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Appraisal of Active Deformation Using DEM-Based Morphometric Indices Analysis in Emilia-Romagna Apennines, Northern Italy.

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ABSTRACT

Analysis of surface dynamics has the potential to identify areas of recent tectonic activity. By using analytical capability of MATLAB and GIS toolbox in conjunction with digital elevation model (DEM) of 5m spatial resolution, the semi-automated morphometric parameters were extracted to document the influence of neotectonics on landscape evolution in the Emilia-Romagna Apennines, northern Italy. The drainage network and sub-basins of Strahler order 4 and 5 were extracted from DEM and analyzed to demarcate areas of active deformation. The main purpose of this study was the assessment of surface dynamic processes and geotectonic setting of the Secchia, Panaro and Reno mountain river basins. The morphometric parameters such as isobase, incision, surface roughness, drainage basin asymmetry and T-index were extracted to recognize tectonic and/or lithologic control on drainage network development, basin morphology and landscape evolution. The results obtained in this investigation are consistent with the recent tectonic uplift of the region and shows strong positive correlation with the geological structures and neotectonic activity of the study area.

Keywords: DEM, Surface dynamics, Morphometric indices, Active tectonics, Emilia-Romagna Apennines.

1. INTRODUCTION

Surface processes models can be examined to differentiate the relative distribution of tectonic processes (Codilean et al., 2006; Shahzad and Gloaguen, 2011). Previous studies have shown the importance of morphometric analysis for neotectonic investigations (Day, M.J. 1979; Filosofov, V.P. 1960; Golts and Rosenthal, 1992, 1993; Cox, R.T. 1994; Grohmann, C.H. 2004; Garrote et al., 2008; Pérez-Peña et al., 2009a, b, c; Grohmann, C.H. et al., 2011). In this study, we anticipate new semi-automated methods of terrain analysis which obtain the morphometric indices such as isobase, incision, surface roughness, drainage basin asymmetry and T-index (Grohmann, C.H. 2004; Schumm et al., 2006; Garrote et al., 2008) by using 5m spatial resolution digital elevation model (DEM) and computerized algorithms (Shahzad and Gloaguen, 2010). Remote sensing analysis of such a multi-index approach identifies anomalies in the drainage pattern and landforms. It also highlight the spatial distribution of anomalously high gradient areas and the areas of variable tectonic activity across the region and hence place important constraints on the dynamic models for the landscape evolution in the Emilia-Romagna Apennines, northern Italy.

2. THE STUDY AREA

2. 1. GEOGRAPHICAL, GEOLOGICAL AND TECTONIC SETTINGS

The study area is located in the northern Apennines, Italy and consists of Secchia, Panaro and Reno mountain river basins (Fig. 1). It comprises the following geological units (Bettelli et al., 1989):

- Tertiary siliciclastic turbidites of the Tuscan units constantly cropping out along chain's axis in the upper Apennines;
- Ligurian units, composed of marine sediments together with Jurassic ophiolites overlain by a thick succession of Late Cretaceous to Middle Eocene terrigenous or calcareous turbidites cropping out in the mid-Apennine;
- Epi-Ligurian succession mainly composed of terrigenous units belongs to Middle Eocene to

Late Messinian period, deposited on the formerly deformed Ligurian units;

- The Plio-Pleistocene terrigenous marine units overlying uncomformably on the Ligurian units and the epi-Ligurian succession and cropping out in the northernmost part of the Apennines in the Po Plain margin.

