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Grain size partitioning in loess–paleosol sequence on the west coast of South Korea using the Weibull function

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ABSTRACT

This study aims to partition the grain size of the loess–paleosol sequence on the west coast of South Korea and investigates the limitations and applicability with the partitioning method, through the help of a laser diffraction grain size analyzer. Two to four components, depending on the samples and theories employed to convert the laser diffraction data to grain size data, are identified through the partitioning process. However, the identification of one component is thought to be contingent upon the theories employed, rather than natural processes. The partitioning results reveal that the sequence consists mostly of fine and coarse components transported by the same mechanisms as in the Chinese Loess Plateau and shares common source areas with the Chinese Loess Plateau. The sequence also contains a small quantity of material from the local sources, and this component is expected to provide crucial information about paleoclimatic variations in Korea. This study suggests that considerations of the theories are essential in modeling processes of grain size because the theories greatly influence the results of grain size analysis and the number of components and that conversions using the Fraunhofer Approximation seem to provide more reliable results than those using the Mie Theory.

1. Introduction

Loess is a terrestrial sediment composed predominantly of silt-size particles, which is formed essentially by the accumulation of wind-blown dust (Pye, 1995). It covers approximately 10% of the land surface of the Earth and is concentrated in the temperate zones and in semi-arid desert margins (Liu, 1985). Grain size properties such as the median values, as well as magnetic susceptibility in loess sediments, have been regarded as one of the most important and meaningful paleoclimatic proxies, although various paleoclimatic proxies such as chemical weathering indices (Chen et al., 1999; Gallet et al., 1996), pedogenic micromorphology (Bronger and Heinkele, 1989) and pollen assemblages (Sun et al., 1997) have been proposed through loess research (An et al., 1991; Liu, 1985; Porter and An, 1995). Grain size properties improve our understanding of loess material source areas and transportation pathways, as well as paleoatmospheric circulations. In particular, the median values showing a finer trend in a NW–SE direction in the Chinese Loess Plateau (CLP; Liu, 1985) have been considered as a good indicator to reflect the strength of winter monsoon.

Grain size analysis measures the size distribution of individual grains in a sample (Gee and Bauder, 1986). It is an important and fundamental analysis in research on soils or sediments, including loess sediments. The results of grain size analysis provide enough information to determine characteristics of agents responsible for transportations (Sun et al., 2002, 2004), a sedimentary environment (Lu et al., 2001; Zhang et al., 2005), and its spatio-temporal variations (Nugteren and Vandenberghe, 2004; Sun et al., 2006; Yang and Ding, 2004).

Various techniques have been developed to determine agents by partitioning of grain size data, and the modality and linear segments in a cumulative curve can be given as the representative methods (Sun, 2004; Sun et al., 2002). For example, a sediment transported by agents having different characteristics shows a distinct grain size distribution by each agent. The number and characteristics of agents can be inferred from modalities such as unimodality, bimodality, trimodality and polymodality. Besides, a bimodal sediment has two linear segments in the cumulative curve. These methods, however, are somewhat arbitrary in data interpretation. Identification of modality is not easy when the proportion of one agent is much less or greater than the proportion of another agent and the difference between the modes is not large enough. Moreover, no accurate acquisition of statistical data on the proportion transported by each agent is available.

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Recently, quantitative methods of grain size partitioning using the Weibull function or other functions have been developed, and their usefulness was confirmed by many applications to determine the characteristics of agents responsible for transportations of loess sediments in the CLP (Qin et al., 2005; Sun, 2004; Sun et al., 2002, 2004, 2008). Lim and Matsumoto (2006, 2008a, b) also applied a partitioning method using the Weibull function to chemically isolated aeolian quartz grains deposited during the middle to late Holocene in a maar on Jeju (or Cheju) Island in Korea. These studies revealed that grain size distributions of loess sediments can be partitioned into fine and coarse components and that the fine components were mainly transported by the westerlies in the upper atmosphere and the coarse components by the winter monsoon in the lower atmosphere. In the CLP, the distribution of fine components indicates variations in the zone or pathway of the westerlies, while the distribution of coarse components shows a finer trend in a NW–SE direction, and Jeju Island indicates finer coarse components than the CLP. Moreover, the results from Jeju Island show independent variations between the fine and coarse components, while these components in the CLP indicate synchronous variations. The limitations with the partitioning method have been, however, little discussed.

Loess studies have been mainly carried out in the CLP (An et al., 1991; Porter and An, 1995) and remote areas such as the Pacific Ocean (Asahara et al., 1999; Rea and Hovan, 1995) and Arctic areas (Biscaye et al., 1997). Little attention has been, however, given to loess sediments in intermediate areas between the Eurasian Continent and Pacific Ocean such as Korea and Japan. Under conditions of insufficient results of grain size analysis on these areas, direct comparison of partitioning results of the chemically isolated quartz grains from the bulk samples on Jeju Island to those from the bulk samples on the CLP can be problematic due to the influence of weathering processes. The aeolian sediment in a maar with a certain water depth can show differences from the loess–paleosol sequence deposited with air exposure. Moreover, the results from Jeju Island reflect the relatively stable paleoclimatic conditions during the Holocene, and until now, the partitioning of loess sediments that experienced the dramatic climatic variations caused by the alternating glacial and interglacial cycles during the Pleistocene has not been attempted in Korea.

