# THE ORIGIN OF THE ACTIVE CRUSTAL STRETCHING AT THE SOUTHERN EDGE OF THE CALABRIA ARC

**S. Catalano, F. Pavano, G. Romagnoli, G. Tortorici**
*Dip. di Scienze Biologiche, Geologiche e Ambientali, Sezione di Scienze della Terra, Università di Catania, Italy*

**Introduction**. In the central Mediterranean the SE-ward migration of the Calabrian arc and the coincident opening of the back-arc Tyrrhenian Basin dominated the post-Tortonian tectonic picture of the region. The current geodynamic models explain both the two processes as the consequence of the roll-back of the oceanic Ionian lithosphere, which drove the forward shifting of the arc with respect to the adjacent Sicily segment of the orogenic belt, colliding with the African continental margin. According to the models, the motions of the Calabrian arc was accommodated, to the west, by the back-arc extension and to the south by dextral motions along NW-SE oriented faults and oblique (righ-lateral) displacements along E-W trending ramps, breaching the previous thrust-nappes of the Sicily collision belt. Whether or not these geodynamics are still active and control the seismicity of the region are still open questions. As a consequence, the seismotectonic models are often contradictive, depending on the adopted reference geodynamic model. A distribution of seismogenic zones mimicking the arcuate shape of the orogeny and marking the separation between the seismogenic extensional features of southern Calabria and eastern Sicily is imposed in the models that start from the evidence of a still active arc migration (Ghisetti and Vezzani, 1982; Meletti and Valensise, 2004). On the other hand, seismotectonic models taking into account the fragmentation of the southern edge of the arc (Monaco and Tortorici, 2000; Catalano *et al*., 2008a), in the Straits of Messina area, have been generally related to a recent modification of the geodynamic picture, due to the propagation of an incipient rift zone, extending from southern Calabria to eastern Sicily.

This paper aims to summarise the outlines of the Late Quaternary (< 1 Myr) deformation of eastern Sicily, at the southern edge of the Calabrian arc, to frame the active crustal extension of eastern Sicily, responsible for the high level regional seismicity, in the long-term geodynamic evolution of the Calabria arc migration.

**Active deformation at the southern edge of the Calabrian arc**. The active tectonic picture of the southern edge of the Calabrian arc is dominated by an incipient crustal stretching which is well constrained, in the Straits of Messina area, by both GPS data (D'Agostino and Selvaggi, 2004) and by the focal mechanism of the catastrophic 1908 earthquake (Cello *et al*., 1982). The geological, structural and morphological data (Monaco and Tortorici, 2000; Catalano and De Guidi, 2003) evidence that the recent faults on the two sides of the Straits of Messina form an antithetic relay ramp, connecting the main west facing normal faults of southern Calabrian (Reggio Calabria and Armo Fault; a and b in Fig. 1) to the east facing Taormina Fault (c in Fig. 1), bounding the Ionian coast of the Peloritani Mountains. The fault belt of the Calabrian side of the Straits originated from the remobilisation of previous extensional features that have also controlled the Plio-Quaternary basins of the peri-Tyrrhenian margin of the arc. The morphological features (marine terraces, fault scarps, triangular facets) indicate that the reactivation of the southern Calabria fault belt started at least since 580 kyr B.P. and then progressively propagated to the south, towards the Straits of Messina region (Catalano *et al*., 2008a). On the opposite side of the Straits, the off-shore NNE oriented Taormina Fault has controlled the uplift of a discrete segment of the Ionian coast of the Peloritani Mountains since about 125 kyr B.P. (Catalano and De Guidi, 2003). In the Taormina area, a synthetic relay ramp links the southern tip of the Taormina Fault to the on-shore active faults which propagated along the eastern flank of Mt. Etna (d in Fig. 1; Monaco *et al*., 1997), in the last 125 kyr (Monaco *et al*., 2000; Catalano *et al*., 2004). The active faults flanking the Mt. Etna overstep the NNW oriented main extensional fault which was detected in the off-shore from Catania to the Hyblean Plateau (Western Fault of Bianca *et al*., 1999; e in Fig. 1). This offshore structure originated from the reactivation of