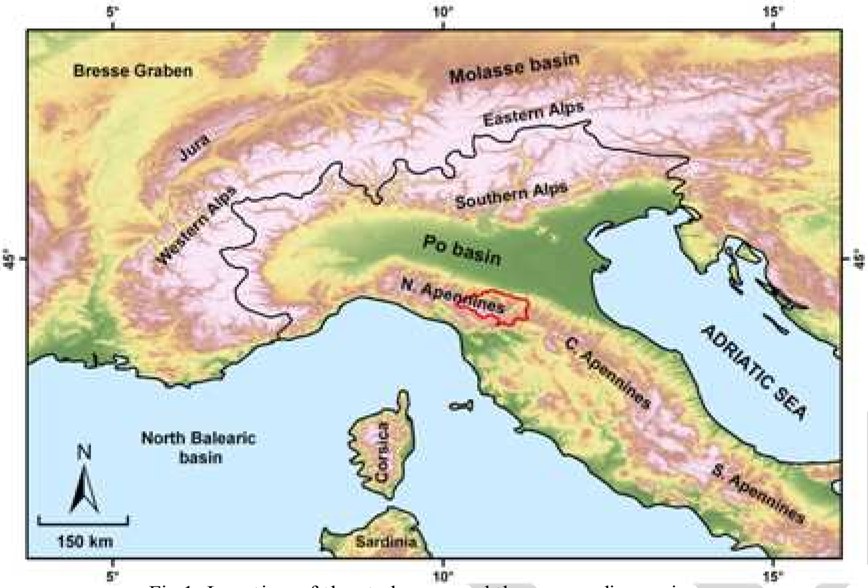

Fig 1. Location of the study area and the surrounding regions.

The distribution and frequency of active surface faults is not uniformly distributed in the region (Fig. 2) however an almost continuous fault system can be identified along the apenninic watershed, coinciding approximately with the Cervarola and Falterona thrust front. Indications of recent tectonic activity along this front derive from morphostructural evidence, for example the morphological contrast along the fault scarp which brings the Macigno and glacial deposits together in the M. Orsaro area and the fluvial capture around the active anticline of Castiglion de' Pepoli. In the upper Apennines also strike-slip and minor extenxional faults are active. Furthermore, several active faults, transverse to the axis of the chain, have been identified in the Secchia valley. However, there are no regional studies indicating areas with different uplift rates and relative tectonic activity. The only study is available (Bartolini et al., 1982) from the middle Pleistocene to Present, which finds that the entire Emilia-Romagna Apennines are uplifted, but it fails to distinguish areas of different growth rates. In order to demarcate areas of relative tectonic activity we have computed morphotectonic indices and prepared morphometric maps showing relative distribution of active surface deformation.

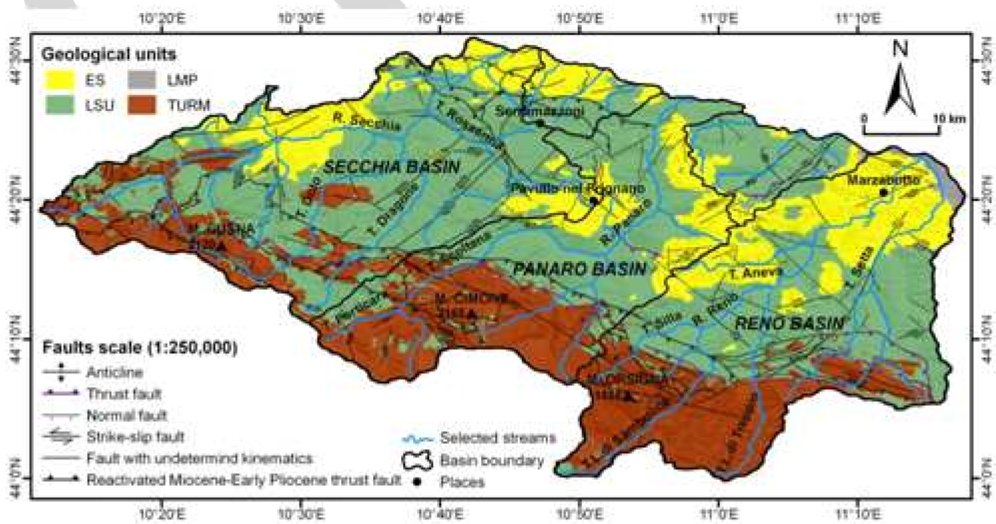

Fig 2. Geological sketch map of the study area. 1. ES-Epiligurian Sequence 2. LSU-Ligurian and Subligurian Units 3. LMP-Late Miocene-Pliestocene Marine Deposits 4. TURM-Tuscan and Umbria-Romagna-Marche Units

3. MATERIALS AND METHODS

In this investigation, we used 5m spatial resolution digital elevation model (DEM) to extract morphometric indices for the surface dynamics analysis. DEM is a representation of Earth's surface. Numerous algorithms have been developed to study the surface characteristics of DEMs and to present a large set of descriptive attributes (Wilson and Gallant, 2000; Shahzad and Gloaguen, 2011). In particular different levels of elevations helps to describe quantify and model surface dynamics using image-processing techniques and extracting the geomorphic parameters. DEM errors such as sinks and peaks were removed in order to eliminate discontinuities in the drainage network using standard GIS methods. The morphometric indices were implemented in the framework of specially designed MATLAB software named TecDEM (Shahzad and Gloaguen, 2010) and ArcGIS 9.3 software.

