**Fault pattern and seismotectonic potential at the south-western edge of the Ionian Subduction system (southern Italy): new field and geophysical constraints.**

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**Abstract**

The south-western edge of the Calabrian Arc in southern Italy has been investigated throughout a joint analysis of field, marine and geophysical data which provided constraints on the fault pattern and on the seismotectonic potential. The study was focused on a poorly known sector of a larger belt of seismically active faults slicing across the NE corner of Sicily, the so-called Tindari Fault System. Our data pointed out that the investigated area, including the mainland and the Ionian offshore, is deformed by oblique faulting with a general NW-SE tectonic trend. Earthquake distribution and seismic profiles pointed out active deformation in the offshore while the mainland is characterized by the occurrence of a NW-SE oriented, more than 20 km-long, structural belt. However, scarce seismicity has been recorded in the last 30 years alongside this tectonic structure, accounting for a possible silent segment of this larger fault system. Tomographic images revealed that the Moho discontinuity is deformed by a NE-dipping lithospheric tectonic structure which has been here retained the main mode of deformation and responsible for coseismic displacement in the area.  As a whole, field and geophysical data agree with a general NW-SE trend segmented pattern of recent/active faults which have the potentiality of generating magnitude 6.5-7 earthquakes.

Keywords: Subduction system, Calabrian Arc, Slab edge tear, active faulting, seismic profiling, earthquakes

1. **Introduction**

The south-western edge of the Ionian subduction system (southern Italy), in the central Mediterranean (Fig. 1) is currently deformed by a major NNW-SSE trending, more than 100 km-long, belt of tectonic structure (known as Tindari Fault System, TFS; Billi et al., 2006) that extends from the central sector of the Aeolian Arc (Lipari-Vulcano complex) to the Sicilian mainland across the Peloritani mountains, as far as the Ionian offshore (Fig. 1). The northernmost part of this larger tectonic belt has been already widely studied in the past decades by many workers (Lanzafame and Bousquet, 1997; Neri et al., 2005; Billi et al., 2006; Mattia et al., 2009; Palano et al, 2012; Barreca et al*.*, 2014; Scarfì et al*.*, 2016; Cultrera et al*.*, 2017). These studies, performed both on field and offshore using different approaches, strongly contributed to constrain the structural style and the current kinematic of this sector. Although several interpretations on its larger geodynamic significance, possible extension and prosecution in the Ionian Sea have been proposed (e.g. the Ionian Fault in Polonia et al., 2011,2016), most of the authors (see Scarfì et al., 2018 and reference therein) agree on the lithospheric nature of the structure accommodating tearing processes at the SW edge of the Ionian subduction system.

Pattern of seismicity (Barreca et al., 2014; Scarfì et al., 2016) and seismic profiling in the Tyrrhenian offshore (Gulf of Patti, see Cultrera et al., 2016), highlight the structural architecture and the active deformation which consists of a NNW-SSE trending, right-transtensional deformation zone with associated én-echelon-arranged minor extensional faults. This tectonic configuration results clearer in the northern tip of the TFS where tectonic pattern and kinematics are well-constrained by earthquakes clustering and surface faulting evidences (Lanzafame and Bousquet, 1997; Billi et al., 2006; De Guidi et al*.*, 2013a; Barreca et al., 2014; Cultrera et al., 2016,2017). On the contrary, despite faulting can be geologically detected on field as far as the Ionian coast, the connection between northern and southern branches of the TFS remains poorly studied and its seismic potential not fully understood. Connection between the northern branch and a fault system located in the Ionian offshore and interpreted as a STEP (the Ionian Fault, Polonia et al., 2011) was tentatively attempted by Polonia et al. (2016), even if, according to the authors, continuation northwards of the Ionian Fault (see Fig. 1 for location) doesn’t match with well-known active faults belt occurring on land (e.g. the Tindari-Rocca Novara fault segment, see De Guidi et al., 2013). Conversely, tomographic images and accurate hypocentres locations (see Scarfì et al., 2018) pointed out the occurrence of a sub-crustal discontinuity further south.

In this contribute we aimed to investigate in detail this possible connection by means of a multidisciplinary approach which has included field and marine geology, accurate earthquakes location and kinematic and seismic tomography. All data were finally merged to assess the seismogenic deformation pattern of this sector of the TFS by deciphering dimension, configuration and kinematics of the fault segments. Focusing on the connection between on-land and offshore structures could have a significant implication for the seismic hazard of the whole region also considering that the analysed sector was probably affected by strong historical seismicity such us the 1780 seismic sequence (Azzaro et al., 2007). Moreover, the distribution of seismic events in the area in the last 30 years (Palano et al., 2015 and references therein) suggests that a “seismic gap” could currently occur between Rocca Novara and Capo S. Alessio localities (see Fig. 1), accounting for a possible more than 20 km-long silent segment of the TFS.

