MORPHOLOGICAL EVIDENCES OF TECTONIC TILTING IN NE SICILY
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Introduction. The NE-Sicily, the southern termination of the Calabrian arc, represents a discrete crustal mobile block (PMB - Peloritani Mobile Block; inset in Fig. 1a) diverging towards the NNE from the rest of the Sicilian collision zone and moving independently from rest of the Calabrian arc (Hollenstein et al., 2003; D’Agostino and Selvaggi, 2004). The marine terraces analysis suggests that this crustal block, since the Middle-Pleistocene (~600 ka) experienced a homogeneous uplift constraining a long-term uplift-rate of about 1.1 ± 0.13 mm/a, with respect to the 0.76 ± 0.05 mm/a measured for the surrounding areas. This change in uplift-rate is accommodated, to the SW, by several NW-SE-oriented normal fault segments, showing rejuvenated fault scarps and providing a short-term vertical displacement-rate of about 0.4-0.5 mm/a. In correspondence of the south-western portion of the PMB a drainage system analysis has been carried out in order to recognize the morphological effects due to local tectonic deformation occurred along the NW-SE oriented faulted belt. Several morphometric features of fluvial network and drainage basins, like basins lateral asymmetry, fluvial hierarchical anomalies and drainage system arranging, have been analyzed. The results of these analysis, show that, since the Middle-Pleistocene, the southwestern portion of PMB, underwent a NE-ward tectonic tilting, complying and geomorphometrically confirming the NW-SE oriented, SW-dipping, normal faults activity.

Tectonic and seismotectonic setting. The NE Sicily is located at the southern termination of the Calabrian Arc, at the intersection between the Neogene Sicilian collision belt and the incipient Siculo-Calabrian Rift Zone (SCRZ – Catalano et al., 2008) (Fig. 1a). The NE Sicily represents an orocline that during the Neogene-Quaternary age has been involved in two main stages of deformation. During the first one, the Calabrian Arc experienced a lateral extrusion towards to the south-east (Boccaletti et al., 1990), accommodating the hinge retreat of the Ionian slab. This process caused the development of a wide system of NW-SE and WNW-
ESE oriented right-lateral shear zones that disjointed the SE-verging orogenic belt (Finetti et al., 1996; Lentini et al., 1996). These processes have been linked to the differential roll back between continental crust of the northern termination of the Nubia plate, facing the Sicilian collision zone, and the adjacent less resistant oceanic crust of the Ionian slab, sub-ducting beneath the Calabrian Arc.

Starting from about 600 ka B.P. the whole NE Sicily has been characterized by a huge tectonic uplift, disengaging from the surrounding domains. The main fault systems that define the PMB have been partially identified, someone of which has been thoroughly studied. To the east, the PMB is bordered by a relevant off-shore NE-SW oriented faults (Taormina Fault) belonging to the SCRZ (Catalano et al., 2008), whose effects of activity are already recognizable along the near Ionian on-shore. The south-western margin of PMB, as also evidenced by geodetic data (Hollenstein et al., 2003; D’Agostino and Selvaggi, 2004) (Fig. 1a), corresponds to a narrow NW-SE oriented fault belt at the Nebrodi-Peloritani boundary (Fig. 1b), represented by a set of normal fault segments showing morpho-structural evidences of Holocene activity (Pavano et al., 2012). Except for some seismic profile, carried out in the Tyrrehanian off-shore, and some seismological data, the location of the north-eastern and north-western edges of the mobile block is quite uncertain.

Recently (June-September 2011) the area around Longi and Galati Mamertino villages has been affected by a swarm of medium-low magnitude seismic events. The main event (M = 4.1 – ISIDe Working Group, 2011) provided a focal mechanism showing a NNE-SSW oriented extension (Fig. 1b), according to the geodetic data. The linkage between this seismic swarm and the fault-controlled south-western border of the mobile block, has been hypothesized.

