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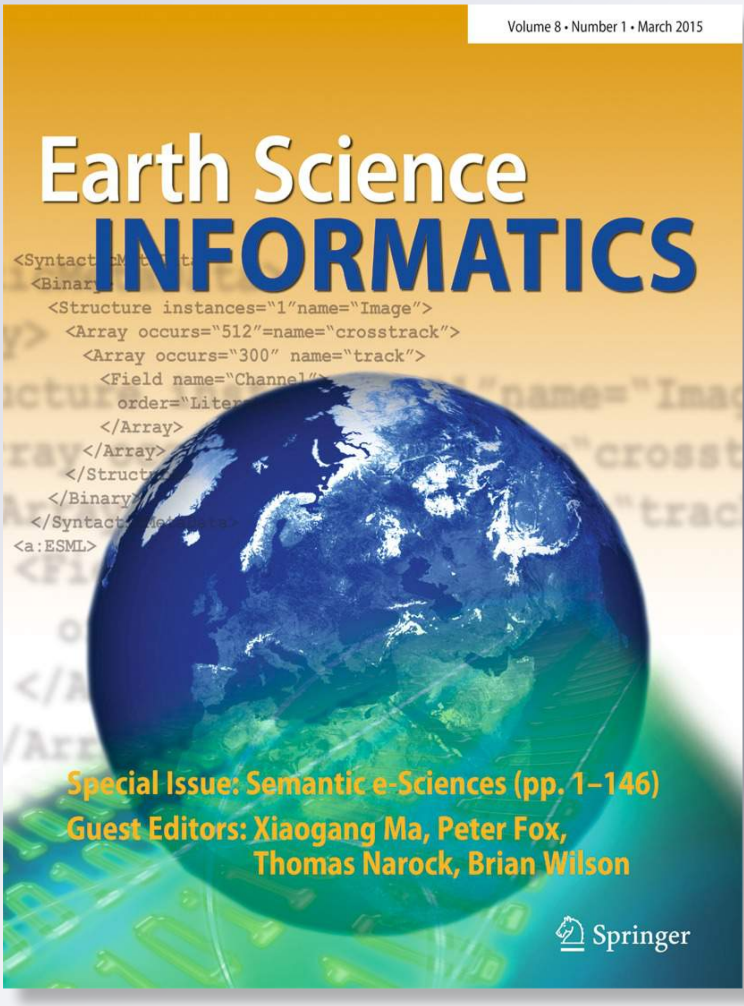

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RESEARCH ARTICLE

Appraisal of active deformation from drainage network and faults: inferences from non-linear analysis

Saima Siddiqui · Mauro Soldati · Doriano Castaldini

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Abstract This investigation reveals the relative susceptibility of the landscape to surface deformation by means of non-linear analysis of drainage network. The geometrical characteristics of the drainage network are quite capable of discriminating the impact of active tectonics. This study uses fractal dimension, lacunarity and succolarity techniques to demarcate numerous zones where the drainage network is tectonically controlled. Rose diagrams are used to compare drainage network orientation with the faults. This investigation is primarily based on the basic concept that the drainage network is subject to linearized and modify from its natural geometrical shape and orientation under the influence of tectonic activity. The areas with similar fractal dimension can be further discriminated by lacunarity and succolarity analysis. A detailed textural investigation of the drainage network (Strahler order ≥2) of Secchia, Panaro and Reno mountain river basins in northern Apennines, Italy is carried out to analyze the linearization, translational invariance and rotation of the stream patterns. The low fractal dimension values of Secchia, Panaro, Reno, Dragone, Dolo and Setta rivers indicate tectonically controlled drainage. The results reveal that the fractal dimension, lineament density and orientation analysis of drainage network and faults is a significant tool to pinpoint areas susceptible to active deformation.

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Keywords Drainage network · Fractal dimension · Lacunarity · Succolarity · Orientation analysis · Lineament density · Active deformation · Northern Apennines

Introduction

A fractal is a geometrical object which is self-similar or identical at any scale (Fig. 1). Self-similarity means that each small portion of an object, when magnified, seems about the same as a larger portion (Lifton and Chase 1992). In landscape analysis self-similarity is a concept used to explain prevailing characteristics from one cycle of development to another, the smaller cycles shows the exact similar behavior and internal structure as their parent cycles, or vice-versa. The geometrical nature of the spatial data can be interpret from the fractal analysis (Mandelbrot 1967; Longley et al. 2005; Hengl and Reuter 2009). Topography contours, rivers, coastlines, lakes and ridges are classic self-similar natural fractals. Many research publications have documented the nearly fractal nature of the landscape (Burrough 1981; Mandelbrot 1983; Mark and Aronson 1984; Culling and Datko 1987; Tarboton et al. 1988; La Barbera and Rosso 1989; Huang and Turcotte 1989, 1990; Golf 1990; Ben-Zion and Sammis 2003; Dombradi et al. 2007; Gloaguen et al. 2007, 2008). The concept of fractal dimension is very popular among geographers, geomorphologists and geologists in studying drainage basins, stream networks, river landforms evolution, drainage structures and other tree-like patterns (Rodriguez-Iturbe and Rinaldo 2001; Dombradi et al. 2007; Gloaguen et al. 2007, 2008; Shahzad et al. 2010). Furthermore, the spatial patterns analysis using non-linear or fractal analysis is getting more attention in wide disciplines of forestry, landscape ecology, tectonic geomorphology, geology, information sciences, food research and peripheric systems (Turcotte 1992; Gerrard and Ehlen 1999; Dougherty and Henebry 2001; Melo et al. 2006; Dombradi

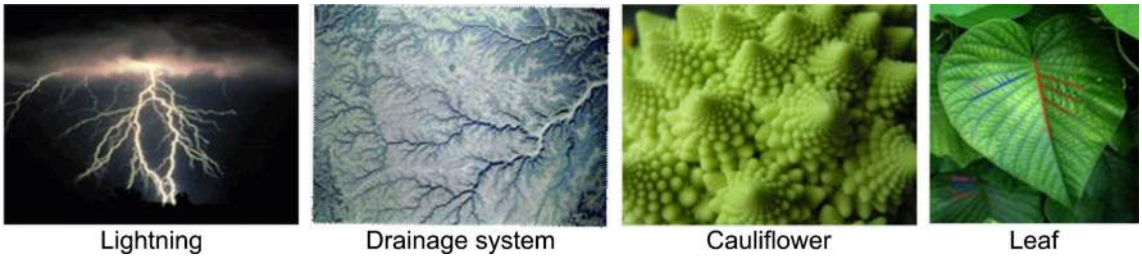

Fig. 1 Some examples of self-similar natural entities, showing fractal like structures

et al. 2007; Melo 2007; Dong 2009; Feagina et al. 2007; Gloaguen et al. 2007; Martinez et al. 2007; Shahzad et al. 2010; Valous et al. 2010).

Landforms and drainage network patterns are evident 'natural geometries' and looks like fractal objects. They are noticeably complex, but definite scaling laws are found among them (Turcotte 2007). The complex geological processes control the organization and development of stream networks (Dombradi et al. 2007). Drainage patterns have been intensely used for a broad range of geological and tectonic investigations (Hobbs 1911; Zernitz 1932; Strahler 1966; Guillermo et al. 2004; Twidale 2004; Vetel et al. 2004; Delcaillau et al. 2006; Dombradi et al. 2007; Gloaguen et al. 2007; Shahzad et al. 2010). The fractal dimension (FD) analysis of drainage network allowed us to quantify the degree of complexity by assessing how a dimension measurement increases or decreases at different scales (Gloaguen et al. 2008).