3. 1. ISOBASE (LOCAL BASE LEVEL)

The relative position of stream segments in a drainage basin is strongly connected to the valley order and topography, where streams of similar Strahler orders relate to similar geological events and are of similar geological age (Golts and Rosenthal, 1993). In geosciences, the word "isobase" reflects the sense of a "line of equal uplift" (Leverington et al., 2002). The isobase lines describe the erosional surfaces which have been formed due to recent tectonic and erosional events (Filosofov, V.P. 1960; Golts and Rosenthal, 1993; Cox, R.T. 1994; Grohmann et al., 2007; Grohmann et al., 2011). Golts and Rosenthal (1993) show that abrupt changes in contour line direction can be related to lithological or tectonic features. The isobase map was prepared using TecDEM (Shahzad and Glaoguen, 2010) by interpolating the elevation at the location of 2^{nd} and 3^{rd} order streams by methods proposed by (Golts and Rosenthal, 1992, 1993; Grohmann, C.H. 2004; Grohmann C.H. et al., 2011).

3. 2. INCISION (RELATIVE RELIEF)

The incision parameter corresponds to the term relative relief (RR) (Evans, I.S. 1972). The geomorphologic characteristic of an area could be well represented by the RR derived from the DEM as it carries sufficient topographic information and can provide an important basis for further quantitative analysis of relief forms. Hill slope erosion increases with increase in RR (Ohmori, H. 1978; Mizutani T. 1981). The computation of RR is influenced by the size and shape of the moving window (Klinkenberg, B. 1992; Guzzetti and Reichenbach, 1994; Ascione et al., 2008). RR is usually measured as an elevation difference on some length scale (Summerfield, M.A. 1991). Kühni and Pfiffner (2001) regarded RR as the elevation difference from the peak of the highest mountain to the valley bottom in a region. The calculation of RR (incision) in this study is based on a fixed size moving square shape window, large enough to include at least two major ridges and/or valleys otherwise the results will not represent relative relief but simply the slope gradient (Evans, I.S. 1972; Shahzad and Gloaguen, 2010).

3. 3. SURFACE ROUGHNESS (VERTICAL DISSECTION)

The roughness of a landscape describes how deep and narrow it is dissected by erosion. Surface roughness (SR) or vertical dissection is a quantitative measure of topographic heterogeneity. This method is useful for morphological characterization since it is related with the shape of landforms and not its elevation (Grohmann and Campos Neto, 2002, 2003, Grohmann, C.H. 2005; Grohmann et al., 2007, 2010). It is quantified by the vertical deviations of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. We calculate the SR by using DEM surface tools v. 2.1.254 (Janness, J. 2010) for ArcGIS. This extension allows us to generate surface area and surface ratio raster files from an existing elevation raster (e.g. DEM).

3. 4. DRAINAGE BASIN ASYMMETRY

The drainage basin asymmetry is equally effective in demarcating active tilt block tectonics in areas of both high and low seismic activity by defining neotectonic structures (Cox, R.T. 1994; Garrote et al., 2008). The asymmetry factor (*AF*) can detect tectonic tilting on drainage basin scales or large areas and is sensitive to tilting perpendicular to the direction of the trunk stream (Hare and Gardner, 1985; Keller and Pinter, 2002). *AF* is defined by the (Eq. 1):

$$AF = \left(\frac{A_f}{A_t}\right) \times 100 \quad (1)$$

where A_r is the area of the basin to the right of the trunk stream, A_t is the total area of the drainage basin and both were measured in ArcGIS. *AF* close to 50, shows no or a little tilting perpendicular to the direction of the trunk channel. *AF* which is significantly above or below 50 results from drainage basin tilting, either due to active tectonics or lithologic control. In order to express the tilting direction of the drainage basins in the study area, we articulated *AF* as the absolute value minus 50 using (Eq. 2):

$$AF = \left(\frac{A_f}{A_t} \right) \times 100 - 50 \quad (2)$$

3. 5. TRANSVERSE TOPOGRAPHIC SYMMETRY FACTOR (T-INDEX)

