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DRAINAGE SYSTEMS AND ACTIVE EXTENSIONAL TECTONICS: AN EXAMPLE FROM CENTRAL APENNINES (ITALY)

INDEX

ABSTRACT

The study of surface drainage patterns leads to a better understanding of fault evolution and their kinematics in areas deformed by active normal faulting. As a matter of fact, the development of drainage networks is especially influenced by the topographic deformations generated by extensional tectonics.

The purpose of this work is to contribute to the definition of the interaction between normal faulting and drainage systems by means of morphological methods in a sector of Central Apennines affected by active extensional tectonics: the Upper Aterno River Valley. The study area is located on the western sector of Meso-Cenozoic calcareous terms belonging to the structural unit of Gran Sasso d'Italia. In the Central Apennines extensional tectonic activity occurred since Upper Pliocene and throughout the Quaternary time; on the meantime a generalised uplift, probably isostatic, took place in this region. Active tectonics in the study area is connected to an extensional stress field, with a NE-SW minimum principal axis of stress tensor producing normal faults, NW-SE and E-W trending, that often displace Upper Pleistocene and Holocene deposits.

A twofold morphological approach is followed with the aim of finding a general relationship between the evolution of drainage systems, the shape of basins and the activity of normal faults.

The study of the morphological field evidence is carried first; it allows to single out the presence of deeply deformed zones, related to the activity of the main faults. Quantitative geomorphic analyses follow; they refer both to stream network patterns and drainage basins. The statistical analysis of preferred stream orientations allows to highlight the strong relation between drainage patterns and the main tectonic directions. In particular, the results related to lower stream orders can provide information about the neotectonic setting of the study area, since they are likely to be controlled by tectonic lines active in very recent time. Moreover, the distribution of the amplitude of relief show several alignments of similar values that emphasise the main structural directions. The mountain front sinuosity has been computed on both sides of the Aterno River Valley to compare the results concerning the active fault slopes with those concerning the "inactive" slopes. Finally, other geomorphic indices have been calculated to define the size and shape of drainage basins within the study area. So far, the obtained data evidence different features of drainage systems as concern those belonging to the footwall block compared with those belonging to the hangingwall block of the main normal faults.

RIASSUNTO

Lo studio dell'andamento del reticolo idrografico conduce ad una migliore comprensione dell'evoluzione della fagliazione e della cinematica associata in aree interessate da una deformazione attiva secondo faglie normali. Lo sviluppo del reticolo idrografico risulta particolarmente influenzato dalle deformazioni del rilievo topografico connesse alla tettonica estensionale.

Scopo del presente lavoro è di contribuire alla definizione dell'interazione tra fagliazione normale e sistemi di drenaggio attraverso metodi morfologici in un settore dell'Appennino centrale interessato da tettonica estensionale: l'alta valle del Fiume Aterno. L'area in studio è localizzata nel settore occidentale dell'unità strutturale del Gran Sasso, costituita dai termini calcarei della serie Meso-Cenozoica. In Appennino centrale la tettonica estensionale inizia a partire dal Pliocene superiore e prosegue attraverso il Quaternario; contemporaneamente un sollevamento generalizzato, probabilmente isostatico, ha luogo in questa regione. Nell'area in studio la tettonica estensionale è collegata ad un campo di stress caratterizzato da una direzione di massima estensione orientata NE-SW che genera sistemi di faglie normali disposte circa NW-SE, che frequentemente dislocano terreni del Pleistocene superiore e dell'Olocene.

Allo scopo di trovare una relazione generale tra l'evoluzione del sistema di drenaggio, la forma dei bacini e l'attività delle faglie normali è stato seguito un approccio di studio di tipo morfologico.

Dapprima è stato effettuato uno studio di campo delle evidenze morfotettoniche; ciò ha consentito di individuare zone profondamente deformate, in relazione all'attività delle faglie principali. Sono seguite analisi di tipo geomorfico quantitativo riferite sia al reticolo idrografico, sia ai bacini di drenaggio. L'analisi statistica delle direzioni preferenziali delle aste fluviali consente di sottolineare la profonda relazione tra l'andamento del reticolo e le principali direzioni tettoniche. In particolare, i risultati legati agli ordini più bassi forniscono informazioni sull'assetto neotettonico dell'area, in quanto essi sono presumibilmente controllati dalle linee tettoniche attive in tempi più recenti. Inoltre, la distribuzione dell'energia del rilievo mostra alcuni allineamenti di valori simili che sottolineano le principali direzioni tettoniche. La sinuosità del fronte montuoso è stata calcolata per entrambi i lati della valle dell'Aterno appartenenti al footwall e all'hangingwall delle faglie principali, allo scopo di comparare i risultati relativi al versante attivo e a quello non attivo della valle. Infine, altri indici geomorfici sono stati calcolati per definire la grandezza e la forma dei bacini di drenaggio dell'area. L'insieme di tutti gli indici calcolati

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mette in evidenza un comportamento differente per i due blocchi di footwall e di hangingwall delle faglie principali attive nell'area in studio.

