MORPHOMETRIC ANALYSIS OF THE WESTERN ASPROMONTE MTS. (SOUTHERN CALABRIA, ITALY): EVIDENCE FOR ACTIVE TECTONICS

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Introduction. Fluvial network development and organisation are influenced not only by climatic and lithological factors but also by tectonic movements, such as regional uplift, subsidence and fault activity causing local landscape modification. Rivers are the most sensitive geomorphological elements capable to record recent tectonic activity, indeed when perturbed by landscape changes they leave their equilibrium state and lose their hierarchical organization. Then, rivers tend quickly to restore equilibrium producing anomalous segments and also create typical features such as fluvial capture, deflections, abandoned channels and so on. Thus, geomorphological and morphometric studies of fluvial network and associated hydrographic basin allow analysing landscape modifications and they can provide information about active tectonics. Numerical calculation of geomorphological indexes (Keller, 1986; Cox, 1994) applied to rivers can be a basic reconnaissance tool in order to determine the influence of faults on the hydrographic network and to identify areas with rapid tectonic deformation (Verrios et al., 2004).

In southern Calabria, NE-SW to NNE-SSW striking and west-dipping normal faults dominate the neotectonic deformation scenario (Fig. 1). Our study focus on the evaluation of active tectonics in the Aspromonte Mts. area by geomorphological, morphometric and morphostructural analyses of two rivers and their basins: the Petrace Fiumara and the Catona Fiumara. These rivers run from the Aspromonte ridges towards the Tyrrhenian Sea and are intercepted by normal faults, whose activity has been recorded by drainage network.

Geological setting. The Aspromonte Mts. are located in the southern part of the Calabrian Arc which connects the Apennines and the Sicily orogenic belts (Fig. 1). The Calabrian Arc, which includes Calabria and the north-eastern side of Sicily, is a forearc terrain which was emplaced to the south-east during north-westerly subduction and roll-back of the subjacent Ionian slab (Malinverno and Ryan, 1986; Neri et al., 2012). During the Late Pliocene-Quaternary, contractional structures of the hinterland part of the forearc were superseded by extensional faults which caused its fragmentation into structural highs and shallow marine sedimentary basins, including the Messina and Gioia Tauro basins and the Messina Straits (Ghisetti and Vezzani, 1982). At present, an active swarm of normal faults runs along the Calabrian Arc and is associated with strong seismicity (Monaco and Tortorici, 2000). Current WNW-ESE-trending crustal extension is documented by focal mechanisms of earthquakes (CMT and RCMT Catalogues; Neri et al., 2004), structural studies (Tortorici et al., 1995; Jacques et al., 2001; Ferranti et al., 2007) and geodetic velocities (Mattia et al., 2009; D’Agostino et al., 2011). Since the Middle Pleistocene, extensional tectonics has been coupled with intense regional uplift which developed flights of marine terraces (Ferranti et al., 2006 and references therein).

Active tectonics in the Calabrian Arc is attested by the uplift of the coast (Westaway, 1993; Ferranti et al., 2007), by landscape imprint (Guarnieri and Pirrotta, 2008), structural evidence (e.g. Tortorici et al., 1995; Jacques et al., 2001; Aloisi et al., 2012) and by the frequent occurrence of strong and moderate earthquakes (Rovida et al., 2011). Southern Calabria was hit by disastrous earthquakes and long seismic sequences during historical times (1659, February-March 1783, 1894 and 1908 earthquakes), that caused thousands of fatalities and several secondary effects including tsunamis (Fig. 1). Although the dramatic impact of these earthquakes on the region, the association with their causative faults is still debated and they are often related to different seismogenic sources (e.g. Valensise and Pantosti, 1992; Jacques et al., 2001; Galli and Bosi, 2002; Basili et al., 2008; Aloisi et al., 2012). The 1783 sequence (mainshock M ~ 7; Rovida et al., 2011) changed the Aspromonte Mts. landscape triggering several landslides, liquefactions and ground fracturing. Long and continuous fractures,
described by contemporary witnesses, were considered as the superficial expression of the seismogenic fault of the main shock, occurred the 5 February. This ground fracturing well fits with the Cittanova Fault (Fig. 1), a NE-SW trending, 30 km long, west-dipping extensional segment bounding the Aspromonte Mts. from the Gioia Tauro basin (Tortorici et al., 1995; Jacques et al., 2001; Galli and Bosi, 2002). Alternatively, this event has been attributed to a blind, east-dipping, low angle fault, located in the Gioia Tauro basin (Basili et al., 2008 and references therein). Northwards, the Mesima Fault was associated with the 7 February 1783 earthquakes (Jacques et al., 2001). Southwards, the Scilla Fault, located along the western coast of southern Aspromonte Mts. (Fig. 1), has been associated with the 6 February event (Jacques et al., 2001). The northern segment of the Santa Eufemia Fault probably ruptured during the 1894 event (Galli and Bosi, 2002); finally the Santa Eufemia Fault and the Armo Fault, more to the south, could have slipped during the 1908 earthquake (Aloisi et al., 2012).

