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MORPHOMETRIC ANALYSIS OF SANSOBBIA RIVER BASIN (LIGURIA, ITALY) AND TECTONIC IMPLICATIONS

ABSTRACT: FIRPO M. & SPAGNOLO M., *Morphometric Analysis of Sansobbia River Basin (Liguria, Italy) and tectonic implications.* (IT ISSN 0391-9838, 2001).

The Sansobbia River Basin (Liguria, Italy) is a morpho-structural area of high interest. Through topographic surveys, photointerpretation and quantitative geomorphology techniques, many landscape aspects of the study area have been analysed. The morphometric analysis of the drainage network, showing high values of the bifurcation ratio (4,5 on average) and of the bifurcation index (1,3 on average), demonstrates a strong structural influence on the evolution of the drainage network itself. The drainage network and topographic anomalies highlighted two main morphotectonic directions: E-W and N-S. The same directions were confirmed by the tectonic lineaments derived from aerial photographs and D.T.M. interpretation. Moreover, the azimuth analysis of the ordered Sansobbia network showed E-W and N-S as the most representative directions of the channels.

Together with previous geological studies of the region and the new data collected, it is possible to conclude that the two main fracture systems (E-W and N-S) have played, and still play, an active role in influencing the morphology of the whole Sansobbia River Basin.

KEY WORDS: Quantitative Geomorphology, Morphotectonics, Tectonic Lineaments, Sansobbia River, Ligurian Alps.

RIASSUNTO: FIRPO M. & SPAGNOLO M., *Analisi morfometrica del Bacino del Torrente Sansobbia (Liguria) e implicazioni tettoniche.* (IT ISSN 0391-9838, 2001).

Il Bacino del Torrente Sansobbia (Liguria) è una zona di elevato interesse morfostrutturale. Attraverso indagini di carattere topografico, fotointerpretazione e tecniche di geomorfologia quantitativa sono stati analizzati diversi elementi morfologici dell'area di studio. L'analisi del grado di organizzazione del reticolo idrografico ha messo in evidenza valori elevati del rapporto di biforcazione (in media 4,5) e dell'indice di biforcazione (in media 1,3) che testimoniano la forte influenza strutturale nell'evoluzione del reticolo stesso. L'analisi delle anomalie idrografiche e topografiche ha messo in luce come direzioni morfotettoniche preferenziali quelle E-W e N-S. Le stesse direzioni sono state confermate dall'analisi del lineamenti tettonici eseguita sulle foto aeree e sul D.T.M. dell'area di studio. Infine, ci si è avvalsi dello strumento informatico per l'analisi azimutale del reticolo idrografico rettificato e gerarchizzato. Anche questo studio ha messo in luce come direzioni preferenziali quelle E-W e N-S.

Sulla base dei risultati ottenuti, parzialmente integrati e comparati con le conoscenze geologiche di carattere regionale già note in letteratura, è possibile concludere che i due sistemi di fratture E-W e N-S hanno giocato e tuttora giocano un ruolo determinante nello sviluppo morfologico dell'intero bacino del Torrente Sansobbia.

TERMINI CHIAVE: Geomorfologia quantitativa, Morfotettonica, Lineamenti Tettonici, Torrente Sansobbia, Alpi Liguri.

INTRODUCTION

The Sansobbia River is one of the rivers in the Ligurian side of the Western Alps that share their main divide with the Po River. Its evolution is characterised by alternating phases of fluvial captures and divide withdrawals. The whole Sansobbia Basin, with its many drainage network anomalies and topographic peculiarities, represents an area of high interest for investigating the relationship between tectonics and geomorphology. In particular, the evolution of its drainage network is highly controlled by the litho-structural characteristics of the Basin.

Through morphometric analysis of the drainage network has been possible to quantitatively verify how strongly the network evolution has been influenced by tectonics. Moreover, the tectonic lineaments analysed from aerial photographs, the study of topographic and drainage network anomalies as well as the azimuth analysis of each network segment have highlighted the principal morphotectonic directions of the study area.

THE SANSOBBIA BASIN, GENERAL FEATURES

The Sansobbia River Basin (fig. 1) covers an area of 72 km^2 and is located in the province of Savona (Liguria region, Italy) partly within the Monte Beigua Natural Park.

