) Sparker profile SP13 (see inset for location) showing gravitational deformation (slumping) along the continental slope. Vertical exaggeration = 3:1 (3X) for both profiles.

Fig. 8 - A) Earthquakes locations (1984-2014 period) in map and vertical sections. Cross-sections (AA', BB') marked in map, incorporate all relocated events within 5 km of the cross-section lines. B) Computed fault plane solutions (lower-hemisphere projection). C) Gis-derived earthquakes density map estimated by using Kernel density algorithm (see text for further detail).

Fig. 9 – Kinematic reconstruction proposed for the Gulf of Patti and its onshore sector (earthquakes density map in the background). The main NW-SE trending right-lateral transtensional fault zones (TNFZ and VMFZ) overlap in right-stepping geometry likely forming a releasing zone in the relay area, where minor ~ N-S oriented extensional faults occur. Note that most of seismicity occurring in the investigated area appear confined within the releasing zone (see text for further detail). Location of computed focal mechanisms and historical earthquakes (red stars, from Rovida et al., 2011) is also reported.

Fig. A1. Grid of single-channel seismic profiles acquired in the Gulf of Patti. Green and black lines indicate Chirp and Sparker profiles, respectively. Dashed rectangle indicates the area of multibeam survey.