**Geomorphological and morphometric analysis.** We performed a geomorphological and morphometric study, both quantitative and qualitative, of the Petrace Fiumara and the Catona Fiumara in order to quantify the geomorphological evolution of the studied area and to individuate possible perturbation of the basins that can be due to active tectonics. The term “fiumara” is used to describe a particular typology of river, with limited length and elevated slope, characterized by deep valleys and torrential regime. These water courses typically flow in north-eastern Sicily and Calabria.

By using a photo-interpretation analysis (scale 1:10,000) we preliminary localized more accurately the Cittanova Fault, S. Eufemia Fault and Scilla Fault, and mapped the drainage geometry of the Petrace Fiumara and Catona Fiumara and their geomorphological elements.

The fluvial network hierarchy has been analysed according to Strahler (1957) ordering. Then, we calculated parameters describing the hierarchical maturity of the drainage and able to highlight anomalies ascribable to active tectonics. Bifurcation index ($R$) highlights possible hierarchical anomalies of the fluvial network providing information on the typology of the
erosive processes and on the degree of evolution of the basin. Index \( A \) represents the number of anomalous fluvial segments. Hierarchical anomaly index (\( \Delta a \)) allows to better quantify drainage anomalies. First order flow density (\( D1 \)) indicates possible areas suffering uplift due to dip slip movements. Also, we calculated some morphometric indexes indicating possible basin asymmetry (Asymmetry factor, \( AF \); Transverse topography asymmetry, \( T \)) and basin differential uplift (Basin elongation Ratio, \( Re \); hypsometric curve and Stream length-gradient index, \( SL \)). Finally, a morphostructural study allowed us to evaluate the relationship between the geometry of the hydrographic network and the trend of the tectonic structures.

Morphometric indexes are very sensitive to lithological change, thus each parameter has been punctually related to the rock type cropping out, classified on the basis of the erosion susceptibility (Fig. 2). \( A \) class includes the crystalline terrains of the metamorphic massif, that is the most resistant lithology. \( B \) class represents the terrains of Tortonian, Pliocene and Lower Pleistocene age, made of conglomerates, sandstones, sands and clays with mid/low resistance to the erosion. \( C \) class includes clays, sands and poorly cemented conglomerates of Pleistocene age and Holocene alluvial deposits. These terrains have low degree of strengthened and are easy to erosion. In some cases, the Catona Fiumara and Petrace Fiumara have been divided in sub-basins with the aim to examine in depth possible perturbation of their drainage.

**Results.** The basin of the Catona Fiumara is 67.47 km\(^2\) wide; most of the drainage flows on the crystalline terrains of the metamorphic massif (\( A \) class) and on Pleistocene marine and continental deposits (\( C \) class), in the lower sector. Trunk stream flows towards NW and changes running towards SW in the final tract (Fig. 2). Fluvial network reaches the V hierarchical Strahler’s order and shows parallel shape pattern and trellis pattern as it regards the I order branches.

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**Fig. 2 – Sketch map of the Catona Fiumara and Petrace Fiumara. Drainage is divided into hierarchical orders according to Strahler (1957) ordering. Terrains are classified on the basis of their susceptibility to erosion.**
The basin of the Petrace Fiumara is 258.29 km² wide, drainage flows on the metamorphic terrains (A class) in the upper part, on marine and continental deposits (Lower/Upper Pleistocene) and partially on clay sediments (Lower/Middle Pleistocene) (C class). Trunk channel runs towards N, in the final tract it changes flowing NW-ward. Fluvial network reaches the VII order and it shows a parallel pattern as it regards high order branches (from IV to VII) (Fig. 2).

For both the Petrace Fiumara and Catona Fiumara basins we observed several geomorphological elements interpreted as markers of perturbation due to active tectonics. Numerous fluvial branches are straight and aligned along the Santa Eufemia Fault as it regards the Catona Fiumara and along the Cittanova Fault for the Petrace Fiumara. Fluvial channels characterized by anomalous stretch and meandering branches are observed on the Santa Eufemia Fault and Cittanova Fault footwall. Deflected streams and alignments of branch deflections, fluvial captures and suspended valleys are evidence of recent modification of the analyzed fluvial networks (Fig. 2).

