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STRUCTURAL AND SEISMOLOGICAL CLUES FOR A LITHOSPHERIC SCALE TEAR FAULT SYSTEM IN CENTRAL-EASTERN SICILY (ITALY)

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Introduction. The convergence between Africa and Europa plates in the central Mediterranean is currently controlled by the NW-wards sink down of the Ionian oceanic lithosphere and its rolling-back (Faccenna *et al.*, 2004). This process, together with the SE spreading of the Calabrian Arc, implies the propagation of intraplate/interplate transfer fault zones. The latter commonly nucleates at the edges of the subduction system and can also propagate in the overriding plate resulting in scattered shear zone segments at the surface. Deformation at slab edges depends on the dynamics of the lower plate whose rolling-back account for detaching along ocean-continent transition and resulting in lithospheric scale tear faults (STEP, Subduction Transform Edge Propagator; Govers and Wortel, 2005). For decades, many researchers have been seeking for STEP at the western edge of the Ionian subduction system (e.g. offshore eastern Sicily), most of which have favored the Malta Escarpment (Argnani and Bonazzi, 2005; Govers and Wortel, 2005; Argnani, 2009) or others normal faults imaged by seismic profiling inside the Ionian accretionary wedge (Polonia *et al*., 2011). However, as postulated by Govers and Wortel (2005), a STEP fault propagates continuously with shallow expression (in the upper plate) that consist of kilometers scale topography in the landscape and progressive wrenching and structural rotations along its path, all characteristics that have never been reported for the supposed STEPs along the Sicilian-Calabrian collision/subduction system.

Recently, high-resolution bathymetry and seismic profiling (Gutscher *et al*., 2014) provided evidences for a ~ 90 km long NW-SE oriented strike-slip fault in eastern Sicily offshore. The authors have accounted this as an active STEP segment pointing straight towards the central part of the Etna volcano.

In this work, we provide clues for a lithospheric scale tear fault system slicing through all over the central-eastern portion of the Sicilian Fold and Thrust Belt through a preliminary analysis of large scale geological features, new field investigations and seismological data.

Tectonic background. In the central Mediterranean, several crustal compartments of a former paleogeographic configuration have been involved in the long-lived convergence between African and European plates (Dewey *et al.,* 1989). In this scenario, blocks with distinct thickness and rheology favoured the setting of collisional/subduction zone with associated accretionary wedges and the development of a complex back-arc/fore-arc/trench system (Scandone, 1979; Malinverno and Ryan, 1986; Patacca and Scandone, 1989, Faccenna *et al*., 2004). The latter's include the Tyrrhenian stretched area, the Ionian subduction complex and the orogenic domains, represented by the Sicilian collision zone and by the Calabrian Arc. The occurrence at the same time of collisional, subduction and back-arc extension reflect on the dynamics of this part of central Mediterranean in which different stage of contractional and/or transpressional and extensional deformation took place from early Miocene to recent times.

Recent geophysical exploration of the Central Mediterranean (Finetti *et al*., 2005) highlight that along the southern Tyrrhenian coast, collisional and subduction processes took place contemporaneously. The subduction beneath the Calabrian Arc (Malinverno and Ryan, 1986) and collision to the west resulted in the development of transfer faults, at the plate boundary or along the orogenic hinge, which have accommodated the differential advancement of the unconstrained Calabrian Arc. This regional deformation process took place in the Sicilian collision zone with the nucleation of dextral ~NW–SE trending transcurrent faults.

This structural picture is corroborated by the present-day distribution of crustal and shallow seismicity, in which focal mechanisms are mostly characterized by strike–slip, normal and reverse-oblique kinematics compatible with low-dip NNW–SSE to NNE–SSW trending P-axes (Neri *et al*., 2005).