1. **Geological background**

The present-day tectonic framework of the Central Mediterranean is the result of long-lasting geodynamic processes mostly driven by the subduction towards the NW of the Ionian oceanic lithosphere, a remnant of the Neo-Tethys oceanic domain (Şengör, 1979). Since late Jurassic-early Cretaceous (Channel et al.,1995), the opening of the south Atlantic Ocean induced the African plate to rotate counter-clockwise until its northern margin began to collide against the European block, located northwards. Tectonic shortening progressively involved the laterally variable pre-orogenic configuration of the northern African margin, formed at that time by both continental and oceanic lithospheres. Accordingly, convergence dynamics leads to the onset of subduction of the denser Ionian oceanic lithosphere beneath the European margin (Malinverno and Ryan, 1986; Jolivet and Faccenna, 2000). Since about 35 Ma, because of the rapid SE-wards rolling-back of the Ionian slab, the tectonic evolution of the Mediterranean has been controlled by the opening of large back-arc extensional basins (i.e. Ligurian-Provençal and Tyrrhenian basins) which produced lateral migration and relative rotation of orogenic wedges (see Faccenna et al., 2014 and references therein). Slab retreating and trench migration towards the foreland were responsible for the final shaping of the Apenninic-Maghrebian Chain, a large orogenic system extending from the Maghrebian region in NE Africa to the Apennines in Italy, across the Calabrian Arc (see inset in Fig. 1). Slab roll back was also accompanied by lateral tearing which split adjacent segments of the subducting lithosphere (Barreca et al., 2016); as a result, the active portion of the subduction system has become progressively narrower (Schellart et al., 2007; Rosenbaum et al., 2008) and it is today confined between central Calabria and north-eastern Sicily.

The Sicilian segment of the Apenninic-Maghrebian Chain is represented by two tectonically superposed structural domains; the Sicilian fold and thrust belt (SFTB in Fig. 1) and the Calabrian Arc (CA in Fig. 1) resulting from the Neogene to Quaternary deformation of the African and European paleo-margins respectively. The Sicilian fold and thrust belt occupies the lower structural position in the orogenic system and encompasses tectonic units of Meso-Cenozoic shallow to deep-water rock series and Neogene terrigenous covers today stacked to form a foreland-verging contractional belt. The Calabrian Arc, including the whole Calabria and the NE corner of Sicily, represents the sub-aerial portion of a larger accretionary prism in the Ionian Sea, formed in response to the Late Miocene-Quaternary subduction towards the NW of the Ionian crust. In NE Sicily, the Calabrian Arc forms a tectonic pile which includes imbricate slices of Hercynian metamorphic rocks and rests of their Meso-Cenozoic covers (Ogniben, 1969). The suture zone between the previously described structural domains occur in NE Sicily along a regional, NW-SE trending tectonic boundary, the Taormina Line (Ghisetti and Vezzani, 1982, Fig. 1). The TFS has developed close to this suture zone at the south-western edge of the Ionian subduction system and has propagated obliquely cutting a multi-deformed and structurally complex compartment of the central Mediterranean.

1. **The Tindari Fault System in the regional geodynamic context**

Several interpretation about the nucleation of the TFS in the frame of Africa-Europe Collision/subduction setting, has been proposed through time: i) the result of a plate reorganization (Goes et al., 2004; Billi et al., 2006) after slab retreating has slowed down; ii) as the surface expression of a STEP (Subduction Transform Edge Propagator), a large tearing in the lithosphere resulting from slab retreat dynamics (Govers and Wortel, 2005); iii) as a discontinuity bounding a region of incipient rifting (Polonia et al., 2016, 2017; Dellong et al., 2018). Although the different interpretations, the scientific community agrees that this tectonic belt is the expression of a lithospheric-scale tear fault rupturing/propagating at the south-western edge of the Ionian subduction system and that today it is playing a primary role in the geodynamics of central Mediterranean, controlling both magmatism and seismicity (Goes et al., 2004; Palano et al., 2012; 2015; Barreca et al., 2014; Cultrera et al., 2017). Albeit its prosecution in the Ionian Sea is still debated (Polonia et al., 2011,2016,2017; Argnani et al., 2007; Argnani, 2014; Gutscher et al., 2016; 2017), accurate relocation of earthquakes and seismic tomography in the area (Scarfì et al., 2018), suggest that the TFS could represents a deep slab-edge tear propagating from the lower to the upper plate, as highlighted by analysing shallow and deep seismic events distribution. It emerges in the Ionian Sea roughly in correspondence of Capo S. Alessio promontory (Fig. 1) and it could extend in the Ionian offshore along the SE direction for no more than 40 km off the Sicilian coast.

