The Neogene-Quaternary geodynamic evolution of the Central Calabrian Arc: a case study from the western Catanzaro Trough Basin.

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Abstract

The Catanzaro Trough is a Neogene-Quaternary basin developed in the central Calabrian Arc, between the Serre and the Sila Massifs, and filled by up to 2000 m of continental to marine deposits. It extends from the Sant'Eufemia Basin (SE Tyrrhenian Sea), offshore, to the Catanzaro Basin, onshore. Here, onshore structural data have been integrated with structural features interpreted using marine geophysical data to infer the main tectonic processes that have controlled the geodynamic evolution of the western portion of the Catanzaro Trough, since Upper Miocene to present.

The data show a complex tectonostratigraphic architecture of the basin, which is mainly controlled by the activity of NW–SE and NE–SW trending fault systems. In particular, during late Miocene, the NW-SE oriented faults system was characterized by left lateral kinematics. The same structural regime produces secondary fault systems represented by E-W and NE-SW oriented faults. The ca. E-W lineaments show extensional kinematics, which may have played an important role during the opening of the WNW–ESE paleo-strait; whereas the NE-SW oriented system represents

the conjugate faults of the NW-SE oriented structural system, showing a right lateral component of motion. During the Piacenzian-Lower Pleistocene, structural field and geophysical data show a switch from left-lateral to right-lateral kinematics of the NW-SE oriented faults, due to a change of the stress field. This new structural regime influenced the kinematics of the NE-SW faults system, which registered left lateral movement. Since Middle Pleistocene, the study area experienced an extensional phase, WNW-ESE oriented, controlled mainly by NE-SW and, subordinately, N-S oriented normal faults. This type of faulting splits obliquely the western Catanzaro Trough, producing up-faulted and down-faulted blocks, arranged as graben-type system (i.e Lamezia Basin).

The multidisciplinary approach adopted, allowed us to constrain the structural setting of the central Calabria segment. The joined onshore with offshore structural data analysis allowed us to image a more faithful geodynamic evolution of the Calabrian Arc, included in the wider geodynamic framework of the Mediterranean region

Moreover, our results show the close correlation between the NE-SW and N-S normal fault systems and evidence of deformed Quaternary deposits. These findings are relevant to seismic hazard understanding in an area which is historically considered at the highest risk of earthquake and tsunami and where are present important infrastructures and Cities.

KEY WORDS: Calabrian Arc, strike-slip faults, normal kinematics, faults reactivation.

1. Introduction and aim of the work

Strike-slip fault systems frequently control the opening of sedimentary basins showing a heterogeneous geometry, due to the development of pull-apart and fault wedge basins at fault bends and oversteps. These are transtensional basins *sensu stricto* (Ingersoll and Busby, 1996) characterized by highly geo-structural complexity (Allen et al., 1998; Ingersoll, 2012), due to local oblique extension with respect to the trends of the main transcurrent faults. Basins formed by transtension are commonly characterized by *en' echelon* arrays of normal faults obliquely oriented to the boundaries of the deformational zone (Allen et al., 1998; Waldrom, 2005; De Paola et al., 2006). Transcurrent tectonics is also common in obliquely convergent settings where interplate strain is partitioned into arc-parallel strike-slip zones within the fore-arc, arc or back-arc region (Fitch, 1972; Beck, 1983; Jarrard 1986; Sylvester, 1988; Diament et al., 1992; Hanus et al., 1996; Sieh and Natawidjaja, 2000; De Paola et al., 2005; Cunnigham and Mann, 2007). Moreover, strike-slip systems, in this geological setting, can rotate and act as elements of accommodation.

The Calabrian Arc (Fig.1) is considered one of the most interesting subduction systems due to the high level of structural complexity. Since the Tortonian time, strike-slip faults play a relevant role during the evolution of this region, favouring southeastward drifting of the arc and its fragmentation (Ghisetti et al., 1979; Turco et al., 1990; Finetti and De Ben, 1986; Van Dijk et al. 2000). In this complex tectonic setting, an active extensional regime has produced along the Tyrrhenian side an extensional belt, running for about 370 km of length from the Crati Basin (CR) to the Hyblean Block (Fig.1). The extensional fault systems are predominantly organized in graben-like structures showing trends spanning from NNE-SSW to NNW-SSE (Monaco and Tortorici 2000; Tortorici et al., 2003; Tansi et al., 2007). This regional fault belt represents the source of several catastrophic earthquakes, indeed, many authors, with different approaches, recognized and analyzed various seismogenic sources (Tortorici et al., 1995; Bordoni and Valensise, 1998; Monaco and Tortorici, 2000; Jacques et al., 2001; Galli and Bosi, 2003; Neri et al., 2004; Galli et al., 2007; Ferranti et al., 2008; Billi et al., 2008; Rovida et al., 2011; Loreto et al., 2013)

The internal structure of sedimentary basins in the central Calabrian Arc is complex with the presence of both longitudinal extensional faults and transversal strike-slip fault systems. In the study area (Fig. 1), the western Catanzaro Trough is bounded by large strike-slip fault zones, crossing the entire emerged Calabrian Arc from the Ionian to the Tyrrhenian Sea (Finetti and De Ben, 1986; Tansi et al. 2007; Del Ben et al., 2009; Milia et al., 2009).

However, the main controlling factors on the origin of transversal strike-slip zones and extensional faults are not completely understood, and their role in controlling of the geodynamics of this area is still under debate.

The aim of this work is to describe the Neogene –Quaternary evolution of western Catanzaro Trough, and to discuss the role played by transverse and longitudinal faults during the development of this area. A multidisciplinary approach, combining onshore/offshore geological and geophysical data, has been adopted here to assess the complex structural framework of this key sector, which develops as element of accommodation between northern and southern the Calabrian Arc.

2. Geological setting

2.1 Geodynamic setting of Calabrian Arc-southern Apennine system

The western Catanzaro Trough represents a Neogene - Quaternary sedimentary basin belonging to a well-developed *arc-shaped* structure, the Calabrian Arc (Amodio-Morelli et al., 1976; Tortorici, 1982). The Calabrian Arc is a fragment of Alpine chain connecting the southern Apennines with the Maghrebide belt. The convergence between the Nubia and Eurasia plates (inset in Fig. 1) controlled the NW-subduction and the SE-ward roll-back of the Ionian slab that, in turn, caused rapid SE migration of the Calabrian block (Malinverno and Ryan, 1986; Mantovani et al., 1990; Dewey et al., 1998; Faccenna et al., 2005). The slab roll-back is accompanied by opposite rotations along vertical axis at its northern and southern NW-SE oriented edges (Mattei et al., 2007), the Pollino and Taormina shear zones, respectively (Fig. 1; Ghisetti and Vezzani, 1982; Van Dijk et al., 2000; Langone et al., 2006; Angi et al., 2010). The E- and SE-ward rapid trench migration also caused the fragmentation of the Calabrian Arc into structural highs and longitudinal and transversal sedimentary basins (Ghisetti, 1979; Tansi et al., 2007; Zecchin et al., 2012; Tripodi et al., 2013; Critelli et al., 2013; Muto et al., 2014; Fabbricatore et al., 2014; Longhitano et al.,2014; Zecchin et al., 2015), including the Catanzaro Trough.

Figure

During Neogene-Quaternary the Calabrian Arc experienced extensional alternated to contractional or transpressional tectonic phases (Van Dijk et al., 2000; Muto and Perri 2002; Tansi et al., 2007). In particular during Middle-Upper Pleistocene, the tectonic regime in the Calabria region passes from transcurrent to extensional regime (Malinverno and Ryan, 1986; Westway, 1993; Van Djik and Scheepers, 1995; Van Dijk et al., 2000; Minelli and Faccenna, 2010). The opening of the Tyrrhenian back-arc basin related to the Ionian subduction beneath the Calabrian Arc is characterized by tensional axes perpendicular to the chain. At the present, according to some authors, the Ionian slab has partially or completely undergone detachment (Wortel and Spakman, 1992; Guarnieri et al., 2006; Neri et al., 2009). In response to the Ionian slab detachment, the whole Calabrian Arc undergoes a general tectonic rebound (uplift), at a rate of 0.5–1.2 mm/yr in the last 1–0.7 My, when the propagating tear passes underneath the plate margin segment (Monaco et al., 1996; Wortel and Spakman, 2000).

All these observations suggest that the roll-back in the Tyrrhenian - Calabrian system has either currently stopped or significantly slowed down (D'Agostino et al., 2004; Serpelloni et al., 2007, 2010).

2.2 Tectono-stratigraphic features of the Catanzaro Trough

The study area is located in the western Catanzaro Trough, along the Tyrrhenian side of central Calabria, and represents a linkage zone between the northern and southern sectors of the Calabrian Arc (Fig. 1), which experienced different tectonic phases leading to the development of both longitudinal and transversal faults systems (Ghisetti, 1979; Monaco and Tortorici, 2000).

Longitudinal fault systems are represented by highly dipping NE-SW and N-S oriented normal faults, that are part of the Siculo-Calabrian rift zone (Fig. 2; Monaco et al., 1997; Monaco and Tortorici, 2000) and bounding N-S and NE-SW elongated basins extending along the Calabrian Arc until eastern Sicily. The several order marine terraces onland-observed along the Tyrrhenian coast are related with the strong uplift that the Calabrian block experienced during the Quaternary (Westaway, 1993; Mihauchy et al., 1994; Tortorici et al., 2003; Bianca et al., 2011).

Transversal fault systems border the northern and southern edges of the Catanzaro Trough (Fig. 2; Van Dijk et al. 2000; Tansi et al., 2007; Milia et al., 2009). Its northern margin is represented by a regional NW-SE-trending left-lateral strike-slip faults system. These structural lineaments consist of three right-stepping *en' echelon* S-dipping major fault segments. The southern segment is represented by the Lamezia-Catanzaro Fault (Fig. 2; Monaco and Tortorici, 2000; Tansi et al., 2007), recognizable by the evident morphological escarpments with triangular and trapezoidal facets. The southern margin of the basin is bordered partially by the WNW-ESE oriented, NNE-dipping Maida –Stalettì Fault Zone (Fig. 2; Ghisetti, 1979; Monaco and Tortorici, 2000; Langone et al., 2006).

Figure 2

The Catanzaro Trough is filled by Neogene- Quaternary sedimentary succession, (Ferrini and Testa, 1997; Cianflone and Dominici, 2011; Chiarella et al., 2012; Longhitano et al., 2014). These deposits unconformably overlie igneous-metamorphic units (Fig. 3, Cavazza and De Celles, 1998).

Figure 3

The basement rocks are made of Paleozoic medium to high grade metamorphic rocks intruded by plutonic bodies, belonging to the *Calabride Complex* (*Sila and Castagna Units* in Fig. 3; Ogniben, 1969; Amodio-Morelli et al., 1976; Messina et al., 1991a, 1991b, 1994; Critelli et al., 2011). These tectonic units are, in turn, tectonically overthrusted on the Jurassic to Early Cretaceous ophiolite-bearing sequences (Bousquet, 1963; Vezzani, 1967; Ogniben, 1973; Amodio-Morelli et al., 1976; Tortorici, 1982; Critelli et al., 2013). These units are referred to the Liguride Complex (*Metapelitic and Ophiolitic Units* in Fig.3; Ogniben, 1969; Knott, 1987; Liberi et al., 2006), which together rest tectonically on the *Mesozoic Carbonate Complex* (Fig.3)

The sedimentary succession of the Catanzaro Trough consists of clastic and carbonate strata (Fig. 4a) of Neogene-Quaternary age.

The basal portion of this succession is depicted by the Serravallian–Tortonian transgressive sequence consisting of thinning- and deepening-upward successions. These units, assimilated to the Serravallian- Tortonian deposits of the Amantea Basin (Colella, 1995; Muto and Perri, 2002), rarely outcrop along the margins of the western Catanzaro Trough.

Then the Messinian evaporitic succession (Calcare di Base and Gypsum Fms; Fig. 4a) starts to be laid down, reaching ca. 100 m of thickness (Cavazza and Ingersoll., 2005; Roveri et al., 2008; Barone et al., 2008; Govers et a., 2009; Manzi et al., 2010; Zecchin et al., 2013a, 2013b; Brutto et al., 2015).

The end of Messinian Salinity Crisis is marked by a late Messinian to Lower Pliocene continental succession, up to 150 m-thick (*late Messinian to early Pliocene Conglomerate*; Fig. 4b). These deposits are coeval to the Carvane Fm (Roda, 1964; Barone et al., 2008; Zecchin et al., 2013b).

The 300 m-thick Pliocene Siltstones and marls (Fig. 4b) outcrop widely in the study area and show an affinity with the Trubi formation cropping out along the peri-Ionian Neogene basins (Cavazza and DeCelles, 2004; Tripodi et al., 2013; Zecchin et al., 2013a). These deposits pass upward to a ca. 100 m-thick succession correlated to the Monte Narbone Fm (Piacenzian) (Fig. 4c; Di Stefano and Lentini, 1995; Cavazza et al., 1997; Bonardi et al., 2001).

Figure 4

The early Pleistocene unconformity (EPSU in Zecchin et al., 2012, 2015) marks the opening of the Catanzaro fault-bounded paleo-strait (sensu Longhitano et al., 2014), characterized by ca. 100

m of mixed, silici-bioclastic, sands and sandstones (Figs. 4d and e; Chiarella, 2011; Chiarella et al., 2012; Longhitano et al., 2012a, 2014).