The non-linear (fractal) analysis of the drainage network is a powerful tool for analysing the drainage patterns with different space filling properties and it can discriminate areas which perhaps show similar results using linear analysis (e.g. stream profile analysis) (Wobus et al. 2006) in areas of variable tectonic activity. In this study the fractal dimension of stream networks is computed to evaluate the influence of faults on the drainage system development by analysing complexity of drainage patterns. We suppose that the drainage network loses its original complexity (or dendritic behavior) and becomes linearized due to the topographic changes triggered by tectonic activity (Gloaguen et al. 2008; Shahzad et al. 2010). In tectonically active areas rivers show distinctive patterns, by flowing linearly along straight or gently accurate faults and folds (Zernitz 1932; Twidale 2004). The space filling style of the drainage network is a strong indicator of the area susceptible to surface deformation. The main purpose of this investigation is to pinpoint the variations (e.g., breaks, linearity and irregularity) in drainage patterns due to the influence of faults by estimating the decrease in complexity as the deformation increases (Shahzad et al. 2010). These ongoing internal and external geological processes modify the landscape and the drainage network has the capability to keep the record of these changes over a long period of time.

The orientation analysis of faults and streams is a valuable tool to study and infer the tectonic influence on drainage network geometries (Ciccacci et al. 1986; Lupia Palmieri et al. 1995, 1998, 2001; Centamore et al. 1996; Del Monte et al. 1996; Currado and Fredi 2000). According to Della Seta et al. (2004) the recognition of dominant directions of faults and streams can help in the detection of tectonic controls on channel development. Study of drainage patterns in the Macaronesian Islands showed a good relationship between ridge trends and stream orientations, which proposes a general tectonic control on the topography and landforms (Scheidegger 2002). The spatial distribution of the faults can also provide significant information for the deformation processes and the fault density represents the deformation intensity. This analysis is useful to identify the concentrations of faults per unit area. The areas having high value of fault density correspond to tectonically deformed areas. According to neotectonic map of Italy scale 1:500,000 (Ambrosetti et al. 1987) the study area is highly deformed. This study is an attempt to demarcate zones of relative deformation intensity using fractal dimension and faults analysis.

Geographical and geological settings

The study area is located in the northern Apennines, Italy (Fig. 2) and mainly comprises Regione Emilia-Romagna. The drainage network in the study area is controlled by spatially inconsistent erosional and tectonic processes and reveals the regions with differential susceptibility to active deformation. The study area comprises following geological units (Bettelli et al 1989; Fig. 3):

1. Tertiary siliciclastic turbidites of the Tuscan units constantly cropping out along chain's axis in the upper Apennines.
2. 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.
3. Epi-Ligurian succession mainly composed of terrigenous units belongs to Middle Eocene to Late Messinian period, deposited on the formerly deformed Ligurian units.
4. The Plio-Pleistocene terrigenous marine units overlying uncomformably on the Ligurian units and the epi-

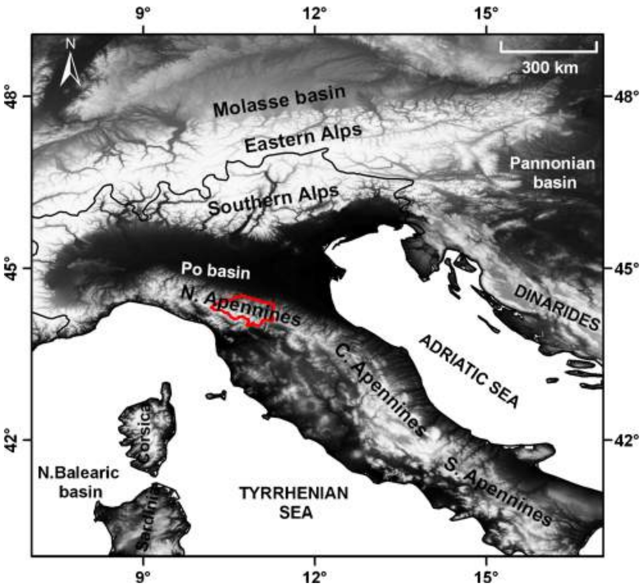

Fig. 2 Map showing the general location of the study area indicated as *red* boundary

Ligurian succession and cropping out in the northernmost part of the Apennines in the Po Plain margin.

The unremitting microseismicity, numerous moderate earthquakes (Fig. 4) related to thrust faulting (oriented NW-SE) and normal and strike-slip faulting (Lavecchia et al. 2003; CPTI 2004; Chiarabba et al. 2005) and the complex, linearized and anomalous drainage network in the study area, motivate for this research to infer the active tectonics by demarcating the zones of relative active surface deformation.

Computing methodologies

The drainage network was extracted from 5 m digital elevation model (DEM) obtained from Regione Emilia-Romagna using D-8 algorithm (O'Callaghan and Mark 1984; Jenson and Domingue 1988). The D-8 flow algorithm computes the possible flow directions at every pixel towards the neighboring eight pixels. Before the drainage network extraction, the holes or depressions in the DEM were removed using ArcGIS 9.3 software. The three fractal analyses (fractal dimension, lacunarity and succolarity) were carried out for the entire study area and for 12 selected deformed regions. We analysed the streams of Strahler order greater than or equal to 2 in order to reduce the noise in the DEM (Tarboton et al. 1991). Finally, the binary image of the drainage network was prepared, where the streams have a pixel value of one and the remaining space is considered as zero (Plotnick et al. 1993, 1996; Melo et al. 2006; Melo and Conci 2008). The Box counting method (Guillermo et al. 2004; Dombradi et al. 2007; Gloaguen et al. 2007) was applied to compute the fractal dimension of the entire drainage network of the study area and for the Secchia, Panaro, Reno, Dolo, Dragone and Setta rivers to ascertain their inconsistent drainage behavior. The fractal dimension procedure simply indicates the degree of drainage network complexity and does not exhibit the pattern description. Therefore, the lacunarity and succolarity (Mandelbrot 1983) techniques were employed to recognize dissimilar drainage patterns. The maps showing relative distribution of fractal dimension, lacunarity ($\Lambda(r)$) and succolarity (σ) were produced for the

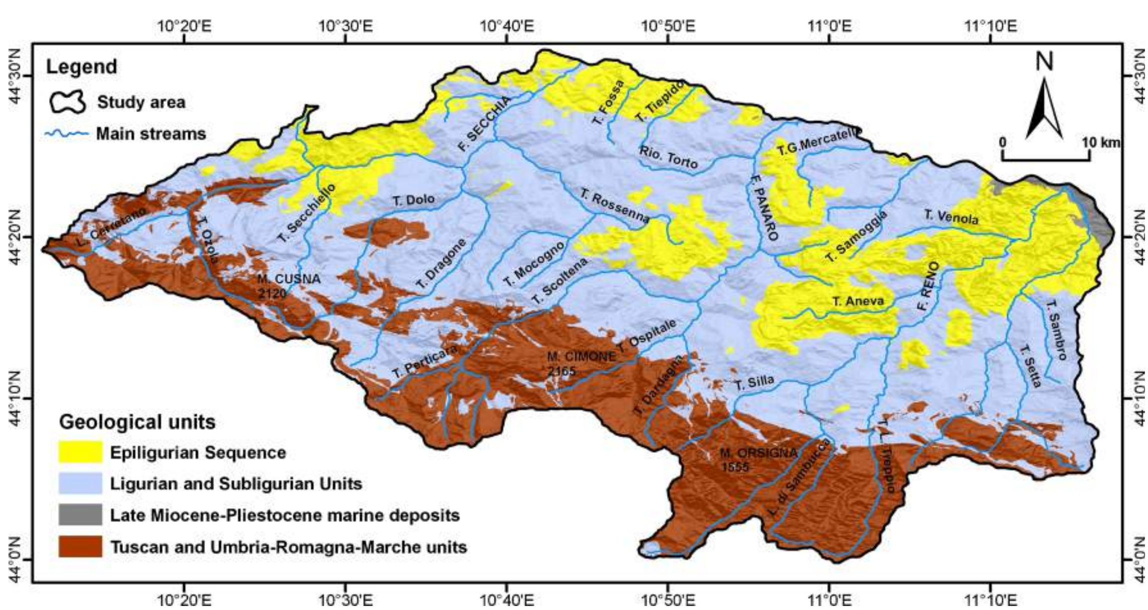

Fig. 3 Geological sketch map of the study area (source: GIS database obtained from Regione Emilia-Romagna)