According to available GPS velocities (Palano et al., 2012; De Guidi et al., 2013a), a diverging motion of about 3.5 mm/yr is registered along the northern sector of the TFS which is currently transferring deformation between two adjacent crustal domains with distinct kinematic: shortening to the West, along the ~W–E contractional belt between northern Sicily and the Tyrrhenian basin (Billi et al., 2006), and extension to the East (Monaco and Tortorici, 2000; Palano et al., 2012), involving western Calabria and north-eastern Sicily where a geodetic extension rate of about 1.5 mm/yr according to a WNW–ESE direction has been registered (D’Agostino et al., 2011) (inset 1 in Fig. 1). Transtensional kinematics along the northern sector of the TFS is also confirmed by field (Billi et al., 2006; De Guidi et al., 2013a; Cultrera et al., 2017) and earthquake rupturing in the area since most of nodal planes indicate right-lateral transtension along the NW-SE direction (Barreca et al., 2014; Scarfì et al., 2016). Moreover, earthquakes distribution and events clustering in the eastern side of the southern Tyrrhenian Basin and NE-Sicily (Barreca et al., 2014; Cultrera et al., 2016; Scarfì et al., 2018) suggest that most of the crustal seismic activity along the TFS is confined on its northern sector, between the Lipari-Vulcano belt to the North and Rocca Novara locality to the south (Fig. 1). From Rocca Novara to the Ionian coastline in the SE, seismic events drastically decrease, then they resume in the offshore clustering along the NW-SE direction (Scarfì et al., 2018). In the sector with scarce seismicity, the only evidences of recent activity are represented by raised Holocene shorelines found along the Capo S. Alessio sea cliff (Stewart et al., 1997; De Guidi et al., 2003). De Guidi et al., (2003b) interpreted the raised shorelines (up to 6 metres a.s.l.) as repeated coseismic displacements related to the activity of the Taormina Fault, a near-offshore NNE-SSW trending normal fault which was supposed to runs parallel to the Ionian coast (see Fig. 1). In this area, evidence of relevant seismic activity in historical times are lacking except for a seismic sequence occurred on March-June1780, (main shock with estimated Io = VII–VIII MCS, Mw = 5.6 on March 28), which caused severe damage along the Ionian coast and was felt all over the north-eastern Sicily (Azzaro et al., 2007). The epicentre of the main shock was located offshore between Capo S. Alessio and Taormina (Fig. 1) and was once again associated to the activity of the Taormina Fault even if neither field nor offshore geophysical evidences have been never found for this tectonic structure (see Argnani et al., 2009).

1. **Field data**

According to available geological maps (Carbone et al., 1993, 1994, 1998; Lentini et al., 2000), the structural pattern of the analysed sector is the results of a multi-phased deformation history. As whole, this area was previously deformed by low-angle Oligo-Miocene thrusting that allowed to the tectonic stacking of several metamorphic units and related Meso-Cenozoic carbonate covers (Fig. 2A). Strike slip tectonics has involved this sector more recently and laterally juxtaposed the previously imbricated Ercinian metamorphic rocks. Strike-slip faults propagation gave rise to a complicate deformation pattern in which major NW-SE oriented right-lateral faults are associated with NNE-SSW left-lateral structures, the latter prevailing towards the Ionian coast. Local transpression can be observed along the NW-SE trending Forza d’ Agrò - Capo. S. Alessio structural culmination, formed by the activity of oblique, high-angle reverse faults (Fig. 2).

* 1. *Mesostructures*

Geo-structural data were collected on 5 selected key areas (crossed-hammer in Fig. 2) along the more than 20 km-long sector of the TFS extending between Rocca Novara locality in the north-west to Capo S. Alessio promontory in the south-east. Structural data were mainly measured on the carbonate outcrops of the Taormina and Capo S. Andrea tectonic units (see legend in Fig. 2) and consisted of mesofaults plane attitude and kinematics, the latter obtained from slickenlines, Riedel fractures and calcite fibres. All data were digitally stored on field by using FieldMove mobile App and finally plotted using FaultKin7 (Allmendinger et al., 2012) by adopting Schmidt lower hemisphere convention.

The Rocca Novara structural culmination (Fig. 2) is characterized by the occurrence of a set of sub-vertical, NW-SE trending right-lateral faults and associated left-lateral NNE-SSW striking structures mainly deforming the Jurassic-Cretaceous limestones and dolostones (Fig. 3A-1) of the Mandanici Unit (see Fig. 2). NW-SE trending structures also propagated within the lower Miocene deposits locally known as “Floresta Calcarenites” (Lentini et al., 2000), where calcite fibres and slickenlines on fault planes clearly indicate oblique, right-lateral motion with a slightly trantensional component (Fig. 3A-2). Slip-data inversion revealed that this sector has been deformed under a 30° plunging, N170E orientedσmax diagram in Fig. 3A)**.** The same trending and kinematics for mesofaults structures have been measured toward the south-east, close to the Antillo village where faults propagated within low-grade metamorphic rocks of the S. Marco D’Alunzio Unit. Here, the sense of movement on fault planes was derived from tectogrooves while rare calcite steps and Riedel fractures allowed to infer their kinematics (Fig. 3 B 1-2). Kinematic inversion of the few measured faults supports right-lateral movement on NW-SE oriented planes (see diagram in Fig. 3B) formed according to a N-S trending, 27° plunging σmax.

In the Limina-Roccafiorita sector (Fig. 2), right-lateral movement occured on NNW-SSE striking mesofaults which mainly propagated within the Meso-Cenozoic carbonate covers of the Taormina (Roccafiorita locality) and Capo S. Andrea (north of Limina) tectonic units. Just East of the Roccafiorita village, mesofaults also propagated within low-grade metamorphic rocks and are characterized by sub-vertical fault planes trending in average N340E with slickensides plunging at 30° toward the N130E direction (Fig. 3C-1). Left-lateral movement on NNE-SSW trending fault planes have been observed on carbonate outcrops south of Roccafiorita (Fig. 3C-2). Compared to the previous sectors, here kinematic indicators on fault planes support transtensional deformation along NNW-SSE trending structures nucleated according to a N190E trending, 40° plunging σmax (see diagram in Fig. 3C).