The Middle -Upper Pleistocene generally made of siliciclastic sands and coarse sandstones with poor fossiliferous content which rest directly on Lower Pleistocene deposits (Figs. 4e and e') and on the crystalline-metamorphic substrate constituting the margins of the basin. The western part of the Catanzaro Trough is dominated by outcrops of Late Quaternary 60 m-thick conglomerate and sand deposits (Alluvial Fans; see geological map in Fig. 3).

3. Materials and methods

The Catanzaro Trough is characterized by a complex geo-structural history with one of the highest seismic moment release of the whole Italy (Gasparini et al., 1982; Westway, 1993; Calò et al., 2012). To improve knowledge of the structural setting of this region, we adopted a multi-disciplinary approach by collecting and analysing new geological and structural data, which have been integrated with onshore and offshore seismic reflection profiles and high-resolution morpho-bathymetry data.

3.1 On-land structural data

Fieldwork has been mainly performed in the western margin of the Catanzaro Trough. Field observations and structural data, such as fault orientations and kinematics, have been collected for brittle features, and have been used to infer their evolution in the study area. More than 500 structural measurements have been collected at 35 stations (Fig.7), and have been analysed and processed using the DAISY software (Salvini, 2002).

In particular, the statistical distribution of faults and their kinematics has been analysed by contouring of fault planes and associated slickensides. Stress inversion techniques relying on rotational axes (rotaxes), which correspond to the σ2 axis of a conjugate pair of andersonian faults, have been performed on sets of fault planes and kinematic indicators to discriminate between the different deformation events, using the Daisy software (Wise and Vincent, 1965; Salvini & Vittori, 1982; Mattei, et al., 1999).

Figure 5

3.2 Multichannel seismic profiles and wells by ViDEPI project

In order to bridge the gap of lack of structural data along the Tyrrhenian coastal areas, four multichannel seismic profiles (located both onshore and offshore) and two wells (Marta and Marisa; Figs. 5 and 6) were analysed. These data were acquired within the Sant'Eufemia Gulf and onshore Lamezia Plain by Eni s.p.a. at the beginning of the 80', and made available in the frame of the ViDEPI project (Fig. 5). In spite of their low quality, the ViDEPI seismic profiles have provided, together with Marta and Marisa wells (Fig. 6), some constraints in the seismo-stratigraphy of the Catanzaro Trough basin.

Figure 6

3.3 High resolution morpho-bathymetry

High resolution morpho-bathymetric map (Fig. 5) acquired during the R/V OGS-Explora campaign in summer of 2010, in the frame of ISTEGE project (Loreto et al., 2012), has been made available by ISMAR - CNR U.O.S. of Bologna. The data were performed with a grid cell size of 20 x 20 m, obtained by using two hull mounted Multibeam echosounders: the Reson Seabat 8111 (nominal frequencies of work: 100 kHz), and the Reson Seabat 8150 (nominal frequencies of work: 12 kHz). More details about acquisition and processing of multibeam data can be found in Loreto et al. (2012).

3.4 Offshore Multichannel seismic data

Multichannel seismic (MCS) profiles have been acquired in the northeastern portion of the Sant'Eufemia Gulf (Fig. 5), in the frame of ISTEGE project (Loreto et al., 2012).

Within the gulf, about 300 km of middle resolution MCS profiles were collected by using 1500 m-long streamer cable, 120-channel array with 12.5 m trace interval. The energy source consisted of two GI-guns with a total volume of 8-liters, shooting every 25 m, with a resulting seismic coverage of 30 for each investigated depth point (Loreto et al., 2012; 2013 for further details). These data allowed the investigation of the entire Pliocene-Pleistocene sedimentary sequence and the upper part of the Messinian rocks. In particular, five seismic MCS profiles (light green lines in Fig. 5), were interpreted to study the offshore tectonics of the western Catanzaro Trough, although only two MCS lines have been showed in this work.

Management and interpretation of seismic profiles were performed using the *Kingdom* software (IHS Gobal Inc.).

3.5. 1-kJoul Minisparker profiles

Eight NNW-SSE striking single-channel seismic profiles (1-kJ Sparker), acquired aboard the R/V Bannock (Trincardi et al., 1987), were integrated with ISTEGE data, even though here, we displayed only Vp9 Sparker profile. Sparker profiles (see location in Fig. 7), acquired with a broad band (100 - 2000 Hz), achieved better acoustic penetration, up to 1 sec in TWT. They were fired every 2s, recorded with a 2-s sweep and a band-pass filter of 100 - 600 Hz (Trincardi et al., 1987).

4. Results

4.1 Structural data

Structural data analysis based on the statistical distribution of fault orientation and associated kinematic indicators (DAISY software; Salvini, 2002), allowed us to identify several fault sets, underlining a prevalence of normal kinematics (Fig. 7). The great variability of faults (Fig. 7), affecting the Neogene-Quaternary basin infill, provides clues on chronological evolution of the area; along the NW-SE and NE-SW major faults, these deposits are brought into contact with Paleo-Mesozoic crystalline-metamorphic and sedimentary rocks of substrate.

Figure 7

Notwithstanding the E-W long-shaped basin, a great number of N-S and NE-SW normal faults have been measured (Fig.7).

Minor NW-striking, strike-slip faults affect the basin (Fig 8a). Evidence of the kinematics of these faults system is highlighted locally when these come into contact with the underlying basement rocks, allowing us to define the main kinematics features of these fault planes (Fig. 8b).

Figure 8

Fault planes, showing more than one set of striations, and cross-cutting relationships between two or more fault systems are used to reconstruct the evolutionary stages characterizing the western Catanzaro Trough. We identified three tectonic phases:

1) In the Upper Miocene-Pliocene basin infill, three main fault systems have been recognized and documented: a) a NW-SE fault system, which shows sub-vertical fault planes, equally dipping both towards SW and towards NE (Fig. 9a). Slickensides document a relative abundance of left lateral strike-slip faults (Fig. 9a'), although normal component of motion have been also measured; b) The faults system striking from WNW-ESE to WSW-ENE is characterized by dip-slip striations with pitches ranging from 60° to 90° (Figs. 9b and b'). These structural lineaments display sub-vertical fault planes and represent, together with NW-SE strike-slip faults, the northern and southern morpho-structural bounds of the Catanzaro Trough. In these tectonic setting, we observed locally, c) secondary NE-SW oriented faults, displaying, in some cases, strike-slip with reverse component of motion (Figs. 9c and c').

Figure 9

2) Three main fault systems have been recognized in the Piacenzian - Lower Pleistocene deposits: a) WNW-ESE to ENE-WNW reverse faults, showing both right and left- lateral component of motion, commonly ca. S dipping (Fig. 10a); and b) NE-SW left-lateral structures, which show slickensides having pitches ranging from 30° to 50°, with sub-vertical fault planes (Figs. 10b and b'). At the mesoscale these faults have been observed widely within the central and eastern portion of the area, influencing locally a dipping change of the Lower Pleistocene mixed strata. c) Minor NW-striking right lateral strike-slip faults have been observed in the area (Fig. 10c), usually superimposed the left lateral striaes on the same fault planes (see above Fig. 9a). This suggests an inversion of transcurrent movement.

Figure 10

3) Within the southwestern side of the study area, a number of NE-SW and N-S faults clearly dislocate the Middle Pleistocene terraced deposits, showing dip-slip movements with rarely strike-slip component of motion (Fig. 11).

Although the structural data show a wide range of fault orientations and kinematics, the NE-SW and N-S oriented normal faults represent the most abundant structures in the study area. These faults correspond with tectonic structures affecting the Quaternary sediments of the basin infill and, in some case, also crystalline bedrock (Figs. 11a and b). At the mesoscale, these structures show a sub-vertical fault planes with orientation spanning from N20 (200) to N60 (240), equally dipping both towards SE/E and towards NW/W (Fig. 11c). The central and eastern border of the basin is characterized by a series of NE-SW oriented structural lineaments strongly controlling the drainage pattern (see geological map in Fig. 3).

Figure 11

4.2. Onshore seismic data

Figure 12 images the W-E oriented CZ-329-78 MCS ViDEPI profile. This profile images the Miocene unit, which top corresponds to an high amplitude and very continue seismic reflector, covered by a better stratified, even if poorly continue, sedimentary unit corresponding to Pliocene-Quaternary deposits. The boundaries between different units are constrained by the seismo-stratigraphic character (Dumas et al., 1987) of the lithologies described in the Marta and Marisa wells and the time to depth conversion assuming, for the Pliocene-Quaternary sediments, a constant seismic velocity of 2200 m/s (Pepe et al., 2010). These units are characterized by numerous discontinuities and fault-controlled dislocations, mainly with normal and, sporadically, reverse kinematics. Amongst shot points (SP) 160 – 190, thickness increase of Pliocene-Quaternary sediments and the evident dislocation of the Miocene top reveal the activity of a W-dipping normal fault (Fig. 12). This newly identified San Pietro Lametino normal Fault is NE-SW oriented, as derived by unpublished ViDEPI profiles and Vigor well data.

Figure 12

4.3 Offshore seismic data

In the offshore, we have interpreted two parallel ViDEPI seismic profiles, ER-77-502 and ER-77-3028, NW-SE oriented (Fig. 13). The well stratified Pliocene-Quaternary sequences lie on the top of the Miocene, which is represented by a highly continuous horizon with high amplitude due to the strong acoustic contrast between conglomerates (Messinian) and marls (Pliocene). In the northeastern part of the ER-77-502 the Upper Miocene-Pliocene sediments are highly deformed (SP 100 - 190) forming a gentle anticline confined within the Lower Pliocene (Structural High), this deformation becomes less pronounced in the ER-77-3028. Whereas in the southeastern part only gently folded units are detectable in both profiles (Fig. 13; *Transpressional/ compressional faults*). The deformations imply a NNE-SSW oriented compressional system.

ER-77-502 and ER-77-3028 ViDEPI MCS profiles show amongst SP 178-200 and 20-40, respectively, a normal fault that controls the deepening of the basin towards the onshore and border the Structural High (Fig. 13). This structure is result of growth of fold anticline related to the propagation of thrust fault and involving the Pliocene deposits. Considering the orientation and location of these two profiles and the previous work (Loreto et al., 2013), we suggest that the recognized faults are part of the NE-trending Sant’Eufemia normal fault, which locally outcrop at the seafloor (see Figs. 5 and 10 in Loreto et al., 2013). Further, in the ER-77-3028 profile, this fault reaches 2.4 s (TWT, two-way traveltime) of depth, displacing ill-defined horizons, here named Deep Horizons. We estimate that the Deep Horizons are offset more than 0,6 s (TWT) (Fig. 13).

Figure 13

In the central part of the gulf, two NE-SW-striking multichannel seismic profiles (Fig.14) show a SW-facing, E-W trending Master Fault and its antithetic lineaments, deforming differently from top to bottom the entire Neogene-Quaternary sedimentary basin. The deformation, confined between Upper Miocene and Lower Pleistocene, produces Pliocene deposits thickening in the hangingwall respect to the footwall across the Master Fault (Fig.14). Although this deformation changes slightly moving from one profile to the other, the fault dislocation measured at the top of the Miocene changes substantially from ca. 0,3 s (TWT), in the GSE10_05 profile, to ca. 0,1 s (TWT) in the GSE10_04 profile. Sediment deformation increases up-ward, indeed the dislocation is replaced by folding with associated anticline growth. This deformation is confined amongst Upper Pliocene and Lower Pleistocene layers (ranging from about 0,8 and 1,6 s-(TWT) for both MCS profiles). Therefore an initially extensional/ transtensional mode of fault (Williams et al., 1989) is replaced by an apparent reversal or transpressional movement.

Figure 14

Three small ridges NE-SW oriented have been identified in the high-resolution morpho-bathymetry map (black fold axes in Fig.15a) and in the Vp9 Sparker seismic line (Fig. 15b) located in the center of the Sant’Eufemia Gulf.

According to our interpretation these structures can be kinematically associated to the right lateral with reverse component of movement of Master Faults (inset a’ in fig. 15) which, during the Upper Pliocene-Lower Pleistocene time, replacing the previous normal kinematics.

Vp9 Sparker seismic profile (Fig.15b), although not perpendicular to the ridges, images the sediments of Quaternary succession deformed in sequence of folds placed in the hangingwall of the Master Fault. The Sparker line shows a more recent *compressional deformation* (Fig. 15b) with similar orientation to the deformation observed in the MCS ViDEPI profiles (Structural High, Fig. 13). The Vp9 Sparker ridges, in turn, are newly displaced by a series of high angle NE-trending faults that record an extensional event (Fig. 15b). The orientation of these faults was defined examining two crossing seismic profiles (Vp9 and GSE10_08, Fig 15a for their location).

Figure 15

5. Discussion

The aim of this work is to define the Neogene-Quaternary evolution of the western Catanzaro Trough, and the role of transverse and longitudinal faults in controlling the evolution of the northern and southern sectors of the Calabrian Arc.

Many authors highlighted how the continental collision in northern Calabria and central-western Sicily caused strong lithosphere deformation in correspondence to a series of tear faults (Fig. 16). After the analysis of geological data and the integration with offshore geophysical data, Guarnieri (2006) placed one of these tear faults within the central Calabrian Arc showing a N120 trending, which provoke the segmentation of this forearc/ backarc system (Fig. 16).