KEY WORDS: Central Apennines, Extensional tectonics, Drainage systems, Drainage catchments, Quantitative geomorphology.

PAROLE CHIAVE: Appennino centrale, tettonica estensionale, sistemi di drenaggio, bacini di drenaggio, geomorfologia quantitativa.

1. INTRODUCTION

Landscape replies to active deformations by changing its morphologies or by generating new morphologies (CICCACCI *et al.*, 1986; BARTOLINI, 1992). The effects on the landscape of active extensional tectonics can be seen in modifications of the topography connected mainly to the vertical component of displacement along normal faults and/or to tilting deformations. In an active extensional regime, these modifications occur rather quickly compared to erosion and deposition velocity especially along slopes produced by active normal faults. As already examined by LEEDER & JACKSON (1993) and JACKSON & LEEDER (1994), the growth and geometry of drainage basins seem to be controlled by the slope evolution connected to the vertical displacement along active normal faults.

The purpose of this work is to contribute to the definition of the interaction between normal faulting and landscape evolution in a sector of central Apennines affected by active extensional tectonics: the Upper Aterno River Valley.

Our approach is to study the morphologies of an area characterised by active normal faulting and, in particular, to examine the drainage network and the features of the drainage catchments. Geomorphological studies progress through several phases that implied the study of morphotectonic field evidence, followed by the evaluation of a series of geomorphological indexes which quantify various drainage basin variables and landscape components connected to active tectonics.

The study area is located in Central Italy. It belongs entirely to the Abruzzo region and includes: the intermountain depression of L'Aquila-Scoppito, the upstream portion of the Aterno River drainage basin and the mountain ridges which makes the eastern divide of the main valley.

2. CHARACTERISTICS OF THE STUDY AREA

The area under investigation is on the western sector of Meso - Cenozoic calcareous terms belonging to the structural unit of Gran Sasso d'Italia including also the Quaternary terms of the L'Aquila – Scoppito basin.

2.1 **Tectonic setting**

The Gran Sasso structural unit is made of platform to basin transitional carbonate rocks (ACCORDI & CARBONE, 1988) overthrusting northwards the pelagic terms of the Umbria-Marche units (PAROTTO & PRATURLON, 1975; GHISETTI & VEZZANI, 1991). Systems of normal faults connected to the post-orogenetic extensional tectonics are superimposed on the compressive orogenetic structures. In Central Apennines extensional tectonic activity occurred since Upper Pliocene and throughout the Quaternary time; on the meantime a generalised uplift (DRAMIS, 1983), probably isostatic, took place in this region. Moreover, tensional tectonics affected landform features, giving rise to the main intermontane depressions, rather frequent in central Apennines. The extensional tectonics partly re-activated pre-existent fault planes with extensional kinematics and partly generated new normal fault systems. These last, in the study area, are often characterised by extensive cataclastic zones and by evident bedrock scarps located along slopes dipping towards south and south-west. Fault scarps in carbonatic Apennines has been studied by several Authors (BOSI, 1975; BOSI *et al.*, 1993; BRANCACCIO *et al.*, 1979a e b) in some cases giving to these morphologies a neotectonic meaning (BOSI *et al.*, 1993; WALLACE, 1977).

In the study area, the active tectonics is connected to an extensional stress field, with a NE-SW minimum principal axis of stress tensor (GIULIANI & GALADINI, 1998). Normal faults are NW-SE and E-W oriented, and they often displace Upper Pleistocene and Holocene deposits. The main fault system is composed of two segments – Mount Marine and Mount Pettino faults – with a continuity of some kilometres, with a right later en échelon step generating a synthetic transfer zone (GAWTHORPE & HURST, 1993). Geological and geomorphological studies testified recent tectonic activity in this sector of the chain (ANGELUCCI *et al.*, 1997; BAGNAIA *et al.*, 1996; BLUMETTI *et al.*, 1997; D'AGOSTINO *et al.*, 1997b; GIULIANI & GALADINI, 1998); seismological data show both a paleoseismological (BLUMETTI, 1995) and an instrumental seismic activity recorded by local seismic networks (DE LUCA *et al.*, 1995).

2.2 **Recent stratigraphy**

The most ancient element of the continental succession is represented by the remnants of an ancient erosive surface carved in the carbonatic bedrock hanging on the present landscape around 1300-1500 m. This ancient surface, similar to others in central Apennines, is referred to a Plio- Pleistocene low-energy landscape by Authors (BOSI & MESSINA, 1991). At lower elevations entrenched continental deposits belonging to different cycles of sediments from Lower Pleistocene terms to alluvial sediments of Holocene outcrop. Most of continental deposits belong to L'Aquila Scoppito Quaternary basin. The finding of a significant vertebrate fauna in the western sector of this basin allows the Author to attribute the first deposits of the basin series to Upper Villafranchian – i.e. Lower Pleistocene (AZZAROLI ET AL., 1986; BOSI & MESSINA, 1991). On the eastern part of the study area, along the main fault slopes the first continental deposit of the area is a carbonatic breccia extensively outcropping in the L'Aquila area (Fig. 1); on the basis of both morphostratigraphic (BOSI & MESSINA, 1991) and magnetostratigraphic data (D'AGOSTINO *et al.*, 1997a) these breccias belong to Lower Pleistocene (BOSI & MESSINA, 1991). Breccias in the area of L'Aquila overlay a lacustrine deposit outcropping at the bottom of the hills eroded by the Aterno River Valley. Figure 1 shows a geological sketch of the study area modified from GIULIANI & GALADINI (1998).