A pervasive set of oblique extensional mesofaults have been measured just west of the Forza d’ Agrò village (Fig. 2). Here, mesofaults propagated within carbonate rocks and have dislocated the previous WNW-ESE trending thrust faults. They mainly consist of sub-vertical, NW-SE oriented structures (Fig. 3D-1) characterized by oblique (slightly right-lateral) normal movement as indicated by slickensides trending and plunging and by calcite fibres. Evidences of fault reactivation have been observed north of Forza d’ Agrò where exposed fault planes (~ E-W trending) exhibit double generation of slickensides. The older kinematic indicators plunge at 37° towards the N254E direction whereas the younger ones plunge at 50° towards the N167E direction.(Fig. 3D-2).

Close to the Sea at the Capo S. Alessio promontory (Fig. 2), outcropping carbonate rocks are mainly deformed by extensional mesofaults. Fault planes are generally oriented WNW-ESE and exhibit oblique slickensides (with rake 140-160°) and steps on calcite fibres indicating a prevalent right-lateral movement (Fig. 3E-1 and 3E-2). Local stress field is characterized by a 40° plunging, N340E trending σmax indicating a general transtensional deformation also for this sector (see diagram in Fig. 3E).

* 1. *Stress field*

The paleostress tensors for the analysed sector has been derived by using directional statistics (e.g. Linked Bingham Analysis, Bingham, 1974) and was based on the slip-data inversion of a total of 45 fault planes with clear kinematic indicators.

As stated in the previous section, a non-homogenous stress field characterize the study sector since wrenching component of movement prevails between Rocca Novara and Antillo village, while a normal component prevails by moving toward the Ionian coast (see pseudo-focal mechanisms in Fig. 3). In particular, between Rocca Novara and Antillo (Fig. 2), the stress field is characterized by a ~N175E trending, 31° plunging σmax and by a sub-horizontal, nearly E-W oriented σmin (Fig. 4A). Slip-data inversion allows also to derive the pseudo-focal mechanism which is characterized by a P-axis plunging towards N174E at 31° and by a sub-horizontal T-axis oriented N83E. Nodal planes orientation and kinematic suggest right-lateral movement along the N313E direction and left-lateral along the N214E one. Computed paleostress tensors for the sector extending between Limina-Roccafiorita and Capo S. Alessio (Fig. 2), indicate instead a prevailing transtensional deformation. The stress field is characterized by a nearly N-S trending, ~ 45° plunging σmax and a sub-horizontal, E-W trending σmin (Fig. 4B). The pseudo-focal mechanism suggests right-lateral movement along N142E trending, mainly NE-dipping fault planes or left-lateral movement along the N40E direction.

As a whole, field measurements along the Rocca Novara- Capo S. Alessio structural belt indicate that the area has been deformed by a strike-slip tectonics regime characterized by a nearly N-S oriented σmax (N179E)plunging at about 25° (Fig. 4C). However, plunging of the σmax varies along the analysed structural belt (Fig. 4 A and B) suggesting a local stress perturbation probably due to different dipping of the analysed fault planes.

1. **Marine seismic reflection data**

*5.1 Data and methods*

The offshore sector was investigated through high-resolution marine seismic reflection data acquired during two distinct oceanic cruises; the M86/2 in December 2011–January 2012 and the ESAT (Eastern Sicily Active Tectonic) in August 2014, during which deep-penetrating and shallow seismic lines were recorded, respectively. Deep-penetrating data consist of multichannel seismic lines recorded on board the Meteor R/V by using a 104-channel Geometrics GeoEel digital streamer with a group interval of 1.56 m. A 1.7 l GI Gun was operated at ~200 bar in harmonic mode with a shot interval of 4 s, resulting in an average shot-spacing of ~8 m, and achieving a general sub-bottom penetration of up to 1 s two-way time (TWT). The seismic profiles were processed using the commercial software package Gedco Vista Seismic Processing. Processing has included a 20/40/ 200/400 Hz band pass filter, despiking, CMP-binning, Normal-MoveOut Correction and debias-filtering. The CMP bin size was set to 2 m, which resulted in an average fold of 14. All data were time-migrated by using the software's finite difference migration method with a constant velocity of 1500 m/s. The shallow seismic data are part of a larger dataset recorded in the Ionian Sea in 2014 (see Barreca et al., 2018) and consist of a single-channel sparker line acquired along the continental shelf of Capo S. Alessio. The acoustic source for this seismic prospecting was a 1 kJ Geo-Source Sparker, with a multi-tip Sparker array and a single-channel streamer having an active section of 2.8 m. Signal penetration was found to exceed 250 ms TWT. Processing of seismic data included: (a) true amplitude recovery using a T2 spherical divergence correction; (b) band-pass (300–2000 Hz) “finite impulse response” filter using a filter length of 256 samples; (c) de-ghosting; (d) swell-filter; (e) deconvolution; (f) trace mixing of three traces for enhancing horizontal signal; (g) time variant gain to boost amplitudes of deeper arrivals. The location of seismic lines is reported in Fig. 5