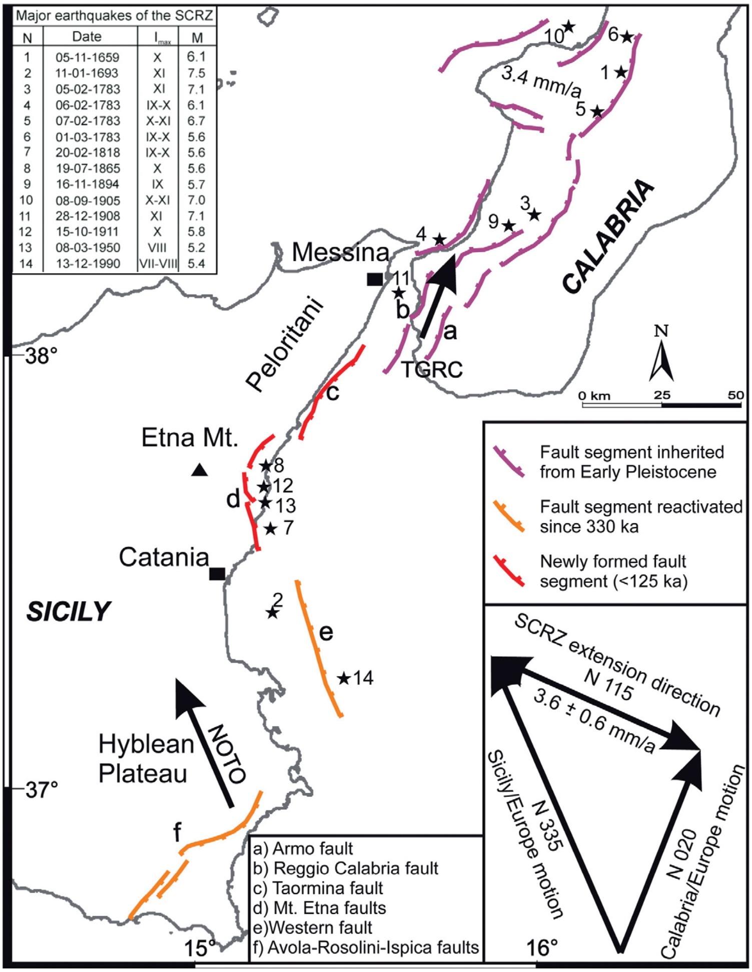


Fig. 1 – Age and distribution of active extensional fault in southern Calabria and eastern Sicily.

part of the Mesozoic Malta Escarpment and borders a series of eye-shaped half-grabens, which are infilled by up to 800 m thick syn-tectonic deposits, suggesting the long lived activity (~ 330 kyr; Bianca *et al.,* 1999) of the fault.

The southernmost extensional features of the region are located along the southeastern margin of the Hyblean Plateau (Avola and Rosolini-Ispica faults, f in Fig. 1). These faults replaced an Early Pleistocene contractional belt (Catalano *et al*., 2007) and accommodated the huge Late Quaternary tectonic uplift of the Hyblean Plateau (Catalano *et al*., 2010).

**South-eastern Sicily**. In south-eastern Sicily, the Western Fault and the Avola-Rosolini-Ispica faults border the eastern portion of the Hyblean Plateau (Siracusa Domain; SD in Fig. 2) that represents an uplifted mobile crustal block of the African Foreland. The tectonic boundaries of the Siracusa Domain consist of inverted tectonics that drove the Late Quaternary (< 850 kyr) motion of the crustal block. The western boundary of the Siracusa Domain is represented by a left-lateral shear zone, inherited from a previous dextral fault (Scicli Line; Ghisetti and Vezzani, 1982). The north-western margin of the mobile block consists of a NNW-verging thrust and fold belt that extends to the north, as far as the southern margin of Mt. Etna. These contractional features derived from the positive tectonic inversion of NE-oriented extensional basins (Simeto Graben and Scordia-Lentini Graben; Fig. 2), that originated in the 1.5-0.9 Ma time interval (Pedley *et al*., 2001), at the peak of the impressive emission of tholeiitic to alkaline volcanic products in the region.