Geological data. Between the Madonie Mts. range and Mt. Etna in eastern Sicily, major NE-SW trending Mio-Pliocene compressive structures (thrust-top and related syncline) are systematically dragged and rotated according to the vertical axis until to assume a hook-shape at their terminations (Fig.1). Although this type of deformation are common in rotational thrust sheets such as the Sicilian Fold and Thrust Belt (SFTB), the geometric setting and the clockwise sense of rotation of such major structures suggests the occurrence of a regional, near 100 km long, dextral bounding fault with a NW-SE direction. Detailed field surveys performed in key sectors revealed that hook-shape geometry is accompanied by strike-slip faulting with right-lateral motion (see Barreca and Monaco, 2013). In the north-western sector (e.g. Madonie Mts.), fault segments show mainly normal-oblique motion and are responsible for the extreme (about 1500 m) down-faulting (zone of Castelbuono town) of the Madonie Mts carbonate units.

In the central sector, Neogene thrust and basins formed by the SE-wards migration of the orogenic system are dragged at their NE termination. This process involves three thrust-top basins of the SFTB (the Gangi, Nicosia and Centuripe synclines) with different degree of rotations. The decreasing of the amount of structural rotations toward the SE (see inset in Fig. 1) suggests a progressive tip propagation of the bounding wrench fault. The south-eastern sector of the fault zone (Mt. Judica area, see Fig.1 for location) is characterized by the occurrence of

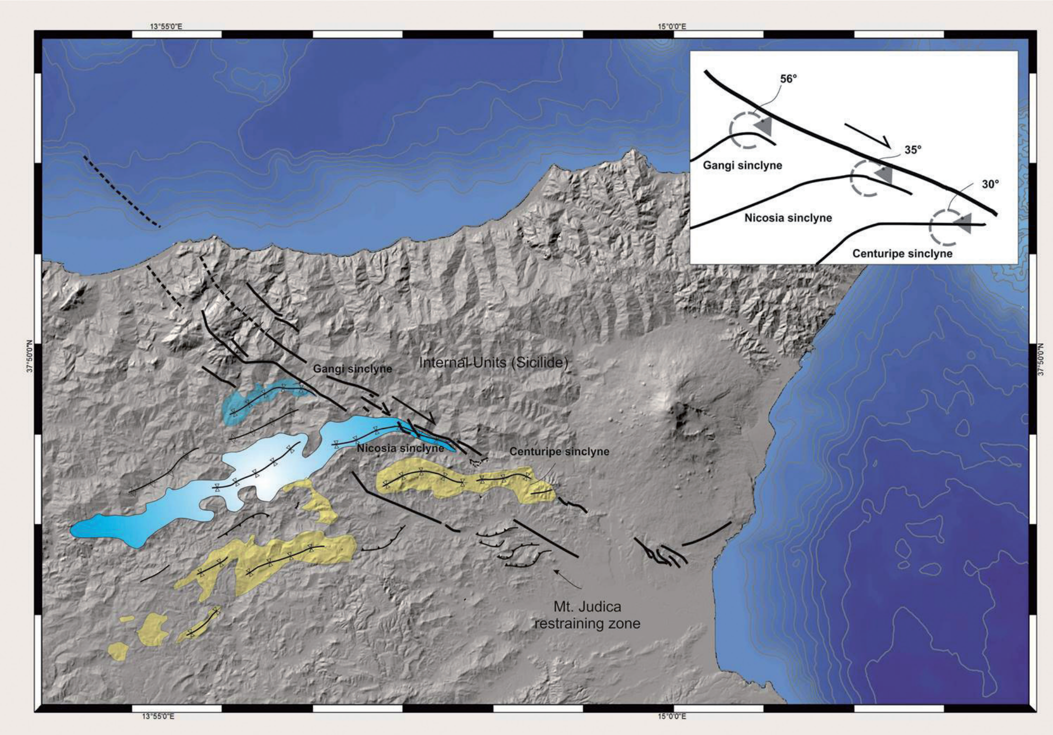

Fig. 1 – Shaded relief rapresentation of central eastern Sicily with draped the major Mio-Pliocene compressive structures (thrust and synclyne). These tectonic features show a hock-shape geometry at their NE termination. This geometric configuration has been related to clockwise structural rotations developed alongside bounding wrench fault.

discrete segments of right lateral strike-slip faults that appear to control the path of major rivers and the clockwise rotations of previous structures. The left-stepping en-chelon configuration of some segments in the Mt. Judica area produced push-up structures such as thrust-related ridges (Monaco and De Guidi, 2006).

