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GIS-based assessment of surface deformation patterns using fractal analysis of topography: Kharmankuh anticline, Zagros Mountains, Iran

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Abstract

Fractal is an applicable implement for evaluation of the complicated patterns of natural features. Geo-informatics allow not only representing data, but also performing geostatistical analysis and building models. This paper investigates the deformation pattern of land surfaces applying Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (ASTER GDEM) through a combined geo-information and fractal approach. The covering divider method is applied in order to extract fractal dimension of the earth surface (D_{surf}) directly for estimating surface roughness of the earth topography through geographic information system (GIS) approaches. Specifying the function of the geomorphologic processes on the spatial variability of fractal properties of the earth surface is accessible through this assessment. Fractal dimension mapping us to ascertain geomorphic domains where variability of fractal dimension of the earth surface represents the roughness of the land form topography and is an assessment of texture of topography. Results show that the presented approach in this research using the presented flow chart provides a rapid and facile procedure to evaluate the spatial distribution of the earth surface deformation within geological regions. Relatively higher fractal dimensions are observed where loose alluvial deposits and irregularities exists whilst the lower fractal dimension represents existence of the competent formations. The results showed that the Kharmankuh anticline has formed in a NE-SW direction and shows nearly symmetrical deformation pattern.

Keywords: Surface fractal analysis; Deformation pattern; Topography; Kharmankuh anticline; Zagros; Iran

1. Introduction

Fractal geometry is observed within many natural objects and phenomena such as mountain chains and rivers (Mandelbrot, 1982; Pentland, 1984; Peitgen et al., 2013; Persson, 2014). Measuring complicated processes of geological phenomena and represent into a single parameter, is one of the advantages of using fractal analysis in the geosciences which would be arduous to measure using just by classic geological approaches (Perugini, and Kueppers, 2012). In addition, applicable information about the landform surface can be obtained through the fractal dimension of the earth surface which is not presented by other morphometric measurements (Fedder, 1988; Klinkenberg, 1992; Sung et al., 1998). A basic assumption in geomorphometry is the close relation between surface characteristics and surface processes (Pike, 2000). This relation is evaluated by applying statistical approaches on the parameters or topographic indices which are determined by using (DEM) and relating them to the presence of certain landforms or geomorphic process areas and soil properties (Etzelmüller and Sulebak, 2000; Etzelmüller et al., 2001; Luoto and Seppala, 2002; McBratney et al., 2003; Luoto and Hjort, 2004, 2005; Hjort and Luoto, 2006; Mahmood and Gloaguen, 2012; Shen et al., 2011; Faghih and Nourbakhsh, 2015a, b). To provide a large set of descriptors attributes from DEM in the studies on surface properties of landforms several algorithms have been proposed (Wilson and Gallant, 2000; Champagnac et al., 2012; Ramisch et al., 2012).

One of the phenomena that possesses fractal characteristics is the earth topography. Topographic features are created during cumulative influence of endogenic and exogenic processes operating on the earth surface (Burbank and Anderson, 2011; Faghih

2. Geological Framework

During Late Cretaceous to Recent, oblique convergence between and the Central-Iranian Microcontinent and the Afro-Arabian continent resulted in the formation of the Zagros Mountain Belt (Talbot and Alavi, 1996; Stampfli and Borel, 2002; Golonka, 2004). From the eastern Turkey to the southern Iran, this belt stretches 2000 km long with NW–SE-trend (Mouthereau et al., 2012). Mountain Front Fault, the High Zagros Fault and the Main Zagros Thrust, that are regional-scale faults, are distinguished by distinctive structural and lithologies features(Mobasher and Babaie, 2008; Sarkarinejad and Azizi, 2008; Faghih and Nourbakhsh, 2015a). They mark several structural zones which are running parallel to the suture zone and are known as classical subdivision of this belt (Sarkarinejad and Ghanbarian, 2014) (Fig. 1). To the northeastern side the Simply Folded Belt is bounded by the High Zagros Fault, separating it from the Imbricate Zone, and delimited to the southwestern side by the Mountain Front Fault (MFF). A clustering of seismic events ascertained the MFF as a regional morphotectonic feature (Jackson and McKenzie, 1984; Berberian, 1995; Engdahl et al., 2006) which the level of the revealed formations of the Zagros sedimentary layers show a sudden change (Falcon, 1969). In the Fars Province the base of this stratigraphic pile is occupied by a thick Neoproterozoic evaporate unit (Hormuz Formation), providing an efficient widespread ductile detachment horizon above the metamorphic basement (O'Brien, 1950; Colman-Sadd, 1978).

