Geomorphology 175–176 (2012) 151–162

Contents lists available at SciVerse ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Fractal properties of landforms in the Ordos Block and surrounding areas, China

Lisi Bi [a,b], Honglin He [a,*], Zhanyu Wei [a], Feng Shi [a]

[a] Key Laboratory of Active Tectonics and Volcano, Institute of Geology, China Earthquake Administration, Beijing 100029, China
[b] Earthquake Administration of Guangdong Province, Guangzhou 510070, China

ARTICLE INFO

Article history:
Received 22 September 2010
Received in revised form 16 May 2012
Accepted 9 July 2012
Available online 15 July 2012

Keywords:
Ordos Block
Fractal properties
Geomorphological zones
Variogram
Cellular fractal model

ABSTRACT

This paper investigates the fractal properties of landforms in the Ordos Block and surrounding areas within China and discusses their geological and geomorphological implications. The Ordos Block is tectonically stable, but the surrounding areas are much more active and are affected by shear-extensional structures. We utilized the variogram method and the cellular fractal model to estimate parameters such as the fractal dimension (D), ordinate intercept (γ), and range (R) from the SRTM3 DEM using a moving window operation. We suggest that the fractal dimension reflects the frequency of variation in elevation, while the ordinate intercept reflects the amplitude of relief. The fractal properties range from 90 m to 30 km. Geomorphological zones can be delineated using the fractal dimension and ordinate intercept. These zones are consistent with known qualitative types of topography. Some basins are characterized by high fractal dimensions and low ordinate intercepts, in contrast to mountainous areas with low fractal dimensions and high ordinate intercepts. Other areas such as the Loess Plateau and deserts also have unique values of fractal properties. The effects of geological and geomorphological processes on the fractal properties are also discussed.

1. Introduction

The Ordos Block in China is a tectonically stable terrain. Driven by the collision among the Indian and Eurasian plates during the Cenozoic, the block was rotated counterclockwise, resulting in shear-extensional structures in surrounding areas (Molnar and Tapponnier, 1975; Tapponnier et al., 1982; Deng et al., 1999). Tectonics and topography within the Ordos Block significantly differ from those of surrounding areas. This type of geologic setting is suitable for analyzing the difference in morphometric properties and their geoscientific implications in two contrasting areas.

This paper estimates the fractal parameters using the variogram method and discusses the fractal properties of landforms within the Ordos Block and surrounding areas. These parameters include the fractal dimension (D), ordinate intercept (γ), and range (R), and were obtained from a DEM in a cellular fractal model, as well as using a moving window operation. Each parameter is interpreted in relation to wave characteristics of topography. The relationship of the parameters with geological and geomorphological processes is also discussed.

2. Fractal in geomorphology

Fractal has provided a way to quantitatively describe self-similar or self-affine landforms (Mandelbrot, 1967). The fractal dimension characterizes the nature of landforms in a systematic way. In early studies, the application of fractal to geomorphology focused on line elements such as coastlines, rivers and faults (Mandelbrot, 1967; Robert, 1988; Kong and Ding, 1991; Nikora, 1991; Zhou, 1991; Jin et al., 1997). With the development of digital terrain analysis, methods of estimating surface fractal dimensions have been proposed. Based on the variogram, two-dimensional power spectral and projective covering methods have been utilized (Huang and Turcotte, 1989; Gallant et al., 1994; Xie and Wang, 1998), and the application of fractal to regional geomorphology presents a potential prospect.

Traditional fractal models usually assume the fractal nature of landforms to be homogeneous, and describe their fractal properties as a uniform fractal dimension (Xu et al., 1993). However, landforms are shaped by a series of competing and complex tectonic and surficial processes (Sung et al., 1998; Werner, 1999). Most studies confirmed that the variation of the fractal dimension over earth surfaces is regionally dependent, as well as scale-dependent (Burrough, 1981; Mandelbrot, 1982; Mark and Aronson, 1984; Herzfeld and Overbeck, 1999). In recent years, some reports have adopted the cellular fractal model to analyze the variation of the fractal properties of landforms, and obtained better results (Sung et al., 1998; Cheng et al., 1999; Sung and Chen, 2004; Long et al., 2007). Thus, it is possible to use the fractal dimension to define the physiographic provinces quantitatively based on the cellular fractal model. Several such studies have already been conducted (Outcalt et al., 1994; Cheng et al., 1999; Sung and Chen, 2004).