A meso-scale structural field investigation has been carried out in order to analyse and kinematically define several normal fault segments. The segments located to the south of Naso village, near Capo d’Orlando (NFZ in Fig. 1b), are characterised by a 2 m high scarp, clearly displacing the Recent (Holocene) talus. Further well defined rejuvenated fault scarps have been recognized between S. Marco d’Alunzio and Galati Mamertino villages (Fig. 1b), belonging to a 8.5 km-long fault zone (San Marco d’Alunzio Fault Zone – SFZ, Fig. 1b; Pavano et al., 2012). These are characterized by 3-5 m high, SW facing fresh bedrock scarp, marked by a basal light coloured strip as an evidence of their Holocene activity (Benedetti et al., 2002; Palumbo et al., 2004). Kinematic markers with pitch of 80° observed on the fault plane, constrain a normal sense of motion. Normal movement indicators (pitch 80°), superimposing on ancient dextral kinematic striations (Pitch 160°), has been found along the fault plane of an associated 3 m-high, 2 km-long antithetic segment.

More to the southeast, further fault segments, showing 2-3 m-high fresh bedrock scarps, have been recognised (Fig. 1b). In the surrounding area of Tortorici, an antithetic 1600 m long, N140° oriented, rejuvenated fault scarp shows clear rests of welded fault breccias along its 3 m high fault plane, as a further evidence of recent activity. Kinematic indicators measured along this latter indicate a normal sense of the deformation (pitch 90°).

Finally, in the same area two measurement sites have been located along a N10 directed, E-dipping, more than 1500 m long fresh bedrock scarp. On these sites striations and accretion and fracture steps indicate both dextral (pitch 30°) and more recent normal (70-80°) motions.

Morphostructural analysis. The tectonic uplift involving the PMB is evidenced in NE Sicily by the presence, around the coastal area, of a marine terraces flight assigned to the Oxygen Isotope Stage (OIS) from 15 (570 ka) to 3 (60 ka) (Catalano and Di Stefano, 1997). Along the Tyrrhenian coast, from Capo d’Orlando to Capo Rasocolmo (Catalano and Cinque, 1995; Catalano and Di Stefano, 1997), the ancient NW-SE and NNW-SSE oriented dextral faults are crossed without interruption, strongly indicating an almost uniform elevation of strandlines around the PMB. In contrast, along the Ionian side of PMB the elevation of the Late Quaternary marine terraces is extremely variable, due to the huge faulting-related deformation at the footwall of the Taormina Fault.
The marine terraces analysis enables to determine an evaluation of the long-term uplift-rate involving the region since the Middle-Pleistocene (~600 ka). Along the Ionian coast, starting from the Alcantara River mouth the values of uplift-rate switch from 0.9 to 1.1 mm/a towards the NE, near Messina area (Catalano and De Guidi, 2003). Between this two localities the uplift-rate values reach a maximum value of about 1.7 mm/y, ascribable to the Taormina fault activity.

Along the western side of the Tyrrhenian coast of the PMB a sharp variation of the long-term uplift-rate has been found between the Capo d’Orlando and San Marco d’Alunzio areas. In particular, in correspondence of the PBM side has been calculated an uplift-rate of 1.1 ± 0.13 mm/a switching to 0.76 ± 0.05 mm/a to the south (inset in Fig. 1b). This 0.3-0.4 mm/y gap is significantly in accordance with the short-term deformation rate (0.4-0.5 mm/a) calculated on the basis of the above discussed structural analysis.

In addition has been calculate the variation of the uplift-rate between the PMB and the southern area, getting a reconstruction of the trend in time of the deformation-rate along the studied faulted zone. As constrained by the obtained data, after an early decrease, lasted until OIS 7.1 (200 ka), starting from the period elapsing between this latter and the OIT stage 3 (125 ka) the deformation-rate along the faulted zone increased from 0.15 to 0.45 mm/a.

Morphometric analysis. A morphometric analysis regarding the drainage system of the south-western sector of the PMB has been carried out. This analysis firstly consisted of a semi-quantitative study of the fluvial network of main drainage basins, roughly NW-SE oriented and flowing to the NW. In addition to defining the relationships between fluvial network and both the faults of the region and the rejuvenated Holocene fault segments, a morphometric characterization of basins has been performed, based on appropriate morphometric indexes generally exploited for tectonic geomorphology studies. The obtained data, as a whole, enable to understand how the Late Quaternary tectonic deformation has driven the landscape evolution and the fluvial network arrangement.