Development of SW-verging folds with NW–SE trending and NE-dipping thrusts in the Phanerozoic sedimentary strata are the result of the SW–NE convergence. These structures are positioned above the Neoproterzoic Hormuz evaporate detachment zone and Afro-Arabian basement (Kadinsky-Cade and Barzangi, 1982; Alavi, 1994). The presence of the Hormuz Formation, which is too deep to be drilled, however, it has been reported from various salt plugs that pierced the whole sedimentary carapace of the Fars Arc and are exposed at surface (Aubourg et al., 2008).

The case study is the Kharmankuh (Fig. 2) that is a dome shaped anticline which is situated at N 14° 29' 00" and E 40° 53' 00".. This mountain has maximum elevation of 3183m and has a steeper left side limb. The Jahrum Limestone Formation and Asmari Formation are exposed on the surface of this anticline (Motiei, 1993). Some researchers suggest that this anticline has formed due to a combination of diapirism of Hormuz Salt and continued movement of the Sarvestan Fault (Dehbozorgi et al., 2010 and references therein).

Some of the previously formed folds deformed by the Sarvestan fault (~78 km length) with dominant strike-slip movements, which is cutting across the Zagros fold-thrust belt (Berberian, 1995). It has also led to several hundred meters uplift of the eastern block and caused the development of prominent fault scarps and uprising of active diapirs such as the Sarvest and iapir (Dehbozorgi et al., 2010).

3. Materials and Methods

Geomorphic features are investigated on their fractal properties by some researchers (e.g. Mark, 1984; Tarboton et al., 1988; Andrle and Abrahams, 1989; La Barbera and Rosso, 1989; Liu, 1992; Nikora and Sapozhnikov, 1993; Klinkenberg, 1994; Andrle, 1996; Rodriguez-Iturbe and Rinaldo, 1997; Goodchild, 2011; Faghih and Nourbakhsh, 2015b).Triangular prism area, box-counting, fractional Brownian model, projective covering divider method and the covering divider method are the variety of methods that have been proposed to determine the fractal dimension of surfaces (Burrough, 1983; Shelberg et al., 1983; Clarke, 1986; Mark and Aronson, 1984; Falconer, 1990; Xie and Wang, 1999; Faghih and Nourbakhsh, 2015b).

The covering divider method is used for taking information about anisotropy and general complication of surface properties of the earth surface features. This approach for determination of the fractal dimension is considered a well-established and commonly applied tool for nearly any arbitrary structure.