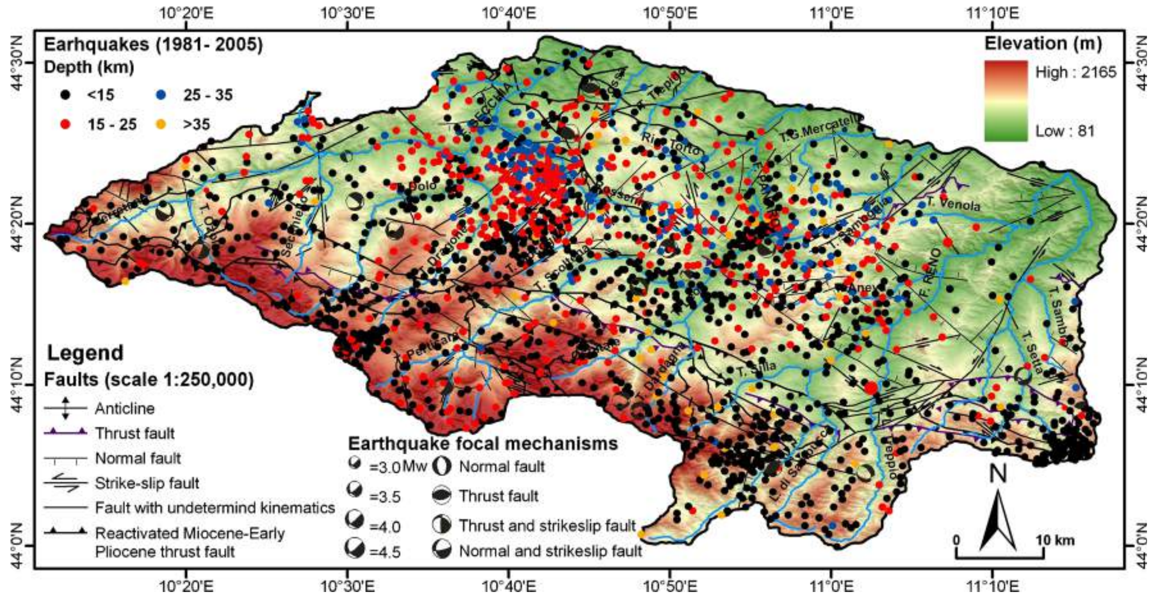

Fig. 4 Digital elevation model of the study area showing seismicity, distribution of focal mechanism solutions, earthquake epicenters and major tectonic units (Modified from Boccaletti et al. 2004b)

extracted drainage network. Twelve deformed regions having similar fractal dimension were chosen to further differentiate their deformation intensity by applying lacunarity, succolarity and orientation analysis because the drainage network of these regions shows dissimilar texture.

Fractal dimension analysis

The fractal dimension measures the irregularities or degree of fragmentation in the spatial objects pattern showing self-similar properties (Moreira 1999). The fractal dimension can be calculated by different computation methods (Mandelbrot 1967), e.g. numerical methods (Mandelbrot 1983; Xie et al. 1998; Schuller et al. 2001; De Melo 2007), statistical methods (Rodriguez-Iturbe and Rinaldo 2001; Russ 1993, 1997), analytical methods (Mandelbrot 1983) or image processing techniques (Veltri et al. 1996; Maître and Pinciroli 1999; De Melo 2007). Some common methods of fractal dimension computation are the triangular prism areas (Clarke 1986), fractional Brownian model (Mark and Aronson 1984), the projective covering method (Xie et al. 1999) and box-counting (Falconer 1990). In this study, the box-counting method (Fig. 5) was used to calculate fractal dimension of main rivers (Secchia, Panaro, Reno, Dragone, Dolo and Setta) and the entire drainage network (Guillermo et al. 2004; Dombradi et al. 2007). The box counting method can be applied to various sets of any dimension and patterns with or without self-similarity (Peitgen et al. 1992). This method uses a moving box of variable size on a binary image to count the number of drainage lines pixels within the box (Batty and Longley 1994; Guillermo et al. 2004; Dombradi et al. 2007). The box sizes (s) and related number of boxes $N(s)$ are counted. The fractal dimension value is computed by using the following equation.

$$FD = \lim_{s \to 0} \frac{\log N(s)}{\log(1/s)} \quad (1)$$

where N(s) is the total number of boxes and (s) is the length of the box side applied. The slope of the best fit line for the log-log plot of N(s) and 1/s is equal to fractal dimension. Using Eq. 1, for a moving window of $2.5' \times 2.5'$ on the binary image of drainage network the fractal dimension values were calculated. The fractal dimension map was prepared based on a colour coded scheme to differentiate areas of high and low fractal dimension distribution. The low fractal dimension value (FD $\leq$1.45), is associated to highly deformed regions (Dombradi et al. 2007; Gloaguen et al. 2008), whereas the fractal dimension >1.45 and <1.55 corresponds to medium susceptibility to active deformation and greater than or equal to 1.55 corresponds to the areas that are almost invariant.

Lacunarity analysis

Lacunarity, Λ(r), is a scale dependent measurement of spatial complexity of a texture or pattern (Plotnick et al. 1993, 1996). This index can be useful in determining the “porosity” of the landscapes (heterogeneity or discontinuity in the structure)

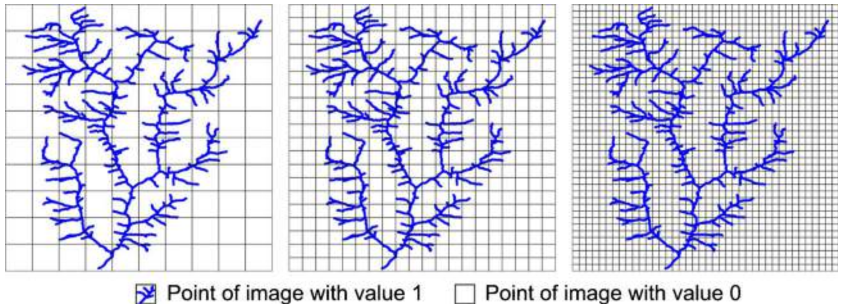

Fig. 5 Diagram showing fractal dimension calculation procedure for a binary image of drainage network using *box* counting method. The point of image where drainage passes (*blue lines*) show the value 1 and the point of image with no drainage line is considered as 0 value. The moving box of variable size on a binary image count the number of drainage line pixels within the box (Dombradi et al. 2007). The *box* sizes (s) and related number of boxes N(s) are counted

and the pattern recognition of the drainage network by analysing the spatial distribution of vacant gaps in the binary image (Plotnick et al. 1996; Dong 2000a). The lacunarity analysis is a powerful tool to differentiate between the dissimilar textures with similar fractal dimension values by measuring the deviation of a fractal object from translational invariance (Mandelbrot 1983). Low lacunarity values corresponds to homogeneous geometric objects because all gap sizes are the same, whereas high lacunarity values corresponds to heterogeneous objects (Dong 2000a). Generally fractals with large gaps or voids, have high lacunarity and dense fractals have low lacunarity. This parameter has been used in various applications of image segmentation, for example, to map surface deformation (Shahzad et al. 2010), sorting of textures on satellite imagery (Alves-Junior and Barros-filho 2005; Barros-Filho and Sobreira 2008), medicine, ecology and other fields (Rauch 2007).