More recently Chiarabba et al., (2008) and Neri et al., (2009), by means of seismic dataset and tomographic inversion, consider that the slab is detached beneath northeastern Sicily and northern Calabria, whereas appears undetached beneath the Messina straits and central Calabria. This leads the authors to suggest that the change between detached/undetached slab occurred within the Catanzaro Trough, producing a tear fault that acts as releasing tectonic element (Fig. 16).

Figure 16

Hence, the study area is placed in a key sector to understand the evolution of whole Calabrian Arc. Combining and analysing onshore and offshore datasets, including structural (more than 500 fault planes measurements) and geophysical data (multibeam data, multichannel and Sparker profiles), we were able to define the different tectonic phases controlling the opening and evolution of the Catanzaro Trough since the Late Miocene.

The data collected and their interpretation suggest that the structural complexity and evolution of the Calabrian Arc are due to multiple reactivation events of pre-existing faults, some of which are in fact polyphase structures. A heterogeneous dispersion of rotaxes demonstrates this hypothesis (Salvini et al., 1982). Indeed, structural data show a scattered distribution of rotaxes (Fig. 17), although two main clusters of sub-horizontal and sub-vertical rotaxes can be identified. The sub-horizontal rotaxes ($\sigma 2$) of normal faults dominate (almost 300 measurements) and are concentrated around the N30 and N70 directions (Fig. 17). These trends are consistent with N–S and NE–SW oriented normal fault systems, displaying a ca. NW-SE oriented extensional direction ($\sigma 3$). The sub-horizontal rotaxes ($\sigma 2$) obtained for reverse faults (Fig. 17) show a greater concentration around the N45 direction; whereas $\sigma 1$ is oriented along the NW-SE direction. Sub-vertical clusters of rotaxes ($\sigma 2$) are obtained for strike-slip faults, they correspond to the left lateral and the right lateral faults which show a greater scattering of the data distribution (Fig.17) suggesting, here too, faults reactivation events during the tectonic evolution of the area.

Fig. 17

5.1. Tectonic events of the western Catanzaro Trough

Three main tectonic events have been recognized based on the ages of the deposits affected by repeated faulting (Fig. 18).

The earliest tectonic phase (Figs. 18a, b, c) is restricted to the Upper Miocene-Lower Pliocene, and it is well recognized within the Messinian deposits (Figs. 9 and 13), in both onshore and offshore datasets from the western Catanzaro Trough. Three main fault systems associated to this tectonic phase have been identified and described onshore: 1- the ca. NW-SE oriented sinistral strike- slip faults parallel to the Lamezia-Catanzaro Fault (Figs. 9, 18a, sensu Tansi et al., 2007); 2- the WNW-ESE and the WSW-ENE oriented extensional faults (Figs. 9b), bounding clearly the northern and southern margins of the Catanzaro Trough; and finally 3 - the NE-SW oriented right-lateral fault systems (Fig. 9c). Combining these three fault systems, affecting only the Upper Miocene- Pliocene deposits, an acceptable stress field emerges consistent with an E-W-trending sub-horizontal σ_1 stress axis (Compressional: P-axis; Fig. 18a).

The ER-77-502 and ER-77-3028 seismic profiles on the Tyrrhenian offshore display NE-SW-oriented transpressional faults, arranged as thrust ramps (Fig. 13). The structures observed on both profiles are compatible with E-W-oriented P-axis, consistent with that inferred from the onshore datasets. In the center of Sant'Eufemia Gulf the SW-facing, the WNW-trending Master Fault (Figs. 14 and 18b) was active at least until the Piacenzian time as a normal fault. The large offset (ca. 300 ms TWT) rapidly disappears eastward next to the NE-trending ridge, in relation to the activity of reverse/transpressional faults, associated with the post-Serravallian ESE-ward drifting of the Calabrian Arc (see also Van Dijk et al., 2000; Muto and Perri 2002; Tansi et al., 2007; Tripodi et al., 2013).

During the Upper Miocene-Pliocene time, the NW-SE faults system assumes, hence, the role of crustal shear zone which divides the Arc into segments of 'tectonostratigraphic terranes' (Van Dijk et al., 2000). In this model the extensional WNW-ESE faults accommodate also the transcurrent movement, and produce a significant increase of the basin-area. This normal faults could act as margin of a transtensional zone (e.g western Catanzaro Trough), such as occurred in the Triassic-Jurassic basins in the High Atlas of Morocco (Beauchamp, 1999). According to Allen et al.

(1998), in many cases, the deformation zone can be accommodated by the rotation of the oblique fault blocks within the basin; even though in this study the rotational axes have not been quantified.

A second tectonic phase (Figs. 18d, e, f) is inferred from onshore observations with WNW-ESE trending reverse/transpressional, NE-SW trending left-lateral faults and minor NW-SE oriented right lateral faults, confined below the Middle Pleistocene deposits (Figs. 10a, b and c). Similar evidences are found in the offshore dataset, where the Lower Pleistocene sediments bounded by the E-W-trending Master Fault locally show positive tectonic inversion (Figs. 14 and 18e). Thus, the stratigraphic sequence of sediments in the hangingwall of the Master Fault evolves from an extensional synrift one, in the Miocene- Pliocene, to a right lateral transpressive one during the Piacenzian- Lower Pleistocene (Figs.14 and 15). Structural and geophysical data confirm the presence of an oblique compressional event, consistent with a stress field where the maximum principal stress axis (σ_1) shows the sub-horizontal NNW-SSE orientation (Fig. 18d). The change in the kinematics (e.g. from left to right lateral motion of NW-SE strike-slip faults) of the major faults is simultaneous to the onset of flexural down-bending and detachment of the Ionian subducted slab which causes the cessation of vertical axis rotation as also suggested by several authors (Westaway et al., 1993; Van Dijk and Scheepers 1995; Mattei et al., 2007; Neri et al., 2009; Maffione et al., 2013).

Figure 18

A third tectonic phase, acting during the Middle – Upper Pleistocene is inferred from NE–SW and N–S normal faults systems observed in the field at the mesoscale (Figs. 18g, h, i). This event is also recorded by the widespread Middle–Upper Pleistocene marine terraces, observed along the Tyrrhenian coastline (Fig.13; Monaco and Tortorici 2000; Cucci and Tertulliani 2010; Bianca et al., 2011). These are produced by the interaction between Quaternary sea-level change cycles and long-term tectonic uplift driven by NE–SW and WNW–ESE striking normal faults (e.g. Sant'Eufemia, Vibo Valentia and San Pietro Lametino Faults) imaged by ViDEPI seismic lines located both offshore and onshore in the western Catanzaro Trough (Figs. 12 and 13). The inferred third tectonic phase is consistent with a WNW-ESE oriented extension (Fig. 18g) as consequence of the complete or partial detachment of the Ionian subducted slab (Westaway, 1993; Wortel and Spackman, 2000; Tortorici et al., 2003; Goes et al., 2004, Neri et al., 2012). These lineaments often offset the late Quaternary deposits and are considered to be seismogenic source (Loreto et al., 2013).

During this last tectonic phase, some NE-SW elongated basins were formed within the Catanzaro Trough, including the *Lamezia Basin* (Fig. 19a). The Lamezia Basin is bounded both to the north and to the south by regional WNW-ESE trending oblique and strike-slip fault systems, and laterally by NE-trending normal faults (Fig. 19a).

The northern termination of the basin is clearly identifiable with the LCF system, whilst the southern one is more uncertain. Here, a structural high, the Capo Vaticano promontory, is present and is bordered to the south by the Coccorino and Nicotera Faults (CF&NF) system (Fig. 19a).

The NE-trending Vibo Valentia and San Pietro Lametino Faults control the evolution of the Lamezia Basin together with the Sant'Eufemia Fault. This basin arranged as a graben-like system is similar to other graben and semi-graben systems, which are widespread in the Calabrian Arc, such as the Crati graben, the Mesima graben, and the Gioia Tauro plain (Monaco and Tortorici, 2000).

The eastern basin edge is bounded by the newly identified W-dipping San Pietro Lametino Fault (SPLF; Fig. 19a), which could represent the northern propagation of the Vibo Valentia structural system, organized as a left-stepping en'echelon segment (overstepping lineaments; Peacock et al., 2000). In this way two segments can join to form a single and much longer fault (Fig. 19a; Peacock et al., 2000; Kim et al., 2004; Fossen, 2010). The asymmetric displacement between these two faults produces a folded overlap zone, namely a relay ramp (Peacock et al., 2000, Fossen, 2010) connecting two overstepping lineaments, which acts as a transfer zone. The presence of small cracks or secondary faults (*Overstepping Fault* - OF - in Fig. 19a, b, and c) across the relay ramp may suggest that the bounding faults could be connected at depth (Peacock and Parfitt 2002), even though we have no field evidence, this structure has been inferred by morphological consideration.

Figure 19

On the western edge, the Sant'Eufemia Fault (SEF) shows a normal kinematics at least since the Pleistocene time. Evidence of fault planes, with same orientation and kinematics, have been recognized even within the onshore area. This suggests that the Sant'Eufemia Fault, extending through the whole Sant'Eufemia Gulf, could also continue on-land reaching the morphological northern edge of the Catanzaro Trough and increasing the 25 km fault length, previously proposed by Loreto et al. (2013), to more than 30 km.

Based on these new onshore and offshore data, the Sant'Eufemia Fault together with the other NE-SW/N-S oriented fault systems assume a much more important role in the frame of the late Quaternary tectonics. This is in agreement with the WNW-ESE extensional regime obtained by the crustal focal mechanisms, computed for the study area by using waveform inversion methods (Li et al., 2007; D'Amico et al., 2010, 2011; Presti et al., 2013).

6. Conclusion

The Calabrian Arc is considered to be at an intermediate evolutionary stage between the still active Aegean subduction system and the mature - inactive Gibraltar Arc subduction system (Mattei et al., 2007). The integration of geological and geophysical data, acquired along the SE Tyrrhenian Sea facing the Central Calabrian Arc, allowed us to recognize at least three tectonic stages (see Fig.18). The first two are characterized by the high rate of rotation during the Late Pliocene-Lower Pleistocene. Initially, this tectonic setting favoured the development of a sub- horizontal E-W-oriented compressive P-axis. Later, during Lower Pleistocene, a change of this stress field is inferred by the ca. NNE-SSW P-axis. Since the Middle Pleistocene, a new tectonic stage characterized the western Catanzaro Trough, which highlights vertical P-axis and WNW-ESE oriented T-axis.

Finally, the NW-SE oriented faults and their associated secondary faults are responsible for opening of a E-W palaeo-strait that connected the Tyrrhenian area to the Ionian Sea during multiphase tectonics until early Pleistocene. The NE-SW and N-S fault systems bound and control the late Quaternary sub-basins, arranged as graben system (i.e. Lamezia Basin) in response to one of the last extensional stages of Tyrrhenian Sea opening.

In this scenario, the Catanzaro Trough is placed amongst two blocks: the northern and southern Calabrian Arc, which represent two different geologic sectors, evolving as two different geodynamic elements. Subduction slab behaviour and oblique continental collision further influenced and marked these differences, making the Catanzaro Trough as one of the most important place to understand the evolution of the entire Mediterranean region.

The data collected and presented in this contribution provides new insights and details about this area**,** providing valuable structural data even for a future assessment of the seismogenic potential of an area historically considered with the highest earthquake and tsunami risk throughout Italy.

7. Figures and figure captions

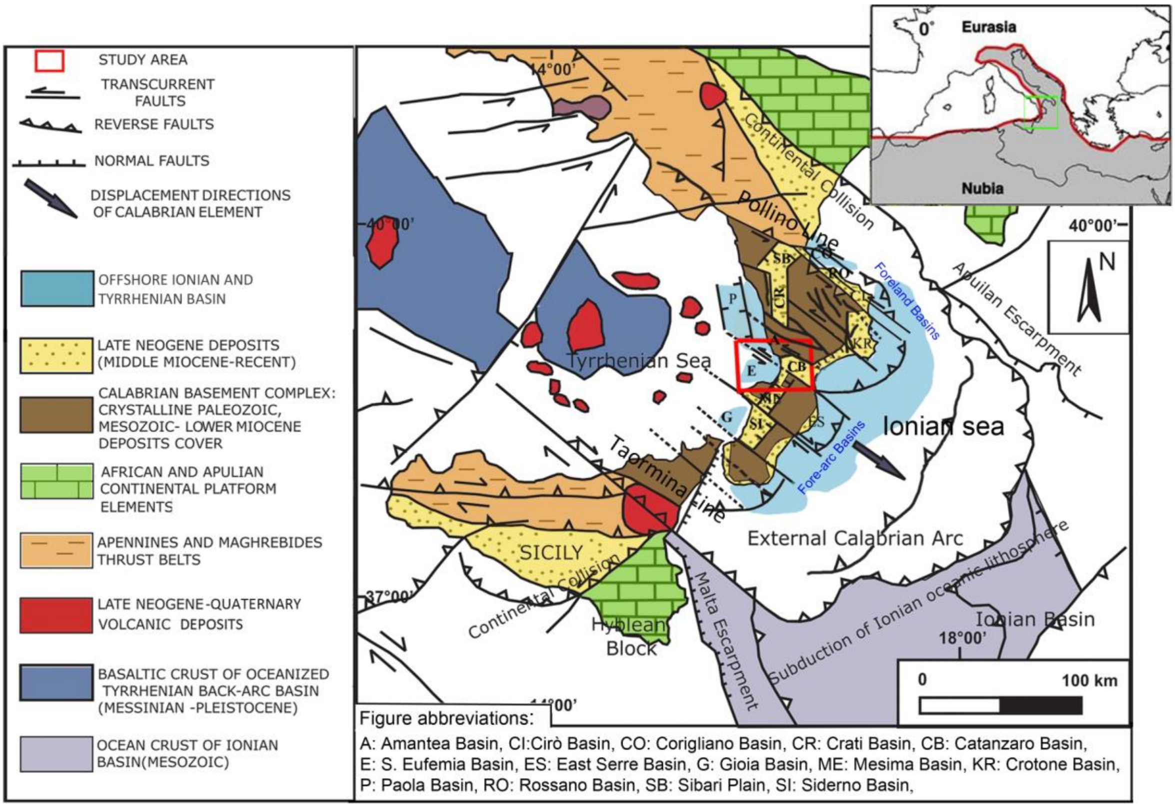


Figure 1: The geological framework of the Central Mediterranean region (modified by Van Dijk et al., 2000 and reference therein).