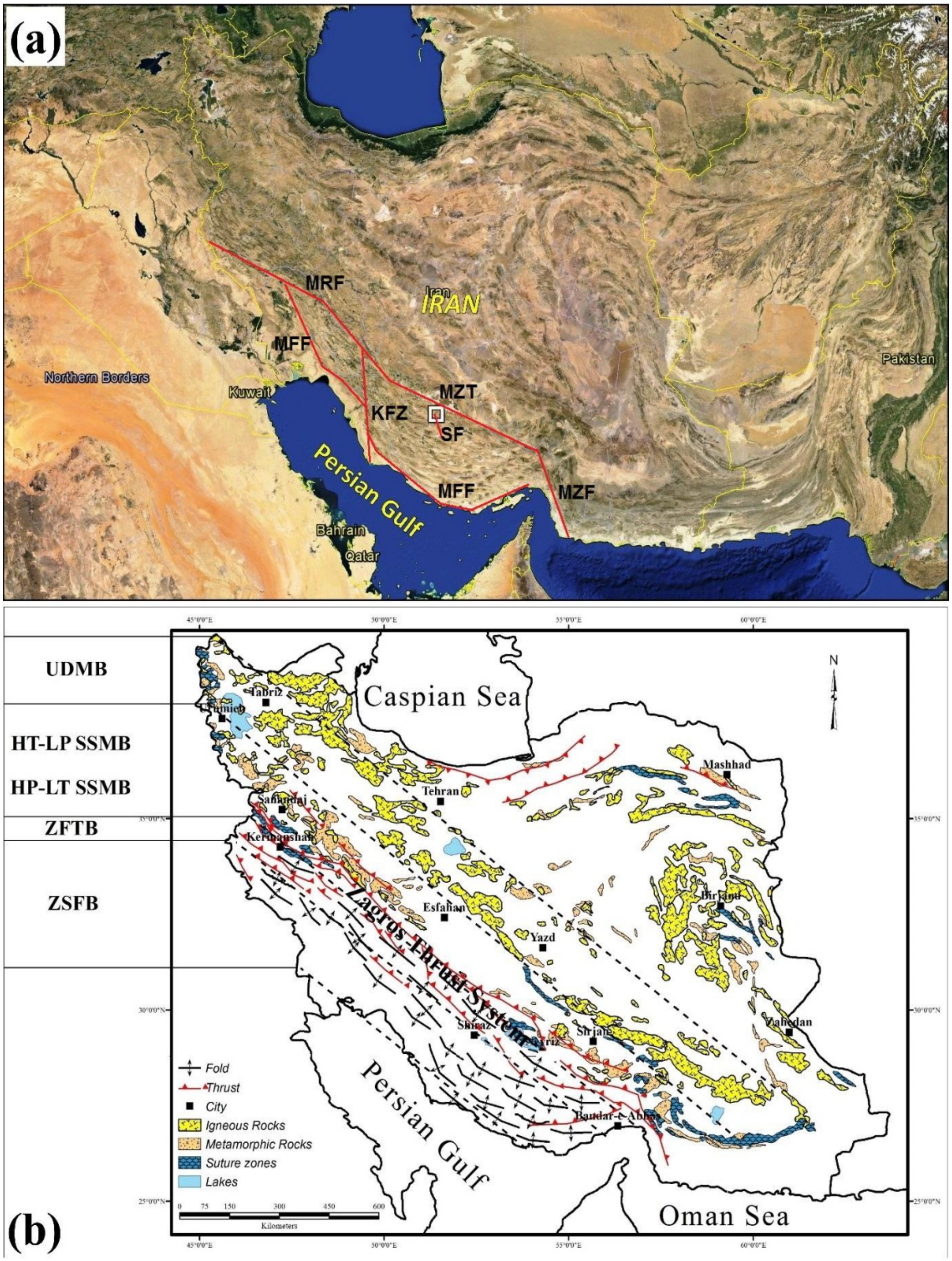

Fig. 1. Maps showing (a) geographical position of study area by a hollow quadrangle at southwestern of Iran, MRF (Main Recent Fault), MZT (Main Zagros Thrust), MZF (Minab-Zendan Fault), SF (Sarvestan Fault), KFZ (Kazerun Fault Zone), MFF (Mountain Front Fault) and (b) the common classification of Zagros Mountain Belt, UDMB: Urumieh-Dokhtar Magmatic Belt, HP-LT SSMB: high pressure-low temperature Sanandaj-Sirjan metamorphic belt, HT-LP SSMB: high temperature-low pressure Sanandaj-Sirjan metamorphic belt, ZFTB: Zagros fold-thrust belt, ZSFB: Zagros simply folded belt. These zones are illustrated with dashed lines through the figure and approximate width of the zones are presented in continuation of dashed lines at the left side of the figure.