Different methods can be used to calculate lacunarity (Dong 2000b; Melo et al. 2006), such as "gliding box method" (Allain and Cloitre 1991), "differential box counting" and "three-term local quadrant variance" (3TLQV). These methods provide comprehensive spatial information (Qinghua 2004). In this investigation we used the "gliding box method" (Fig. 6), which operates under the same principles of geomorphometric algorithms, where a sliding window (square box of side r, Fig. 6) scans the fractal image along all possible directions (WE and NS direction) using Eq. 2 (Melo et al. 2006; Dombradi et al. 2007; Zhang et al. 2007). The total number of drainage pixels (mass "s") is calculated during this process. The process is repeated with sliding boxes of gradually increasing size (i.e. r + i).

Plotnick et al. (1993) suggested that the gliding box should be of size $r=1$ to some fraction of image length (M). Accordingly, a frequency distribution of mass "s" with variable box size (r) is obtained. Then this frequency distribution is converted into a probability distribution P(s,r) by normalizing with the number of total boxes N(r) of size r. The dimensionless lacunarity Λ(r) is computed by the first and second moments of this distribution.

The following equation is used for the lacunarity calculation (Plotnick et al. 1993, 1996; Shahzad et al. 2010).

$$\Lambda(r) = \frac{\sum_{r=1}^{N} s^2 P(s,r)}{\left[\sum_{r=1}^{N} sP(s,r)\right]^2} \quad (2)$$

The colour coded map of lacunarity distribution was prepared using a moving window of 2.5′×2.5′ on drainage network binary image. In each moving window, the underlying image of 2.5′×2.5′ was taken as sub image and the box size of $r=1$ to 20 (less than half of the moving window length as suggested by Plotnick et al. (1993) was used to compute the lacunarity values. We need a single value of lacunarity for any region of interest instead of the whole lacunarity distribution. This single value needs to be carefully selected because it changes with the dataset resolution, for instance, large box sizes (e.g. $r=20$, 25) will give low lacunarity and small box sizes (e.g. $r=1$, 2, 3) will give high values of lacunarity (Plotnick et al. 1993). Therefore, we selected a middle value of box size at log(r)=1 to overcome less mean error and an identical value of lacunarity was obtained. The lacunarity value can change from low to high depending upon the data resolution and moving window size. We obtained a single lacunarity value at each pixel and this method is repeated for all moving windows to obtain a spatial distribution map of lacunarity values. This method was also applied for 12 selected areas of interest (AOIs) where similar fractal dimension values were found and a composite plot of lacunarity values for different box sizes was prepared to identify the relative susceptibility of these areas to active deformation. The high lacunarity values (≥1.5) are attributed to the dissimilar drainage patterns and highly deformed regions, while low (≤1.2) lacunarity values correspond to relatively low deformed regions.

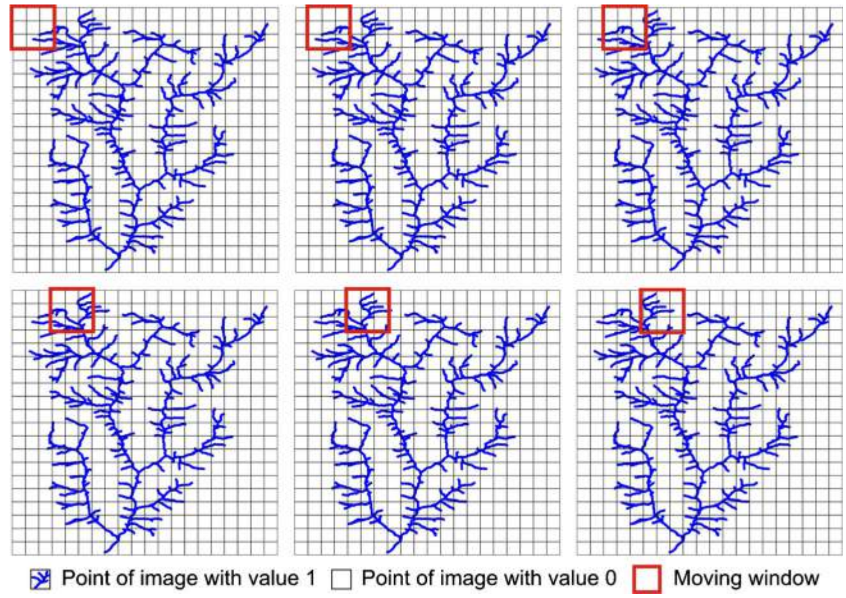

Fig. 6 Diagram showing "gliding box algorithm" procedure for lacunarity calculation. A sliding window (*Red square box*) scans the fractal image along all possible directions (WE and NS direction) using Eq. 2 (Dombradi et al. 2007; Zhang et al. 2007). The point of image where drainage passes (*blue lines*) show the value 1 and the point of image with no drainage line is considered as 0 value. The total number of drainage pixels is calculated during this process. The process is repeated with sliding boxes of gradually increasing size

Succolarity analysis

Succolarity measures the draining or percolation capacity of an image i.e., how much a given fluid can flow through this image (Mandelbrot 1983; Melo et al. 2006; Melo and Conci 2008; Shahzad et al. 2010). The succolarity index is a capable tool for the recognition of natural textures and becomes more useful when the input texture has both the direction and flow information (e.g. drainage patterns). The succolarity of an image can be measured along all potential directions i.e., top to bottom (vertically), left to right (horizontally) and vice versa (Fig. 7). The succolarity analysis (σ) was performed on the binary image to identify the drainage network which is influenced by the orientation of the regional tectonic structures. The drainage texture comprises two types of pixels, i.e., vacant gaps and impassable mass (e.g. stream network). The procedure for succolarity computation is as follows:

- The mean succolarity of the drainage pattern binary image was analysed in four possible directions, i.e., horizontal (from left to right and right to left) and vertical (top to bottom and bottom to top) (Fig. 7b, c, d, e, f). The empty pixel on the image (points with value 0) means that a fluid can pass and flood this pixel and neighboring 4 pixels (top, down, right and left), while the material pixel (points with value 1) are considered as hindrance to the fluid. This procedure is recursively executed on all the pixels until the impenetrable mass (material pixels) is determined.
- Then the flooded image was divided in equal box sizes using box counting method (Fig. 7g, h). In this procedure the boxes of variable size k (where $k=1$ to n and n is the number of possible integer of divisions) were placed on the image and the number of flooding pixels, NP(k) were counted within each box (Melo and Conci 2008; Shahzad et al. 2010).
- A pressure matrix equal to the size of the flooded image was created which consists of linearly increasing weight from left to right and right to left on the horizontal direction; and from top to bottom and bottom to top on the vertical direction (Fig. 7g, h). The pressure (PR) at any x or y location (pc) for box size (k) represents the centroid of the box. The pressure matrix depends upon the size and position of the box because it is applied on the centroid of the box and indicates the amount of pressure over it.
- Finally, the succolarity(σ) for a specified percolation direction (dir) is computed using following equation:

$$\sigma(dir) = \frac{\sum_{k=1}^{n} NP(k).PR(pc,k)}{\sum_{k=1}^{n} PR(pc.k)} \quad (3)$$

Using Eq. 3 we obtained dimensionless succolarity values. The succolarity analysis can be performed in different ways (i.e., along all directions of the flooded image or using the mean value of succolarity). In large analysis areas we can use the mean value of succolarity to determine the draining characteristics of the binary image.