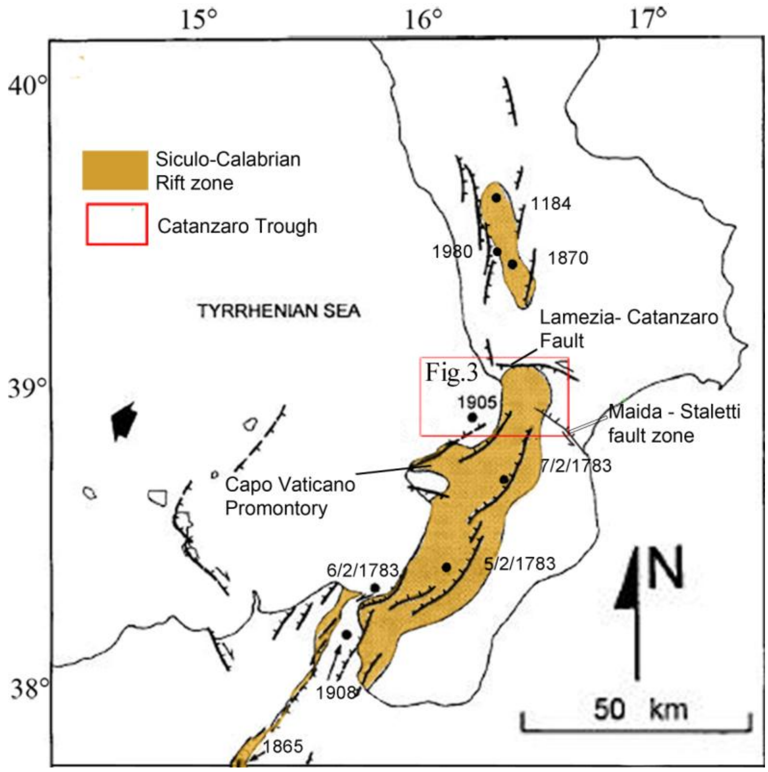


Figure 2: Historical earthquakes and faults along the Siculo-Calabrian Rift zone (modified from Monaco and Tortorici, 2000).

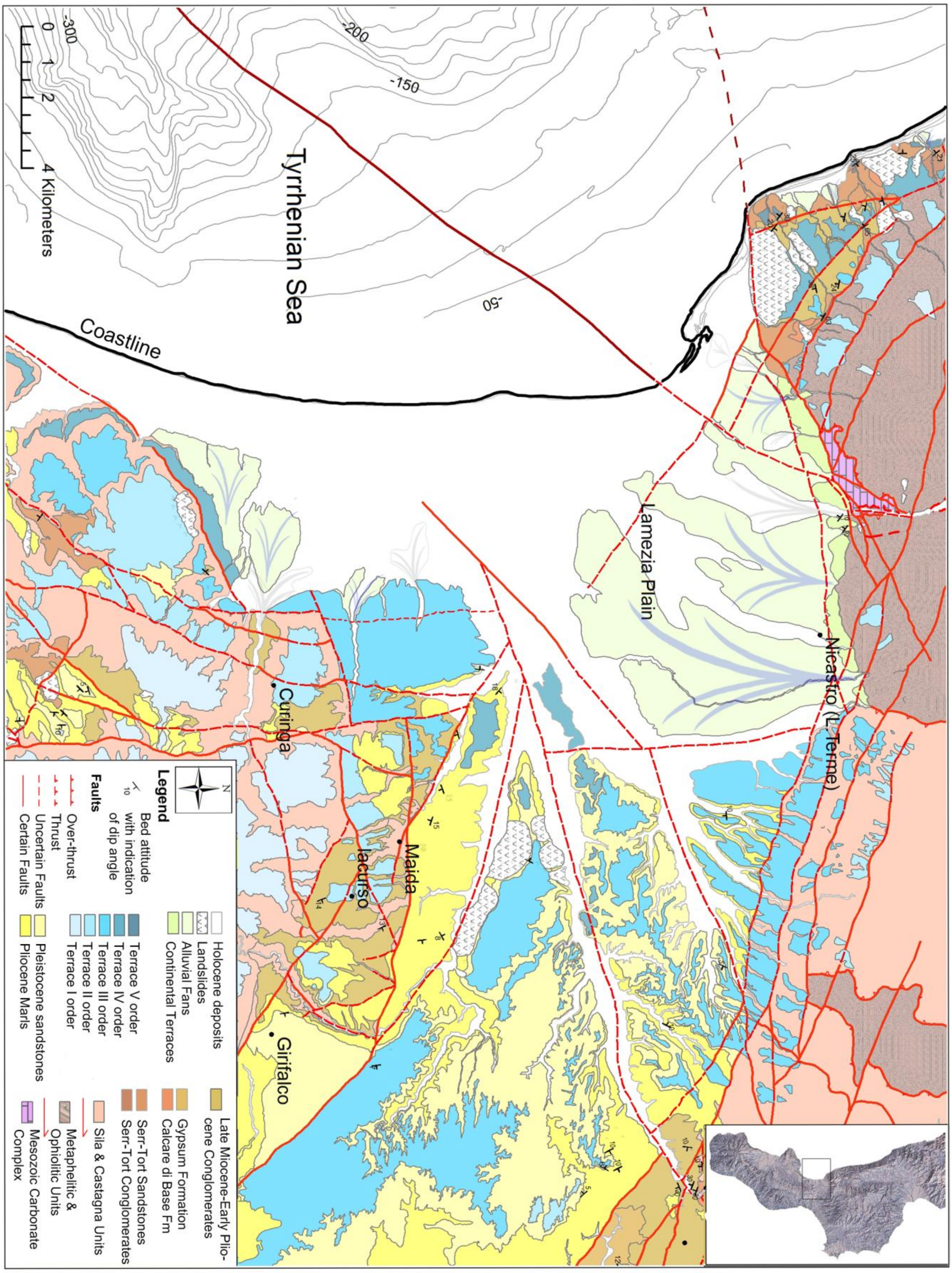


Figure 3: Geological map of the study area.

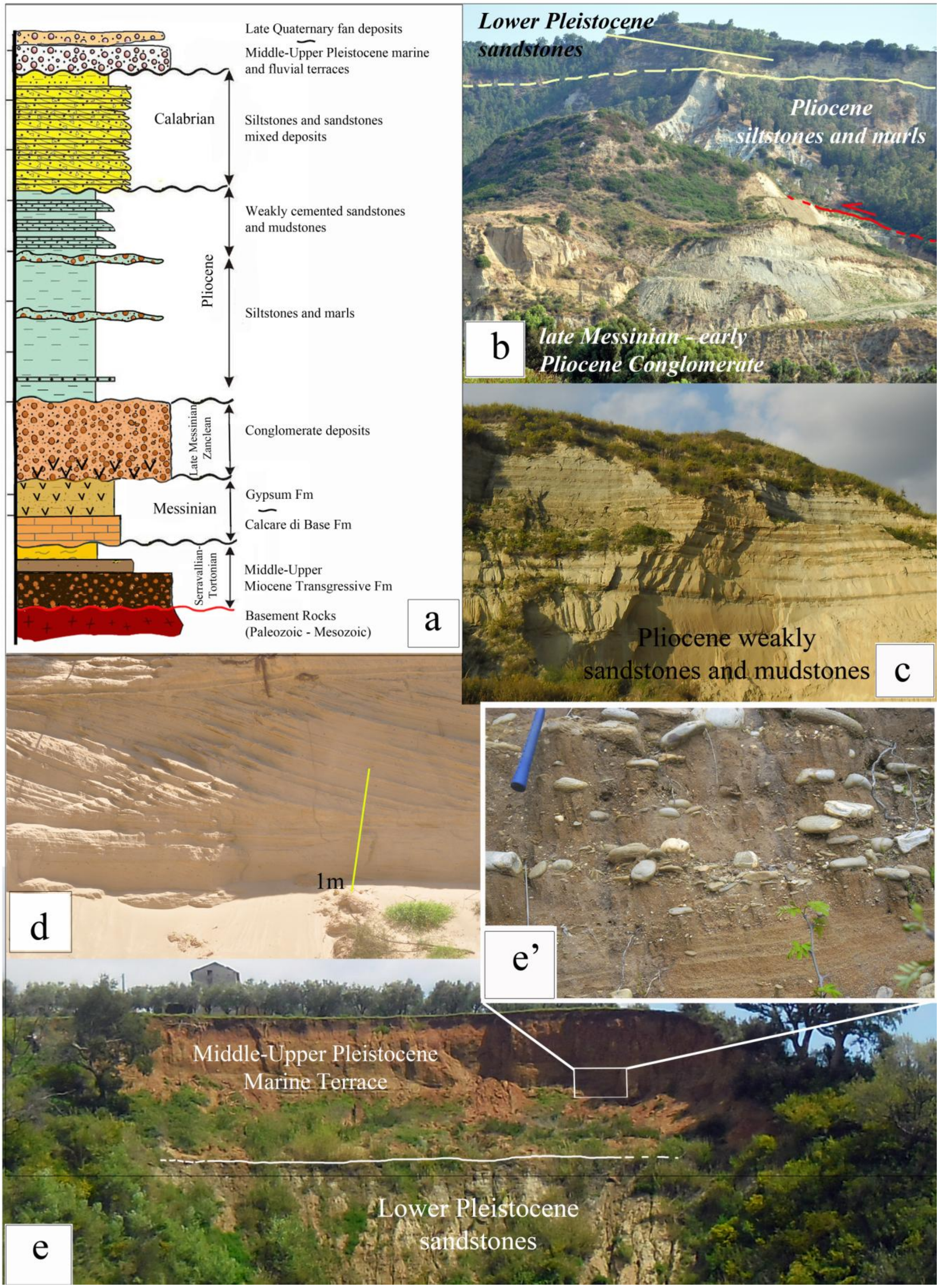


Figure 4: a) General stratigraphy of the study area (modified from Chiarella et al., 2011); b) Messinian to Lower Pleistocene units outcropping in the southeastern portion of the area, showing tectonic contact between Conglomerate

and Pliocene marls, and unconformity between Pliocene and Pleistocene deposits; c) Pliocene weakly sandstones and mudstones outcropping in the area; d) Lower Pleistocene mixed sands and sandstones showing foresets organized in trough cross-strata close to Pianopoli Village; e) Erosional contact between Lower Pleistocene biocalcarenites and sand-wave deposits and Middle Upper Pleistocene Marine Terrace, *inset* e') Detail of Middle- Upper Pleistocene Marine Terrace outcrop.