Basins asymmetry. Since the studied area is affected by a NW-SE oriented SW-dipping normal faults system, defining several faulted blocks, it was reasonable expecting a tectonic tilting towards the north-east. In order to detect and numerically evaluate the tectonic tilting of the region, it was applied an useful index employed in region involved in neo-tectonic processes (Hare and Gardner, 1985; Cox, 1994); it is represented by the Asymmetry Factor (AF) of the drainage basins (Hare and Gardner, 1985). In the studied sector of the PMB, regardless of hierarchical order, were analysed 10 basins in order to cover as much as possible the investigated area. The results (<50%) suggest an almost significant asymmetry of basins to the right (facing downstream) constraining a NE-ward tectonic tilting (Fig. 2a). Only a small basin shows an AF value slightly more than 50%. The valleys asymmetry, associated with the NE-ward tilting of the faulted-blocks, testifies the tectonic deformation cumulated along the NW-SE oriented, SW-dipping, normal faults. Another asymmetry index is represented by the Transverse Topographic Symmetry Factor (T) (Cox, 1994), whose obtained values confirm the AF data, providing a more detailed distribution of asymmetry along the basins (Fig. 2a).

Across the faulted belt several NE-directed swath profiles have been realized (Fig. 2b). It is possible to firstly appreciate the NE-ward tilted summit surfaces of the landscape, dislocated by SW-dipping faults, and the clear NE-ward asymmetry of the transverse subsequent valley, showing their northern flank steeper than the southern one.

Fluvial network arrangement analysis. The fluvial network analysis has been performed for the main basins lying on the south-western side of the PMB and flowing towards to the Tyrrenhian sea. After the reconstruction of the fluvial network, the stream system has been hierarchized as proposed by Strahler (1958). Afterwards sectioning the streams in several trunks, each fluvial hierarchical order, from 1 to 7, has been separately processed. The same procedure has been followed for the tectonic structure that lie inside the studied area and for the Holocene fault scarps recognized within the aforementioned faulted zone. Firstly, the analysis
has focused on the rivers azimuthal distribution, in order to understand the relationships between faults and drainage system arrangement.

The data show that the overall faults and active faults segments have the same NW-SE preferential orientation, at about N140-150° (Fig. 2c). This means that the fresh bedrock scarps are the result of the reactivation of previous faults, in accordance with the collected kinematics data measured along the fault planes. The azimuthal distribution of the subsequent IV-VII orders streams, show a clear main direction of about N130-150° (Fig. 2c), coincident with the azimuthal orientation of the overall faults. In contrast, this analysis indicates that the I-III order streams are widely distributed, with a slightly marked main direction focused between 30° and 50° (Fig. 2c), perpendicularly to the main faults. This group of streams would include both relicts of the heads of basins of the ancient drainage system and the new tributary channels flanking the NW-pointed subsequent streams.

In order to thoroughly understand the relationships between the faults activity, the behaviour of the drainage system and the fluvial network arrangement, a more detailed analysis has regarded the evaluation of the streams flow-directions (rose diagrams in Fig. 2d). The results, obtained for several streams of different hierarchical orders, show that the IV-VII order subsequent streams flow towards the north-west. In contrast, the flow-direction orientations of the I-III order channels show anomalous differences between the streams flowing towards the northern sector and those flowing towards the southern one. The first group covers a 180° wide range of directions, without a clear main value, while the channels flowing to the opposite sense are mostly confined in a narrow azimuthal range, focusing between 200° and 270° (Fig. 2d).

These anomalous distributions has been explained considering that the streams pointing towards the northern sector are represented by both sub-sequent and re-sequent channels belonging to an inherited drainage system. In addition, they result from fluvial captures of previous smaller basins that complied in time the NE-ward tilting of the faulted blocks.
In contrast, the channels pointing towards the southern sector are channels developed on the steeper cumulative SW-dipping fault slope, locally coincident with the right hillside of the valleys.