Estimating the fractal dimension and other fractal parameters is a way of quantitatively describing landforms (Xu et al., 1993). Different

* Corresponding author. Tel.: +86 10 62009215.
E-mail addresses: bi_lisi@126.com (L. Bi), honglinhe123@vip.sina.com (H. He).

0169-555X/$ – see front matter © 2012 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2012.07.006

dimension values can be obtained with different methods even for the same landform (Carr and Benzer, 1991; Klinkenberg and Goodchild, 1992; Xu et al., 1993; Gallant et al., 1994). Although the ruler method and the box counting method can determine the fractal dimensions of linear phenomena quite well, they yield the meaningful result only when linear objects are self-similar, and the format of the data used is generally vectorial with a string of coordinate pairs on a plane (Gilbert, 1989; Xu et al., 1993). These requirements cannot be satisfied for topographic relief, which is generally self-affine and is expressed mainly with a gird-based DEM (Goodchild, 1980; Turcotte, 1992; Xu et al., 1993). A similar problem occurs for the box counting method, which usually deals with only self-similar linear objects (Xu et al., 1993). Although the power spectral method is available to estimate the surface fractal dimension of a self-affine object, the conventional techniques of estimating the power spectrum would lose some essential information and introduce noise. The drawbacks of these methods have not been solved effectively (Gilbert, 1989; Carr and Benzer, 1991; Xu et al., 1993; Gallant et al., 1994).

In contrast, the variogram method has proved to be a more intuitive and better way to measure the surface fractal dimension of self-affine landforms (Agterberg, 1982; Gilbert, 1989; Huang and Turcotte, 1989; Klinkenberg and Goodchild, 1992; Xu et al., 1993). The method can handle grid-based DEMs, and the obtained variogram not only gives the fractal dimension, but also the ordinate intercept and the range. The method obtains the surface fractal dimension on the assumption that the surface has statistical properties similar to those of the fractional Brownian surface (Mandelbrot, 1975). Fractional Brownian motion may be the most useful mathematical model for the random fractals in nature, particularly for geomorphological analysis (Xu et al., 1993). A number of investigators have used the variogram method to compute the self-affine dimensions to describe the fractal properties of topography and classify physiographic provinces (Mark and Aronson, 1984; Klinkenberg, 1992; Chao, 1995; Carr, 1997; Sung et al, 1998; Sung and Chen, 2004).

Although the fractal parameters from variograms provide a succinct summary of topographic characteristics (Klinkenberg, 1992), a remaining issue is how to explain the significance of information contained in the parameters. Some authors indicate that the fractal dimension appears to capture some new information that traditional parameters did not contain (Klinkenberg, 1992; Xu et al., 1993). Xu et al. (1993) explained that the fractal dimension characterizes more than mere terrain “irregularity” or “roughness”. Chase (1992) pointed out that the fractal dimension of topography reveals how the variability of the topography changed with the distance. Sung et al. (1998) and Sung and Chen (2004) proposed that the surface fractal dimension is a measure of texture of a topographic surface. Besides the significance of the fractal parameters, the links between the fractal parameters and the physical processes producing the fractal characteristics are also the important issues in need of further research.