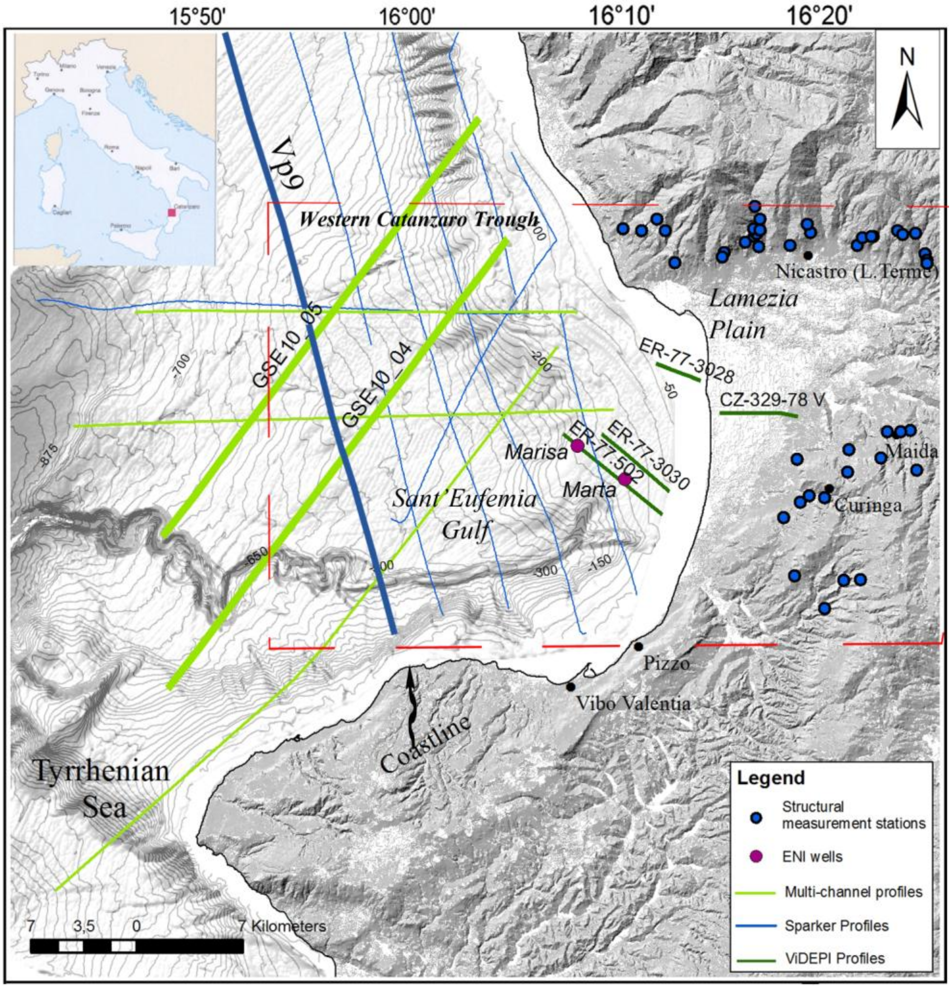


Figure 5: Location map of the multichannel seismic (MCS) profiles (light green lines; part of the ISTEGE project), Sparker profiles (blue lines; part of the VP 87 cruise I.G.M. Geological Marine Institute of Bologna onboard the RV Bannock 1987), ViDEPI multichannel profiles (green lines; ViDEPI project; unmig.sviluppoeconomico.gov.it/videpi/), and Eni wells (violet dots), and the 35 stations of structural measurements (blue dots) studied in the western Catanzaro Trough and in the Sant'Eufemia Gulf (SE Tyrrhenian Sea).

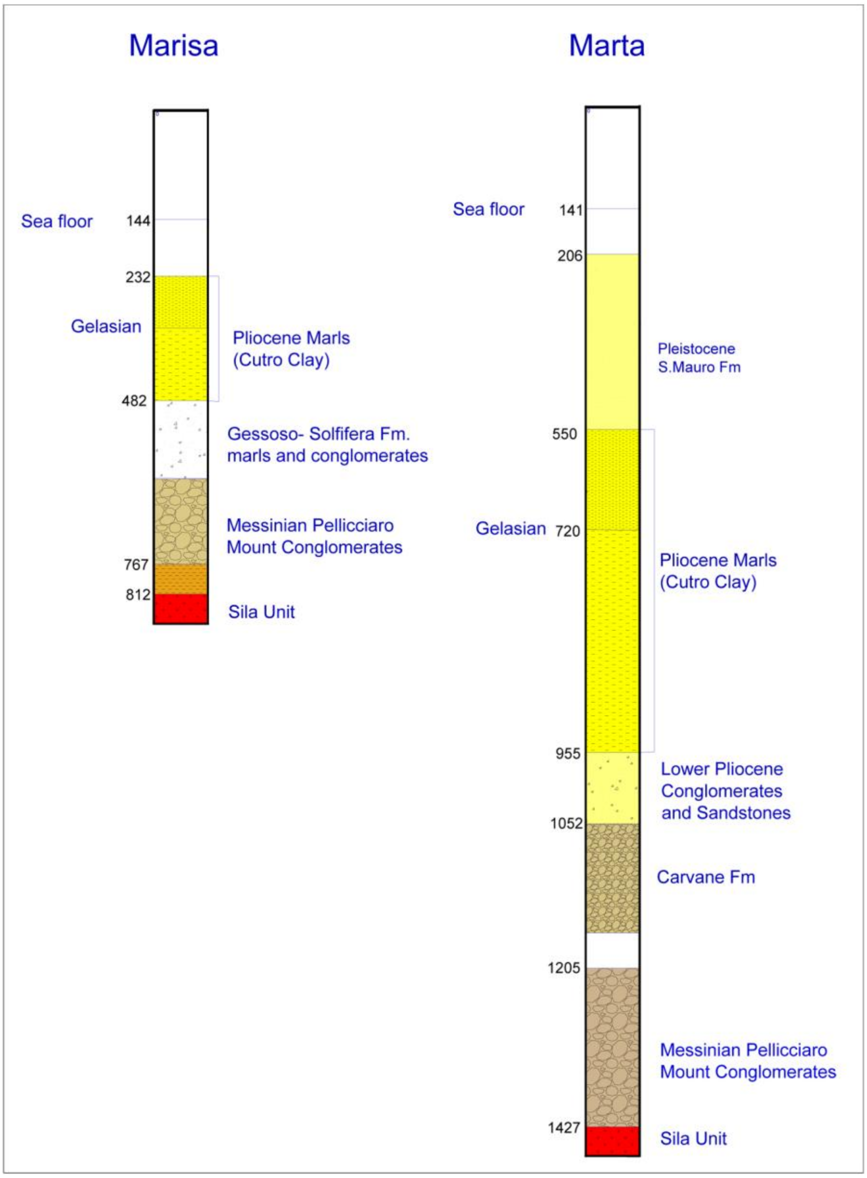
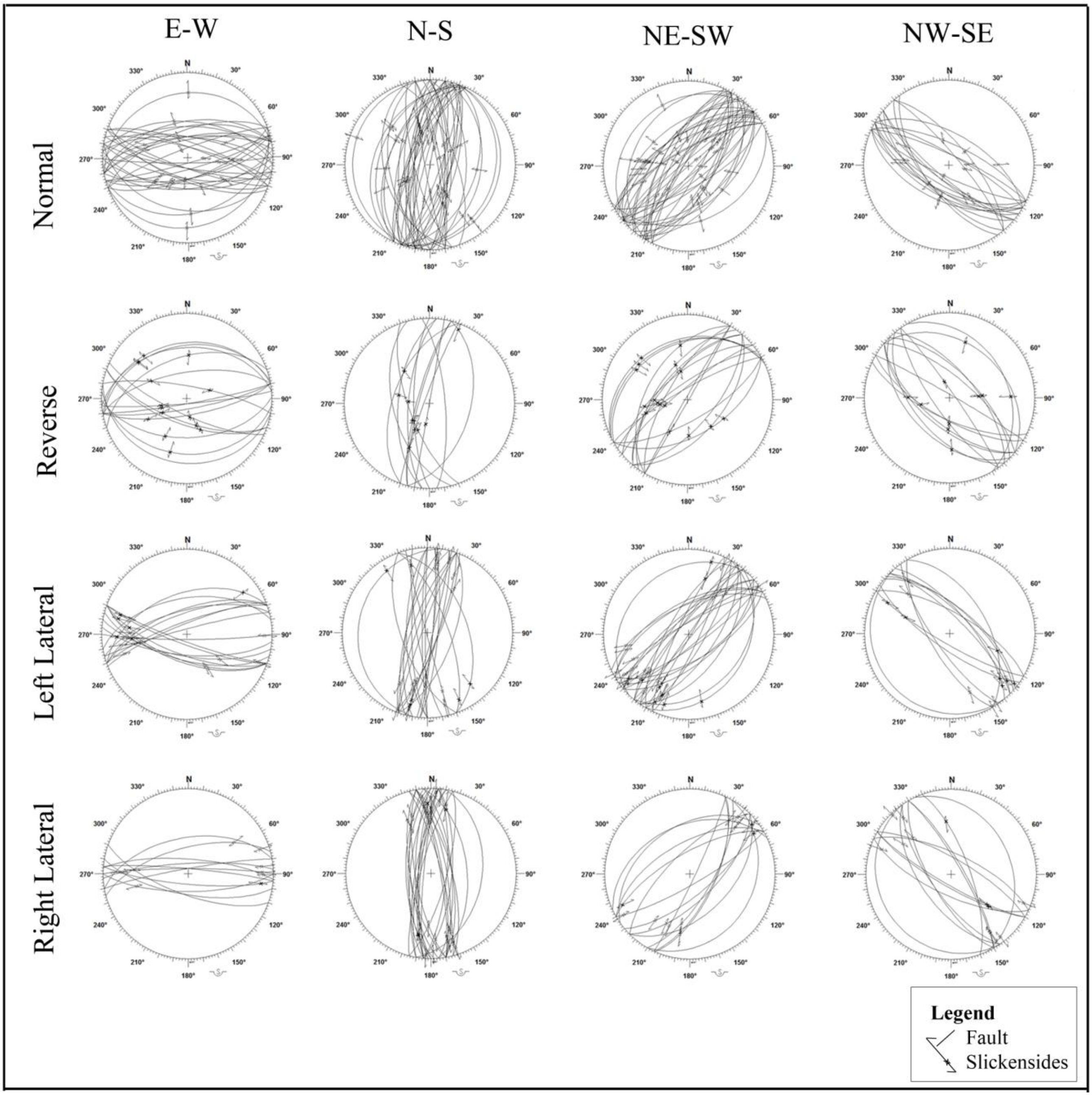


Figure 6: Stratigraphic columns reconstructed by using the Eni wells.



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530 Figure 7: Structural data of the western portion of Catanzaro Trough which show orientation and kinematics of fault

531 planes.

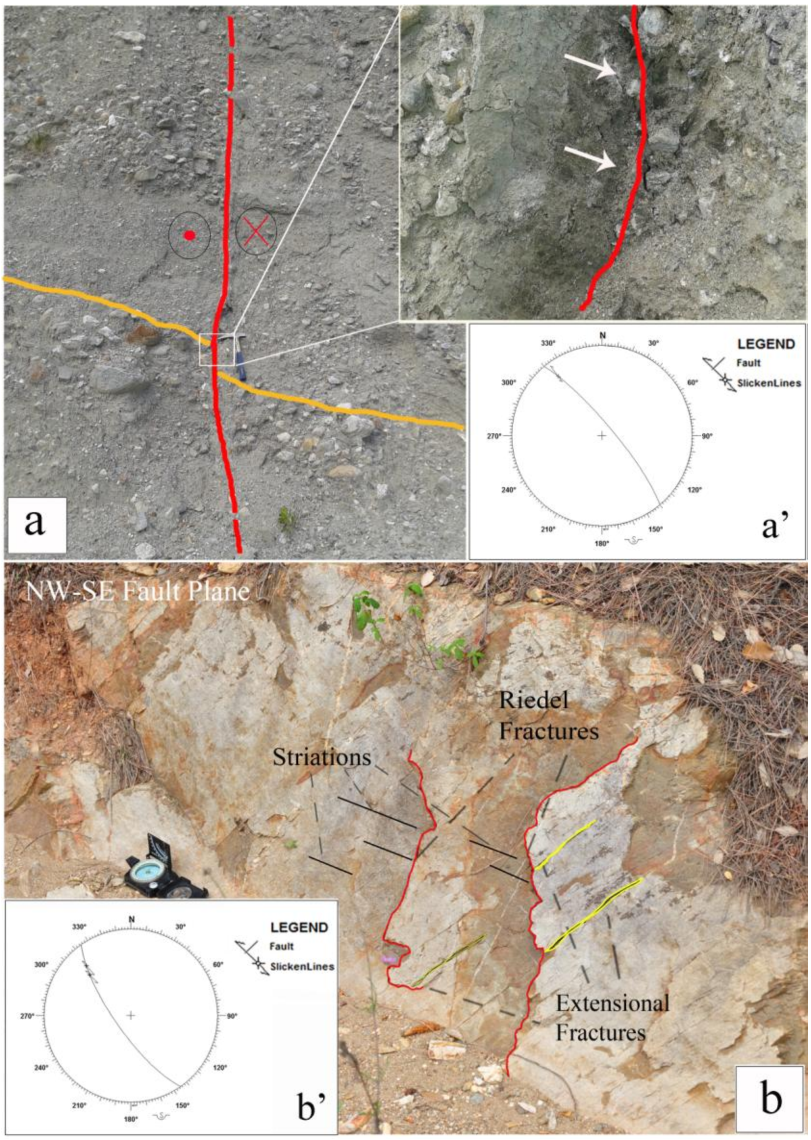


Figure 8: NW-SE left-lateral strike-slip fault planes dislocating a) Messinian conglomerate with stereographic plot in inset a' (detail in the box shows white arrows related to the left lateral kinematics) and b) basement rocks close to the Nicastro town with stereographic plots in inset b': red, black and yellow lines represent Riedel fractures, extensional fractures and striations, respectively