Both deposits belonging to L'Aquila Scoppito terms of Lower Pleistocene and breccias of the same age outcropping in the L'Aquila area are deeply deformed by extensional tectonics showing tilted layering and prints of micro and mesostructures (GIULIANI & GALADINI, 1998).

2.3 Morphological setting

The study area consists of the Plio-Pleistocene basin of L'Aquila Scoppito, now partially occupied by the Aterno River Valley and its carbonatic slopes eastwards.

The main faults bounding the Aterno River valley are located along Mount Pettino and Mount Marine slopes. The morphological setting of the study area is deeply influenced by active extensional tectonics by means of carbonatic slopes controlled by steeply dipping normal faults NW-SE trending along the north-eastern side of the Aterno River Valley. These faults are evidenced by bedrock scarps 4-5 km long that constitute major morphological features of the area. These faults are often associated with broad longitudinal areas of cataclastic material. In this material one can observe forms of accelerated erosion due to cataclasite, particularly prone to erosion. This lithology is extensively present in the slopes of Mount Marine and Mount Pettino and is affected by lamdforms similar to "bad land".

The structural setting of the area allows to identify two different sectors: the hangingwall block which corresponds to the right of the main stream and the footwall block on the left valley-side, each of them showing peculiar drainage pattern.

The main stream of the drainage network is the Aterno River with a NW-SE trend parallel to the one of the main active faults, while the streams of the lowest order (after STRAHLER, 1957) are mainly oriented perpendicularly to the main fault planes. These streams belonging to the