Cox (1994) suggested that the stream migrations can be studied using the transverse topographic symmetry factor (T-index). This approach helps us to rapidly assess the stream asymmetry and identify tilted drainage basins in the active orogens. Statistical analysis of the computed vectors was employed to determine the most dominant direction of stream migration, the magnitude and a measure of dispersion. The dominant direction is found by calculating the resultant vector (Davis, J.C. 2002) and its direction is the mean direction (θ) of all the calculated vectors. This method has been applied by (Cox, R.T. 1994; Cox et al., 2001; Garrote et al., 2006), where the asymmetry of the drainage basins was interpreted as the result of tectonic tilting. T-index was calculated for the basins of Strahler order 4 by measuring the ratio of the distance of the theoretical basin mid line to the actual stream location and basin boundary (Cox, R.T. 1994; Cox et al., 2001; Garrote et al., 2006, 2008). The transverse topographic symmetry factor is computed using (Eq. 3):

$$T = \frac{D_a}{D_d} \quad (3)$$

where D_a is the distance from the longest channel to the basin midline (measured perpendicular to a straight line segment fit to the channel), and D_d is the distance from the basin divide to the basin midline. If the stream is right in the middle of its basin, then D_a= 0 and in the relation, $T = D_a / D_d$ becomes $T = 0$, almost perfect symmetrical drainage basin. The value of T-factor increases and approaches to 1, as the stream migrates away from the basin midline and towards one of the divides. We calculated the T-factor of the drainage network by dividing the length of the streams in equal segments of 1 to few kilometres depending upon the length of the stream in study area. The values of T-index was calculated for each segment and represented as a two-dimensional vector. The length of the vector (arrow) is equivalent to the T-index, and its direction is perpendicular to the segment of the stream. The direction of arrow indicates movement of the river segment, with respect to the basin midline.

4. RESULTS AND DISCUSSIONS

4. 1. ISOBASE (LOCAL BASE LEVEL)

The local base level map (Fig. 3) generated from second and third order streams shows differential fluvial incision in the study area. The results from local base level map are consistent with the regional-scale morphostructures (e.g base level anomalies related with large structures can be easily identified along NW-SE and SW-NE oriented thrust and strikeslip faults). The base level values are decreasing downstream where streams of low Strahler order have gentler slopes. The high base level values are mainly located in the SW part of the study area and are positively correlated with the high relative uplift rates (Boccaletti et al., 2004a; Thomson et al., 2010).

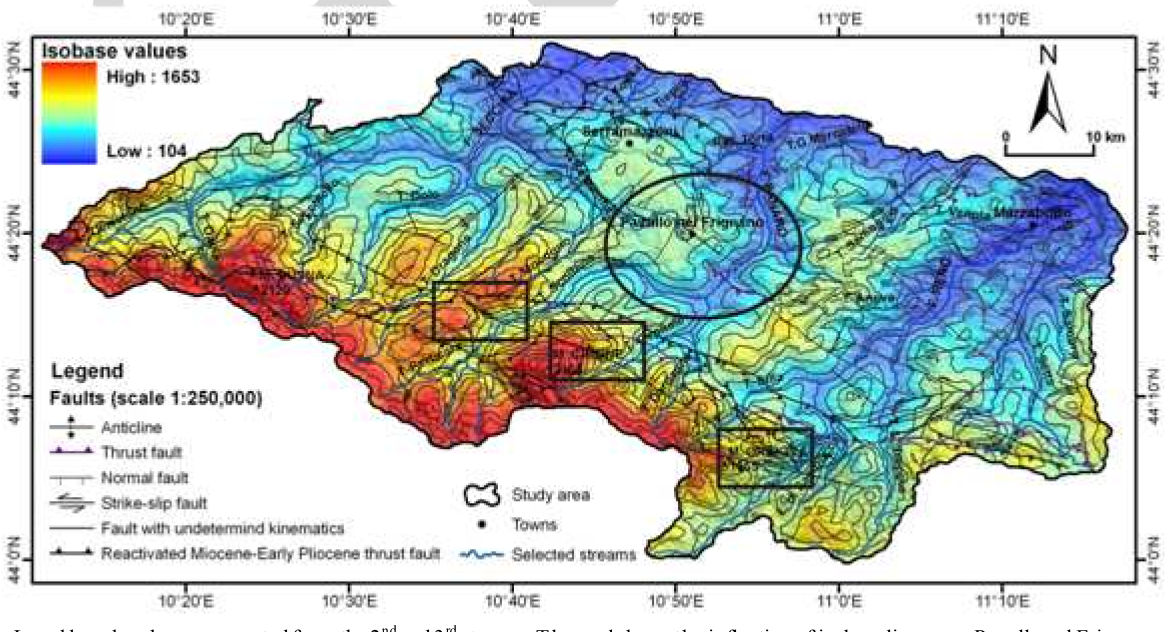

Fig 3. Local base level map generated from the 2nd and 3rd streams. The oval shows the inflection of isobase lines near Pavullo nel Frignano. The rectangles shows the inflection of isobase lines due to the SE-NW oriented strike slip faults movement.

