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A fractal evaluation of particle size distributions in an eolian loess-paleosol sequence and the linkage with pedogenesis

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A R T I C L E I N F O

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A B S T R A C T

The changes of soil particle size distributions (PSDs) can be used as a proxy for soil development intensity and an indicator of soil formation processes. The fragmentation fractal dimensions can describe PSDs of soils in a single parameter. The objective of this research is to use mass-based fragmentation fractal dimension models to describe PSDs and evaluate the relationship between the fragmentation fractal dimension values (D_F) and pedogenesis in loess-paleosol. Based on the theory of fragmentation fractal dimension, particle size data from 837 eolian loess samples from the lower part of Chaoyang section uniform loess deposits were analyzed with mass-based models using linear regression and piecewise linear regression. A single power-law exponent can characterize the PSDs across the domain of 0.1–54.4 μm. The trend of fragmentation fractal dimension values is consistent with chemical weathering indices, magnetic susceptibility, and < 1 μm clay contents. The D_F value of PSDs can be used to assess the degree of particle fragmentation and intensity of pedogenesis for loess-paleosols. A paleosol has a greater D_F value than a loess; indicating that the greater the D_F value, the greater the effect of energy events that have occurred. Loess particles in paleosols were fragmented to finer particles with an average median grain size ($\varphi = 6.21 \pm 0.24$, CV = 3.94%) and were poorly sorted to very poorly sorted (So = 1.922 ± 0.128) due to strong pedogenesis under a prominent warm-wet climate. In contrast, particles in loess experienced fewer fragmentations and had a greater average median grain size ($\varphi = 5.89 \pm 0.35$, CV = 5.89%) due to weak pedogenesis under prominent cold-dry climate. These results confirm the use of fractal characteristics to reflect the loess particle size reduction process. Two domains within the 0.1–54.4 μm domain, F1 and F2, were identified where power-law scaling was applicable. The close transition point from F1 to F2 is 7.64 ± 1.21 μm. The fragmentation fractal dimensions of the two domains decreased in the order: D_{F1} (close to 3) > D_{F2} (close to 2). The energy dissipation for fragmenting larger particles from coarse silt (CSI) to fine silt (FSI) is identified in the volume and for fragmenting smaller particles from fine silt (FSI) to clay (CL) it is substantially on the surface. This research indicated that fragmentation fractal model is a good descriptor for the PSDs and D_F can be a value quantifying the intensity of loess-paleosol pedogenesis.

1. Introduction

1.1. The linkage between fragmentation fractal dimensions and pedogenesis

Previous laboratory experiments imply that fractal dimensions can be used as a tool to estimate the degree of particle comminution and ascertain past size reduction events (Taşdemir, 2009; Thomas and Filippov, 1999). Results from laboratory simulations, suggest that the D_F of loess PSDs has potential as a parameter to indicate the efficiency of size reduction and its variation can reflect high energy efficiency in early stages of the comminution process (Lu et al., 2003). Although some meaningful estimates of fractal dimension characteristics of loess have been obtained, more field studies and further exploration of the relationship between fractal dimension D_F and pedogenesis are still needed. We hypothesize that the fractal dimension of PSDs can be used to assess the degree of particles fragmentation and the pedogenesis intensity for loess-paleosol sequence formed under different paleo-climates. This implies that the greater D_F, the greater the intensity of pedogenesis that has occurred, the greater the proportion of fine particles, and the more well-graded the PSDs in the loess-paleosol.

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Understanding linkage between fragmentation fractal dimension and pedogenesis can help identify the mechanisms controlling the fragmentation process.

1.2. The influence of pedogenesis on PSDs

The loess particle forming process is a complex, nonlinear geological process (Liu et al., 1999). The physical, chemical, and biological actions associated with weathering result in rock fragmentation and soils dominated by silt-sized particles. When particles are wind transported, the order of deposition is size-dependent. Post-deposition pedogenesis, including chemical and biological weathering, results in finer fragmented particles under certain paleo-climate conditions (Liu, 1985; Pye, 1995) and occurred for longer or more intense period of pedogenesis which results in finer loess particles (An et al., 1991). Pedogenesis is related to the energy input available for fragmentation and this is related to the paleo-climate and the loess-paleosol formation environment (Schaetzl and Anderson, 2005).

1.3. The fragmentation fractal dimension as an indicator for loess-paleosol PSDs

Particle size distributions (PSDs) in soils are an important and fundamental soil physical property (Bittelli et al., 1999). Considerably different PSDs might be found in a certain textural class from a textural diagram (Soil Survey Staff, 2014). Fractal mathematics characterizing PSDs in soils (a fractal distribution) have been found to be a more accurate and useful description tool (Bittelli et al., 1999; Turcotte, 1986; Tyler and Wheatcraft, 1992; Wu et al., 1993). The fractal concepts derived from the fragmentation model of Matsushita (1985) and Turcotte (1992) were often used to describe PSDs. PSDs were often denoted as cumulative functions; either as the mass of particles smaller than a certain diameter (the mass-based approach), or as the number of particles larger than a certain diameter (the number-based approach). Number-based and mass-based approaches of fragmentation power-law relations were proposed by Turcotte (1992) and the exponents were interpreted as fractal dimensions of the distribution (Matsushita, 1985; Turcotte, 1986). The fragmentation fractal dimension value (D_F) denotes a uniform property of a granular system (Lu et al., 2003). The number-based approach is inconvenient because in experimental data, soil PSDs are usually given by weight (Gee et al., 1986). The assumed uniform shape and density of particles could also introduce systematic error to the dimensional process (Hyslip and Vallejo, 1997). Compared to the number-based approach, fractal dimensions from the mass-based approach are less sensitive to the assumed scale and is independent of density and size of particles (Tyler and Wheatcraft, 1992).