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The river begins on the western slope of Monte Beigua (1287 m a.s.l.) and flows into the Ligurian Sea, between the seaside resorts of Albissola Marina and Albisola Superiore. The total length of the river network is approximately 420 km. The main stream roughly follows a NNW-SSE direction and the asymmetric tributaries are more developed on the orographic right side. The basin is characterised by a higher drainage density (5,8 km/km^2) than the neighbouring basins.

From a climatic point of view, this area is critically influenced by two main factors: to the South, the presence of the Ligurian Sea and to the North the unusual topography with high altitudes at a relatively short distance from the coast. In certain areas, the main Padano-Ligure divide is only 6 km away from the sea. The mean annual rainfall is relatively high with peak values of 1500 mm in the rainy seasons of autumn (37% of the yearly rainfall average) and spring (30% of the yearly rainfall average). The low winter temperatures in the mountains, often below 0°C, justify the prolonged presence of snow on the ground, occurring mainly on the northern slopes. The area, which has not been urbanised or cultivated, is generally covered by tree vegetation (i.e. copses of *Castanea Sativa L.*) which plays a key role in reducing soil erosion by rainfall.

GEOLOGICAL SETTING

The basin, characterised by complex geology, has been formed on the Ligure-Piemontese, Piemontese and Brianzonese domains (fig. 1). In the study area many different lithologies can be found. The pre-Cenozoic polimetamorphic and poli-deformed substratum of the Ligurian Alps (Savona Crystalline Massif, Voltri Group and Montenotte Nappe l.s.) is covered in discordance by the sedimentary Oligo-Miocene formations belonging to the Piemontese Tertiary Basin (BTP) and to the Pliocene and Quaternary terrains of the coastal area.