According to Melo and Conci (2008) the average value of succolarity $(\overline{\sigma})$ can be computed by the arithmetic average along four possible directions using following equation.

$$\overline{\sigma} = \frac{\sigma(0^{\circ}) + \sigma(90^{\circ}) + \sigma(180^{\circ}) + \sigma(270^{\circ})}{4} \quad (4)$$

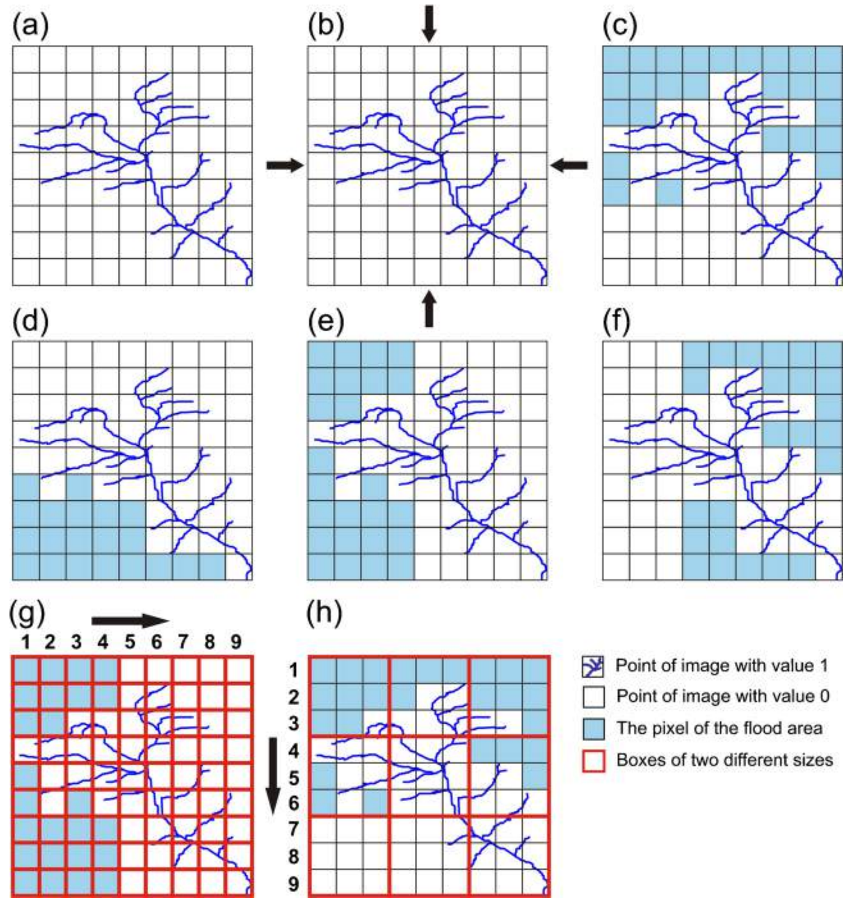

Fig. 7 Drainage network image (9×9 pixels) to show succolarity computation. **a** Original image; **b** The *arrows* indicate four possible directions that a fluid can try to flood the image; **c** *Top* to *bottom* direction; **d** *bottom* to *top* direction; **e** *Left* to *right* direction; **f** *Right* to *left* direction; **g** Example of pressure over 1×1 boxes; **h** Example of pressure over 3×3 boxes. The drainage texture comprises two types of pixels, i.e., vacant gaps (with value 0) and impassable mass (e.g. stream network with value 1)

We prepared the succolarity map of the study area using the minimum mean succolarity with a moving window of size 2.5′×2.5′. The succolarity value ranges from 0 to 1 and shows the percentage of percolation degree in the image. In tectonically active areas the high succolarity values (>0.6) represent an increased susceptibility to active deformation because of the high percentage of vacant space and the existence of lengthy filaments (Shahzad et al. 2010). These filaments may be developed by the presence of neotectonic lineaments. The low succolarity values (<0.4) corresponds to nearly flat areas (showing high drainage density) where the geological settings did not allow the development of tectonic structures.

Orientation analysis of drainage network and faults

Water flows mainly within geologically weak areas that is caused by joints, fractures, lineaments and faults. Analysis of drainage network orientation is an important geomorphic investigation that can be used for more meaningful interpretation of the structural control on the stream network geometries in tectonically active areas (Ciccacci et al. 1986; Caputo and Caputo 1988; Centamore et al. 1996; Currado and Fredi 2000; Lupia Palmieri et al. 2001; Della Seta et al. 2004; Della Seta 2004; Hosini and Ghoorchi 2010). Drainage network of Strahler order greater than or equal to 2 and faults digitized at 1:10,000 scale were considered for the orientation analysis. To display the drainage and faults orientation the rose (azimuth-frequency) diagrams were constructed using GEOrient software for 12 selected areas (Anudu et al. 2011; Holcombe 2012). The rose diagrams are a method for statistical evaluation of data (e.g., stream and faults) orientation within a specified area.

Lineaments/faults density

The objective of the lineaments (faults) density analysis is to compute the frequency of the faults per unit area (Greenbaum 1985). This analysis is useful to identify the concentrations of faults in an area. The areas having high value of fault density correspond to tectonically deformed areas. The fault density map reflects the ratio of empty pixels versus fault pixels within a moving window grid and the input data consist of digitized faults shape files. Investigation of faults density was carried out by getting sum of faults length per unit area km/km^2. The selection of a suitable window size is very important as it depends upon the level of required accuracy. The window size also depends on the spatial distribution and the density of the faults, it is observed that the small window size yield more suitable results for high densities. For this purpose, it is thus necessary to test different window sizes, for the generation of lineament density map. The analysis of faults density is based on the faults shape file at 1:10,000 scale obtained from Regione Emilia-Romagna, Italy. We tested different window sizes (500 m, 1 km and 2 km), but a window size of 1 km yielded more precised results.