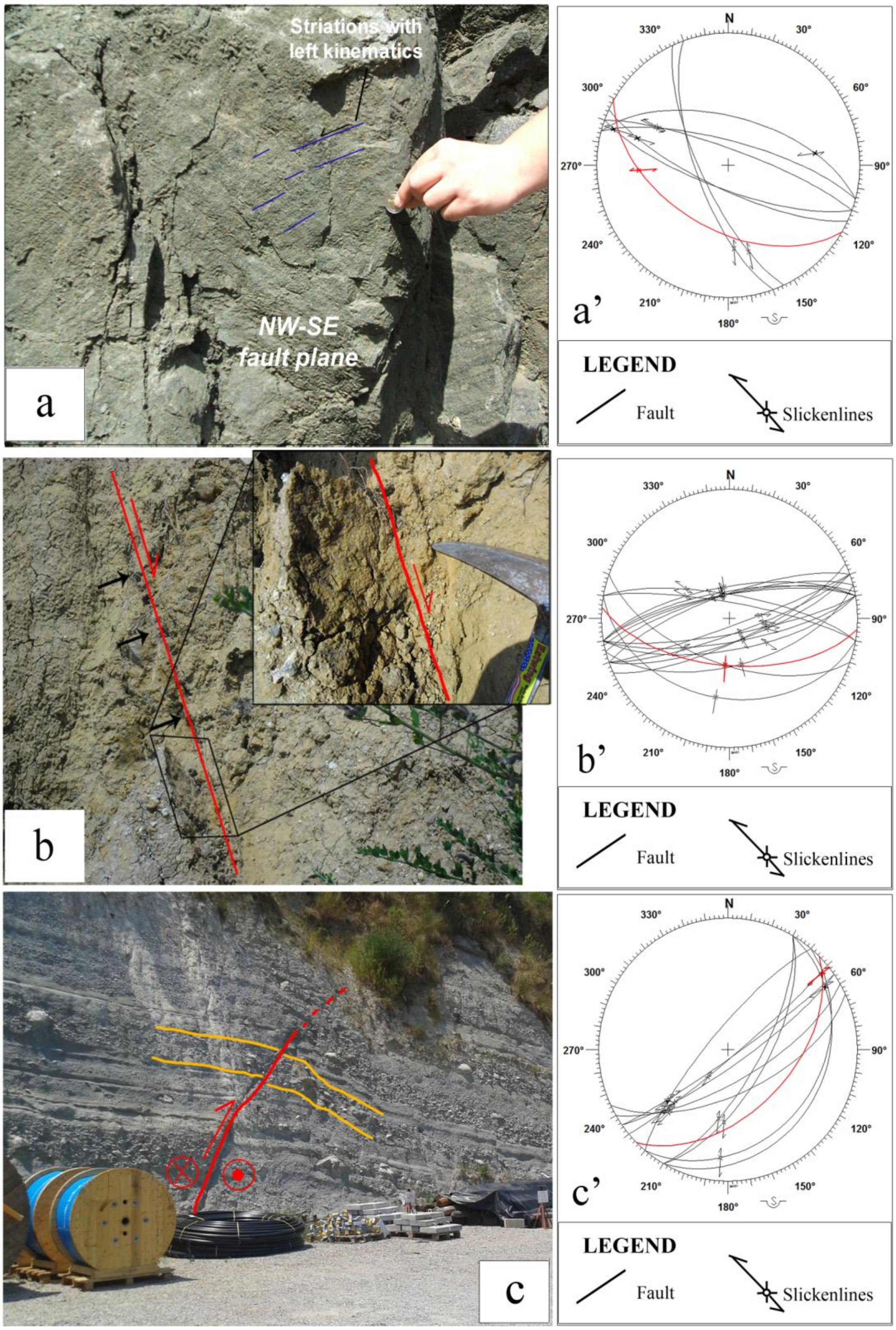
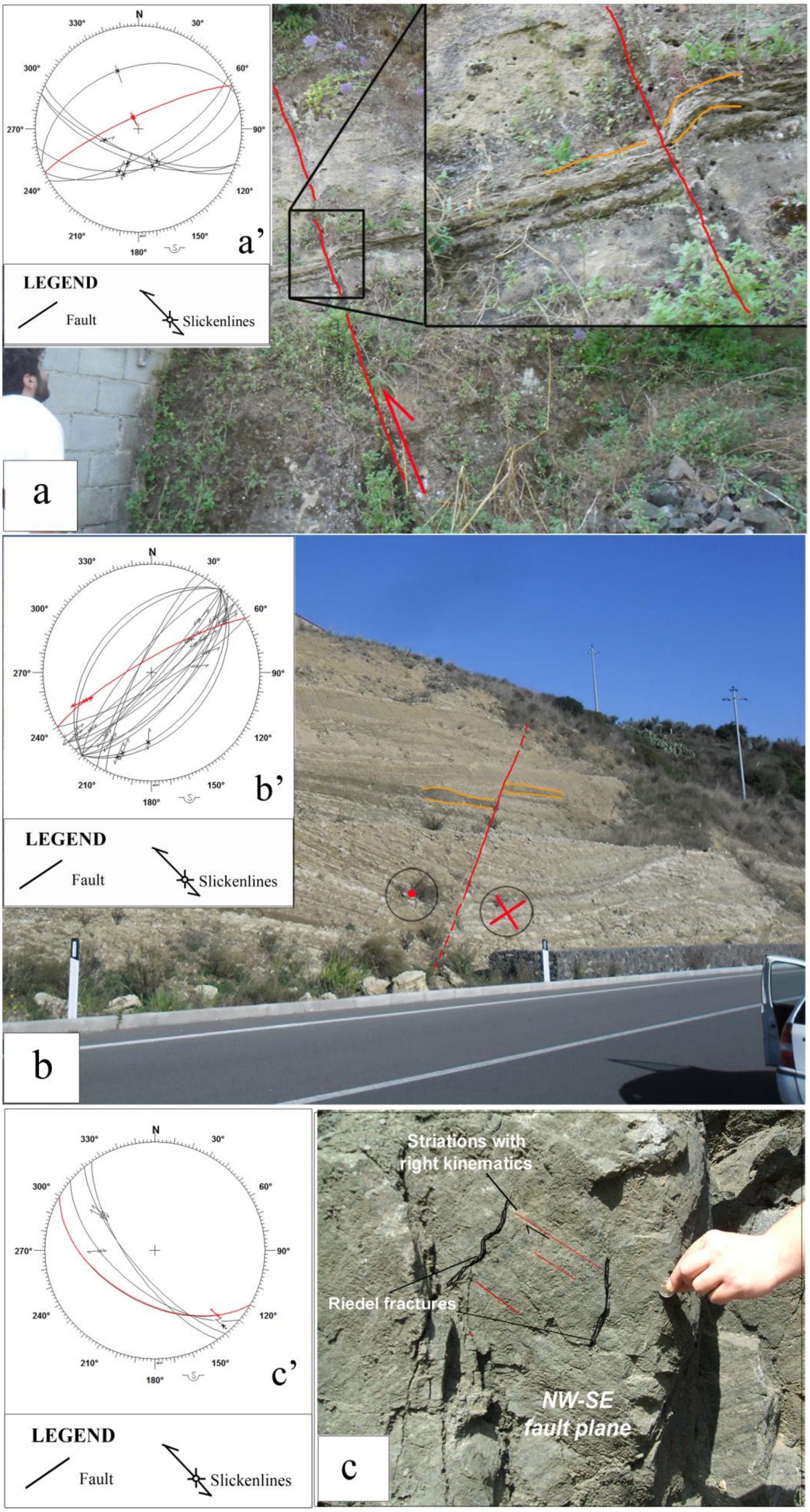


Figure 9: Fault associations offsetting the Upper Miocene -Pliocene deposits. a) NW-SE strike-slip faults showing left-lateral kinematics (blue lines), inset a') stereographic plot related to the NW-SE left lateral kinematics, red fault shows the kinematics in figure a; b) WNW-ESE and WSW-ENE extensional faults systems, inset b') stereographic plot related to the WNW-ESE normal kinematics, red fault shows the kinematics in figure b, c) NE-SW right-lateral strike-slip, inset c') stereographic plot related to the NE-SW right lateral kinematics, red fault shows the kinematics in figure c.



N
330°
30°
300°
60°
270°
90°
240°
120°
210°
150°
180°
a'
LEGEND
Fault
Slickenlines
a
b'
b
c'
c
Striations with
right kinematics
Riedel fractures
NW-SE
fault plane

Figure 10: a) WNW-ESE reverse fault, inset a’) stereographic plot related to the WNW-ESE reverse kinematics, red fault shows the kinematics in figure a; b) NE-SW left-lateral fault, inset b’) stereographic plot related to the NE-SW left-lateral kinematics, red fault shows the kinematics in figure b; and c) NW-SE strike-slip faults showing right lateral kinematics (red lines), inset c’) stereographic plot related to the NW-SE right lateral kinematics, red fault shows the kinematics in figure c

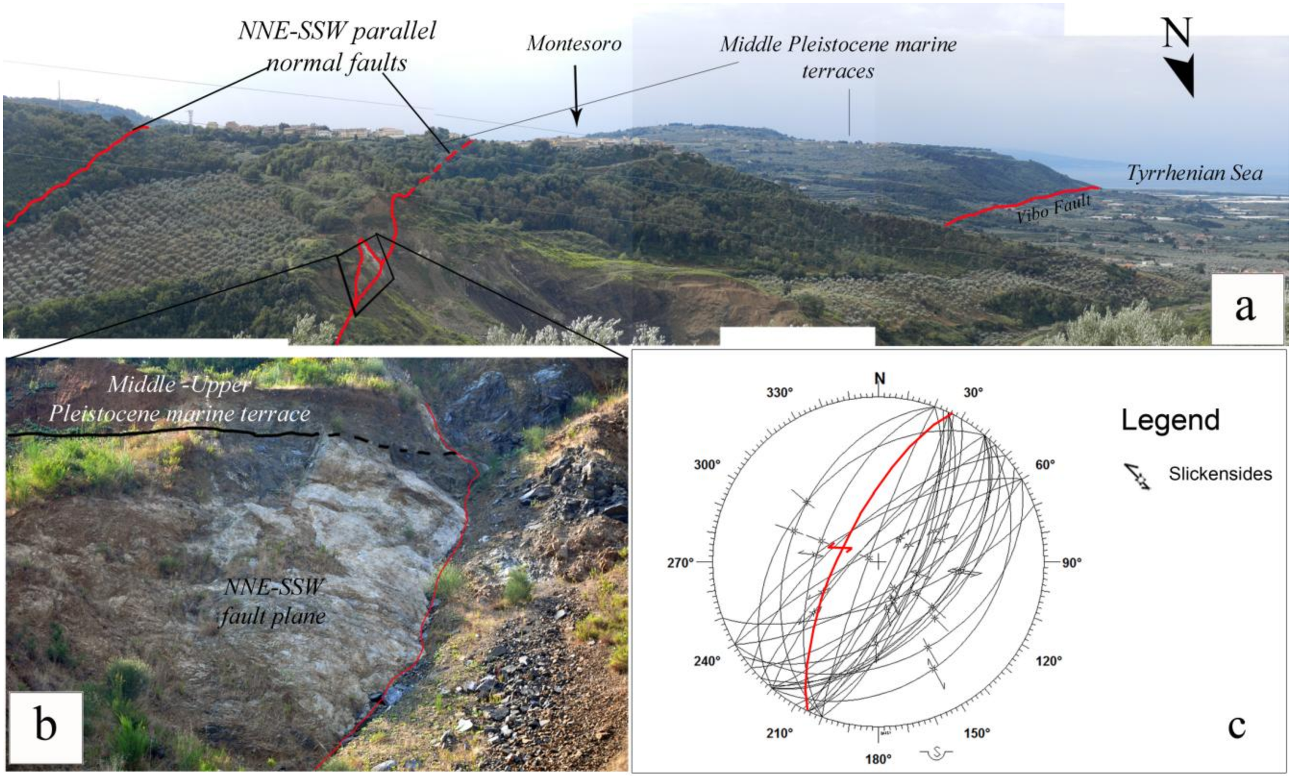


Figure 11: a) Overview of southwestern margin of the study area, b) Evidences for recent fault activation along tectonic contact between basement rocks and Pleistocene Marine Terraces, inset c’) stereographic projection of the NE-SW normal faults (red line represents the fault kinematics in Fig. 11b).