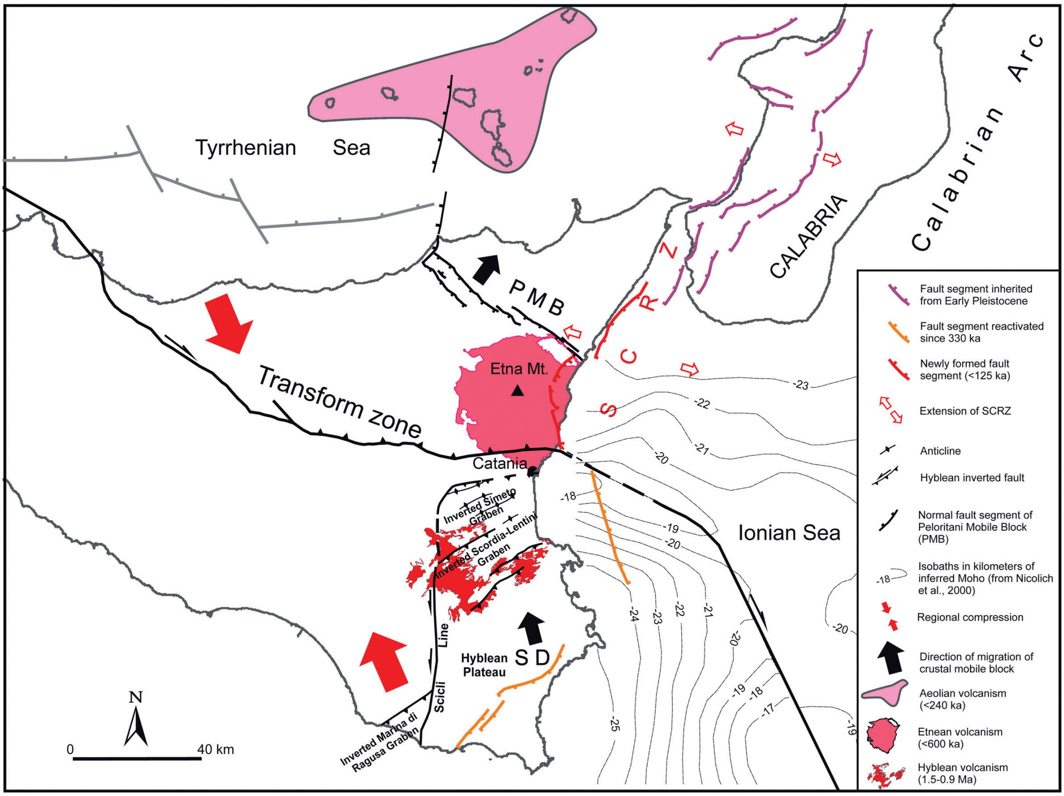


Fig. 2 – Main Quaternary tectonic and volcanic features of eastern Sicily.

The Siracusa Domain is contoured by a flight of Late Quaternary marine terraces, that have been assigned to the Oxygen Isotope Stages (OISs) from 21 (850 kyr) to 3 (60 kyr). The geometry of these marine platform constrain a regional scale tilting associated to a tectonic uplift, faster than the adjacent sectors, which was regularly increasing towards the NNW, in the direction of the active thrust and fold system controlling the northwestern margin of the block (Bonforte *et al.*, 2015). The rate of deformation measured along the bordering structures indicate that the amounts of contractional-rate along the northwestern border of the block, estimated at about 1.2 to 1.3 mm/a (Catalano *et al.*, 201), has been completely accommodated by the 1.4 mm/a rate of left-lateral motions along the western border (Scicli Line; Catalano *et al.*, 2008b) and by the 1.3 mm/a extension-rate, which has been measured along the southeastern edge (Avola Fault; Catalano *et al.*, 2010). The kinematics of the borders of the Siracusa Domain are consistent with the NNW-SSE oriented compression which has been obtained by inversion of seismological data (Musumeci *et al.*, 2005) and fit the residual GPS velocity relative to Eurasia, with respect to rest of the foreland domain (Bonforte *et al.*, 2015).

**Mt. Etna region**. In the Mt. Etna region, the contractional domain at the northern margin of the Hyblean Plateau is abruptly interrupted by a NW-SE oriented alignment, marked by dextral active fault segments, that represents the onshore prolongation of the Africa-Ionian tectonic boundary, recognised by seismic lines in the offshore of Catania (Fig. 2) (Nicolich *et al.*, 2000). The crustal significance of this tectonic boundary, already interpreted as a transform zone (Catalano *et al.*, 2004), is demonstrated by a N-S trending seismic line across the volcano (Cristofolini *et al.*, 1978) that shows a sharp increase of the depth of the Moho, almost corresponding to the location of the alignment. The southern portion of the seismic line, crossing the contractional domains, shows the continental crust of the African margin, flooring the southern flank of Mt. Etna. The northern prosecution of the seismic line pictures a thickened crust sector, which consists of two superimposed distinct crusts. This part of the seismic lines can be interpreted, taking into account that the cross-section cuts parallel to the hinge of the Ionian subduction zone. The deeper crustal horizon, whose top is at depth of 21 km, represents the flexured Ionian Crust (Vp = 7.5 - 6 km/s) and the upper crustal horizon consists of the Calabrian Arc continental crust (Vp = 6.0 km/s) and its sedimentary cover (Vp = 3.0 - 5.0 km/s). An intermediate, low-velocity layer (Vp=5.0-5.5 km/s), located at depth from 12 to 21 km is interleaved between the two superimposed crusts.