A strong NW-SE, SW-NE and finally SE-NNW orientations of the isobase lines (shown in black oval) over the inflection of Panaro-Scoltenna rivers near Pavullo nel Frignanao is identified as a major river capture which is associated with the presence of active structures in this area (Panizza, M. 1975; Boccaletti et al., 2004a). In the SW of Rossenna river the isobase values are higher in Monte Acute and Lama Mocogno areas and the orientation of the isobase lines is in correspondence to the NW-SE oriented thrust fault. It is inferred that the distribution of high and moderate local base level values correspond to the uplifted blocks. In the south-west of the study area where the first and second order drainage incision is most prominent the isobase lines and drainage network is inflected and linearized due to possible movement of SE-NW oriented strikeslip fault.

4. 2. INCISION (RELATIVE RELIEF)

Analysis of incision map (Fig. 4) shows that most of the study area belong to mountainous relief and correspond to steep gradients (e.g., Guzzetti and Reichenbach, 1994). Growing trend of incision rates from NE to SW corresponds well with the higher relative uplift and steep slope gradients, associated with the NW-SE oriented out of sequence thrust faults and strikeslip faulting (Boccaletti et al., 2004b). In the south-west sector of the study area near the mountain divide the streams are deeply incised into the sandstone formations. The magnitude and occurrence of high or low relative relief (RR) values in the highest, high and mid-mountain areas is fairly distributed, which means that higher relative relief is not related to higher elevation or vice versa. We assume that the areas showing high incision rates have experienced a significant uplift in correspondence to steep slopes and high stream gradients.

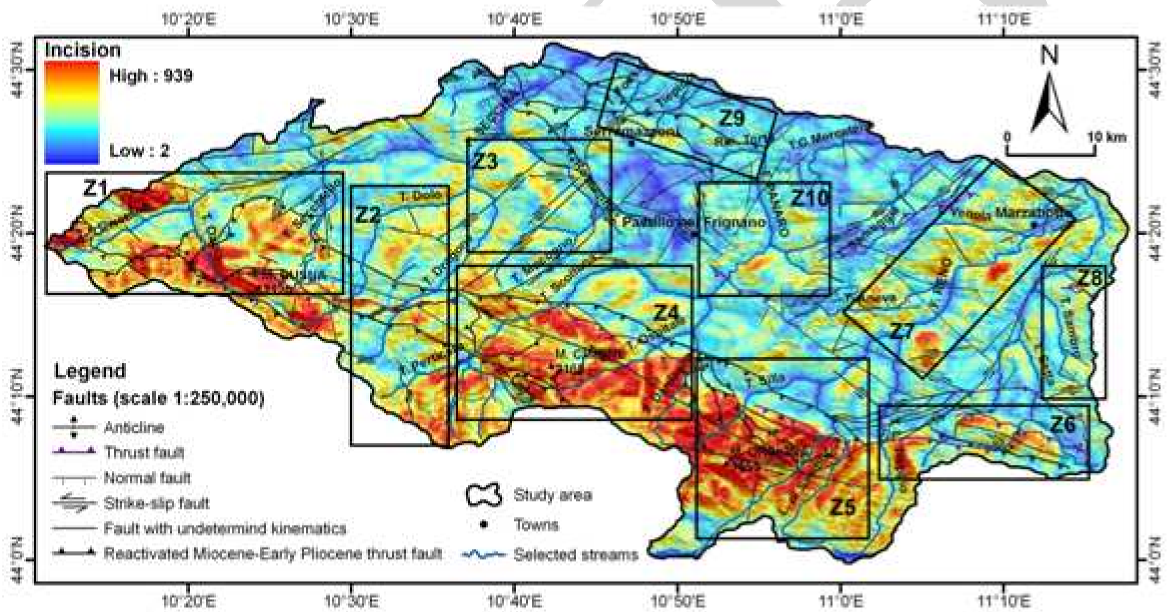

Fig 4. Incision map of the study area. The rate of incision is increasing from NE to SW and corresponds well with the relative uplift and basin tilting. The rectangles showing the areas of high and moderate relative uplift rates and it is noticeable that the incision values are also high in these areas.