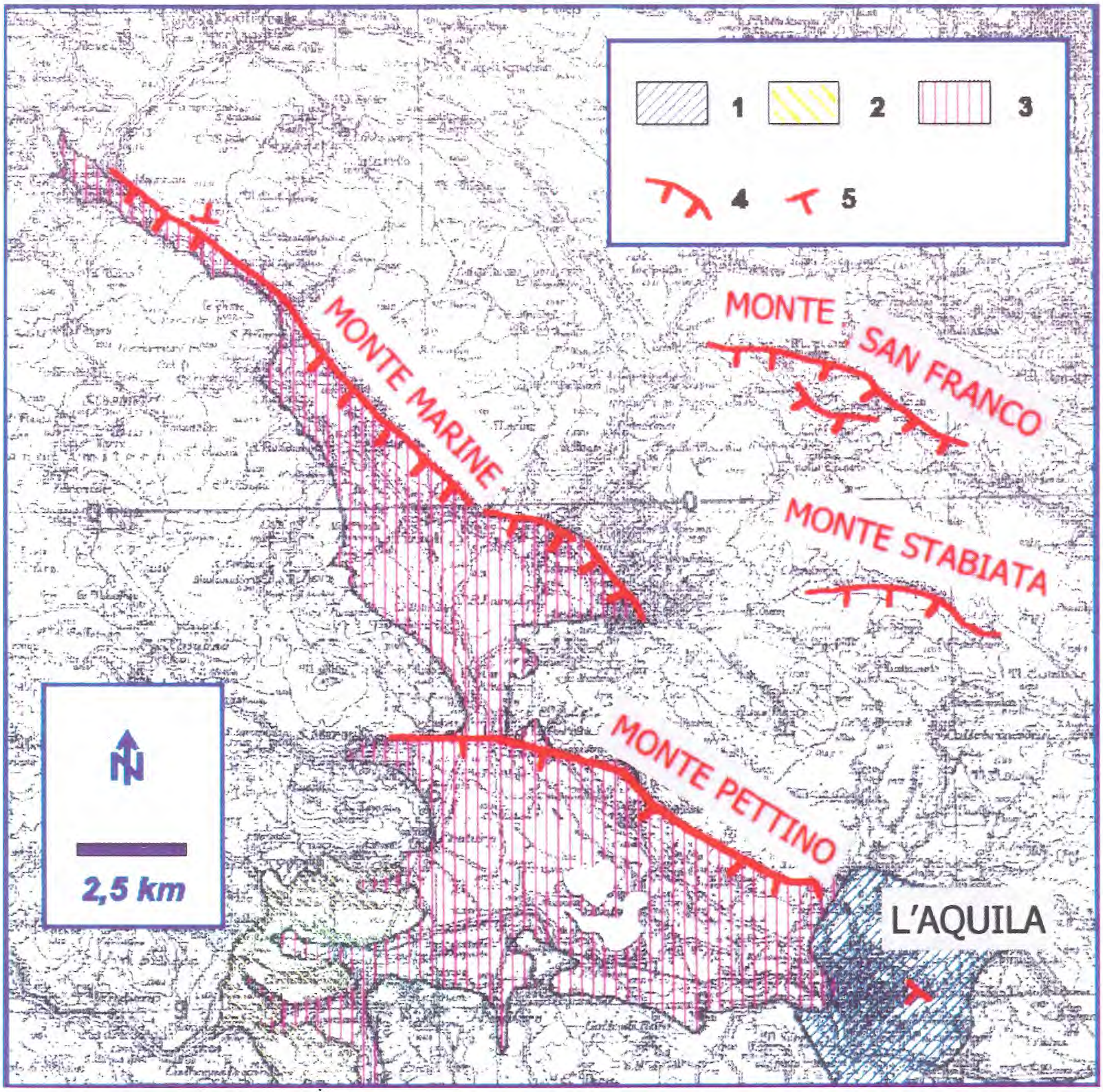


Fig.1 - Geological sketch map. LEGEND: 1) L'Aquila breccias (Lower Pleistocene); 2) lacustrine and fluvial deposits belonging to "Madonna della Strada Complex" (Villafranchiano in Bosi & Messina, 1991); 3) recent and ancient alluvial deposits (Middle Pleistocene - Holocene); 4) active normal faults 5) bedding

footwall block drain narrow and linear basins emplaced on high-gradient slopes. On the contrary, the low-gradient slopes of the hangingwall give rise to broad basins. The transfer zone of right step en échelon between the Mount Pettino fault and Mount Marine fault is characterised by a more complex drainage pattern: an oblique drainage that extends behind the first order catchments on the main slopes. The transfer zone is occupied by a tributary of the Aterno that drains Mount Stabiata hangingwall block and a series of valleys located NE of Mount Pettino. This area is a ramp with a dip direction almost parallel to the strike of faults where the stream flows from the footwall of the Mount Pettino fault to the hangingwall of the Mount Marine fault following the natural slope created by the en échelon step of about 2 km between the two faults.

3. METHODOLOGY

This study followed two parallel ways: the first aimed at identifying all the morphological features connected to the tectonic activity, the second concerned the quantitative geomorphic analysis of both drainage basins and stream network pattern.

The study of the *morphotectonics field evidence* in the Upper Aterno River Valley has been performed by the use of aerial photographs interpretation as well as by field surveys. Among the morphological features surveyed, those identifiable as surface expression of tectonic conditioning have been chosen; on these bases a map has been drawn which represents all the morphological evidence of neotectonic interest, affecting both the slopes (fault scarp-slopes, free face, break in slope, counterslopes, straight ridges, crests) and the hydrographic elements (fluvial bends, stream piracy, straight stream, hanging small valleys, etc.). Generally speaking slope morphologies are to be considered directly linked to fault activity, while hydrographic elements are indirectly generated by tectonic activity. All the significant alignment of such morphological indicators of tectonics have been interpreted as faults or inferred faults (Fig. 2).

As to the quantitative geomorphic analysis some morphometric parameters with a neotectonic meaning have been considered.

Quantitative geomorphic analyses have concerned both drainage basins and stream network pattern and some morphometric parameters with neotectonic meaning have been calculated. To quantify the orographic configuration of the whole study area, the *amplitude of relief* (i.e. maximum difference in elevation in areas of 1 km^2) has been calculated; the neotectonc significance of this parameter has been tested through several analyses carried out in wide areas of Central Italy (Centamore *et al.*, 1995; Del Monte *et al.*, 1996; Lupia Palmieri *et al.*, 1995, 1998). The spatial variability of this parameters has been shown on a map (Fig. 3) which helps to identify areas experiencing phenomena of differential uplift or subsidence.

The control exerted by the main tectonic directions on the drainage pattern has been highlighted through a known methodology which allows the automatic identification of *preferential directions of streams* on the basis of the statistical analysis of azimuthal distribution of stream segments (Ciccacci *et al.*, 1986).

The obtained data are usually represented as a series of rose-diagrams showing some peaks which express the preferential orientations or "domains" of the whole drainage network and of each stream order (Fig. 4). In particular, previous works showed that the preferential orientations of lower stream orders can provide information about the neotectonic setting of the study area, since they are likely to be controlled by tectonic lines active in very recent time (Ciccacci *et al.*, 1986; Buonasorte *et al.*, 1991; Centamore *et al.*, 1995).

Considering the morphostructural setting of the study area, some morphometric parameters have been considered which can evidence the possible differences in the morphological features of the hangingwall and the footwall sectors. The *mountain front sinuosity* (Smf) is a geomorphic index of active tectonics (Keller & Pinter, 1996); it is defined as the ratio of the length along a given topographic escarpment to the straight length of the mountain front. Since mountain fronts associated with active tectonics and uplift are relatively straight, their Smf values will approach 1. On the other hand, as the rate of tectonic uplift is reduced, erosive processes will produce irregular profiles along the mountain fronts and the Smf values will be larger. Substantially, the meaning of this parameter is based on the tendency of active mountain front to preserve its planimetric profile straight (Keller & Pinter, 1996).