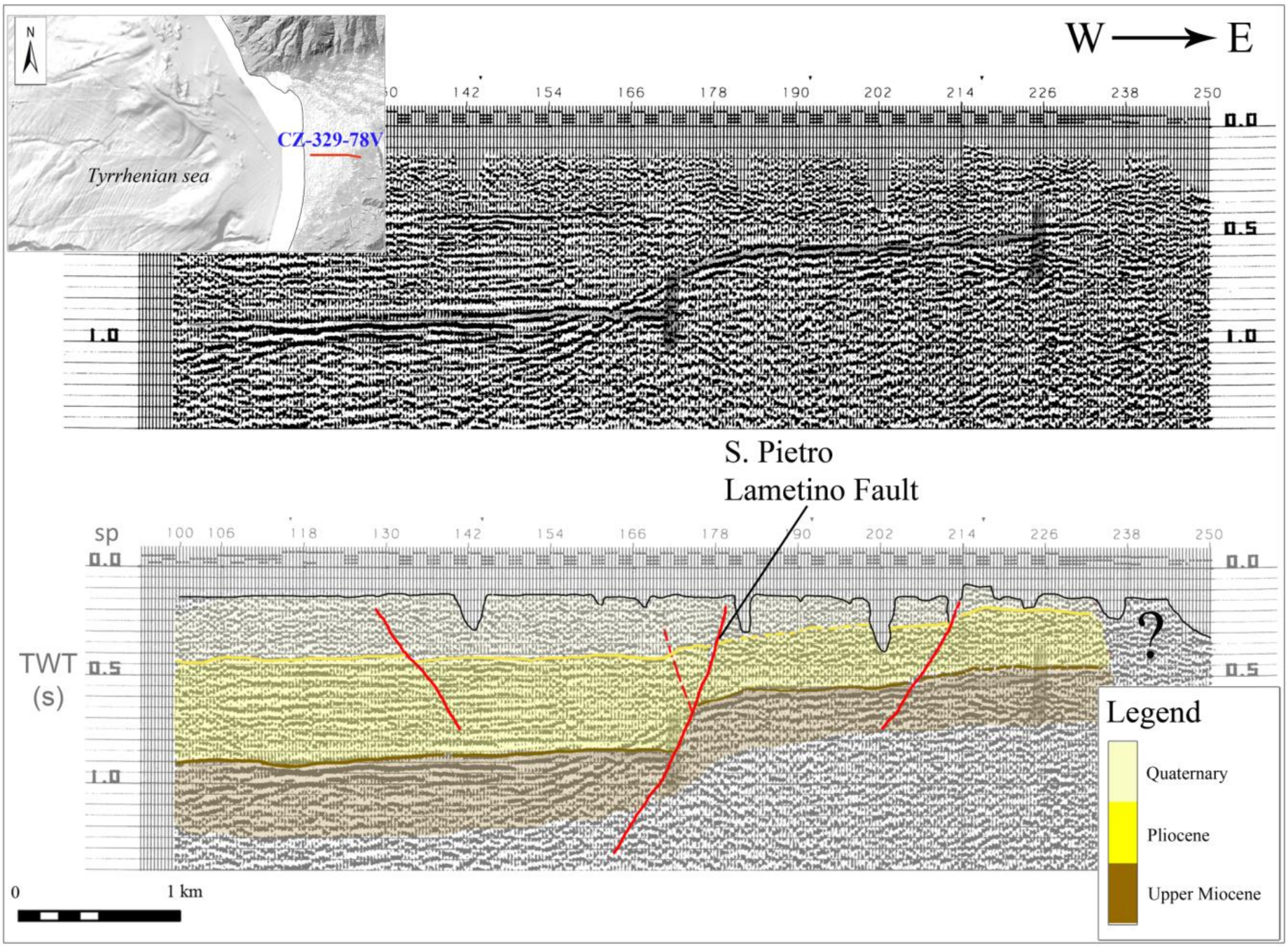


Figure 12: CZ-329-78 ViDEPI seismic profile (above) and the same with the interpretation (below), location is marked with a red line in the box. Brown line marks the top of Miocene; Yellow line marks the Pliocene-Pleistocene transition.

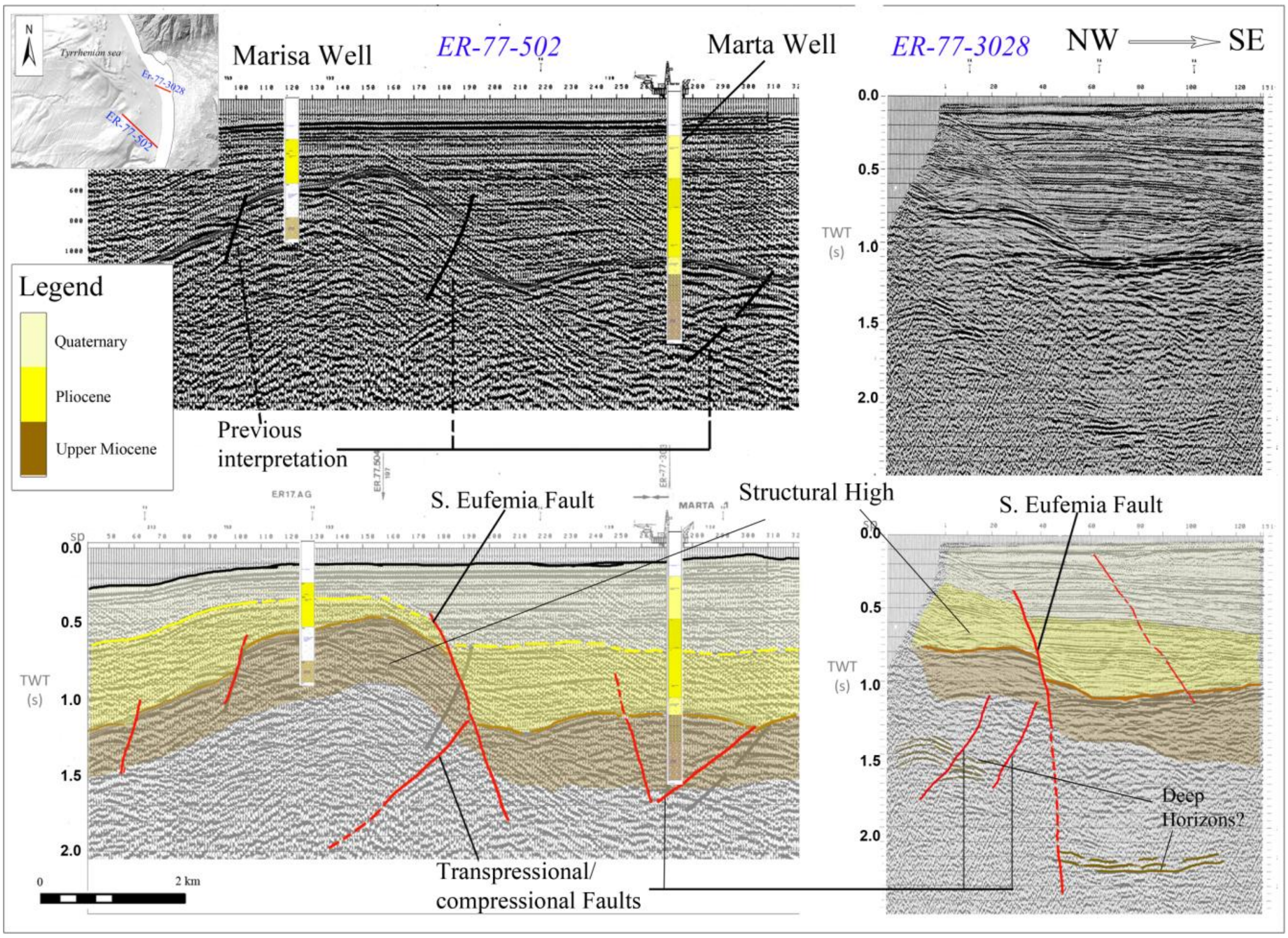
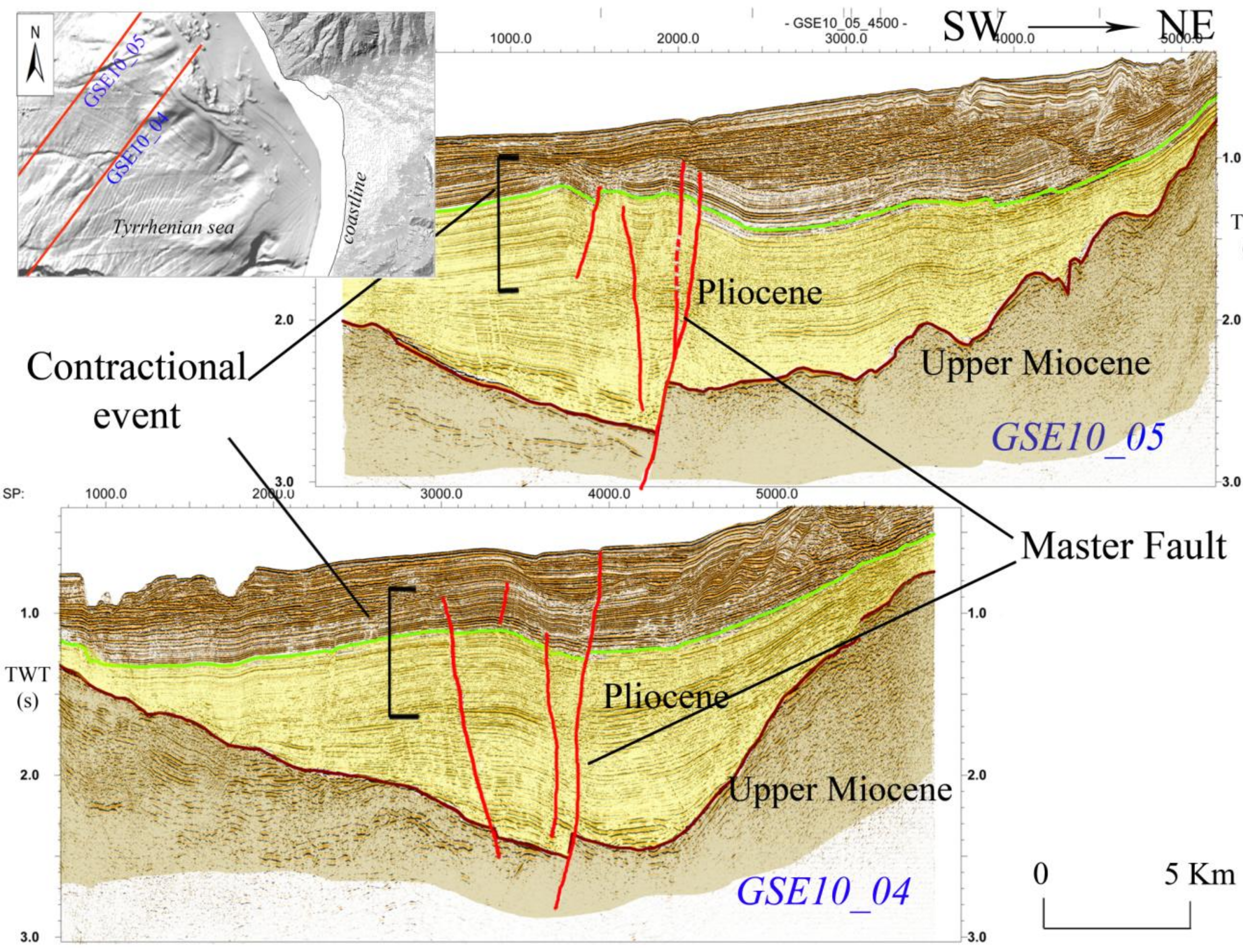


Figure 13: Two ViDEPI seismic profiles (above): the ER-77-502, on the left; and theER-77-3028, on the right, location is marked with a red line in the box. On the interpretation (below): brown line marks the top of Miocene; yellow line marks the Pliocene-Pleistocene transition.

561 

562 Figure 14: MCS profiles acquired in the frame of ISTEGE project, location is marked with a red line in the box. The
563 green and brown reflectors represent the top of the Pliocene and Miocene, respectively, whereas the red lines represent
564 the main recognized faults. The interpretation has been made by using the Kingdom software (HIS Global Inc.).

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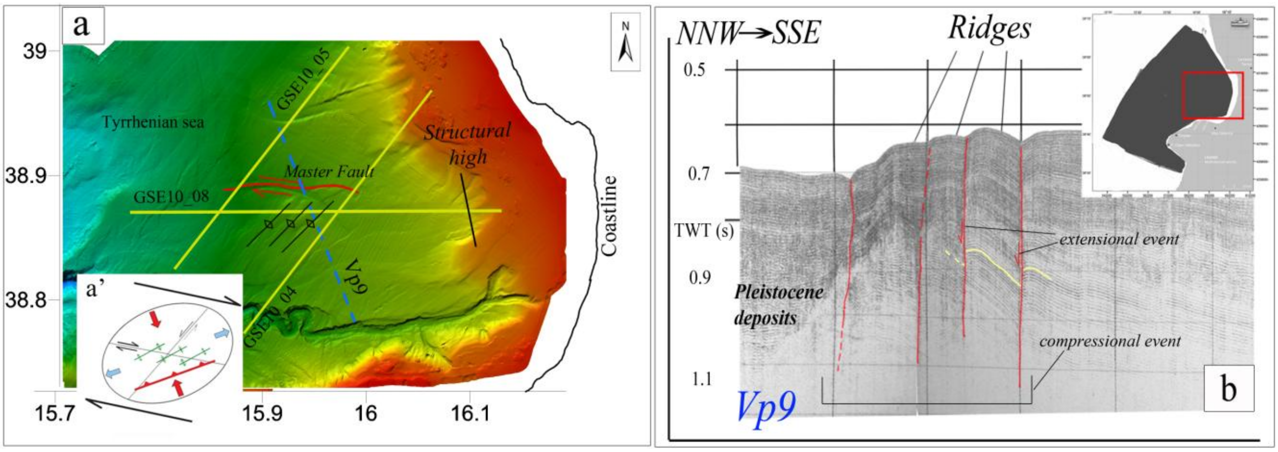
566 

567 Figure 15: a) High- resolution morpho-bathymetric map showing three small ridges, indicated with black fold axes and
568 located in center of the Sant'Eufemia Gulf. Blue dotted and yellow lines represent Vp9 Sparker and MCS profiles,

respectively, inset a') a sketch of destral stress regime, applied in the area related to Master Fault kinematics; b) Vp9 Sparker seismic profile imaging the three small tectonic ridges.