4. 3. SURFACE ROUGHNESS (VERTICAL DISSECTION)

The SR is correlated proportional with the slope degrees, stream gradients, incision and hypsometric integral values. The vertical dissection map reveals an inhomogeneous distribution of bands of high and low values of surface roughness in the study area (Fig. 5) which are represented as differential colour bands separating high and low dissected regions. Thus, the bands of high values of SR are interpreted as the uplifted block locations along thrust and strikeslip fault zones (Burbank and Anderson 2001; Keller and Pinter 2002). The high surface roughness values are also consistent with the young highly dissected areas. High surface roughness in the SW part of the study area give rise to more incised relief and it gives clues about the active deformation and recent tectonic uplift. In some instances, the incised valley segments occur along faults transverse to streams, a good example can be found in streams incised when they cross the reactivated Miocene Early Pliocene thrust fault in the SW part of the study area. This situation is also probably related to the recent tectonic uplift. Slope analysis and surface roughness calculation both indicate a southwest-ward increasing roughness and consequently a greater dissection of the landscape.

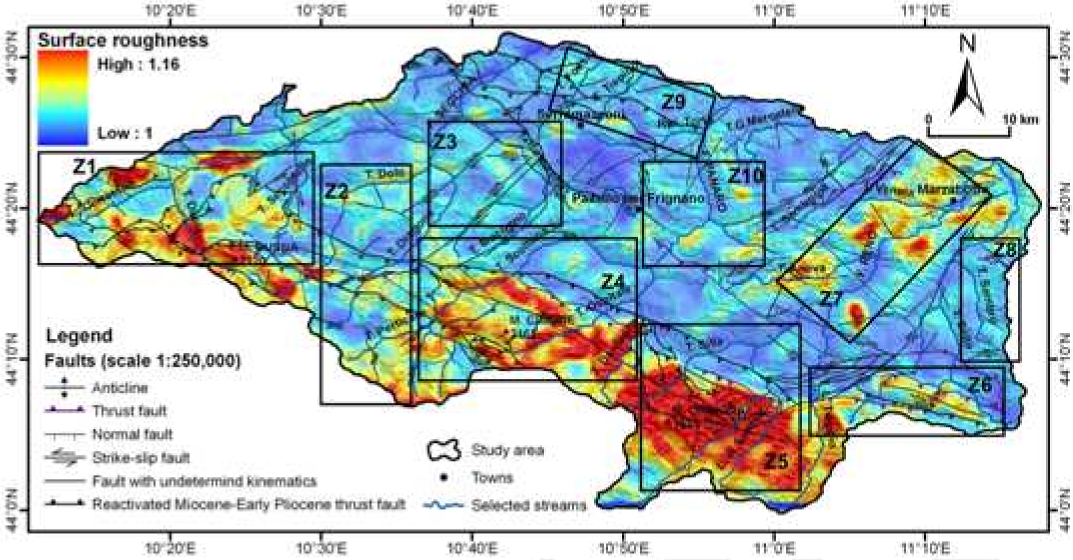

Fig 5. Map showing surface roughness values of the study area. High values in red orange and yellow color ramp define crests and incised valleys, characterizing the mountainous relief of the study area. The surface roughness shows increasing trend towards SSW direction which is also consistent with the increasing tectonic activity towards this direction (Boccaletti et al., 2004b). The black rectangles are showing the zones of relatively high surface deformation.

4.4. DRAINAGE BASIN ASYMMETRY

Seven rivers and sub-basins were analysed for tilt based tectonic analysis. The drainage network and respective sub-basins were extracted from DEM using Archydro GIS extension so that to join several small sub-basins to make a principal river basin. In the study area, the values of *AF* computed from equation 2 varies from 5.82 (almost symmetric; sub-basin 6) to 22.08 (highly asymmetric; sub-basin 2) and the arrow indicates asymmetry direction of the tilted drainage basins (Fig. 6). All the sub-basins with the exception of sub-basin 6 shows high asymmetry factor which is in well correspondence with the NW-SE oriented thrust faults and tectonically uplifted areas. The high values of basin asymmetry (i.e., *AF* = 12.40 to 22.08), are associated with high relative uplift rates and recent tectonic activity in this area.