3. Regional setting and DEM data

The Ordos Block, located between the North China plate and the Tibetan Plateau plate, is the western part of the ancient China–Korea para-platform. At the end of the early Proterozoic, the crystalline basement of the Ordos Block was formed. Then the Ordos Block underwent multiple cycles of uplift and subsidence in the Middle–Late Proterozoic and Paleozoic, which resulted in several depositional breaks. During the Mesozoic it became a large-scale basin, preserving the lake-basin deposits of the Triassic to Early Cretaceous. In the Late Cretaceous and Paleocene, the Ordos Block was shifted from a basin to a plateau, and eroded in response to durative uplift. Since the Eocene the block has experienced the sinistral rotation influenced by the Himalayan movement, with fault-depression belts around the block developing as well (Ye, 1983; Ye et al., 1987; The Research Group on ‘Active Fault System around Ordos Massif’, State Seismological Bureau, 1988). Presently, almost no tectonic activity exists within the block. However, strong tectonic activity frequently occurs in the areas surrounding the block. The southwest border of the block is squeezed by the Tibetan Plateau, leading to the NNW-trending arcuate thrust faults and the compressive folds. Along the eastern boundary lies the Shanxi Graben System. Along the western boundary there is the Yinchuan–Jartai fault-depression basin belt. The eastern and western boundaries are both controlled by the NNE-trending oblique slip faults, composed of both normal and dextral slip. In contrast, the southern and northern boundaries, where the Weihe and Hetao fault-depression basin belts lie respectively, both are controlled by the sub-latitudinal oblique slip, composed of normal and sinistral slip (Fig. 1; The Research Group on ‘Active Fault System around Ordos Massif’, State Seismological Bureau, 1988; Xu et al., 1994; Deng et al., 1999, 2003). According to GPS observations, the western and northern boundaries show movement in the NNE and E directions, respectively. Both the eastern and southern boundaries show movement in the SSE direction (Zhang et al., 2002).

Similar to the tectonic environments, the landforms in the Ordos Block and surrounding areas are different from each other (Fig. 1). The Ordos Block is inclined to the southeast, with weak deformation within the block itself. In terms of topography and lithology, the block is divided into two regions. The northern region is the desert at ca. 1000–1400 m a.s.l., while the southern region is the Loess Plateau at ca. 1300–1500 m (Di et al., 2003). Along the northern boundary of the block lies the Hetao Basin Belt which consists of three large basins. Along the southern boundary is the Weihe Basin where small fault-block mountains and hummocky terrains exist. The Yinchuan Basin trends N–S and lies along the western boundary. The Shanxi Graben System lying along the eastern boundary is composed of more than ten fault-depression basins discontinuously distributed (The Research Group on ‘Active Fault System around Ordos Massif’, State Seismological Bureau, 1988; Deng et al., 2003).

The extent of our study area (Fig. 1) was determined based on the result of the active block regionalization of China (Zhang et al., 2003) and the Map of Active Tectonics of China (Deng et al., 2007). The SRTM3-DEM data with a resolution of 90 m was chosen, as the resolution is suitable to study an area of ca. 5×10^5 km^2 and the derivation of realistic fractal information is possible.

4. Methods

4.1. Variogram method

The essence of the variogram, for the DEM data $Z(x,y)$, is that the statistical variation of elevation changes with distance, which is described by:

$$E\left[(Z(x,y)-Z(x+\Delta x,y+\Delta y))^2\right]=\left[\left(\Delta x^2+\Delta y^2\right)^{\frac{1}{2}}\right]^{2H}, \tag{1}$$

where $E[(Z(x,y)-Z(x+\Delta x,y+\Delta y))^2]$ is the mean square of the elevation difference between points with the distance of $\left(\Delta x^2+\Delta y^2\right)^{\frac{1}{2}}$, and H is the Hurst exponent with the range from 0 to 1. Eq. (1) exhibits a power law relationship. The fractal dimension D has the following relationship with H for the surface fractals:

$$D=3-H. \tag{2}$$

The fractal dimension is estimated from the slope of the least-square regression line associated with the log of the distance between points versus the log of the mean-squared difference in the elevation for that distance. The coefficient of determination of the fitted line should be higher than 95%. The intercept of the fitted line with the ordinate at the nearest distance between points is defined