Seismological data. In order to study the seismotectonic pattern of the studied region, we worked on a seismic dataset extracted from the Italian seismic database of Istituto Nazionale di Geofisica e Vulcanologia (available online at http://csi.rm.ingv.it/ and http://bollettinosismico.rm.ingv.it/index.php for the 1981–2001 and 2003–2012 periods, respectively). Selected earthquakes, with minimum 10 P- and S-wave readings and magnitude of 1.0, were used as data source for a simultaneous inversion of a 3-D velocity structure and the hypocentre parameters. This resulted in more accurate foci locations and into mapping the velocity anomalies, which, being strictly dependent on the crustal structure, is of help in the seismotectonic interpretation.

The seismic velocity modelling of Sicily was carried out by applying the LOTOS algorithm by Koulakov (2009). This code, which allows to determine the VP, VS and VP/VS, has some important features, such as quasi-continuous parameterization, which makes the resulting model grid independent. In particular, the grid nodes are installed according to the distribution of rays in the 1D model. The spacing of the grid is kept considerably smaller than the expected size of the anomalies in order to reduce the bias of the resulting models due to the grid configuration. Moreover, in order to further decrease the influence of the parameterization on the results, the inversion is repeated using several grids configurations with different basic orientations (e.g., 0°, 22°, 45°, and 66°). The results obtained for these grids are combined into one model by simple averaging. The obtained velocity images and the foci distribution depict a relevant