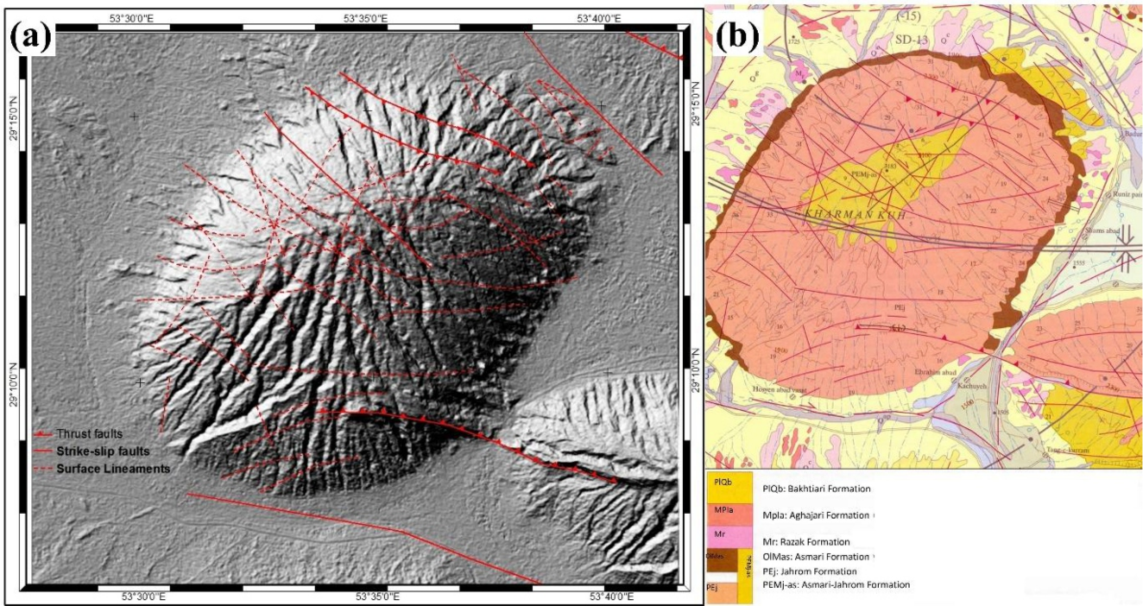

Fig. 2. The study area (a) Hillshade image of the Kharmankuh anticline with representation main structural elements within the study area and (b) geological map of the study area.

To compute (D_{surf}) some of researchers applied the covering divider method (Richardson, 1961; Mandelbrot, 1967; Goodchild, 1982; Aviles et al., 1987; Snow, 1989; Beauvais and Montgomery, 1997; Wilson and Dominic, 1998; Xie et al., 1998). Fractals considered as self-similar when an object is exactly or approximately similar to a part of itself or self-affine or self-affine when objects are scaled by different amounts in the x- and y-directions. Surface roughness of Earth surface is considered as self-affine fractals (Turcotte, 1997). This work is a complementary study on the Faghih and Nourbakhsh (2015b) methodology with more resolution and enhanced by a geo-information technique. In our previous work, a window size of 250m x 250m was applied for the extraction of σ of elevation data as the smallest detecting window but, in the current work this is 100m x 100m. Also, in the present work we have presented a flow chart that with aid of GIS-based spatial analysis algorithms enhanced extraction of fractal dimension of earth surface topography. In this study we have prepared a flow chart (Fig. 3) of the previously methodology presented by Faghih and Nourbakhsh (2015b) that is done with aid of ArcGIS spatial analyst algorithms. Between standard deviation of surface height and sampling window area of the surface, which is considered as a self-affine fractal, a power low relation exists (Rahman et al., 2006).

Roughness-surface derives from the following formula(Turcotte, 1986, 1997):

$$\sigma = \tau^{H} \text{ , (1)}$$

Here σ stands for the average standard deviation of elevation data for corresponding τ -area subdivisions of the earth surface. Hurst exponent *(H)* (Fedder, 1988) contribute in calculation of roughness-surface fractal dimension (D_{surf}) through a relationship as follow:

$$D_{surf} = 3 - H \text{ . (2)}$$

Where in a double logarithmic diagram of the τ and σ, we can rewrite the relation (1) as follow:

$$Log\ \sigma = Log\,\tau^{H}\text{, (3)}$$

σ can be calculated using an equation as follow:

$$\sigma = \sqrt{\frac{\sum (x - \bar{x})^2}{n}} \quad \text{, (4)}$$

where x is a value in the elevation data set, ẍ is the mean of all values in the elevation data set and n is number of values in the elevation data set. Initially, τ equals the area of the surface and is subsequently diminished in size by a factor of 4 at each step.