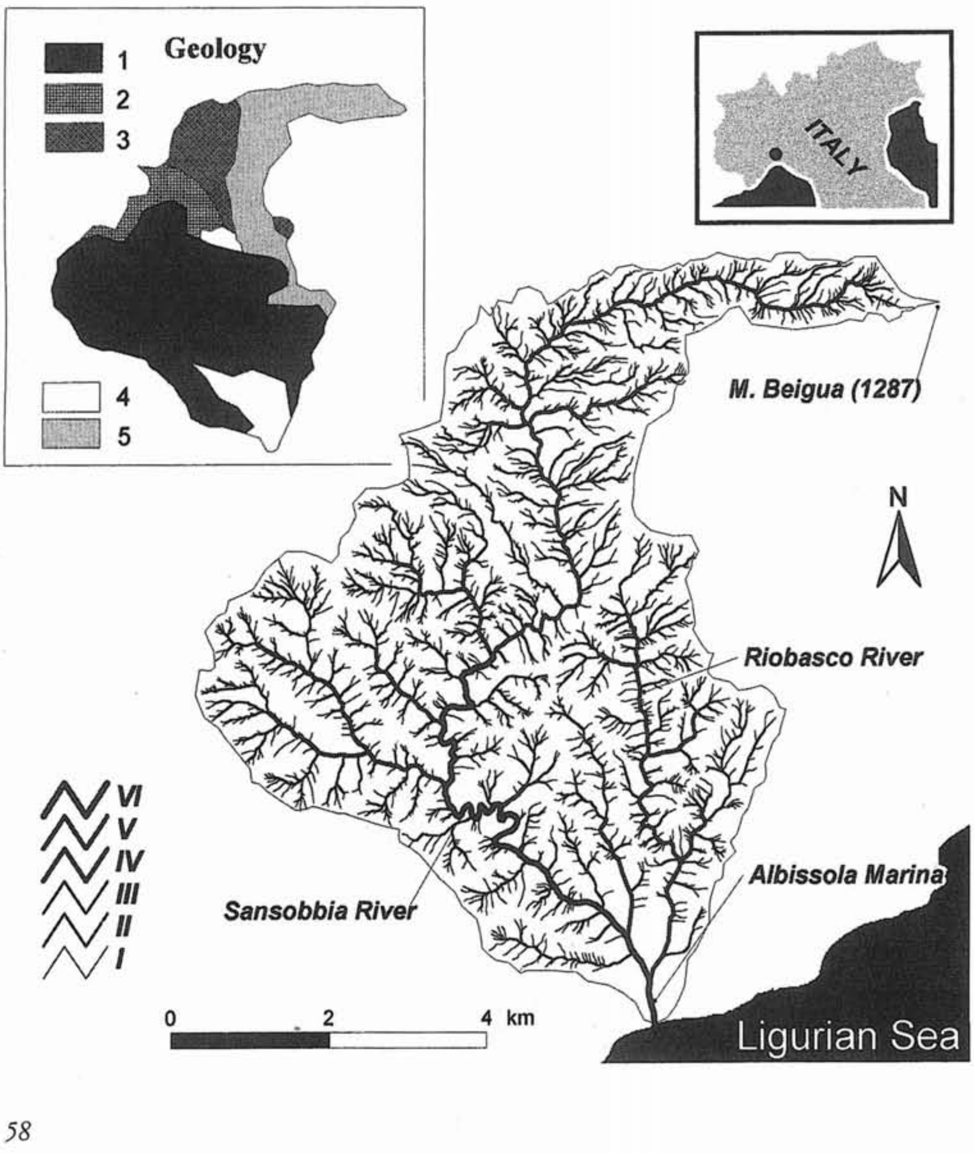

FIG. 1 - The ordered drainage network of the Sansobbia River Basin and a geological sketch of the area: 1 - Crystalline Massif of Savona; 2 - Montenotte Nappe; 3 - Piemontese Tertiary Basin; 4 - Quaternary deposits; 5 - Voltri Group.

The Crystalline Massif of Savona

This term refers to an allochthonous portion of pre-Upper-Carboniferous basement characterised by the absence of tegument and cover; it belongs to the inner Brianzonese basin. Lithologically, it refers to two main groups: firstly, granite and ortogneiss elements and secondly amphibolite and paragneiss masses (Vanossi & *alii*, 1984). Within the Sansobbia River Basin, rock outcrops of the Crystalline Massif can be commonly found in the southern sector.

The Voltri Group

Among the many formations belonging to the Voltri Group, the most frequently observed are polimetamorphic ophiolite and ultra-femic rocks, but in addition quartzite, marble, calcareous schist and mica schist are also found. At first, the Voltri Group was subdivided in different structural units (Chiesa & *alii*, 1975). In the study area, four main units can be found. The Beigua Unit (mainly serpentinite and eclogite) is partially covered by strips of the Alpicella Unit (metabasites and calcareous schist) and is bordered to the South by the Varazze Unit (metagabbro and ultra-mafite with green schist type paragenesis) and by the Voltri-Rossiglione Unit (calcareous schist, calcareous and dolomite marbles, quartzite, quartzite schist and prasinite).

Montenotte Nappe l.s.

This term refers to the allochthonous composite nappe made up by a pre-Cenomanian ophiolite succession (Piemontese-Ligure domain) and relative cover (Montenotte Unit s.s.) tectonically connected to Triassic-Liassic carbonate sequences (Pasquarè, 1968). The peculiarity of the Montenotte Nappe is the presence of ophiolite lithologies, which are highly similar to the Northern Apennines sequences but are characterised by an Alpine-type metamorphic evolution. Intrusive gabbroid rocks and serpentinite crossed by basaltic dykes, rare massive volcanites, oceanic ophiolite breccias, radiolarite and clay-calcareous sediments all belong to the Montenotte Nappe (Anfossi & *alii*, 1984). The Nappe is also characterised by a surface of plane movement, dipping to SSE and not showing the fragile discontinuities typical of the Savona's Crystalline or the Voltri Group (Capponi & Gianmarino, 1982). In the study area the Nappe can be found in the northern sector covered by pre-Quaternary deposits in marly and conglomerate facies (Molare Formation).

Oligocene and Plio-Quaternary Covers

The sedimentary rocks belonging to the BTP originated from the structuring and consequent uplift of the Alps from the Upper Eocene onwards. The basal sedimentary sequences show remarkable facies and thickness diversities (Capponi & Gianmarino, 1982) and include areas of various morphology and lithology. In the study area it is possible to find breccias, conglomerate, marl, siltite and pelite.

The coastal area of the basin is characterised by the presence of deposits belonging to the Lower Pliocene period, enclosed within tectonic-type structures, having a coastal sub-parallel trend. Over these deposits, mainly formed by marl and clay (Ortovero Clay), lie Quaternary terraced deposits of alluvium.