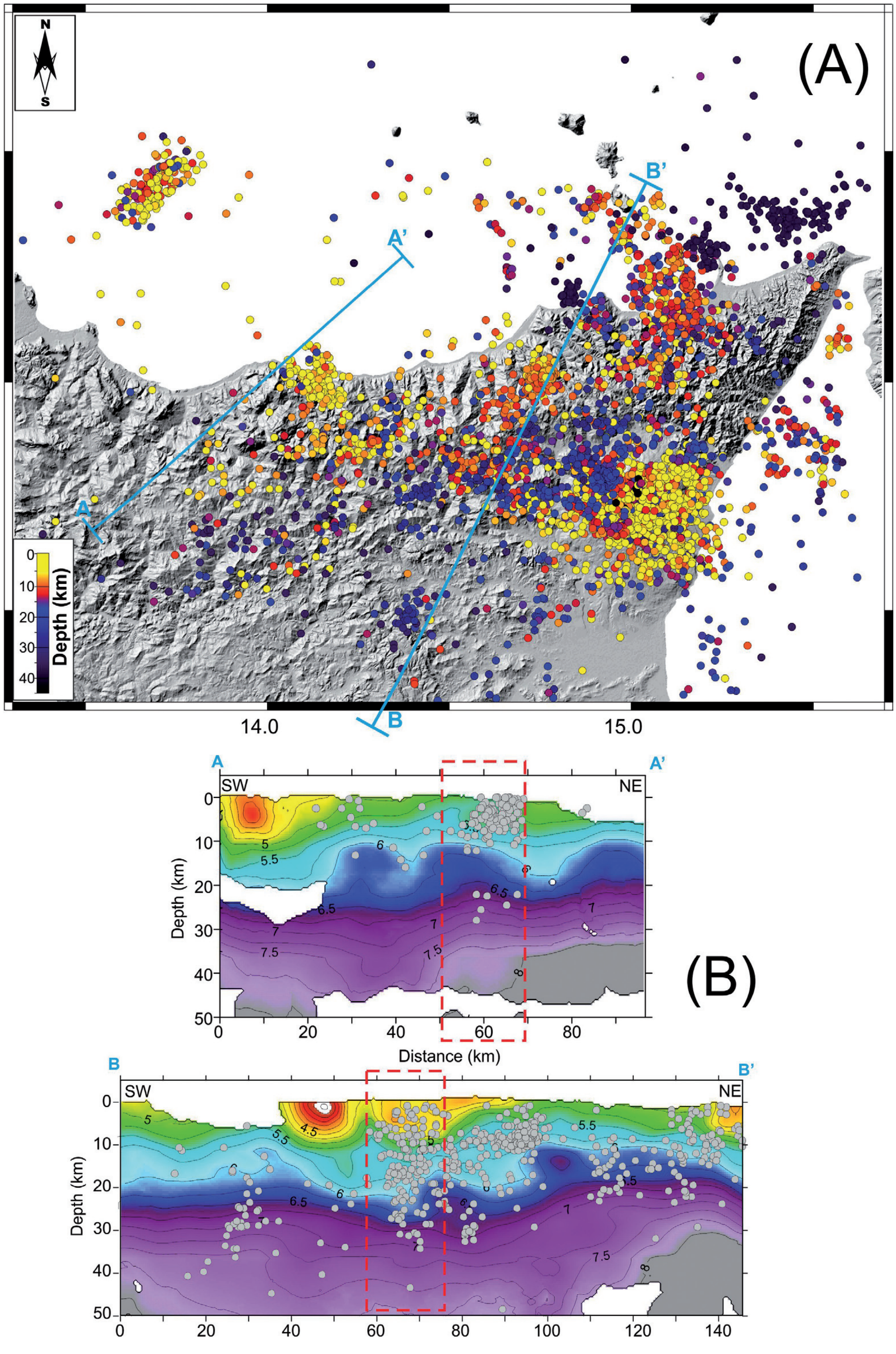

Fig. 2 – A) Map view and depth distribution of the earthquakes selected for the tomographic inversion. B) Vertical sections through the VP model. Contour lines are at an interval of 0.25 km/s. Relocated earthquakes, within +10 km from the sections, are plotted as gray circles. The traces of the sections are reported in the map.

NW-SE oriented seismic boundary, roughly located between Cefalù and Mt. Etna volcano. In particular, this boundary splits a sector with high concentration of earthquakes northwards from a zone with relative paucity of seismicity southward (s ee Fig. 2 A). The possible presence of a major structural discontinuity is emphasized also by lateral velocity perturbations found in the same area and visible down to about 20-30 km of depth (Fig. 2 B). Moreover, looking to the vertical cross-sections, the obtained velocity structure clearly points out to a crustal thinning; i.e., high velocity layers are shallower towards northeast.

To further investigate this issue, we considered the kinematics characterizing the events located in the studied seismic sector, analyzing the focal mechanisms available in the Sicily and Calabria focal mechanism database by Scarfì *et al.* (2013), including some data from Neri *et al.* (2005) and from Musumeci *et al.* (2014). All types of mechanisms are represented, although it is noteworthy that the land stripe between Cefalù and the Ionian Sea is characterized by a strike-slip regime (Fig. 3), while further northeast normal type focal mechanisms prevail, with nodal planes striking NW-SE.

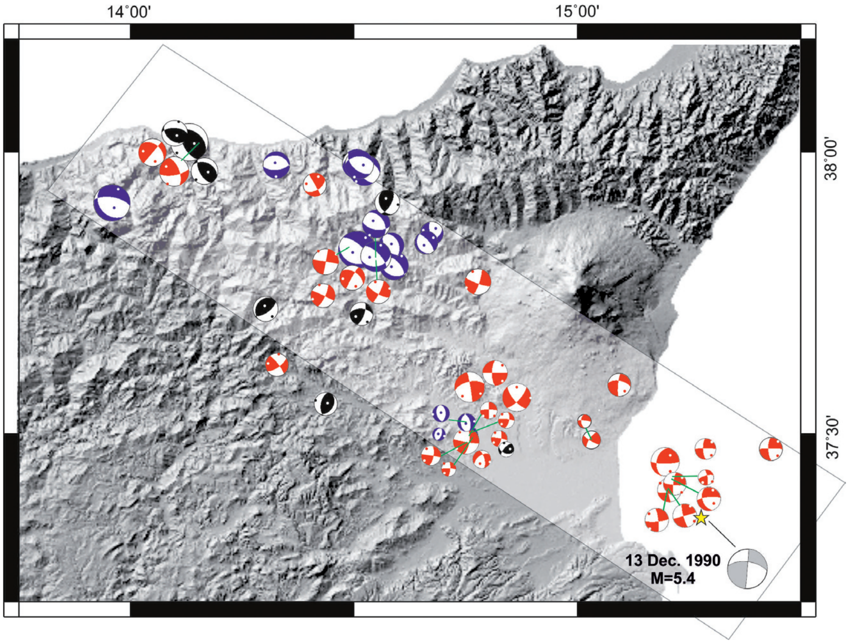

Fig. 3 – Focal solutions for the studied area, as extracted from the INGV database (http://sismoweb.ct.ingv.it/focal/index.asp). Plunges of P- and T-axes have been used to divide focal mechanism datasets into the main stress regime, according to the Zoback (1992) classification: red, strike-slip fault; blue, normal fault; black, inverse fault.