Furthermore, a morphological local effects of the Late Quaternary tectonic deformation along the studied sector of the PMB is represented by a well defined distribution of the basins extent values (Fig. 3a). In order to carry out this analysis, the III order basins has been taken into account, due to their more homogeneous spatial coverage. In particular, the smaller basins are concentrated close to the faults, in correspondence of their SW-dipping cumulative slope, while the larger III order basins lie on wider and flatter surfaces of the opposite flank of the valleys. These evidences highlight a different significance and evolution history between the two group of basins with the same hierarchical order.

The landscape of the studied area, as well as being dominated by the effects of the regional deformation (marine terracing, river entrenching), is characterized by local fault-controlled morphological features connected to the tilting of faulted blocks, such as the diffuse and wide N/NNE-ward fluvial captures. Each captured fluvial channel, flowing from the uplifted sector towards the depressed areas of the tilted blocks, caused a rearrangement of the drainage system. The main effects of this geomorphological processes are represented by an increase in terms of hierarchical orders of the subsequent valleys and the consequent decrease in order of the hosting streams. As a consequence, the forced phase of the drainage system reorganization determined the development of fluvial network anomalies through the tilted blocks, as showed by the distribution of the Hierarchical Anomaly Index (Da) (Avena et al., 1967) calculated for the III order basins (Fig. 3b).

Fig. 3 – a) Map of the distribution of the III order basins extent displaying the NE-ward tilted surfaces. b) Hierarchical Anomaly Index (Da) Map calculated for the III order basins.

Discussion and conclusions. The NE Sicily can be designed as a crustal mobile block (PMB) diverging towards the NNE respect to the rest of the Sicilian collision belt (Hollenstein, 2003), disengaging from the rest of the Calabrian Arc. As suggested by the analysis of the marine terraces carved along both the Tyrrhenian and Ionian coasts of NE Sicily, starting to the Middle-Pleistocene the PMB has experienced a huge uplift inferring a difference in uplift-rate of about 0.3-0.4 mm/y between the PMB (~1.1 mm/a) and the surrounding area (~0.75 mm/a).
Along the south-western margin of the PMB this divergence in uplift is accommodated by a 10 km wide normal fault zone, represented by several NW-SE oriented, SW dipping fault segments that show clear evidences of Holocene activity, such as 2-5 m high fresh bedrock scarps (Pavano et al., 2012), that recently was home of a low magnitude (M = 4.1, INGV) seismic swarm (June-September 2011). The tectonic deformation inferred a NE-ward tilting of several faulted blocks, imprinting the main features of the landscape, such as the drainage system.

The morphometric analysis reveals evidences of huge fluvial captures, picturing a rearrangement of the fluvial network as a consequence of the tectonic tilting. The inherited main sub-sequent rivers, identified as the IV-VII order streams and flowing to the NW, maintained their orientation pushing to the NE the earlier symmetry of their basins. As regarding the I-III order streams, they should be considered as two main groups, distinguished on the basis of the flow direction data. The first group regards the streams pointing to the northern sectors, that, in addition to including streams inherited from the heads of previous basins, have complied the NE-ward tectonic tilting. This resulted in an increase in terms of length and basin extension. The second group is represented by steeper and shorter streams, flowing towards the SW as ob-sequent side streams, developing, as also evidenced by the NE-SW oriented swath profile, in correspondence of cumulative SW-dipping fault slope.

The rightward basins asymmetry, the N-pointed fluvial captures, the NE-ward tilting of the summit surfaces and the general rearrangement of the fluvial network through the faulted block represent the morphological response of Late Quaternary tectonic activity occurred along the NW-SE oriented, SW-dipping normal faults, that bound the south-western margin of the PMB. These evidences enable to conclude that the active tectonic processes affecting the NE-Sicily since the Middle Pleistocene, strongly influenced the landscape evolution of the region, and in particular the drainage system.

References