This study partitions the grain size data of the loess–paleosol sequence in the Haemi area, Seosan-si, Chungnam Province, South Korea whose geochemistry was previously reported by Yoon et al. (2011). This study also investigates the applicability and limitations of the grain size partitioning using the Weibull function for the Korean loess. The transportation modes and source areas for the Korean loess are also discussed. Although this study mainly discusses the partitioning method using the Weibull function, some discussions can be applied to other grain size partitioning methods and are not confined to the partitioning method using the Weibull function.

2. Weibull function and grain size partitioning

2.1. Backgrounds for the partitioning method using the Weibull function

The Weibull distribution was named after the Swedish physicist, Waloddi Weibull, who proposed it for the first time in 1939 in connection with his studies on material strength; it has been extensively used in life testing and reliability problems (Amhad, 1994). The distribution is expressed as the following equation:

$$f(x,\alpha,\beta)=\frac{\alpha}{\beta^{\alpha}}x^{(\alpha-1)}\exp^{-\left(\frac{x}{\beta}\right)^{\alpha}} \qquad (1)$$
$$\alpha,\beta>0$$
$$x\geq 0$$

where α is the shape parameter relevant to the distribution shape, β is the location or position parameter relevant to the position of distribution on the X-axis, and x is an independent variable. If applicable to grain size, α is mainly related to grain size parameters such as sorting, skewness and kurtosis, and β is mainly related to grain size parameters such as mean, median and mode. In this study, β will be referred to as the modal size of the Weibull function. The sum of the y values is 1, when the y values on both sides of the distribution converge at the X-axis (i.e., $y = 0$), because the Weibull function is a probability density function. Suitable grain size distribution can be obtained through multiplication by 100, because grain size results are expressed in percentages (%).

As defined by the Weibull function, both α and β should be >0 and x should be ≥ 0. If $x < 0$, the Weibull function equals 0 regardless of α and β. When $\alpha \leq 1$, the function produces a strange distribution like an exponential function different from the general grain size distributions. Therefore, α should be >1 for the partitioning of grain size. When a grain size distribution is partitioned using more than one Weibull function, the function can be expressed as the following equation:

$$f(x,\alpha_1,\beta_1,c_1,\alpha_2,\beta_2,c_2,\ldots,\alpha_n,\beta_n,c_n)=c_1\frac{\alpha_1}{\beta_1^{\alpha_1}}x^{(\alpha_1-1)}\exp^{-\left(\frac{x}{\beta_1}\right)^{\alpha_1}}$$
$$+c_2\frac{\alpha_2}{\beta_2^{\alpha_2}}x^{(\alpha_2-1)}\exp^{-\left(\frac{x}{\beta_2}\right)^{\alpha_2}}+\ldots+c_n\frac{\alpha_n}{\beta_n^{\alpha_n}}x^{(\alpha_n-1)}\exp^{-\left(\frac{x}{\beta_n}\right)^{\alpha_n}}$$
$$\alpha,\beta>0$$
$$x\geq 0$$
$$0\leq c\leq 100$$
$$c_1+c_2+\ldots+c_n=100(\%) \qquad (2)$$

where parameter c is the percentage of each function or component, and thus the sum should be 100. Moreover, because c indicates percentage, it should be ≥ 0 and ≤ 100.

After determining the number of components or functions, a grain size distribution can be partitioned by the calculation of parameters α, β, and c which are in accordance with a minimum error, usually expressed as Sum of Squared Error (SSE), with respect to the real grain size data and which simultaneously meet the given conditions of the parameters. This procedure is similar to the curve fitting or optimization algorithm. Therefore, by the calculation of parameters α, β and c with a minimum SSE, a given grain size distribution can be partitioned by the Weibull function (Sun et al., 2004).

The fundamental assumption in the partitioning of grain size using the Weibull function is that a given grain size distribution resembles one or more Weibull functions. Therefore, a grain size distribution can be expressed by the sum of one or more Weibull functions because the distribution of each component can be expressed by one Weibull function. The largest strength of the partitioning method using the Weibull function is its flexibility (Sun et al., 2002). Moreover, a simple algorithm of this partitioning method enables us to easily apply to other grain sizes.

2.2. Limitations with the partitioning method using the Weibull function

This partitioning method using the Weibull function also has limitations. First, both number and interval of size classes (independent variable) influence the partitioning results. To estimate differences in partitioning results due to size class, this study examines the grain size analysis results of the two samples (HM50 and HM150) collected from the loess–paleosol sequence of the Haemi section which are extracted in 1 Φ, 1/2 Φ, 1/4 Φ and 1/8 Φ intervals. Then they are partitioned into any two components (Fig. 1). The results of sample HM50 in 1 Φ intervals (Fig. 1A) indicate modal sizes of approximately 3.26 μm (40%) and 19.33 μm (60%), while modal sizes of approximately 4.13 μm (49%) and 20.35 μm (51%) are obtained in 1/8 Φ intervals (Fig. 1G). The percentages of each component also show differences; the percentages of fine components in sample HM150 in 1 Φ and 1/8 Φ intervals are approximately 62% (7.05 μm) and 52% (5.58 μm), respectively (Fig. 1B and H). The SSEs generally decrease with increases in the