The evolution of the Etna volcanism was clearly controlled by the existence of the Africa-Ionian tectonic boundary. The earlier emissions of tholeiitic products, ranging in age from 540 kyr to 225 kyr, were in fact localised at the main transtensional features that were active along the southern margin of Mt. Etna (Catalano *et al.*, 2004), while the following emissions of the alkaline products (< 225 kyr) mainly developed within the extensional domain, to the north of the transform zone.

**North-eastern Sicily.** The north-eastern corner of Sicily, comprising the Peloritani and part of the Nebrodi Mountain Belts, form an uplifted crustal block (Peloritani Mobile Block; PMB in Fig. 2) that is now diverging from both the Sicily collision zone and the southern Calabria sector of the arc. The geodetic data in the Nubia reference frame (D'Agostino and Selvaggi, 2004) evidence that the NE Sicily diverges, with rates of about 5 mm/a along a N160 direction, from the rest of the Calabrian arc, which is still migrating towards the E. This relative motion is consistent with the rate and the direction of the extension obtained by the inversion of structural data on the fault planes in the Straits of Messina area, which are also fitting the focal mechanism of the 1908 event.

The geodetic measurements in NE Sicily also evidence a NNE-ward divergence of the PMB from the rest of island, at rates of about 5 mm/yr (see FOSS vs Nubia in D'Agostino and Selvaggi, 2004). Recent geological analyses carried out at the southern border of the PMB pointed out an active extensional fault belt, which remobilized segments of the previous NW-SE oriented dextral fault system, at the southern edge of the arc (Pavano *et al.*, 2015). This reactivated extensional feature has been related to the June-September 2011 seismic swarm in the area of Longi-Galati Mamertino. It consists of about 430 events that followed the 23/06/2011 event, characterized by a 4.1 magnitude (ISIDe Working Group, 2010). This main event provided a focal mechanism (Scarfì *et al.*, 2013) indicating a NNE-SSW oriented extension, matching that obtained by GPS data and structural analyses of rejuvenated fault planes (Pavano *et al.*, 2015).

The PMB is contoured by marine terraces, which have been referred to successive OISs from 15 (570 kyr) to the OIS 3 (60 kyr) (Catalano and Cinque, 1995; Catalano and De Guidi, 2003; Catalano and Di Stefano, 1997). They undercut a raised transgressive, neritic-to-batial marine sequence that ranges in age from 900 to 600 yr (Naso sequence; Catalano and Di Stefano, 1997). The Naso sequence pre-dates the tectonic uplift of the PMB that started, thus, at about 600 yr. Along the entire Tyrrhenian coast of the PMB the strandlines of the marine terraces show a constant elevation that constrain an almost uniform uplift-rate of about 1.1 mm/yr, since 600 kyr B.P.. In particular, the strandlines of the marine terraces cross undisturbed the main NW-SE dextral fault segments that dissect the region (e.g. Tindari Fault). Along the Tyrrhenian coast, the tectonic boundary of the mobile block is evidenced by a sharp decrease in the elevation of the marine terraces, ranging in age from the OIS 15 (570 kyr) to the OIS 3 (60 yr).

To the north of the mobile block, the active volcanic belt of the Eolian Islands, whose oldest products have been dated at about 225 kyr B.P. (Crisci *et al.*, 1991), is represented by the islands of Volcano, Lipari and Salina, that are located at the main releasing bends along a seismogenic NNW-SSE dextral shear zone (Catalano *et al.*, 2009).

**Discussion and conclusions.** The active extensional belt which extends from southern Calabria to the south-eastern Sicily is composed by two branches (southern Calabria and south-eastern Sicily) deriving from the reactivation of older faults, which are now linked by faults that