*5.2 Interpretation*

The ~ 10 km-long, NNE-SSW trending sparker line was acquired very close to the coastline across the offshore prolongation of Capo S. Alessio promontory (Fig. 5 and 6A). Although the very shallow water column produced a lot of disturbance (multiples) in the seismic line which limited the seismo-stratigraphic interpretation, some structural and morphological features are still recognizable. In particular, the seismic data well images the continental shelf, which appears as an almost flat surface (sloping ~ 2° towards the north) slightly incised by submarine channels (Fig. 6B). The continental shelf, which represents the most recent geomorphological feature, is preserved only in the SW sector of the line while it didn’t probably form in the NE sector. A prominent, apparently N-dipping and 250 ms-high scarp (about 190 m considering 1500 m/s for seawater velocity) occurs in-between the two sectors. The scarp most likely represents a fault-controlled geomorphological feature resulting from the tectonic activity of a N-dipping extensional fault system (Fig. 6C). The continental shelf probably formed in the already structured/uplifted footwall of this tectonic structure and then was modelled by the waves during the LGM stage (about 20 ka ago, Waelbroeck et al., 2002). Fanning out sediments in the hangingwall and gently tilted beds in the footwall of the fault provide clues for its recent activity.

The M86/2 dataset consists of seven, N-S and E-W trending seismic lines recorded in the Ionian offshore between southern Calabria and the coast of Capo S. Alessio (see traces in Fig. 5 and 7). As a whole, seismic-stratigraphy is well illuminated and includes at the bottom a chaotic seismic facies interpreted to represents the Peloritani metamorphic units and their carbonate covers. The upper boundary of this unit is given by an irregular surface above which a nearly transparent seismic facies unconformably lies. This latter has been interpreted as Lower Pliocene deposits of the Trubi Formation (see also Argnani et al., 2009; Argnani and Bonazzi, 2005). Upwards, a well-layered package of laterally continuous, high-amplitude reflectors occur and has been interpreted as middle Pliocene to Quaternary sequences (Fig. 7). Displaced reflectors allowed to trace the main tectonic features. A positive and slightly asymmetric flower structure has been imaged on the westernmost part of the E-W trending L2 line (Fig.7A, see top-right panel for location) just along a NW-SE oriented alignment of transpressive earthquakes (see below, Fig. 8). The tectonic structure is formed by high-angle reverse fault segments whose activity has caused the overall uplift of the lower units and gently folded the whole Plio-Quaternary series. Syn-tectonic sedimentation is testified by diverging geometries mostly observed within the Pliocene layers on the E-side of the tectonic structure. On the W-side, reflectors appear highly-deformed by folding up to assume an elbow-shape close to the main fault plane (see line drawing in Fig. 7A). The flower structure appears to propagates up to the base of the Quaternary deposits, gently folding also the seafloor. A branch of this traspressive structure has been also caught on the southern portion of the N-S oriented L1 line, which runs parallel to the coast, allowing deriving, by correlation, a NW-SE trending for the positive flower structure. Tightly-spaced and sub-vertical extensional fault strands were instead observed along the southern termination of the L3 line (Fig. 7B, see top-right panel for location) where they form a 1km-wide transtensional deformation zone. Here, faults propagate up to the seafloor also displacing contourite deposits. No clear evidences for faulting have been found in the other seismic lines of the M86/2 dataset (see supplementary material).

1. **Seismological data**

In order to investigate structures and current kinematics of the study area, we referred to earthquake locations and seismic velocity images from Scarfì et al. (2018) who performed a high-resolution tomography at a regional scale by using earthquakes recorded in the central Mediterranean region in the time span 1981-2014. In the analysed area, the epicentres (about 600 events with 1<M<4.5 and formal location errors of 0.3 km on average both on vertical and horizontal dimension) point out a paucity of seismic events between the coast and the Mts Peloritani ridge, while a lot of events are located in the offshore, where they highlight at least two sub-parallel, NW-SE trending alignments, extending for about 40 km in the Ionian Sea (Fig. 8A). In particular, section view and computed focal solutions show that the southern fault segment in the sea is characterized by shallower and vertically-clustered events that seem to point out a steeply (about 75°), SW-dipping fault plane roughly rupturing in the 7-15 km depth range (Fig. 8B). Focal solutions suggest right-lateral transpression along this tectonic structure (Fig. 8A). Conversely, oblique extensional kinematics characterize the northern branch which, according to the hypocentres, consists of a major NE-dipping, NW-SE trending structural feature rupturing down to 40 km of depth (Fig. 8B). More general studies (e.g., Scarfì et al., 2016, 2018) indicate that this seismicity links with the earthquake clusters that are located between the Aeolian Islands and Capo S. Alessio and that characterize the TFS. Focal mechanisms allow to calculate the seismic stress field in the CSA offshore, by using the ZMAP tools (Wiemer, 2001) and Gephart’s algorithm (Gephart, 1984). Although the applied method provides a not well constrained solution (confidence regions of the solution are quite large), due to the limited number of focal mechanisms and their heterogeneity, it indicates a strike slip regime with a 9° plunging, N155E trending S1 (Fig. 8C). The lithospheric structural architecture of the area has been also investigated through three, NNE-SSE trending, tomographic sections passing orthogonally to the previously detected tectonic structures (Fig. 9). In the tomographic images a major discontinuity was found, consistent with the earthquake distribution. In particular, section A-A’ (Fig. 9B) crossing the area just south of Rocca Novara (Fig. 1), points out how some geophysical layers, including the Moho discontinuity (identified where P-wave velocity of 7.6-7.8 km/s is exceeded, e.g. Rabbel et al., 2013), are clearly displaced by the inferred NE-dipping transtensional fault. Moving toward the SE in the Ionian Sea, the layer displacement is less pronounced and, in section C-C’, it seems to be only hinted. It is also worth noting that this discontinuity coincides with a zone of crustal thickness variation, noticeable not only to the passage between areas with continental and oceanic crust but also along the axis of the Mts Peloritani (see section A-A’ in Fig. 9).