The interaction between normal faulting and drainage development in active extensional basins has been described by Leeder (1991) and Leeder & Jackson (1993, 1994). In their papers, the Authors show that tilting changes slope gradient and slope length both of which influence drainage basin size and shape; as a consequence, the footwall catchments are generally smaller, shorter and steeper than those on the hangingwall block. To compare the features of the several drainage basins located in the study area their size and shape have been expressed as geomorphic indices. The size is obviously described as the area (km^2), whereas the shape is defined as the *ratio width/length* (parallel to the main trunk) for each drainage basin.

4. DISCUSSION OF RESULTS

The map of morphotectonics evidence identifies deeply deformed zones, almost coincident with main normal active faults of the area. In fact, the most significant morphological alignments are NW-SE oriented. Particularly along the slope from Mount Castiglione to Arischia, counterslope segments NW-SE trending, breaks of slope, symmetric straight ridges and a series of valleys parallel to the main slope have been recognised. All these elements show a trend parallel to the one of the main fault scarp. Perpendicularly to this trend, transversal linear elements, such as flat floored valleys, straight hanging channels, are broken off by the fault scarp suggesting a normal kinematics for this element. Mount Pettino zone exhibits a similar morphotectonic setting with flat floored valleys parallel to the main ridge. The alignment of some stream elbows or elbows of fluvial capture suggest a pre-existent drainage direction opposite to the present one for such valleys. This drainage inversion could probably be related to the tectonic activity of Mount Pettino fault.