Main Structural Lineaments

Many authors have attempted to define the main tectonic directions which controlled the structural evolution of the region. Haccard & *alii* (1972), describing the Oligo-Miocene basins, refer to tectonic deformations in the Ligure-Piemontese domain following three principal directions: NNW-SSE (the oldest), E-W (especially in the northern portion of the Voltri Group) and N-S (the youngest). Chiesa & *alii* (1975), attempting a tectogenetic synthesis of the area, underline the importance of relatively recent compressional phases following directions which are changing with time from E-W to N-S. They found E-W faults in the southern margin of the Voltri Group as well as at its southernmost contact with different paleo-geographic units. Even for the western sector they indicate the presence of E-W or ENE-WSW faults and, less frequently, N-S and NNW-SSE. They also underlined a series of NW-SE (-Celle-Sanda line and vicarious) and WSW-ENE (Ellera-Arenzano and vicarious) dislocations that separate the Voltri Group with the Savona Crystalline Massif. Boni (1984), referring to the Ligurian Alps, mentions well-defined lineaments 20°N and 60°N, as well as E-W and N-S. Even Anfossi & *alii* (1984), with regard to the Montenotte Nappe in the area between Sansobbia and Letimbro rivers, refer to two main fault systems N-S and E-W. In addition, Marini (1987), referring to the Ligurian Pliocene deposits, highlights the two main directions of N-S and W-E. Finally, Capponi & *alii* (1987), in the central-southern sector of the Voltri Group, refer to a post-metamorphic fault system with N-S (170°-180°N) and E-W as main directions.

TECTONIC INFLUENCE ON RIVER NETWORK EVOLUTION

In order to evaluate the tectonic influence on the Sansobbia River evolution, a morphometric analysis of the network was carried out. The Sansobbia drainage network was first traced on topographic maps with the contour crenulation method (scale 1:10,000 and 1:25,000). Eventually it was checked with the use of several aerial photographs, a Landsat7 satellite image, and field surveys. Every identifiable course of channelled runoff was taken into account and the resulting network was then ordered following the classic Strahler method (Strahler, 1957). Finally, the Sansobbia drainage network was computed to evaluate some important morphometric parameters (tab. 1) such as:
- Bifurcation ratio Rb (Strahler, 1957)
- Direct bifurcation ratio Rbd (Avena & *alii*, 1967)
- Bifurcation index R (Avena & *alii*, 1967)
- Segmentation index (Perotti & *alii*, 1988)

TABLE 1 - Morphometric analysis of the Sansobbia River network: u = stream order; Nu = number of channels of u order; Tu = number of segments of u order; Rb = bifurcation ratio; Ndu = number of channels of u order that flows in a u+1 order; Rbd = direct bifurcation ratio; R = bifurcation index; Lu = cumulative length of u order channels (m); Lu/Nu = mean length of u order channels; Tu/Nu = segmentation index

u	Nu	Tu	Rb=Nu/N (u+1)	Ndu	Rbd=Ndu/N (u+1)	R=Rb-Rbd	Lu	Lu/Nu	Tu/Nu
I	1600	22905		1177			233518	146	14.32
			4.21		3.10	1.11			
II	380	9824		237			103474	272	25.86
			4.87		3.04	1.83			
III	78	4589		56			46037	590	58.83
			5.20		3.73	1.47			
IV	15	2624		12			25941	1729	174.93
			3.75		3.00	0.75			
V	4	1502		4			14838	3710	375.50
			4.00		4.00	0			
VI	1	1021					10047	10047	1021.00

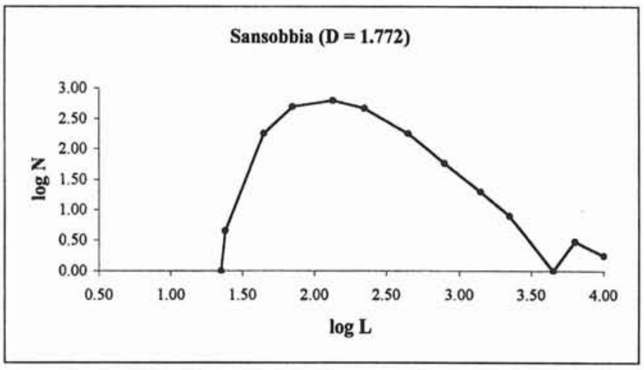

FIG. 2 - Fractal dimension analysis of the Sansobbia drainage network: L - mean length of channels; N - number of channels for each interval of given length.