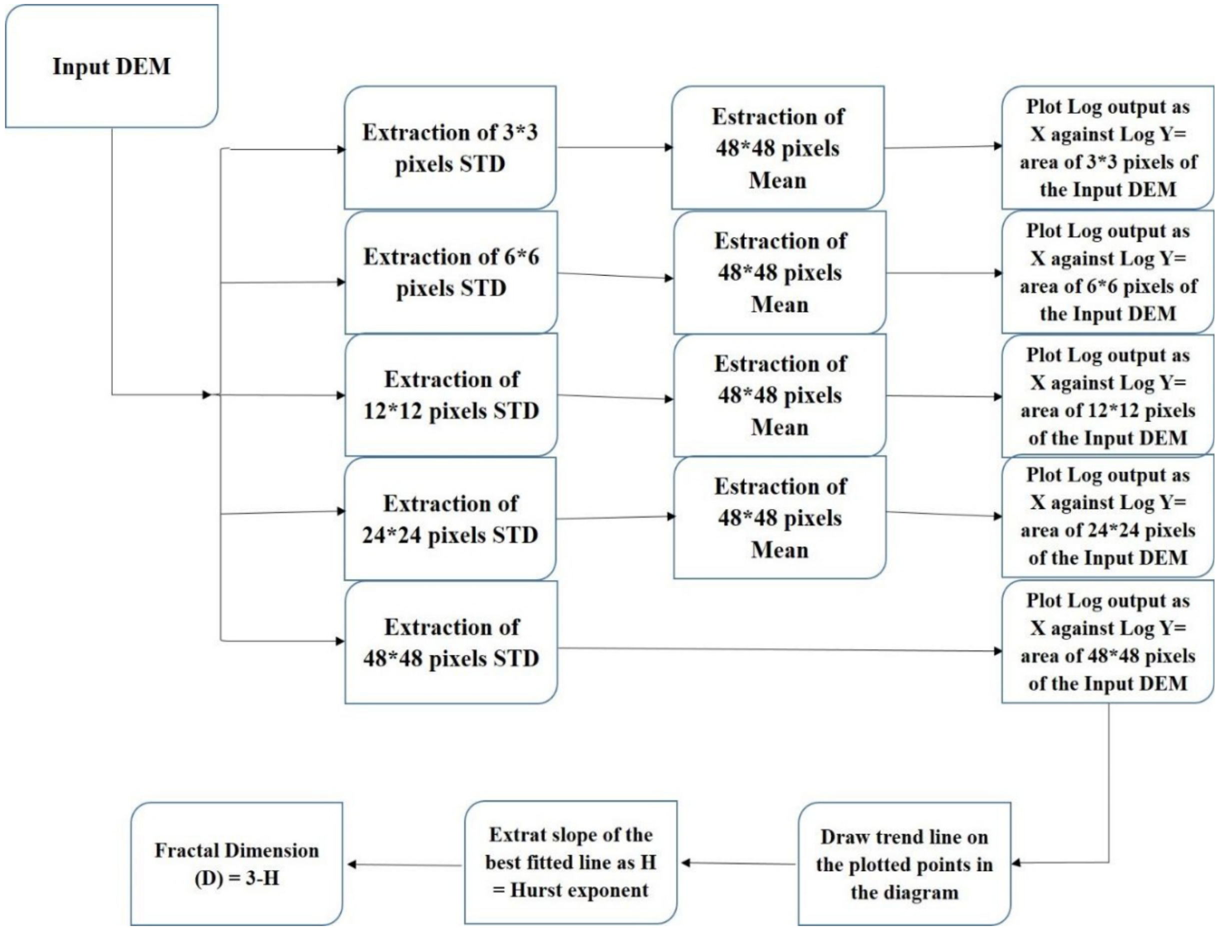

Fig. 3. The presented flow chart in this study with aid of GIS-based spatial analysis algorithms enhanced extraction of fractal dimension of earth surface topography.

As the (τ) decreases, σ in 1, and then 4, 16, 64, etc. subdivisions of the surface is derived from the average standard deviation of the elevation data (Figure 3). If data possess fractal distribution, then double logarithmic diagram of the τ and σ show linear trend and have slope H (Fig. 4). This approach is used to calculate the (D_{surf}) in this study. In this research we have used 15m resolutions ASTER GDEM V.2 with (Tachikawa et al., 2011) as the source of elevation data. For extracting σ an area with 100m x 100m dimension is considered as the smallest window which is include10 true elevation data pixels of DEM. The target window is 1500m x 1500m which includes over 2500 pixels of DEM. In total168 target windows have been analyzed, which cover the Kharmankuh anticline and its surrounding land forms.