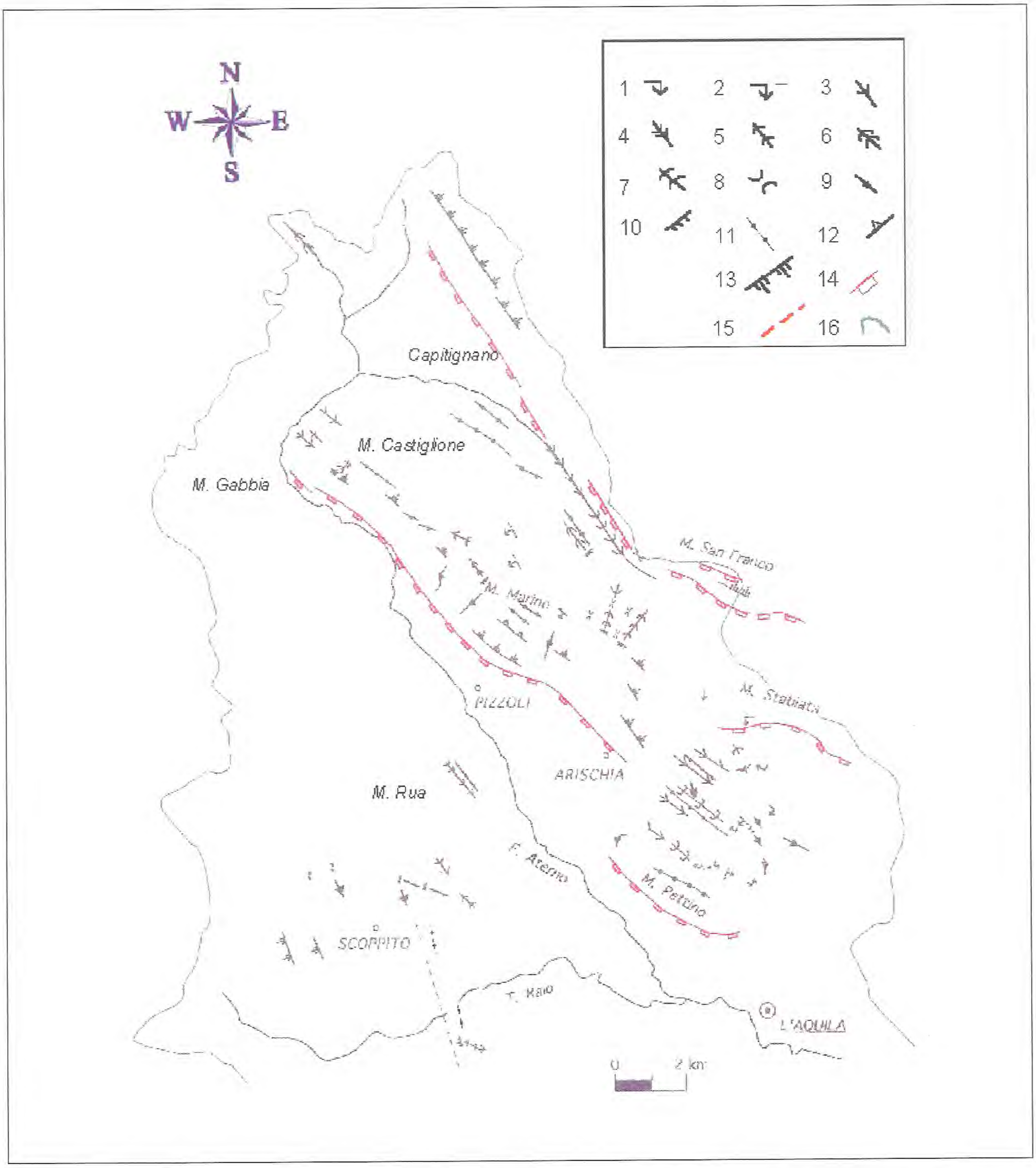


Fig. 2 - Map of morphotectonics field evidence. LEGEND: 1) stream elbow 2) elbow of fluvial capture 3) straight channel 4) valley counterslope outlet 5) straight valley 6) through floored valley 7) flat floored valley 8) saddle 9) downcutting straight channel 10) hanging valley threshold 11) symmetric straight ridge 12) break of slope 13) counter slope 14) normal fault scarps 15) inferred transcurrent fault 16) drainage divide.

Shortly, the all of the morphotectonics evidence for this area underlines an important NW-SE trending normal fault; moreover, the high degree of preservation of the morphological evidence of tectonics testifies to the possible recent activity of this tectonic dislocation which is confirmed by structural data (GIULIANI, 1998; GIULIANI & GALADINI, 1998).

As far as the south-western sector is concerned, several morphotectonics elements N-S trending have been identified. In particular the Raio valley seems to be cut by a linear morphological element underlined by some elements as it can be noticed in figure 2.

These NS trends are probably related to the surface expression of the tectonic structures recognised in the area by the Authors (CELLO *et al.*, 1998) and interpreted as left strike-slip faults.

Results of geomorphic quantitative analysis are in accordance with the morphostructural setting so far outlined for the study area.

The distribution of the *amplitude of relief* (Ar), repre-

FOOTWALL	LITHOLOGY	BEARINGS	LENGHT (km)	Smf
MOUNT CASTIGLIONE M. MARINE	CALCAREOUS BEDROCK	NW-SE	19.4	1.01
HANGINGWALL	**LITHOLOGY**	**BEARINGS**	**LENGHT (km)**	**Smf**
M. GABBIA M. RUA	CALCAREOUS BEDROCK	NW-SE	12	1.5

Table 1 – Footwall and hangingwall block mountain front sinuosity (Smf)

sented in the mosaic map (Fig. 3), shows several alignments of similar values that emphasise the main structural directions, which are in agreement with the results of the previous analyses; in particular, the NW-SE main fault is clearly discernible. Moreover, the high Ar values on the northeastern side of this tectonic dislocation suggest the possible recent uplift of this sector.

The analysis of preferential distribution of stream directions evidenced a sharp difference in the footwall and hangingwall sectors (Figg. 2 and 4). The NE footwall sector is characterised by drainage networks almost emplaced according to the NE-SW domain, i.e. perpendicular to the normal "main fault". This can be explained considering that drainage networks are located on the upthrown side and are controlled mainly by the local slopes induced by the recent

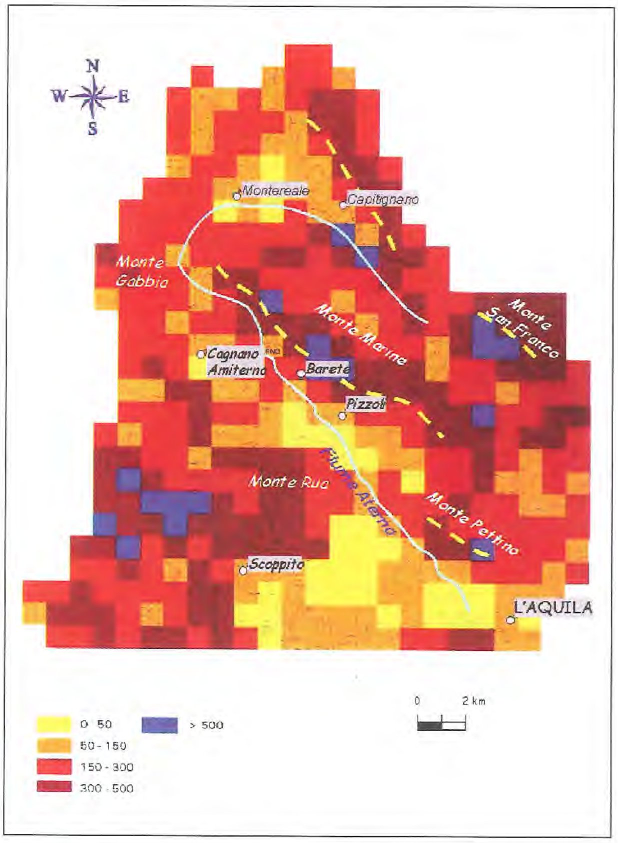


Fig. 3 - Amplitude of relief map. Yellow dashed lines represent bedrock fault scarps.