Sometimes a single fractal dimension is not sufficient to characterize a PSDs for the entire range of particle sizes (Bittelli et al., 1999; Paz-Ferreiro et al., 2010; Posadas et al., 2001; Wang et al., 2008). Segmented domains of particle diameter can be assumed according to the natural organization of PSDs, over which a critical value X_C and a different fragmentation fractal dimension value can exist (Millán et al., 2003). A piecewise model based on single fractal dimension model can describe the possible fractal structure of PSDs (Millán et al., 2003). Two power laws are separated by X_C which also indicates ln-transformed data would be fitted as two straight lines separated by a cutoff $\ln(X_C)$.

The fragmentation fractal dimension of PSDs might be an intrinsic property of loess and offer promise for representing the loess formation mechanism (Lu et al., 2003). The loess-paleosol sequence derived from eolian deposits is closely associated with variations of East Asian monsoon climate over the past 2500 ka BP, which is thus regarded as an excellent geological record of monsoon climate changes (An, 2000; Liu, 1985). As loess particles are the main components of the loess-paleosol sequence, environmental evolution information was primarily preserved in the PSDs (Lu and An, 1998). A large body of research has been conducted on the PSDs of loess-paleosol sequences, and PSD parameters such as mean or median grain size were used as indicators to retrieve the variability of East Asian monsoon influence (An, 2000; An and Porter, 1997; Ding et al., 2002; Ding et al., 1994; Liu, 1985; Lu and An, 1998; Sun et al., 2006; Xiao et al., 1992; Zhang et al., 1994a). However, eolian depositions have been modified to various degrees by pedogenesis processes with the result of producing clay and non-clay fractions (Guo et al., 1991; Liu, 1985; Xiao et al., 1992). The changes of PSD can be used as a proxy for pedogenic intensity or soil age, and an indicator of soil formation processes (Minasny et al., 2016). The weathering process fundamentally determines the loess PSD, but its intensity is difficult to quantify. PSD of loess is fractal in natural (Lu et al., 2003), after modification by an external force (pedogenesis). The loess particles still have good statistical self-similarity, so the particle size fractal dimension of this kind of sediment has been proposed as a new particle size index (Taşdemir, 2009; Zhang et al., 2010). Changes in the fractal PSDs can be described by the fragmentation fractal dimension value (D_F). The fragmentation fractal dimension was estimated from the size distribution of the fractal fragments (Taşdemir, 2009). The fragmentation fractal dimension together with some traditional particle size parameters will be used to make a breakthrough in the theoretical research and practical application of loess-paleosol.

2. Materials and methods

2.1. The loess section and sampling

The Chaoyang section evaluated in this study is located at Chaoyang (N 41°33′9.6″, E 120°30′20.8″) in the northeast part of China's loess distribution and has a mean annual temperature and precipitation of 9 °C and 450–500 mm, respectively.

The Chaoyang section, about 19.85 m in thickness, consists of one Holocene soil (S0) and five loess (Lx) units interbedded with four paleosols (Sx) (Fig. 1). Stratigraphic descriptions and detailed morphological features were provided by Sun et al. (2016a). The section was derived from eolian loess ("Eolian loess" refers to silt-sized material deposited on the Earth surface by winds (Liu, 1985; Sun et al., 2016a)) except for some local reworked loess by water occurring from 0 to 228 cm (Sun et al., 2016a). The loess below 228 cm (lower part of the Chaoyang section, LOP) has been deposited continuously since 423 ka BP (Chen et al., 2009; Sun et al., 2016a). The LOP was determined to have no discontinuity and the section has generally uniform loess deposits (Sun et al., 2016a).

In the LOP, 17 paleosol and 18 loess samples were used for geochemical and mineralogical analysis. From the bottom the section to the surface, 837 samples were collected at 2 cm intervals to assess particle size distributions (PSDs).

2.2. Laboratory methods

Soil samples were air-dried at room temperature, and then gently crushed and passed through 2 mm, 0.149 mm, and 0.075 mm sieves. X-ray Fluorescence Spectroscopy (XRF) was used to measure elemental composition (Cesareo, 2010) of soil samples < 0.075 mm. To monitor the quality of analysis, GBW(E)-070041 and GBW(E)-070042 (two national standard soil samples in China) were added and determined synchronously. The results showed that relative errors were < 5% and the standard deviation of one randomly chosen sample measured in triplicate was < 3%. Particle size was determined using a CIS-100 laser diffraction particle size analyzer produced by Holland Ann Mead Company used according to the analytical procedure described by Lu and An (1997). Particle sizes ranging from 0.1 μm to 3600 μm can be measured following a pretreatment procedure consisting of removal of organic matter with 10 ml 10% hydrogen peroxide (H_2O_2) solution, removal of carbonates with 10 ml 10% hydrochloric acid (HCl) solution, and separation of fine earth particles (< 2 mm) by 10 min of ultrasonic treatment in a 10 ml 0.05 mol/l Na-hexametaphosphate (HMP)