4. Results and Discussions

The fractal dimension can be obtained from the slope of linear alignment of data points in a double logarithmic diagram of the τ and σ. The study area is designated as 18 km × 21 km which covers the Kharmankuh anticline and its surrounding landforms. To extract the surface deformation pattern, the fractal dimension of 168 target windows is calculated. The measured values of the (D_{surf}) show a range of 2.49 to 2.79 which are spatially distributed across the study area (Fig. 5). The output of geo-informatics is often associated with a map. A map is only one way to work with geological data in a geo-information approach and only one type of product generated by geo-informatics. Furthermore, geo-informatics can provide more problem-solving capabilities than simple mapping programs (Nourbakhsh, 2014). In the study area, variability of (D_{surf}) is shown by a map which represents the obtained data.

When the surface variability is small locally, but with distance rises rapidly, H increases toward its upper limit, whereas,

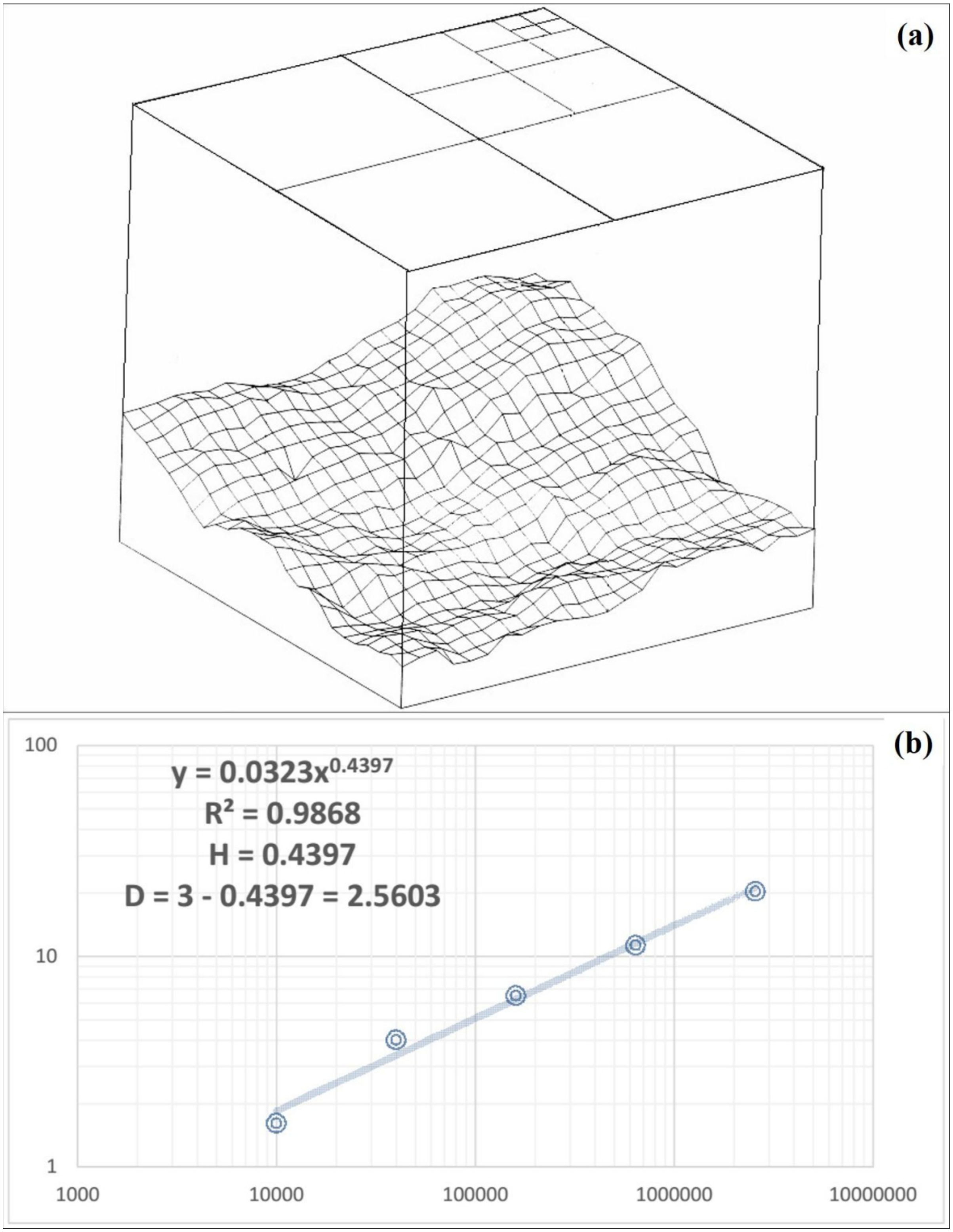

Fig. 4. A sample of procedure for calculation of the surface fractal (a) Schematic representation of the covering divider method that shows subdivisions of the surface with decrease in size by factor 4. (b) An example of the Log-Log plot of the average standard deviation of topography versus widows' area that is calculated within the study area. H is Hurst exponent and D is fractal dimension.

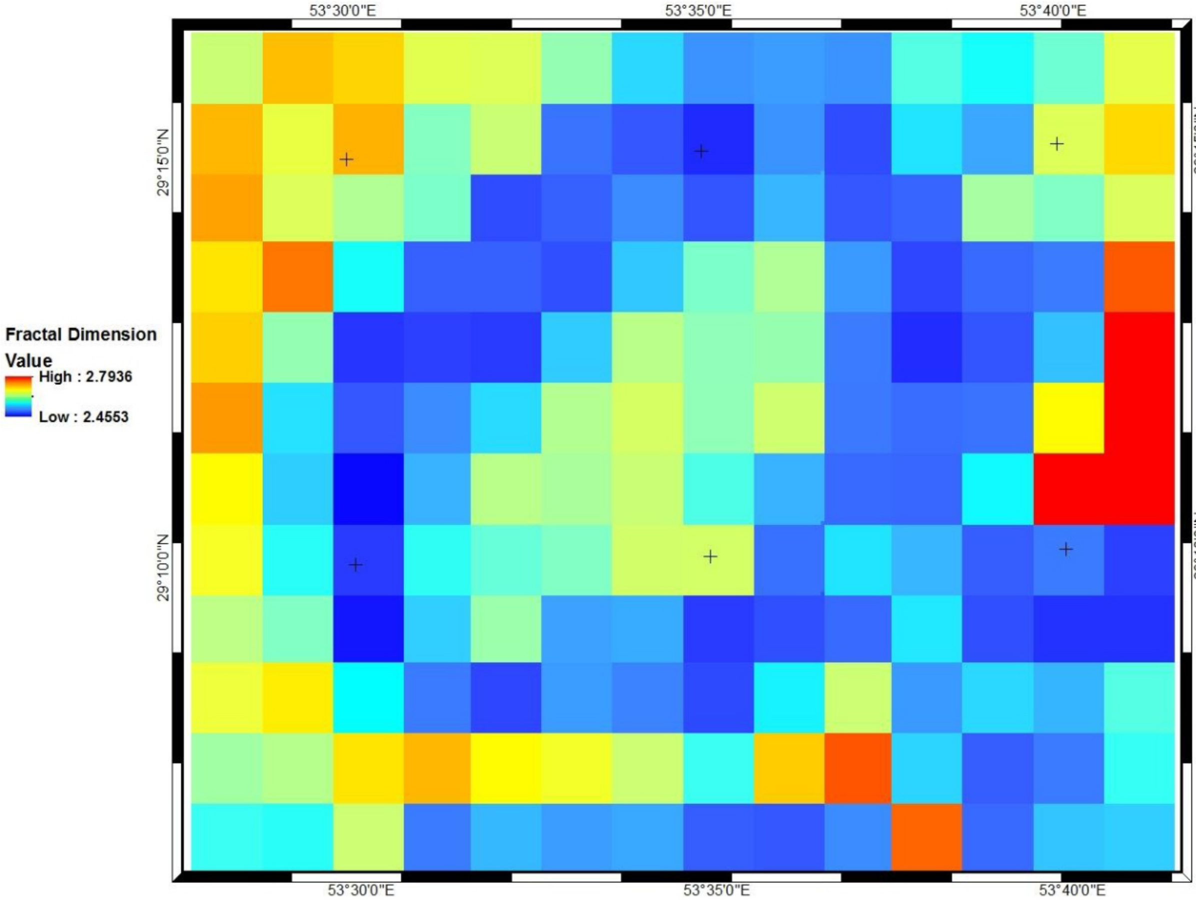

Fig. 5. The presented map showing spatial distribution of surface fractal dimension (Dsurf) of the landscapes in the study area. The roughness-surface fractal dimension of 168 target windows for extraction of surface deformation pattern is calculated that have a range from 2.45 to 2.79.