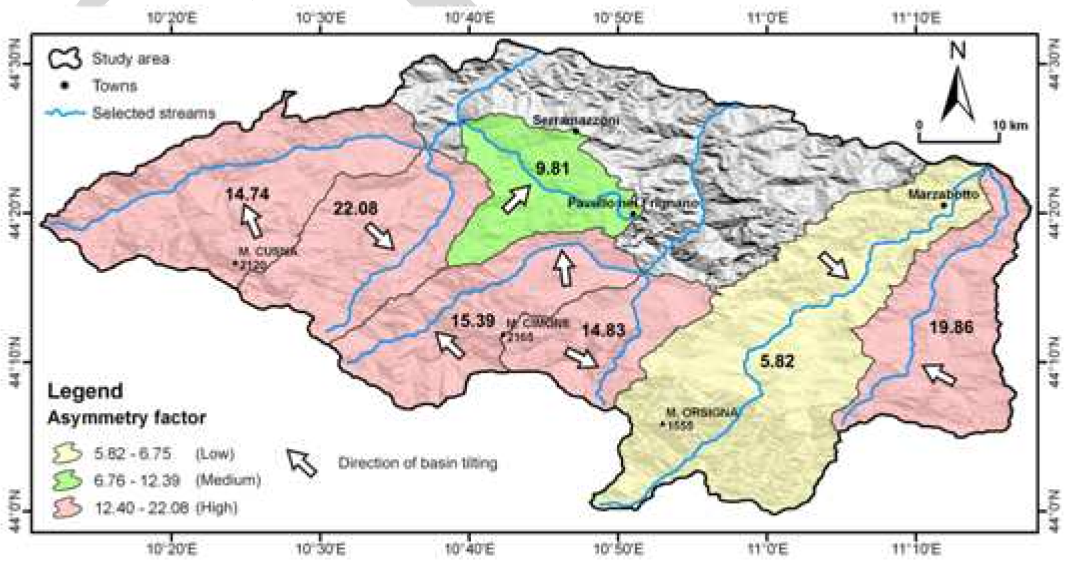

Fig 6. Map showing widespread basin asymmetry factor and tilting direction related to relative active tectonics. High, medium and low asymmetry factor shown with different colours.

4. 5. TRANSVERSE TOPOGRAPHIC SYMMETRY FACTOR (T-INDEX)

The T-index method was applied to the Strahler order 4 drainage basins (Fig. 7). It ranges from 0.22 (symmetrical) to 0.85 (highly asymmetrical). The

Secchia (basin 1), Panaro (Basin 4) and Setta (basin 7) rivers are characterized by NW lateral migration (Fig. 7, as suggested by the mean direction of the resultant vectors. However, the Reno river (basin 6), T. Dragone (basin 2) and T. Dardagna (basin 5) mainly indicate SE lateral migration. The rose and polar plots for these basins also agree with the NW and SE migration of these rivers, with the exception of a small middle segment of Reno river which shows north-westward migration. The arrow length and colour correspond to the value and extent of T-index. The high values of T-index for the selected streams and the movement direction is in well agreement with the relative tectonic movement of the analysed basins.