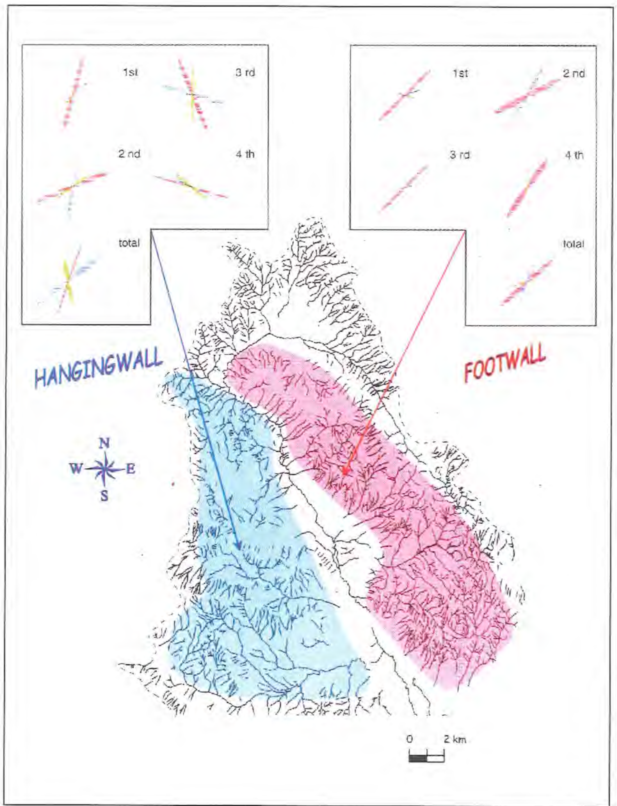
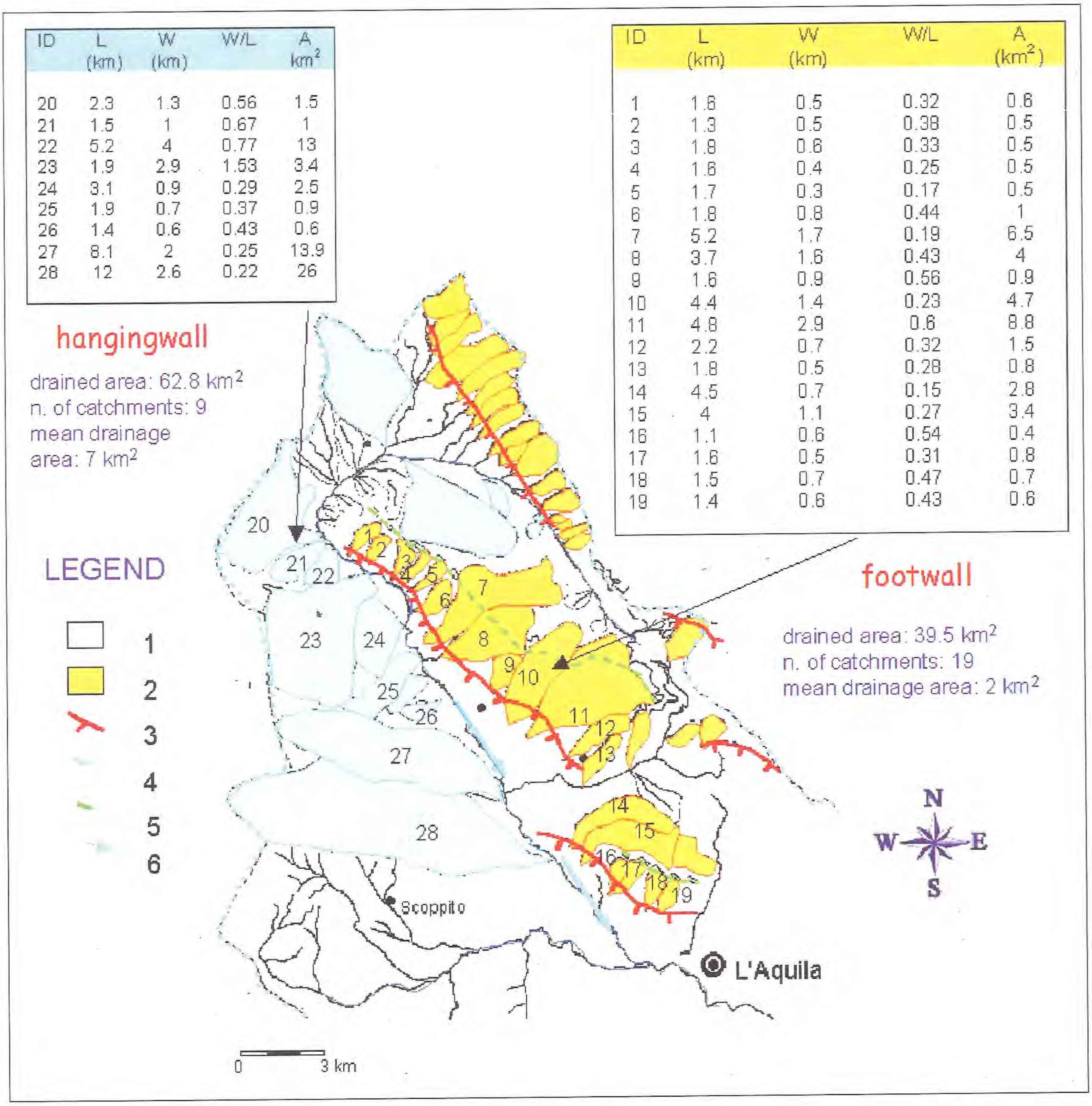