Results and discussion

In most of the study area the fractal dimension distribution shows very low values, frequently close to 1.4 (Fig. 8a), typical of the stream networks strongly influenced by active tectonics, faults and folds (Twidale 1980; 2004; Shahzad et al. 2010 and references therein). Lowest found values of fractal

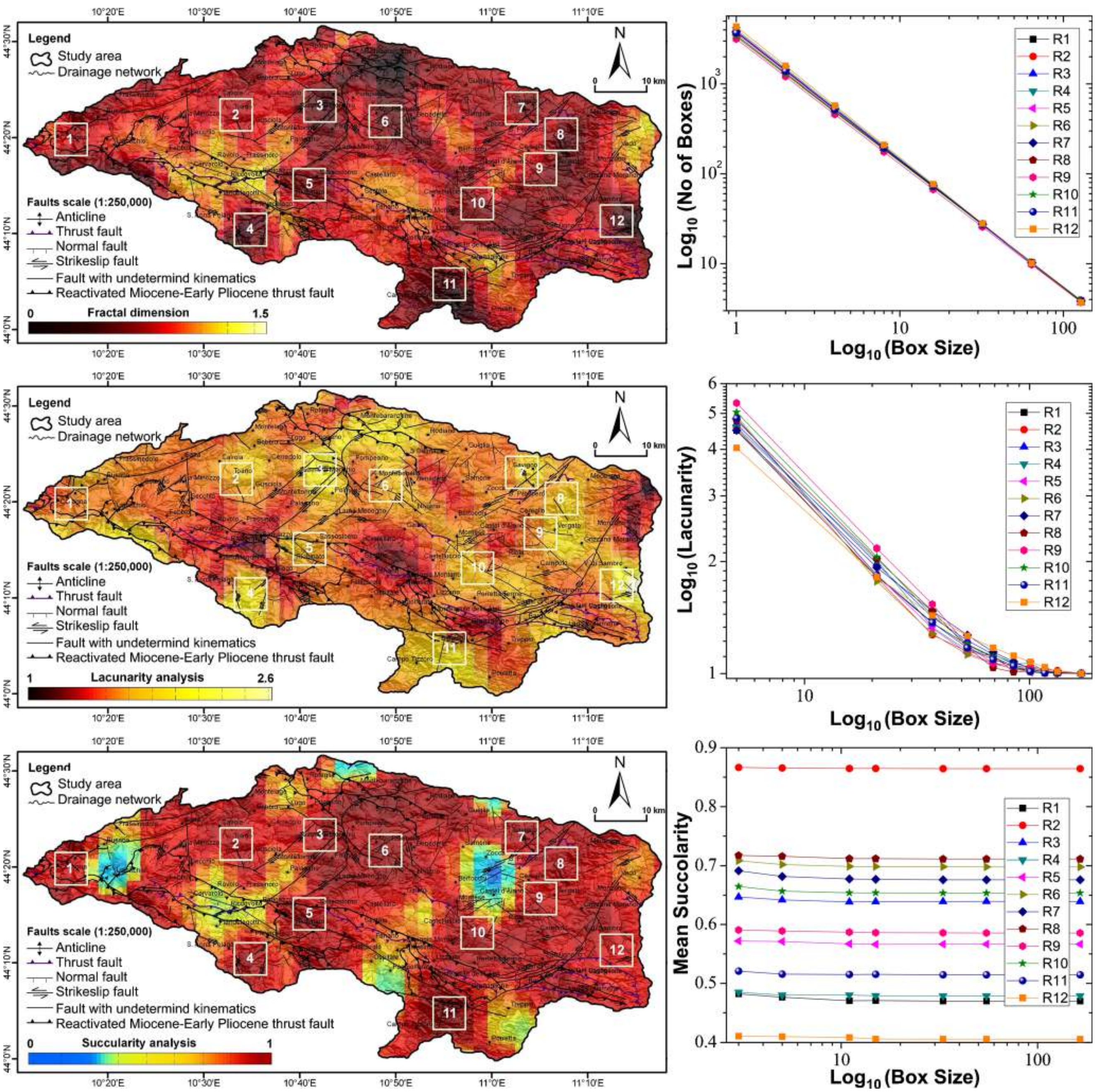

Fig. 8 **a** Map showing fractal dimension distribution in the study area. The low fractal dimension values correspond to highly deformed areas; **b** Map showing lacunarity distribution. The high values are associated with actively deformed areas; **c** Map showing succolarity distribution. The high values indicate extremely deformed regions. The low values of fractal dimension and high values of both lacunarity and succolarity indicate highly deformed regions showing high drainage density. Twelve areas having the same fractal dimension values were analysed to differentiate the relative susceptibility to active deformation and the comparison is shown in composite plots; **d** fractal dimension plot; **e** lacunarity analysis plot and **f** succolarity analysis plot. The spatial location of 12 areas of interest is shown on the map view

dimension are indicative of rectangular, sub-parallel or trellis channel patterns, controlled by the steep slope gradient and orientation of tectonic structures. In the study area the low fractal dimension values corresponds to greater landscape dissection and surface roughness (Taud and Parrot 2005). Phillips (1993) suggests that a low value of fractal dimension shows that a drainage network is more controlled by geological processes. The tectonic and erosional processes change the drainage network geometry from dendritic to linear and sometimes disconnect due to uplift. In Emilia-Romagna Apennines the most drainage networks are structurally controlled. The drainage patterns are linearized along faults and shows stream inversions, wind gaps and breaks in drainage pattern due to ongoing recent tectonic activity (Boccaletti et al. 2004a, 2011). The nearly similar distribution of low fractal dimension values in the study area indicates that the region is highly susceptible to active deformation. However, in this way the dissimilar drainage patterns with varied vacant gaps can show same fractal dimension. To distinguish areas showing similar fractal dimension we further analyzed the drainage network binary image by identifying the size of vacant gaps (or deviation from translation invariance) between drainage network lines using lacunarity analysis (Fig. 8b).

The results of lacunarity analysis indicates that the areas showing low fractal dimension corresponds to high lacunarity values which means that the drainage pattern is variant (Shahzad et al. 2010). The high lacunarity was observed in areas of steep slopes with high relative uplift rates, incision, topographic roughness and anomalous elevation zones. The sites with low fractal dimension and high lacunarity index can be further distinguish by succolarity analysis. When the drainage network reveals same style of translation invariance, by lacunarity analysis then succolarity analysis allow us to calculate their orientation (Shahzad et al. 2010). The high succolarity values are found along active tectonic structures of the study area (Boccaletti et al. 2004a), mainly thrust faults oriented SE-NW and strikeslip faults and also corresponds well with the regional seismicity trend (Fig. 8c).

Twelve regions of low fractal dimension values (Fig. 8a, d) were selected to infer relative (low to high) susceptibility to active deformation by calculating lacunarity and succolarity values. The low values of fractal dimension (Table 1, Fig. 9) in these selected areas is related to the relatively steeper landscape. The areas with low fractal dimension values show high lacunarity values which means that drainage in these zones is variant from natural flow pattern. However, the lacunarity plot (Fig. 8e) for these selected sites shows that it is not easy to differentiate between 12 zones because the curves are merged or overlapping each other. Since, the drainage patterns in these areas shows the same gap filling style therefore, the succolarity (Table 1; Fig. 9) becomes an inevitable tool to differentiate areas showing similar fractal dimension and lacunarity values (Fig. 8f). The lowest fractal dimension values (≤1.39) and high lacunarity and succolarity values shows that sites 6, 9 and 10 are extremely deformed. The active deformation in these deformed regions is related to the active normal faults oriented SE-NW (Michetti et al. 2000). The low fractal dimension values (≥1.40 and ≤1.42) of regions 1, 2, 3, 5, 7, 8 and 11 correspond to highly deformed areas mainly due to strikeslip faulting. Regions 4 and 12 shows comparatively moderate fractal dimension 1.43 and 1.45 respectively which show relatively less susceptibility to active deformation (Table 1). This variation in the relative distribution of 3-fractal (fractal dimension, lacunarity and succolarity) values in the study area clearly reveals that the drainage network is attributed to the presence of differential tectonic activity.