1. **Discussion**

Extensive field measurements performed on-land between the Rocca Novara and Capo S. Alessio localities in north-eastern Sicily pointed out the occurrence of a structural belt formed by right-lateral, NW-SE trending strike-slip to oblique normal fault segments and associated antithetic structures. Since most of the tectonic structures deform rocks not younger than the lower Miocene, the age of their last activity is not clearly determinable in the field but can be only inferred. in fact, Middle Pleistocene fan-delta deposits outcropping just north of the studied area along the Ionian coastal domain provide clues for the age of deformation. They are, in fact, preserved only in the down-faulted NE-side of the Rocca Novara-Capo. S. Alessio structural belt (see Fig. 2) and their sedimentological feature indicate syn-tectonic deposition within a structural depression (Monaco et al., 1996). Further north, the same deposits are affected by extensional joints related to a WNW-ESE oriented minimum stress axis (De Guidi et al., 2013 b), an orientation that supports oblique NW-SE trending right-lateral/transtensional faulting compatible with that derived from field measurements along the Rocca Novara-Capo. S. Alessio alignment (see Fig. 4C). Stress field orientation along the Rocca Novara-Capo S. Alessio structural belt was derived from fault-slip data inversion and provides a roughly N-S trend for the max stress axis and E-W trending for the minimum one. Sub-horizontal max stress axis clearly indicates the occurrence of a prevalent strike-slip tectonic regime for the analysed sector. Furthermore, inversion of all slip data yields a pseudo-fault plane solution (Marrett and Allmendinger,1990) characterized by right-lateral movement on NW-SE (N315E) striking nodal plane. Related P and T axis direction well match with those derived for the offshore seismic events (Fig. 7C). This may suggest that also the on-land 20 km-long fault system may have been formed or reactivated under this modern stress field. Field evidence of fault reactivation along the Rocca Novara-Capo S. Alessio structural belt were found close to the sea north of Forza d’Agrò (see section 4.1 and Fig. 4D). Here strike-slip faulting has been overprinted by oblique normal faulting suggesting the older kinematic (right-lateral) as related to the shifting towards the SE of the Calabrian Arc and the younger one as produced by down-faulting due to slab retreating; dip-slip faulting are expected in the upper plate near the edge of the subducting slab (see Govers and Wortel 2005; Barreca et al., 2016).

Data suggest a very recent age for the NW-SE oblique strike-slip faulting in the area. Nevertheless, according to the paucity of recorded earthquakes (Fig. 1, see also Neri et al., 2006; Scarfì et al., 2018), none of the on-land fault segments appear to have been seismically active in the last decades. This behaviour has been attributed to aseismic deformation in response to a ductile behaviour of the crust (Jacques et al., 2001; Palano et al., 2015) or, more probably, it may account for a recently un-slipped (silent) segment of the TFS, since no low–velocity layer was found at the seismogenic depth (see Fig. 8). As demonstrated by a number of earthquakes, seismic faulting instead occurs in the offshore where clustering of events depicts two nearly-parallel alignments with a NW-SE direction. Associated nodal planes (Fig. 7A) indicate distinct kinematics for these fault segments. In particular, local transpression occurs on the southern one which consists of a shallower SW-dipping, NW-SE striking tectonic structure deepening up to 15 km of depth.

Conversely, oblique extensional kinematics characterize the northern branch which consists of a deeper, NE-dipping, NW-SE trending tectonic structure. Seismic tomography and accurate 3D-earthquakes location revealed that transtensional deformation occur along a first-order tectonic element cutting through the whole crust also displacing the Moho discontinuity (see section A-A’ in Fig. 8). This finding supports slab edge tear-deformation in the area.

As regard faults prosecution towards the SE in the Ionian Sea, our data confirm what has been claimed in Scarfì et al., (2018), namely that lithospheric deformation (cutting through the lower-upper plate tectonic sandwich) stops 35-40 km off Capo S. Alessio. Moreover, faults location and geometry differ from that of other crustal discontinuities found in the deep Ionian Sea (e.g. the Ionian Fault, see Polonia et al., 2011 and Fig. 1 for location). Lacking of faulting in the whole M86/2 dataset north of the studied area (see supplementary material and Fig. 5 for location) support the contention that the Ionian Fault does not continue northwards in the Messina Strait (Polonia et al., 2011, 2016). Further, tomographic images (Fig. 9) clearly highlights that the Moho is deformed just south of Rocca Novara and that this kind of deformation vanish toward the Ionian Sea (see section 6). This suggests that other supposed major faults close to the study area (e.g. the Ionian Fault) are probably confined in the upper plate where they are accommodating (or have accommodated) differential tectonic motion within the Ionian accretionary wedge.