As demonstrated by the authors that first defined them, all the above parameters can be read as indexes of tectonic influence on channel network evolution. In fact, a drainage network like the Sansobbia characterised by high values of these parameters is likely to be strongly controlled by tectonics. In particular, for the Sansobbia River, the high values of the bifurcation ratio (even more than 5 in the III° and IV° orders ratio) and the bifurcation index (Avena & *alii*, 1967) may be underlined. The bifurcation index differs from 0 (for an ideal perfectly hierarchized drainage network, with Rb=Rbd=2) to 2 (for a network totally influenced by tectonics) and in the Sansobbia River it is usually bigger than 1 (even 1,59 between the II° and the III° order).

One more tool is given by fractal dimension analysis. In fact, the drainage network of a river, even though apparently irregular from a geometric point of view, is characterised by a partial order variously dependent on the structural conditions of the area while it was evolving. Following the Del Monte & *alii* (1999) method, the fractal dimension D must be evaluated for a significant interval following the formula $D = - \Delta \log N / \Delta \log L$ (where L is the mean length of the streams and N is the number of streams for each interval of given length). In the case of the Sansobbia River (fig. 2), considering the interval for log L between 2,25 and 3,5 (when the correlation coefficient is very significant, $r^2 = 0{,}999$), the fractal dimension is D = 1,77. Since this dimension differ from 1 to 2 assuming higher values as the structural influence is stronger, with a fractal dimension of 1,77 it is very likely that the Sansobbia River evolution has been strongly conditioned by tectonics.

MORPHOTECTONIC EVIDENCE

To quantitatively evaluate the morpho-structural conditions of the Sansobbia River Basin, the main morphotectonic evidence were detected by using aerial photographs, digital terrain models (D.T.M.), high-detailed topographic maps and field checks. Using aerial photointerpretation, the most common tectonic lineaments were detected. The 1954 photographic series at a scale of 1:53,000 (I.G.M. 1954) was found to be extremely helpful here due to its small scale and absence of urbanised features. A similar analysis was carried out on the shadow relief images obtained with specific GIS functions from the D.T.M. of the study area (20 m of resolution). As the structures perpendicular to the light source are better illuminated, four different hill-shading directions were chosen: two perpendicular (50°N and 230°N) and two parallel (140°N and 320°N) to the main chain with a constant light inclination of 30°. The four shadow relief images obtained were then analysed to determine other important tectonic lineaments and to check those previously obtained by photointerpretation. The main directions found with these two analysis are: N-S, NE-SW, E-W, and NW-SE (fig. 3, left). Also the most known fluvial capture episodes that occurred in the Sansobbia River network shows a similar azimuthal trend and sometime they coincide with some of the found lineaments. This is the case, for example, of the famous capture (Rovereto, 1904) that moved the Sansobbia River westward to its present

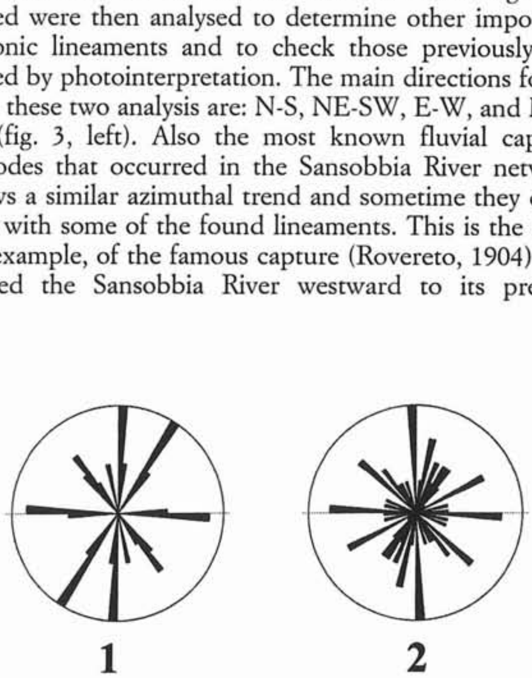

FIG. 3 - Rose diagrams: 1 - main directions from aerial photographs and shadow relief analysis; 2 - main directions from topographic and drainage network anomalies.

course, loosing its paleo river-bed now represented by the Riobasco River tributary (fig. 4).