Table 1 Fractal dimension, maximum lacunarity and mean succolarity for 12 selected areas of interest

Region #	Fractal dimension (FD)	Maximum lacunarity (LA)	Mean succolarity (SA)
1	1.41	1.50	0.47
2	1.42	1.67	0.86
3	1.42	1.55	0.64
4	1.43	1.62	0.48
5	1.41	1.52	0.57
6	1.38	1.52	0.70
7	1.42	1.54	0.68
8	1.40	1.55	0.71
9	1.38	1.65	0.59
10	1.39	1.59	0.65
11	1.41	1.54	0.52
12	1.45	1.49	0.41

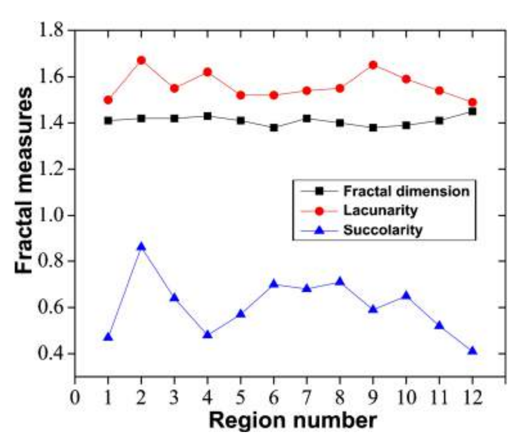

Fig. 9 Composite plot showing correlation between fractal dimension, lacunarity and succolarity for the 12 selected deformed regions. Low values of fractal dimension correspond to high values of both lacunarity and succolarity index

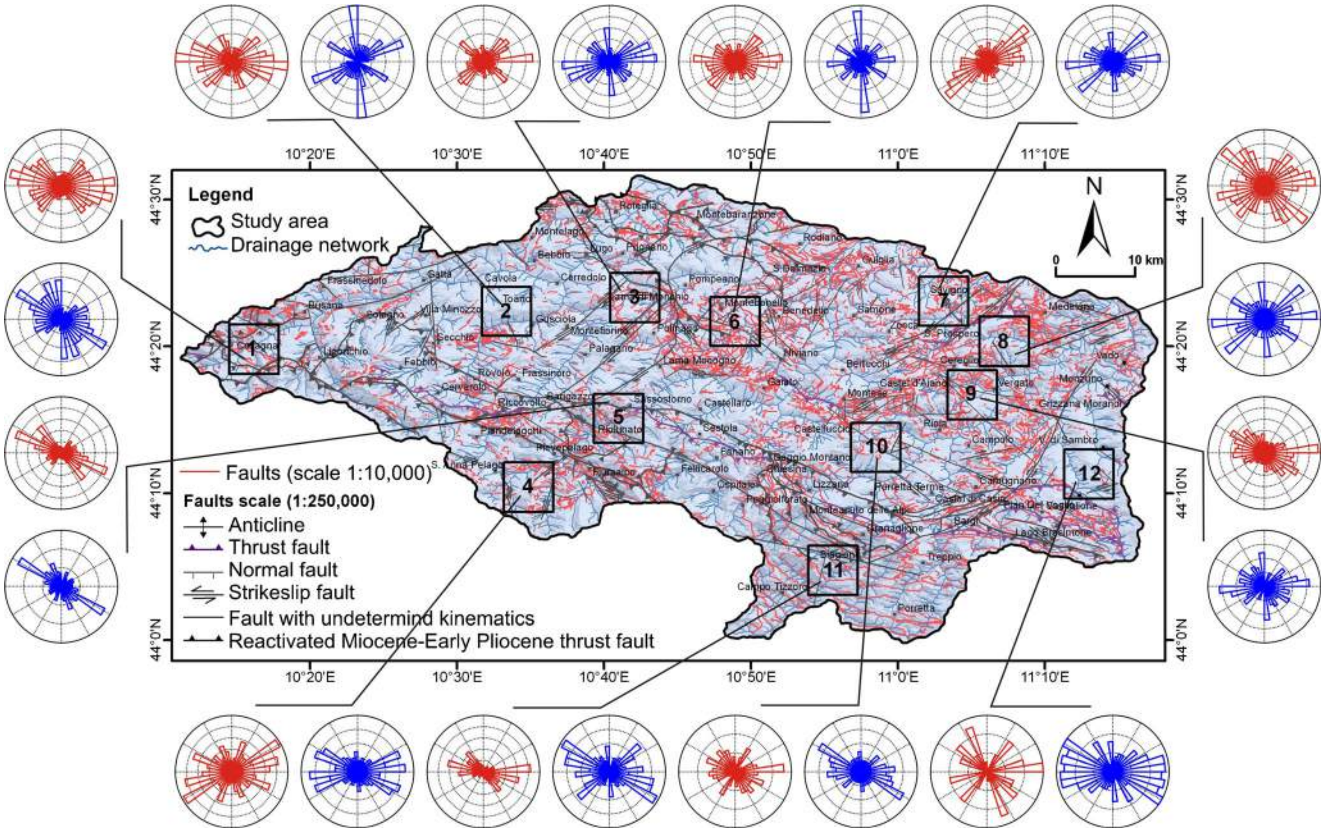

Fig. 10 Orientation analysis of drainage network (shown in *blue*) and faults (shown in *red*) using rose (azimuth-frequency) diagrams for the 12 selected deformed regions

To further analyze the control of tectonic lineaments on the drainage network development we have performed orientation analysis of both faults (at 1:10,000 scale) and drainage network (Strahler order ≥2) in 12 selected deformed areas using rose (azimuth-frequency) diagrams. In the entire study area the faults length vary between <1 m and ~5 km. Most of the faults are less than 700 m long with the exception of the three faults that have lengths of more than 6 km. The total number of mapped faults in the study area is 24,445 (ArcGIS database of faults scale 1:10,000 from Regione Emilia-Romagna),

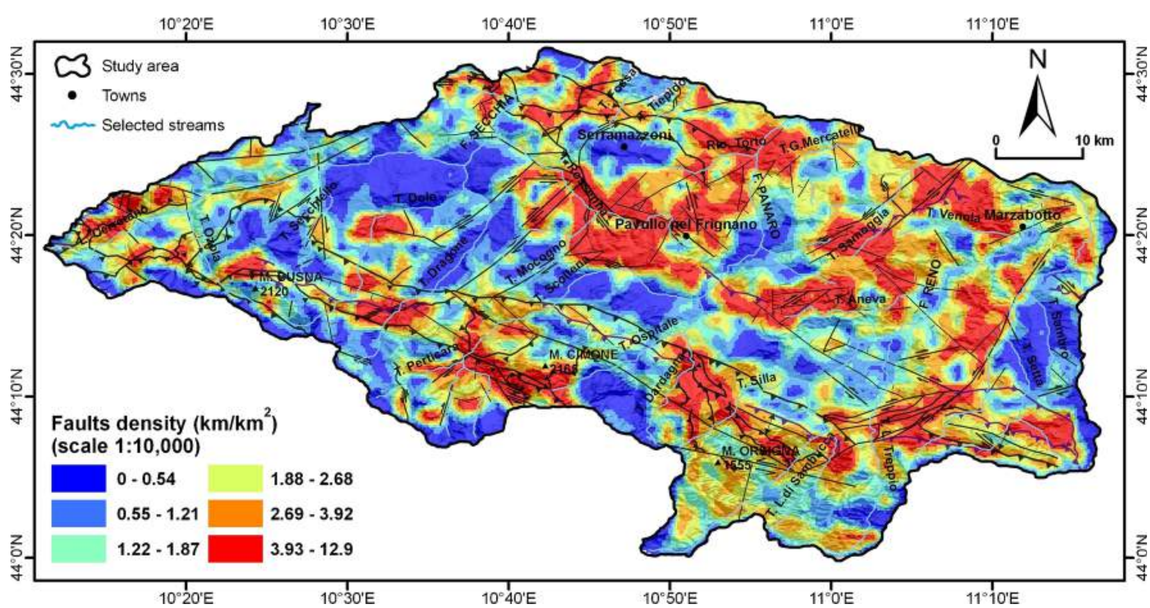

Fig. 11 Fault density map, maximum density anomalies are shown by *red* and *orange* patches