As a whole, all analysed data are consistent with a general NW-SE tectonic trend of recent/active faults while no clear seismotectonic evidences have been found for the NE-SW trending structures inferred by previous authors in the near offshore from Messina to Taormina (i.e. the Taormina Fault of Catalano and De Guidi, 2003), by accounting for the differential elevation of 5.5 MIS (125 ka) terraces preserved along the Ionian coastal domain. In our model, this offset (i.e. 115 and 95 metres a.s.l. in the Taormina and Messina areas respectively, see Antonioli et al., 2006), could be explained by the activity of major NW-SE segments of the TFS (the Rocca Novara-Capo. S. Alessio structural belt), after the 5.5 MIS terrace formation. Moreover, between Capo S. Alessio and Taormina, a slight tilting towards the south of both 5.5 MIS coastal terraces and Holocene marine notches has been pointed out by their respective elevations (Stewart et al., 1997; Catalano and De Guidi, 2003; De Guidi et al., 2003; Ferranti et al., 2006; Spampinato et al., 2011). This late Pleistocene-Holocene deformation has been related to the activity of the southern sector of the Taormina Fault. Alternatively, considering that tilted morphological features lie also on the footwall of the Rocca Novara-Capo S. Alessio structural belt, it is more realistic that such coseismic displacement could be charged to the last activity of this large, 35 km deep transtensional tectonic structure, as moreover evidenced by offshore seismic profiling (Fig. 7). Accordingly, the “seimic gap” in the area (Stewart et al.,1997; Monaco and Tortorici, 2000; Neri et al., 2006) should be referred to this major fault and its origin could be interpreted as due to the crustal thickening occurring on the hangingwall block of the Rocca Novara-Capo S. Alessio fault system (see Fig. 8) which may account for isostatic rebound in the area as therefore supported by raised marine terraces just north of this alignment (see De Guidi et al. 2003). Hanging wall uplift process has probably counteracted to the down-faulting along the Rocca Novara-Capo S. Alessio structural belt reducing the differential stress in the area and inhibiting hanging wall vertical motion, leading to the recent locking of this segment of the TFS. According to this last hypothesis, empirical scaling relationships (see Wells and Coppersmith, 1994) put forward a high seismic potential for this silent transtensional fault belt, since it could be capable of generating earthquakes with magnitude greater than 6, considering a surface rupture length of 20 km. It is also worth noting that both the seismic potential (inferred from fault length -about 15 km- and from the down-dip rupture width - about 10 km-, see Fig. 8B) and the offshore position of the previously described transpressive fault branch (see Fig. 8A), match quite well with the estimated magnitude of the 1780 seismic sequence main shock (M= 5.6) and its offshore macroseismic location (see Azzaro et al. 2007).

1. **Conclusions**

Through a multidisciplinary analysis, which included field and geophysical data, we investigated the poorly known SE sector of the TFS (Tindari Fault System), a seismically active belt of tectonic structures slicing across the NE Sicily. Our data highlight with a better detail faults pattern occurring across the Peloritani mainland (between Rocca Novara and Capo S. Alessio) and the Ionian near-offshore (Fig. 10). Field and geophysical investigations highlight that the studied sector has been deformed by oblique (right-lateral) NW-SE trending faulting. Earthquake distribution and seismic profiling evidenced active deformation primarily in the Ionian offshore whereas in the mainland only a recent activity (after Middle Pleistocene) can be inferred. In spite of that, on-land stress field is coherent with that derived from focal solution offshore strongly suggesting that connection between the northern and southern sectors of TFS occurs through a potentially active (silent) fault segment, the Rocca Novara-Capo S. Alessio structural belt (Fig. 10 C) where scarce earthquakes have been registered in the last 30 years. Accordingly, this structural segment has been here retained to be the best candidate for coseismic displacements (see De Guidi et al., 2003 and reference therein) in the area, given its length (more than 20 km-long) and it sub-crustal nature.

Fault pattern and geometry, together with seismic tomography and accurate 3D-location of earthquakes, provided evidences about the lithospheric deformation in the area, which is dominated by active transtensional tectonics along a large, NE-dipping fault which also deforms the Moho discontinuity (Fig. 10 A). These findings confirm that slab-tear deformation (Fig. 10 B) occur (as expected) close to the active portion of the Ionian subduction zone. Finally, data merging allows to better depict the seismotectonic pattern of the area which is characterized by a segmented oblique fault zone where transtensional and transpressional deformation take place simultaneously, as usually expected along large strike-slip zones (Fig. 10 C). Although further analyses are needed to better constrain fault activity, empirical scaling relationships (Wells and Coppersmith, 1994) suggest that most of the detected fault segments has the potentiality of generating magnitude 6.5–7 earthquakes, putting forward the studied region as one of the most dangerous areas of central Mediterranean from the seismic point of view.