For both the studied rivers, hierarchical parameters indicate a poor organization of the fluvial network and the presence of uplifted and rejuvenated sectors. Indeed, the bifurcation index, R, reaches high values (Tab. 1) as it regards the segments with low order, I and II, that are the youngest fluvial segments more susceptible to active tectonics. Similarly, the anomaly parameter, A, indicates that there are numerous anomalous branches of I and II orders, particularly high value is detected for the first order of the Petrace Fiumara. Finally, D1 parameter highlights a high density of I order segments with respect to the flowed area due to differential uplift of specific sectors.

Tab. 1 – Hierarchical parameters and morphometric indexes of the Catona Fiumara and Petrace Fiumara: see the text for the description. AF index for the Catona Fiumara was also calculated for its 10 sub-basins.

<table>
<thead>
<tr>
<th>Sub-basin</th>
<th>AF</th>
<th>Catona Fiumara</th>
<th>Petrace Fiumara</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0,46</td>
<td>R1  1,3</td>
<td>A1  271</td>
</tr>
<tr>
<td></td>
<td>1,5</td>
<td>R1  1,5</td>
<td>A1  536</td>
</tr>
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<td>II</td>
<td>0,14</td>
<td>R2  2,7</td>
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<tr>
<td></td>
<td>1,4</td>
<td>R2  1,4</td>
<td>A2  94</td>
</tr>
<tr>
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<td>0,03</td>
<td>R3  0,8</td>
<td>A3  21,18</td>
</tr>
<tr>
<td></td>
<td>0,5</td>
<td>R3  0,5</td>
<td>T3  9</td>
</tr>
<tr>
<td>IV</td>
<td>0,12</td>
<td>R4  0,8</td>
<td>A4  33,10</td>
</tr>
<tr>
<td></td>
<td>0,4</td>
<td>R4  0,4</td>
<td>A4  2</td>
</tr>
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<td></td>
<td>73,53</td>
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<td>A5  0</td>
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<td></td>
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<td>T5  0,12</td>
<td>A5  0</td>
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<td></td>
<td>73,53</td>
<td>T6  0,14</td>
<td>A6  0</td>
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<tr>
<td></td>
<td>52,90</td>
<td>T7  0,35</td>
<td>Re  0,69</td>
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<td>T8  0,64</td>
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</tr>
<tr>
<td></td>
<td>74,26</td>
<td>T10  0,21</td>
<td>AF  70,78</td>
</tr>
</tbody>
</table>

Catona F. 56,06
AF index of the Catona Fiumara approaches to 50, indicating no asymmetry, thus this index has been evaluated for the 10 sub-basins. Results show that both the sub-basins on the left side and that on the right side of this fluvial basin are asymmetric due to the differential uplift of specific sectors. Re index highlights an elongated shape of the Catona Fiumara basin indicating an immature stage. Hypsometric curve and SL index evaluated for this river highlight uplifted and rejuvenated sectors where it meets the Santa Eufemia Fault and Cittanova Fault. Furthermore, hypsometric curves of the sub-basins 1, 8 and 10 evidence a localized uplift affecting the northern sector of the Catona Fiumara that lies on the Scilla Fault footwall (Fig. 3).

AF and T indexes of the Petrace Fiumara indicate that the basin is asymmetric and the trunk channel flows close to the left side of the watershed (Tab. 1). Hypsometric curve shows a mature stage of this river with a rejuvenated sector in proximity of the Cittanova Fault where SL index shows localized uplift.

Conclusions. Geomorphological and morphometric analyses performed on the Catona Fiumara and Pettrace Fiumara highlight that their drainage is perturbed by recent tectonic movements. In particular localized uplift causes rejuvenation of specific sectors where drainage is trying to restore equilibrium. The Petrace Fiumara evolution seems to be controlled principally by the Cittanova Fault whose recent activity produced a depocentre in the northern sector of the basin. The Catona Fiumara mainly suffers the activity of the Santa Eufemia Fault and Scilla Fault and also of the Cittanova Fault. In particular the counterclockwise rotation and the rejuvenation of part of the basin can be ascribed to the recent activity of the Scilla Fault, which caused local uplift and tilting. This is shown by the rotation of sub-basins 1 and 4 occurred through fluvial captures, as testified by several suspended valleys (Fig. 3). Our results contribute to constrain the seismotectonic setting of southern Calabria supporting the hypothesis that the normal faults intercepting the drainage network have Holocene activity and they can have slipped during recent earthquakes.
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