Other morphostructural directions were highlighted after studying particular morphological parameters such as drainage network anomalies, peak alignments and rectilinear ridges. To take into consideration only the most significant data certain thresholds were applied: maximum distance of 500 m between the aligned peaks and minimum length of 400 m for the rectilinear ridges. All the rectilinear sections of channels (longer than 200 m), the fluvial straight angle bends and the double fluvial straight angle bends were analysed as drainage network anomalies. The peak alignments, the rectilinear ridges and the network anomalies showed main directions of N-S, E-W, ENE-WSW, NW-SE and NNE-SSW (fig. 3, right).

AZIMUTH ANALYSIS of STREAMS

The azimuth analysis of a drainage network has become an important tool in order to identify the main structural lineaments of a basin area. Moreover, when the study can be carried out within each stream order, a relative temporal reconstruction can also be outlined. In fact, lower order streams of relatively recent emplacement are likely to have been influenced in their development by more recent tectonic movements while higher order streams by past tectonic movements (Ciccacci & *alii*, 1986; Lupia Palmieri & *alii*, 1998).

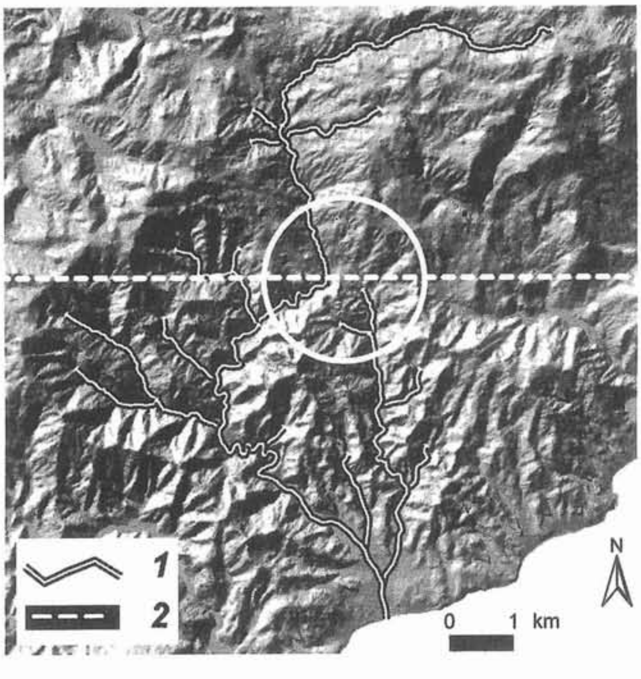

FIG. 4 - Shadow relief image of the Sansobbia Basin: 1 - the main channels; 2 - one of the lineament detected; white circle - the area of the fluvial capture.

To obtain a precise and quantitative azimuth analysis of the streams the entire channel network was acquired by using a digitizer; the digitising process results in a semi-automatic rectification of the network itself. Afterwards, through specific programs in MSDOS, the digitised network was statistically processed in order to find the most important directions of each stream order (their frequency and standard deviation) as well as the relative length and the total number of segments for each order. To give an indication as to how many data was analysed, for the first order more than 7000 streams and 22000 rectilinear segments (for a total length of 226 km) were processed. The final results are shown in the rose diagrams of fig. 5 where it is possible to clearly identify the main directions for each order. The most important evidence observed in these diagrams is an E-W (88°-94° N) main direction, characterised by high frequency and very low standard deviation. Other important directions shared by almost every order are:

- 0-4°N (in every order, particularly frequent in those of high grade)
- 111-114°N (absent in the 5° order)
- 140-144°N (absent in the 5° order)
- 49-56°N (particularly in the low orders).

CONCLUSION

The Sansobbia River, with its many network anomalies and evidence of morphotectonic influence, seems to be the result of a complex evolution. In fact, the present course of the river could be read as the product of two main elements: firstly the tectonics (uplifting, tilting, fragile deformation, etc.) and secondly the water course itself with its erosive strength. As a whole, the present network is probably the product of alternate episodes of fluvial captures and divide withdrawals. In a complex situation like this, being able to correctly identify the main tectonic directions and their connection with the morphological features becomes a critical step in understanding the evolution of the drainage basin itself. For this reason the different data layers collected were analysed and compared, giving particular emphasis to those obtained by the azimuth analysis of each order. In this way five main directions were identified:

- 88-94°N: this nearly E-W direction seems to be the most important one for the whole channel network development and in particular for its northern and eastern sections. In fact, this is present in every order with a very high ratio between frequency and standard deviation; furthermore this direction is confirmed by the shadow relief and aerial photograph analysis as well as by the study of drainage network and topographic anomalies
- 0-4°N: irregularly represented in each order, especially in those of higher grade, this direction emerges also from the shadow relief and aerial photograph analysis as well as from the study of drainage network and topographic anomalies

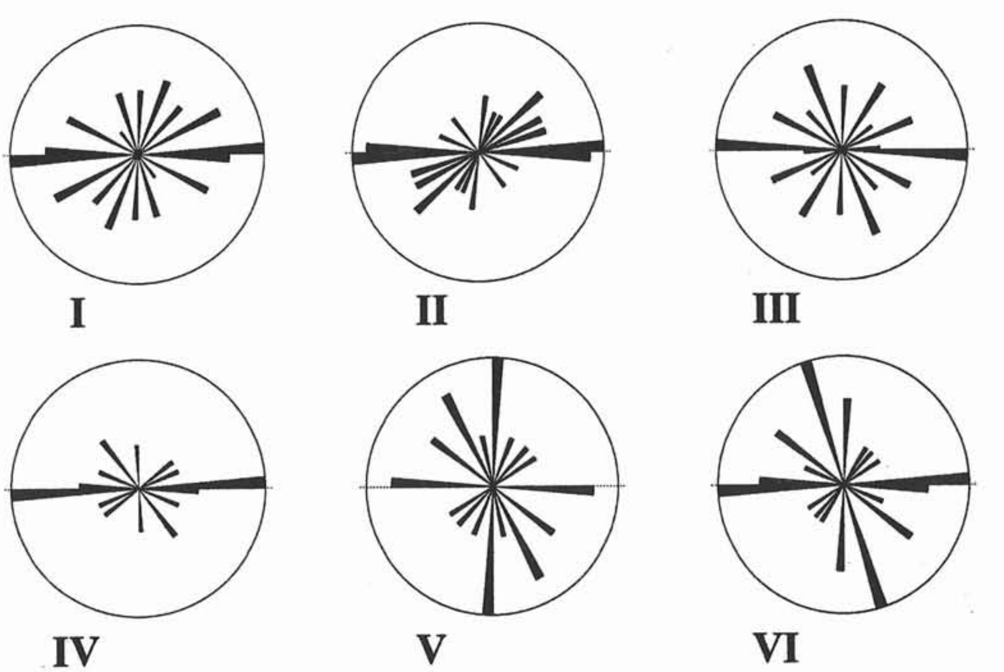

FIG. 5 - Rose diagrams showing the main directions for each channel order (I to VI) of the Sansobbia River.

- 140-144°N: this nearly NW-SE direction is important for the highest order channels and is confirmed by the study of drainage network and topographic anomalies
- 49-56°N: this direction emerges from the study of drainage network and topographic anomalies and it is also important for the low order channels
- 29-36°N: irregularly represented in the low order channels, this direction is also confirmed by the aerial photograph and shadow relief interpretation.

Comparing these results with those of the aforementioned past geological studies it is possible to draw some general conclusions. It is evident that both the E-W and N-S directions have played the most important role. In particular, the high occurrence of the E-W direction in all the orders taken into account may suggest an active role of this direction not only in the most recent network evolution (which would justify an eventually higher frequency only in the lower orders) but also in the past. In other words, this direction is likely to correspond to fractures and faults, which are an expression of past tectonic movements (as testified by its high frequency in the highest orders as well) recently reactivated. This interpretation is also consistent with the ones suggested by structural studies of the Alps-Appenines boundary area (Marini, 1982) and of the Ligurian continental margin (Fanucci & Nosengo, 1979) A similar situation could be considered for the N-S direction but in this case a higher frequency in the higher orders (especially the fifth) may suggest that the recent reactivation has not been as strong as it was for the E-W direction. Apart from these two, there are at least two more directions worth mentioning: the first is the nearly SE-NW, highly represented by the higher orders and presumably of paleo-tectonic significance. The other one, almost NE-SW, showing the opposite situation of the previous direction, could be the result of neo-tectonic movements.

Finally, it is important to underline that, as already suggested by Lorenz (1984), the Sansobbia River Basin and the whole Ligurian Alps represent an area still in evolution where the altimetric equilibrium of the chain (and consequently of the morphology and hydrography) has not yet been reached.

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