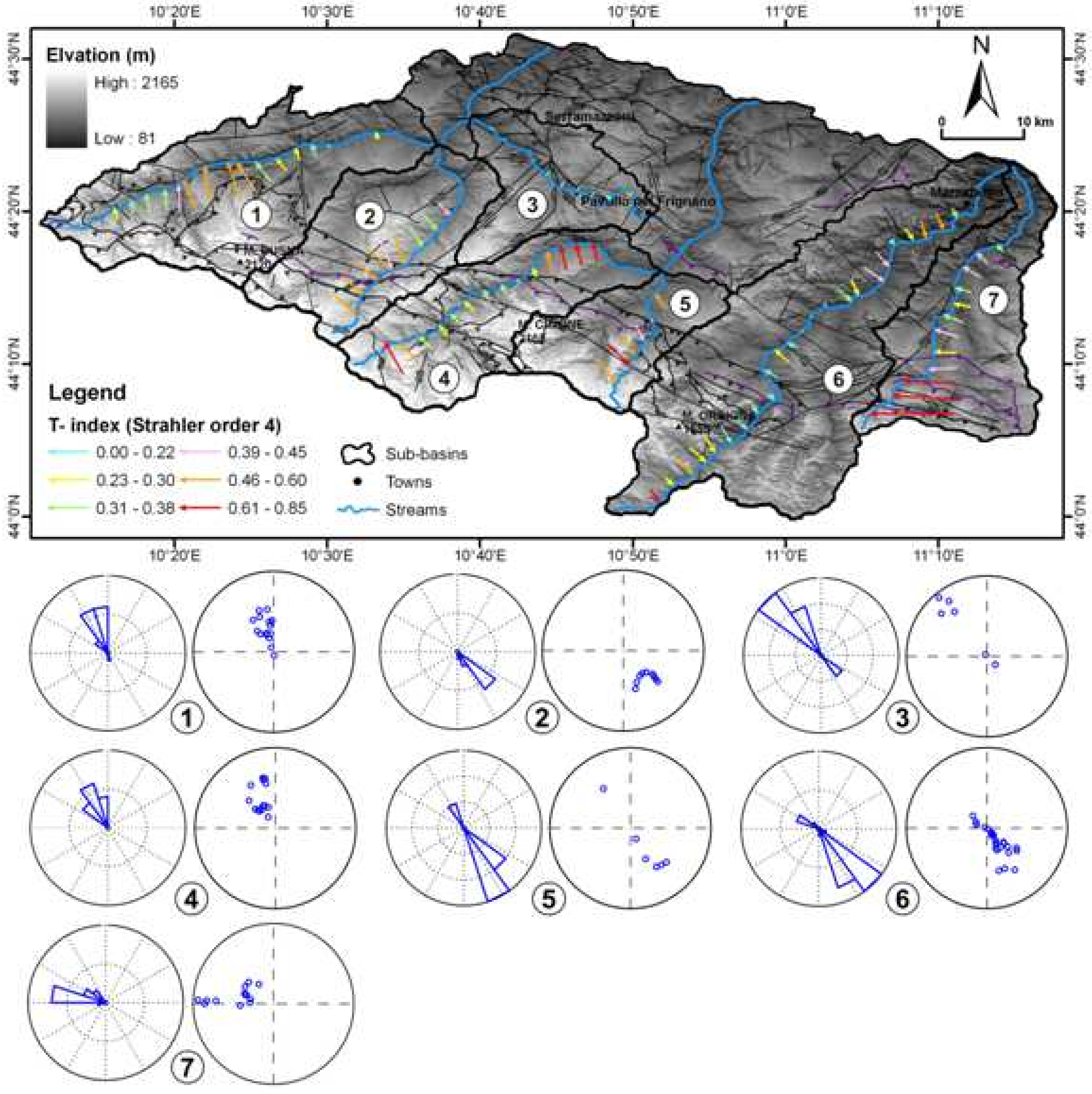

Fig 7. T-index for Strahler order 4 basins. The coloured arrows (T-indexes) denote the migration of the river with respect to the corresponding basin midline (inferring lateral stream migration). The polar and rose plots showing the preferred lateral migration direction of the basin asymmetry factor respectively.

5. CONCLUSION

The morphometric indices from GIS and DEM applications appear to be effective to detect neotectonic activities and to understand the differential relative uplift. Analysis of morphometric indices showed that these are strongly correlated with tectonically uplifted areas and regional geological structures. The high index values from morphometric analysis are corresponding with the hanging-wall of the active thrust faults and the certain segments of the strike-slip and normal faults. The isobase-level anomalies are capable of identifying younger, probably neotectonic features. Our results also allowed the identification of widespread tilt block tectonics interpreted from the migration direction of asymmetry factor that is indicative of reactivation of some faults. The major advantage of DEM-based T-index and asymmetry factor (AF) analysis is that no information is lost and it allows the explanation of preferred directions of lateral stream migration as a result of recent tectonism such as differential uplift. The asymmetry patterns of high order drainage basins reflects the dominant long-term trend of stream migration under the influence of regional tectonic activity and the low order drainage basin asymmetry is may be due to a more recent tilting. Base level analysis also shows that the south-west part of the study area is more incised that can also be related to the general tilting shown by basin asymmetry analysis. Growing trend of incision rates and surface roughness from the NE to SW corresponds well with the relative uplift and basin tilting.

The results are consistent with the tectonically uplifted areas. The results obtained, in conjunction with the available datasets shows that the analyses of DEM based morphometric indices have the potential to yield results significant to the tectonics and geology of the study area, which can be useful for the broader discussion on the active deformation along with the implementation of appropriate monitoring, management, design and remediation strategies in the identified deformed areas mainly in the context of human safety.

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