Fig. 4 - Drainage network and rose diagrams of streams belonging to footwall block (red area) and hangingwall block (light blu area).

activity of the fault (Fig. 5). The SW hangingwall sector of main active faults shows an higher variability of the preferential stream directions also testified by the dentritic pattern of network. It is significant that first order streams are mainly N-S oriented, which could suggest the existence of a N-S tectonic direction active in very recent times, at least in this sector (Fig. 4).

The parameter mountain front sinuosity (Smf) can be measured both from topographic maps and aerial photographs. To make possible the comparison between the sides of the study valley, it has been necessary to select appropriate mountain fronts; both the chosen escarpments are located on calcareous bedrocks. On the left valley-side, the index has been calculated along a NE-SW oriented break in the slope that characterised Mount Castiglione (1317 m), Mount Marine (1491 m) and Mount Pettino (1147 m) for 19.4 km. The obtained value is 1.01 (Tab. 1). Being S_{mf}



ID	L (km)	W (km)	W/L	A km²
20	2.3	1.3	0.56	1.5
21	1.5	1	0.67	1
22	5.2	4	0.77	13
23	1.9	2.9	1.53	3.4
24	3.1	0.9	0.29	2.5
25	1.9	0.7	0.37	0.9
26	1.4	0.6	0.43	0.6
27	8.1	2	0.25	13.9
28	12	2.6	0.22	26

ID	L (km)	W (km)	W/L	A (km²)
1	1.6	0.5	0.32	0.6
2	1.3	0.5	0.38	0.5
3	1.8	0.6	0.33	0.5
4	1.6	0.4	0.25	0.5
5	1.7	0.3	0.17	0.5
6	1.8	0.8	0.44	1
7	5.2	1.7	0.19	6.5
8	3.7	1.6	0.43	4
9	1.6	0.9	0.56	0.9
10	4.4	1.4	0.23	4.7
11	4.8	2.9	0.6	8.8
12	2.2	0.7	0.32	1.5
13	1.8	0.5	0.28	0.8
14	4.5	0.7	0.15	2.8
15	4	1.1	0.27	3.4
16	1.1	0.6	0.54	0.4
17	1.6	0.5	0.31	0.8
18	1.5	0.7	0.47	0.7
19	1.4	0.6	0.43	0.6

Fig. 5.

close to 1, it is possible to hypothesise the presence of an active fault that tends to maintain straight the relative profile in plan view.

On the right valley-side the S_{mf} has been measured along the topographic escarpment singled out by aereal photographs that runs for 12 km from Mount Gabbia (1263 m) to Mount Rua (1236 m). In this case S_{mf} is 1.5 (Tab. 1). The larger value of the geomorphic index for this side of the Upper Aterno River Valley suggests that erosive forces have been acting along the base of this mountain front for a longer time. The values of the calculated index are in agreement with the results so far obtained: the footwall mountain front shows lower sinuosity than the hangingwall mountain front, thus confirming the recent activity of the NW-SE main fault.

The interaction between normal faulting and drainage in active extensional basins has been described by LEEDER & JACKSON (1993). In their paper the Authors show that the footwall catchments are generally smaller, shorter and steeper than those on the hangingwall block.

To compare the features of the several drainage basins located in the study area, their geometry have been expressed as geomorphic indices. The size can be described as the area (km²), whereas the shape is defined as the ratio of width to length for each drainage basin.

The studied catchments are those that drain directly into the main trunk – the Aterno River –, larger than the second hierarchic order (STRAHLER, 1957). The watersheds relevant are numbered from NW to SE (Fig. 5). Once again the blocks of the study area are clearly different: the footwall has a drainage area of 39.5 km² with 19 main catchments, giving a mean drainage area of 2 km². The hangingwall has a drainage area of 68.2 km², with 9 main cathcments, giving a mean of 7 km². Moreover, the basins on the footwall are long and narrow; on the other hand, the ones related to the hanginwall are rounded and variously shaped. As a matter of fact, the mean value for the left valley side is rather low (0.35), whereas the mean value for the right side higher (0.56).

5. REMARKS

Morphological analyses evidenced a morphostructural setting of the study area in good agreement with geological and structural data known in literature. Moreover deep differences have been evidenced in the morphological features of the hangingwall and footwall blocks concerning mainly the drainage system assessment. Once the reliability of the morphological methods followed in the present study will have been tested, by extending the analysis to different cases, they can then be applied to areas where independent evidence regarding active tectonics is not available.

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