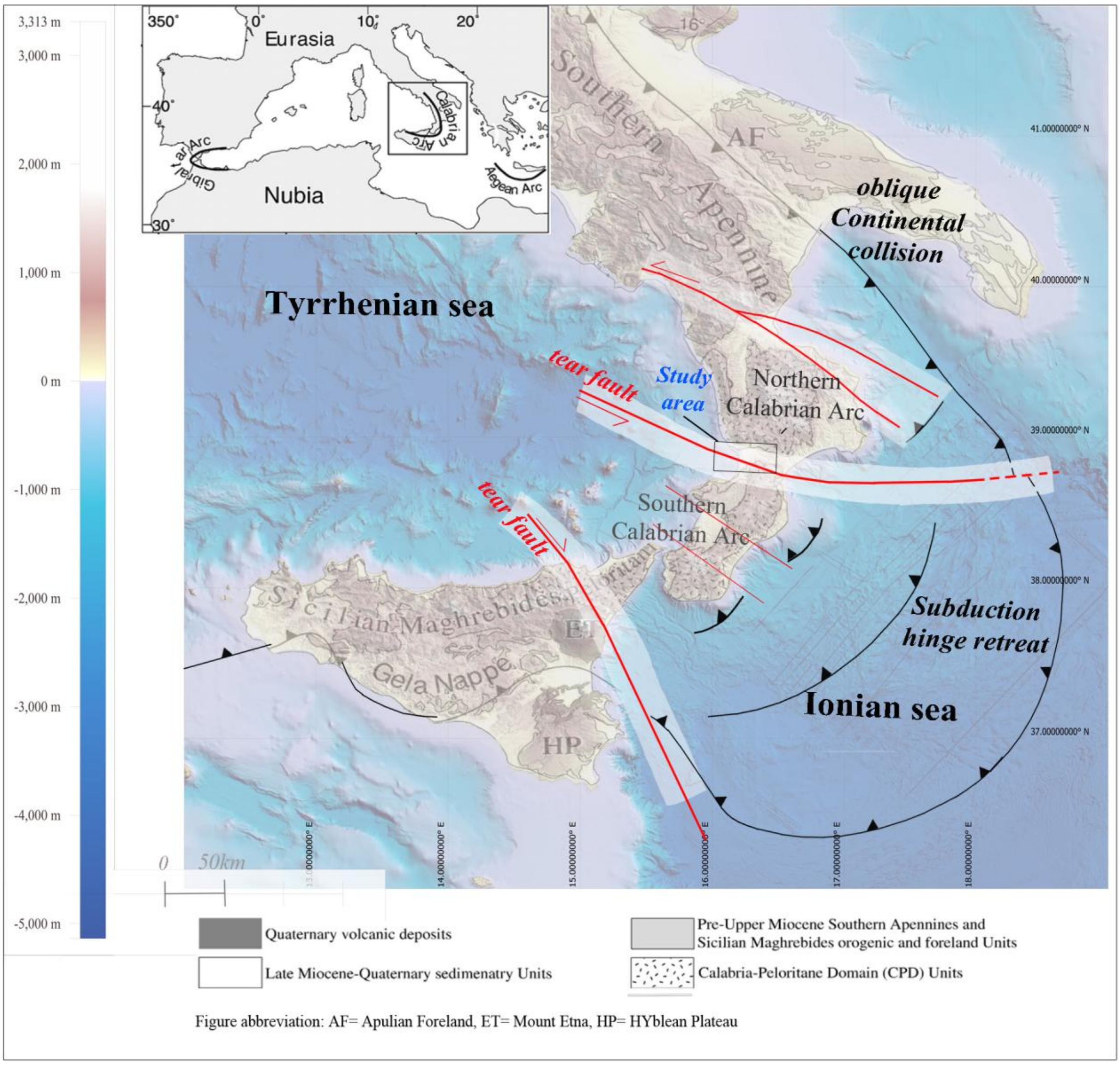


Figure 16: Western Mediterranean subduction system (inspired from Van Dijk et al., 2000; Guarnieri et al., 2006; Mattei et al., 2007; Neri et al., 2009; Cuffaro et al., 2011).

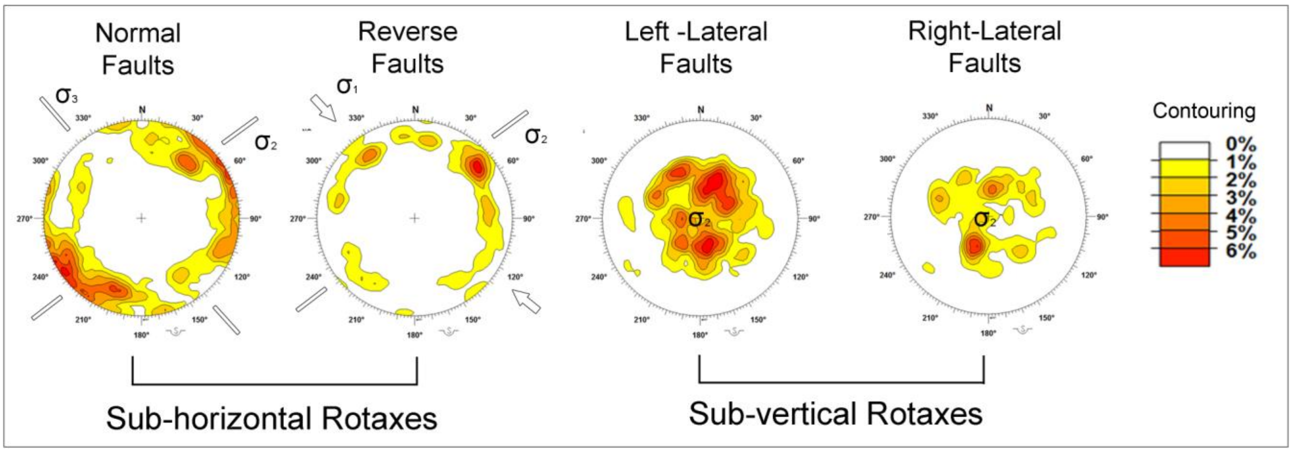


Fig. 17: Contours of the rotaxes used to discriminate the different deformational events.

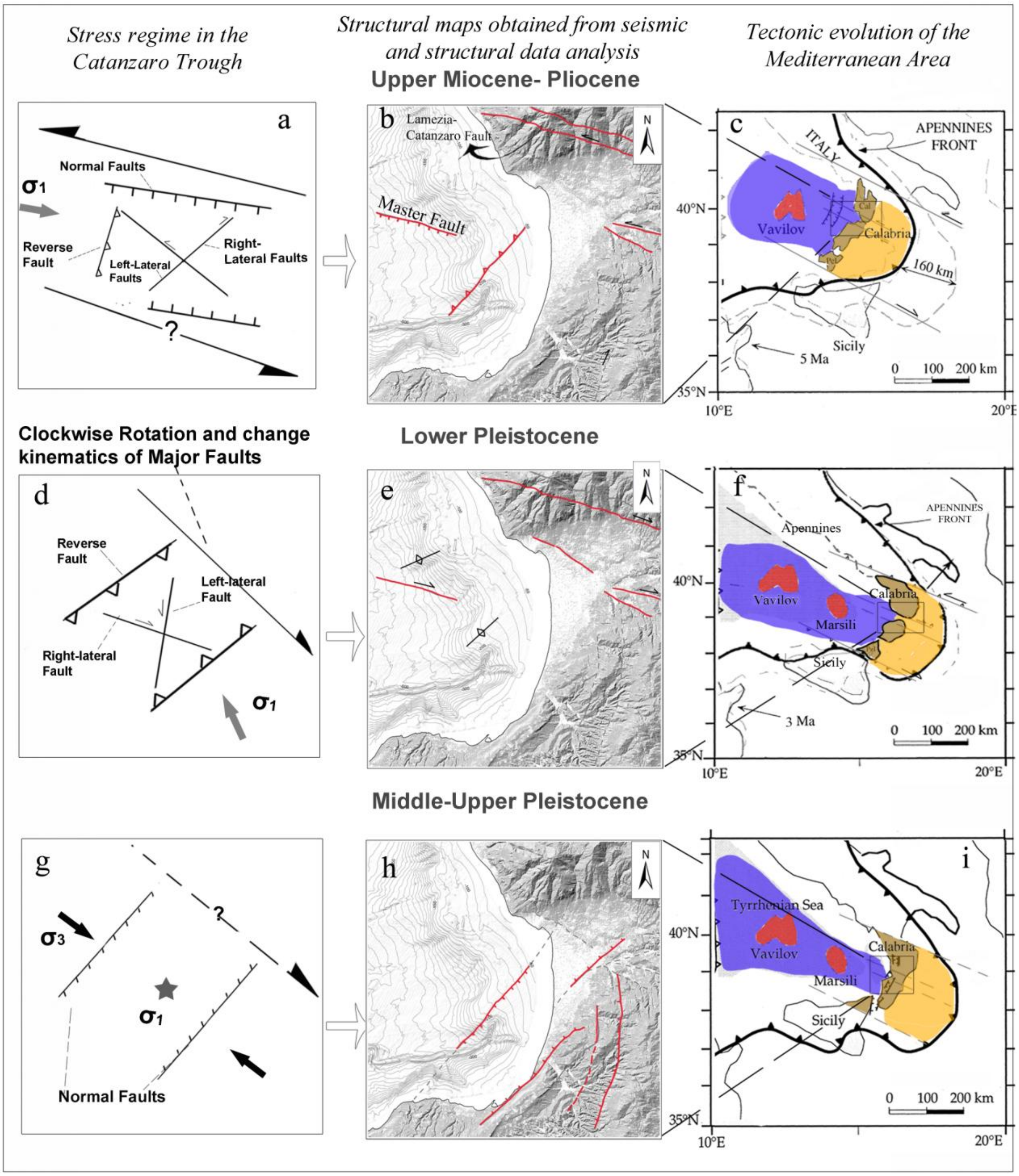


Figure 18: Palinspastic reconstruction of Catanzaro Trough and of Southern Apennine system; for more details, see the text (inspired in Gueguen et al., 1998; Zecchin et al., 2015).

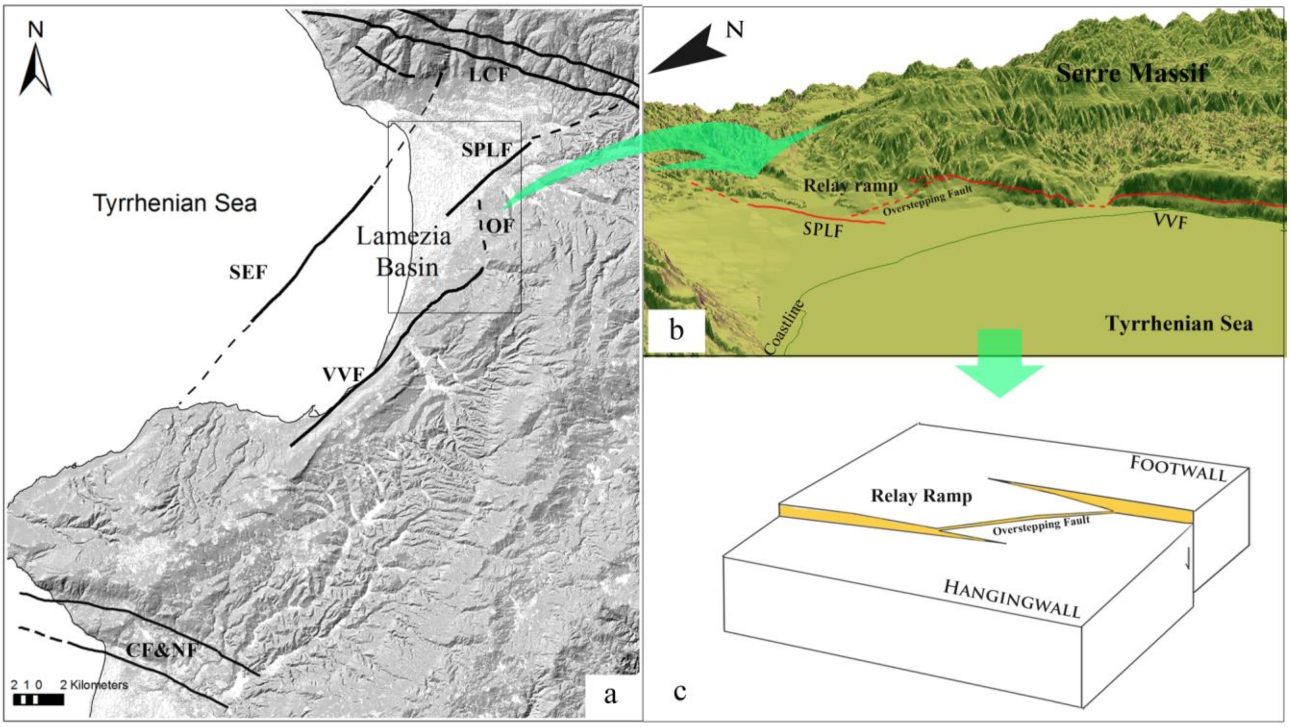


Figure 19: a) Structural map of Major Faults: (LCF) Lamezia –Catanzaro Fault, (SEF) Sant'Eufemia Fault, (SPLF) San Pietro Lametino Fault, (OF) Overstepping Fault, (VVF) Vibo Valentia Fault, (CF&NF) Coccorino & Nicotera Fault. b) Hillshade of morphological map along Vibo Valentia and San Pietro Lametino Faults, c) Schematic representation of relay ramp (Peacock & Parfitt 2002).

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