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**Figure captions**

**Fig. 1** – Seismotectonic map of the NE Sicily-Southern Calabria structural domain showing major Quaternary faults and earthquakes distribution (from Scarfì et al., 2018, modified). The TFS is considered an incipient and seismically active transfer zone (Billi et al., 2006; Palano et al., 2012; Cultrera et al., 2017) separating a contractional domain to the west from an extensional one to the north-east (Inset 1) as suggested by focal solutions of strong (M > 5) earthquakes (Pondrelli et al., 2006; Anderson and Jackson, 1987; Gasparini et al., 1982; Dziewonski et al., 1987). The on-land studied sector is comprised between Rocca Novara and Capo S. Alessio. Red area is the zone of possible seismic gap (see also Neri et al., 2006 and reference therein). The yellow star represents the macroseismic location of the 1780 seismic sequence (main shock Mw=5.6 see Azzaro et al., 2007). TF: Taormina Fault (De Guidi et al., 2003), TL: Taormina Line (Ghisetti and Vezzani, 1982), IF: Ionian Fault (Polonia et al., 2011), NAF or AEF: North Alfeo Fault or Etna Alfeo Fault (Gutscher et al., 2016; 2017; Polonia et al., 2016). CA and SFTB means Calabrian Arc and Sicilian Fold and Thrust Belt, respectively. Topo-Bathymetric data is a combination of Emodnet bathymetry (http://www.emodnet-bathymetry.eu) and SRTM 30 plus topography (http://topex.ucsd.edu/WWW\_html/srtm30\_plus.html).

**Fig. 2** – Geological sketch map (after Carbone *et al*.,1998; Lentini *et al*., 2000) of the Rocca Novara-Capo S. Alessio sector showing the main fault segments and location of the sites (crossed hammers) where structural measurements were performed.

**Fig. 3** – Fault planes and related kinematic indicators measured during the field surveys carried out along the Rocca Novara- Capo S. Alessio structural belt. Diagrams on the right (Schmidt lower hemisphere) show faults plane attitude with red arrows indicating movement on the respective hangingwalls and pseudo-focal mechanisms. Note how faulting mechanisms change moving from the Rocca Novara-Antillo area (near to pure strike-slip) to Limina-Roccafiorita-Capo S.Alessio where the normal component of movement increase. Acronyms are: RF Riedel fractures; CS calcite steps; CF Calcite fibres; SL slickenlines.

**Fig. 4** – Stress field derived from slip-data inversion for the Rocca Novara-Antillo sector (A), Limina-Roccafiorita-Capo S. Alessio (B) and for the Rocca Novara-Capo S. Alessio structural belt(C). The area has been deformed under a slightly transtensional tectonic regime characterized by a ~ 25° plunging, about N-S trending σmax.

**Fig. 5 –** Seismic lines map-location; red lines are the M86/2 dataset; blue line is the sparker seismic line from the ESAT dataset. The shaded-relief base map (offshore contour interval of 150 m) is a combination of Emodnet bathymetry (http://www.emodnet-bathymetry.eu) and SRTM 30 plus topography (Shuttle Radar Tomography Mission, http://topex.ucsd.edu/WWW\_html/srtm30\_plus.html).

**Fig. 6** – NNE-SSW trending Sparker seismic line acquired across the seawards prolongation of the Capo S. Alessio Promontory (CSA) (A). The line shows the sub-seafloor setting of near-offshore area (B) and point out the occurrence of active faulting transversally oriented with respect to the coastline. Active deformation is supported by the diverging geometry of younger deposit at the hangingwall and tilted beds at the footwall of detected faults (c).

**Fig. 7** – Multi-channel seismic profiles acquired in the Ionian offshore during the M86/2 oceanic cruise. A) E-W trending L2 seismic line (top-right panel for location) showing transpressive deformation by the propagation a positive flower structures (see drawing line in the left-bottom panel). Note that lower units have been exhumed along the tectonic structure and that fault activity has also deformed the top of Plio-Quaternary (PQ) series (dashed light-blue line). Lower Pliocene (LP) sediments fun out towards the East testifying syn-tectonic deposition during that time. B) About N-S trending L3 seismic line (top-right panel for location) showing a 1 km-wide active transtensional deformation zone (see drawing line in the left-bottom panel).

**Fig. 8** – Map (A) and section-view (B) of earthquakes location and focal solutions (from Scarfì et al., 2013, 2018 modified). Direction and thickness of the cross-section are shown on the map. Asterisks indicate some focal mechanisms reported in the section. (C) Seismic stress field obtained by inverting the focal solutions on the Ionian offshore (see text for further details).

**Fig. 9** - Vertical sections through the VP model, in km/s (after Scarfì et al., 2018, modified). Relocated earthquakes, within ±5 km from the cross-section lines, are plotted as grey circles. Black dotted lines indicate main structural features inferred in this study. Topographic profiles at the top of the sections are only indicative of the geographic location. The traces of the sections (AA', BB', CC') are reported in the sketch map. CSA: Capo S. Alessio.

**Fig. 10** – A)simplified 3D-model of the study area (view from the SE), reconstructed according to detected faults, hypocentres location and seismic tomography. Vertically clustered earthquakes and displace/deflected Moho discontinuity allowed to interpret the observed on land-offshore deformation as part of large lithospheric slab-tearing at the SW edge of the Ionian subduction system (B–view from the NW). Moho surface is reconstructed by interpolating the 7.6-8 km/s velocity provided in Scarfì et al., 2018. C) Map view of the TFS compiled according to the fault segments detected in this work (red) and known from the literature (blue). Light grey circles represent earthquakes recorded alongside the TFS in the last 30 years.

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