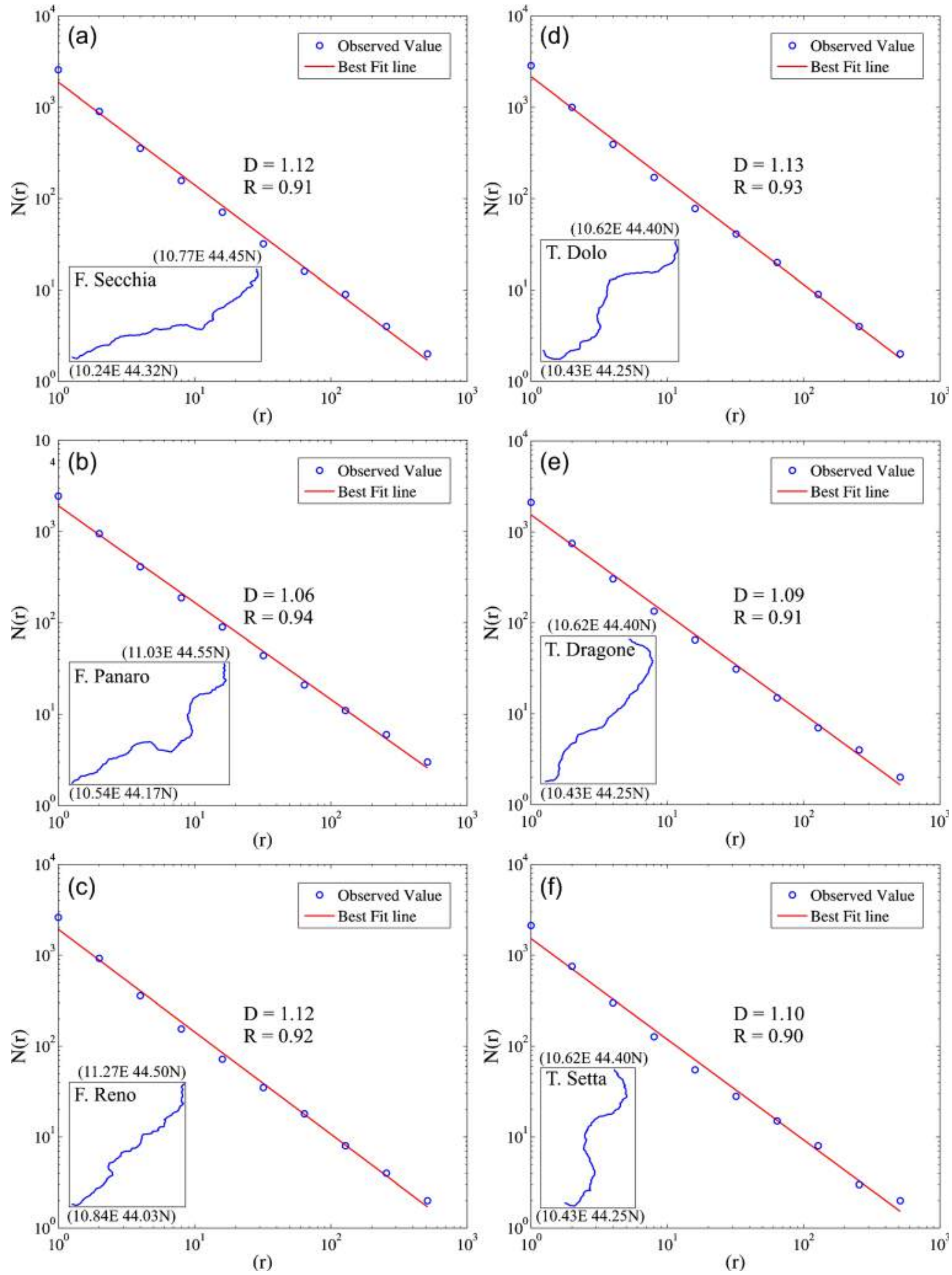

Fig. 12 Fractal dimension for Secchia, Panaro, Reno, Dolo, Dragone and Setta rivers with insets showing the flow direction and geographical location of the river

whereas the total faults length is about 3,640 km. The orientation analysis of both faults and drainage network reveals NW-SE, NE-SW, NNW-SSE and E-W directions (Fig. 10). The same orientation style of drainage and faults within each region of interest reveals that drainage network is linearized along faults while the opposite directions shows disconnected drainage due to uplift conditions. Thus the parallel anomalies in drainage network represent neotectonic control.

The faults density analysis indicate that the zones of maximum faults density anomalies and their orientation is in correspondence to the regional strikeslip and thrust faults (Fig. 11). The density anomalies of the SW and NE sectors of the study area indicate a same pattern of maximum lineament density (shown in red and orange patches). The lineament density anomalies of these sectors are associated with low fractal dimension values and thus related to highly deformed regions. The distribution of lineament density offers one way to correlate these deformed regions with active tectonics and linearized drainage network. Furthermore, the high lineament density shows positive correlation with anomalously high elevation and tectonically uplifted areas.

The fractal dimension of six main rivers (Secchia, Panaro, Reno, Dolo, Dragone and Setta) was also delineated to evaluate the influence of faults on the river flow direction and to ascertain rivers freedom degree (Guillermo et al. 2004). Using box counting method the number of cells intersecting the river are counted and this procedure is repeated using grids of different cell size. This process is continued until it becomes impossible to be calculated the fractal dimension value. The calculated fractal dimension values are then converted to $\log_{10}$ and plotted on log-log plot (Fig. 12). The slope of the best fit line for the log-log plot of $\log_{10}$ of the number of cells calculated, N(r) against $\log_{10}$ of 1/cell size is the fractal dimension. The lowest computed fractal dimension values (<1.13) of main rivers corresponds well with the fractal dimension values calculated for rivers in other tectonically active areas (Phillips 1993; Montgomery et al. 1996; Veltri et al. 1996; Shahzad et al. 2010), which reveals that the main rivers in the study area are also under strong geological control.

Conclusions

The non-linear analysis (i.e., fractal dimension, lacunarity and succolarity analysis) is a very useful method to examine the textural characteristics of the drainage network by investigating the linearization, translational invariance and rotation of drainage network due to tectonic structures. This analysis is significant to detect zones of active tectonic deformation. The regions with low values of fractal dimension (≤1.45) and high values of both lacunarity and succolarity corresponds well with the tectonically active areas identified by previous studies (Boccaletti et al. 2004a). The relatively high uplift rates, steep slopes and high stream gradients are in good agreement with the results obtained from fractal dimension analysis. The recent active structures caused the drainage network to be linearized (mainly along strikeslip faults) and disconnected due to local uplift conditions. We conclude that the three fractal measures are complimentary in nature, that if two regions have the similar fractal dimension they can be distinguished by lacunarity analysis, on the same way, the succolarity analysis makes possible to distinguish the zones having same fractal dimension and lacunarity values or vice-versa. In tectonically active regions (e.g., northern Apennines) the non-linear analysis of drainage network can be useful to distinguish areas of differential active deformation and to prepare a relative surface deformation susceptibility map that can be useful together with seismic microzonation maps and geophysical investigations, for appropriate management, planning and infrastructure development in identified hazardous areas, especially in the context of human safety.

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