H is small when the surface shows slow increase at large distances and high local variability (Sung et al., 1998; Sung and Chen, 2004). It suggest that high fractal dimension points out a slow change of topography at a large distance and a quick change of topography in a local area, on the other hand a small local change in topography and large change at a long distance possess low fractal dimension (Sung et al., 1998; Sung and Chen, 2004).This statement can be seen in the Figure 4 that the steep limbs with quick change in elevation have lower fractal dimension and the surrounding low lands and top of the dome shaped anticline have relatively higher fractal dimension. Figure 4 suggests that the surface deformation is nearly symmetrical and elliptical in shape with a NE-SW strike. The deformation style of the Kharmankuh anticline and its nearby landforms represented in the hill-shade image in Figure 2a.

Topography at long wavelength produced by tectonic movements thus led to low fractal dimension of the earth surface (Sung et al., 1998; Sung and Chen, 2004; Bi et al., 2012; Ramisch et al., 2012). At the midway of the limbs the fractal dimension is relatively lower than the lower and upper parts of the limbs. Increasing surface roughness is the consequence of erosional processes and play a role in determination of the fractal dimension of earth surface. Lithology is a significant parameter that affect erosion, and consequently the related fractal dimension. Smooth surfaces are the result of diffusive and depositional processes which result in lowering of fractal dimensions. High fractal dimension is characteristic of the loose alluvial deposits that facilitate producing of high frequency component topography (Sung et al., 1998; Sung and Chen, 2004; Bi et al., 2012; Ramisch et al., 2012).

Slope and time are two affecting factors on diffusive processes. Longer history of development make landforms with underlying more competent rocks has been smoothed to a certain extent by diffusive processes and consequently possesses lower fractal dimension. Whilst high fractal dimension can be observed in recent sediments and incompetent lithologies which has not been affected by diffusive processes (Sung et al., 1998; Sung and Chen, 2004). Insensitivity of competent formations to erosion lead to low frequency competent of topography and consequently lower fractal dimension. Furthermore, this low fractal dimension is the result of diffusive mass-wasting processes that make mountainous areas smooth (Chase, 1992; Sung and Chen, 2004; Bi et al., 2012). Nearly all of the Kharmankuh anticline in the study area consists of carbonate composition of the Asmari-Jahrum Formation with more competency than the loose sediments that cover the surrounding landforms. The high frequency competent is not produced in the Asmari-Jahrum Formation because it is more resistant to erosion and this contrast in competency causes a relatively lower fractal dimensions (Faghih and Nourbakhsh, 2015b).

The southern and southeastern side of the Kharmankuh anticline have more considerable drainage system than the northern and northwestern side of it, causing higher variability of topographic characteristics, more alluvial deposits and steep slopes formed by erosion which consequently led to a relatively higher fractal dimension.

5. Conclusion

The fractal dimension of the earth surface gives beneficial information about the earth surface and for differentiation of rock units in different geological environments is considered as an applicable parameter. For a better understanding of complete topographic characteristics of the earth's surface it is essential to apply a direct determination of the fractal dimension approach. Covering divider method applied in this work to calculate the texture of topography within a region of the Zagros Mountain of Iran. Direct determination of the earth's surface fractal dimension is outcome of the obtained data. High fractal dimension is the result of tectonic activities that causes to formation of loose alluvial deposits and irregularities possess high fractal dimensions and the competent formations show lower fractal dimensions. The roughness of landform that is a measure of the variability of topographic heights is shown by the fractal dimension of the earth surface. Integration of geo-information approach with covering divider method for direct extraction of roughness-surface fractal dimension of topography yield a rapid and facile way to determine the distribution of the earth surface deformation pattern in different regions. The presented flow chart in this research with aid of GIS-based spatial analysis algorithms enhanced extraction of fractal dimension of earth surface topography.

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