Conclusion. A preliminary analysis of large scale geological features and seismological data provides clues for a regionally-extended structural discontinuity slicing through all over the central-eastern portion of the Sicilian Fold and Thrust Belt, between the Madonie Mts. range and south of Mt. Etna region.

Along this area, major NE-SW trending Mio-Pliocene compressive structures (thrust-top and related syncline) are systematically dragged and rotated according to vertical axis until to assume a hook-shape at their terminations. The clockwise sense of rotation of such major structures suggests the occurrence of regional, near 100 km long, dextral wrench fault zone with a NW-SE direction. More detailed field surveys performed in key sectors (e.g. Madonie Mts. and Mt. Judica region) reveal that this crustal discontinuity probably consists of a wider deformation band that in the near-surface scattered into a series of discrete segments which sometimes overlap to form zone of releasing/restraining stopovers.

The analysis of the seismicity of the studied region helped us to achieve further information about the characteristics of this shear zone. Results point out a relevant NW-SE oriented seismic boundary that splits a sector of high concentration of earthquakes northeastwards from a zone with relative paucity of seismicity southwestward. Computed focal solutions revealed prevailing dextral strike-slip kinematics along this boundary. Further, the possible presence of this major structural discontinuity is emphasized by a strong wave velocity contrast found in central Sicily and visible down to about 30 km of depth. Tomographic sections (Fig. 2B) also revealed that the shear zone develops at transition between distinct continental crustal sectors, a thicker in the SW and a thinned (transitional to the Ionian domain) in the NE. Moreover, the shear zone is currently characterized by earthquakes with moderate magnitude although a destructive seismic event (M=6) occurred in the past (about 2ky ago) alongside the inferred shear zone (see Barreca *et al*., 2010). This has strong implication in the seismic hazard of central-eastern Sicily.

The occurrence of a narrow extensional area affecting the Nebrodi Mountains (Fig. 3), in agreement with previous seismologic (Neri *et al*., 2005; Lavecchia *et al*., 2007), geodetic (Devoti *et al*., 2011; Palano *et al*., 2012) and geological (Billi *et al*., 2010) data can be variously interpreted i) as incipient extension as ensuing from upper crustal stretching above an active thrust belt (Lavecchia *et al*., 2007), ii) as reactivation of pre-existing faults and upwelling of melt mantle material (Billi *et al*., 2010) or, alternatively, iii) as a residual crustal STEP-related tearing in the upper plate. Anyway, the whole data set allow us to interpret this shear zone as a crustal discontinuity that probably played a role of STEP during Plio-Pleistocene times, and that currently contribute to the recent geodynamic reorganization in the south-central Mediterranean area (Goes *et al*., 2004; Palano *et al*., 2012).

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THE SPATIO-TEMPORAL PATTERN OF SUBSIDENCE IN THE PO BASIN MONITORED BY DIFFERENT TECHNIQUES

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Introduction. The Po basin has been affected in the last sixty years by a strong subsidence due to groundwater pumping from a shallow well-developed multi-aquifer system and oil & gas production from a number of onshore and offshore reservoirs. Once this phenomenon was identified, several monitoring campaigns were carried out by different techniques since the 1897 (Arca and Beretta 1985): precise topographic levelling, GPS, SAR and vertical extensometers. The relatively large amount of observations so far acquired offers the opportunity of monitoring the spatial pattern of land subsidence in the Po Plain, especially for the second half of the 20 th century, when the subsidence dramatically increased.

The large diffusion of the space geodetic techniques, as GPS and SAR, in the last twenty years has provided two new tools which have a relatively low cost, and can improve significantly the spatial and temporal monitoring of the subsidence phenomena. So currently, the monitoring