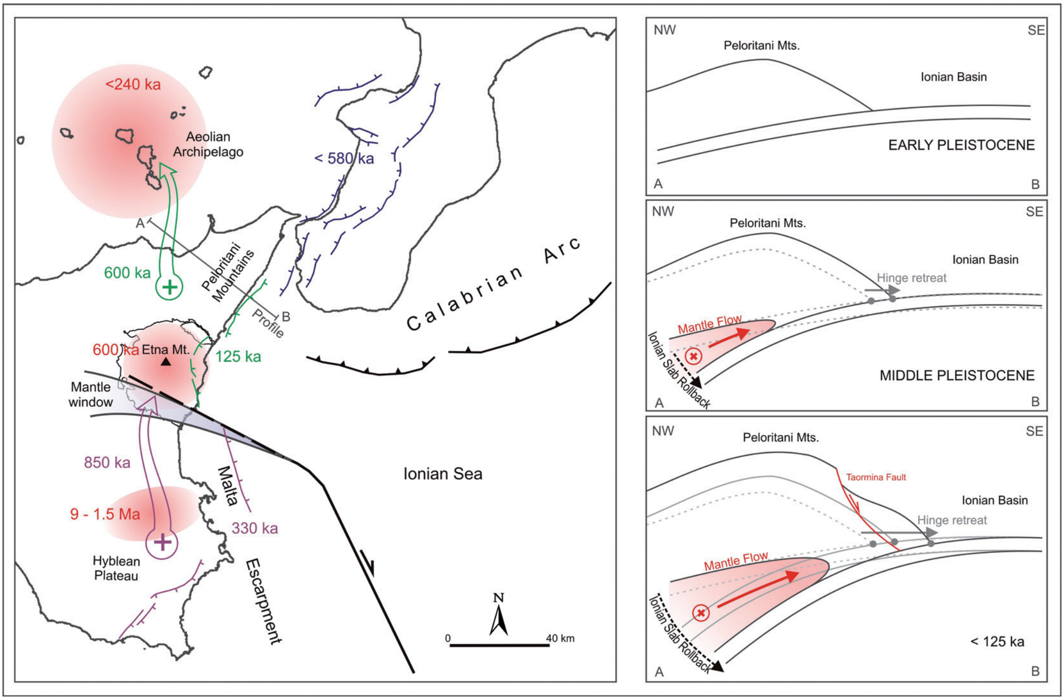


Fig. 3 – Sketch map illustrating the timing of the propagation of the mantle-flow beneath eastern Sicily and the relation with the volcanism and the crustal extension.

propagated since about 125 kyr from the eastern flank of Mt. Etna to the offshore of NE Sicily. Our investigations point out that an impressive tectonic uplifting, affecting isolated crustal blocks, associated with the development and the progressive migration of the volcanism, from the Hyblean Plateau to the Aeolian Islands, heralded the reactivation and the propagation of the normal faults in eastern Sicily.

The normal faults of south-eastern Sicily activated since ~330 kyr at the borders of a mobile crustal wedge that started to move and uplift since ~850 kyr. The normal faults of north-eastern Sicily propagated since ~125 kyr, along the margin of an actively uplifting crustal block which, in turn, started to move at ~600 yr. Our data also evidence that the mobilisation of block anticipated the onset of the volcanism at the leading edge of the moving crustal blocks (Fig. 3). This aspect, together with the mode and the rate of deformation along the bounding faults, suggest to relate the remobilization of the crustal blocks to upraising mantle wedges beneath these (see also Catalano *et al*., 2010). It is remarkable that the process started at the main transform zone separating the subducting Ionian slab from the buoyant Hyblean continental crust, to the south of Mt. Etna. The opening of a mantle window along this transform zone has been proposed as the cause of the mantle plume which induced the Etna volcanism since 600 yr (Gvirtzman and Nur, 1999). This process matches the indication of a NE-ward remobilisation of the mantle beneath the continental crust of the adjacent Hyblean region, dragging the Siracusa Domain mobile block towards the Etna region since ~850 yr. The Etna volcanism started together with the remobilisation of the Peloritani Mobile Block that also marked the deactivation of the main dextral faults at the southern edge of Calabrian arc. The end of the strike-slip deformation could be strictly related to a NE-directed mantle flow fed by the mantle window. The activation of the flow paralleling the hinge of the Ionian subduction have supplied large volumes of materials, balancing the accommodation space due to the Ionian rolling back, thus causing the end of the dextral crustal shearing at the surface. The reconstructed tectonic evolution of eastern Sicily clearly points out that the propagation of the active normal faults of eastern Sicily occurred on the flank of the uplifted crustal blocks, 500 kyr after the onset of their remobilisation caused by the mantle perturbation. The crustal extension governing the propagation of the seismogenic normal faults of eastern Sicily can be thus interpreted as the delayed surface expression of an incipient active rifting which causes the gravity sliding of the crust from the uplifted mantle wedge towards the still retreating Ionian slab. In conclusion, active extension at the southern edge of Calabrian arc totally replaced the dextral crustal shearing in accommodating the Calabrian still active arc migration. This evidence candidates the extensional features of eastern Sicily as the main seismogenic sources of the region.

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