Geochemical indicator of original eolian grain size and implications on winter monsoon evolution

PENG Shuzhen (彭淑贞)[1,2] & GUO Zhengtang (郭正堂)[1]

1. Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China;
2. Tai'an Teacher's College, Tai'an 271000, China
Correspondence should be addressed to Guo Zhengtang (email: ztguo@mail.igcas.ac.cn)

Received July 17, 2001

Abstract Grain size of eolian deposits from the Loess Plateau in China has been widely used to reconstruct the history of the East Asian winter monsoon. However, the grain size of bulk samples is only partially indicative to the strength of the winter monsoon because post-depositional weathering processes have significantly changed the grain size of original eolian particles. Here, non-weathered loess samples were separated into eight different particle fractions, and major chemical elements were determined in order to establish a geochemical indicator of original eolian grain size. The results show that SiO_2 and Al_2O_3 contents and the SiO_2/Al_2O_3 ratio in different fractions vary regularly with grain size, and that a good linear relation exists between the SiO_2/Al_2O_3 ratio and grain size for the fractions <50 μm. Because Al and Si are among the most stable elements and pedogenic processes in the Loess Plateau cannot affect the SiO_2/Al_2O_3 ratio, this index can be used to reflect the grain size of original eolian particles. Application of this index in the Weinan and Luochuan loess sections of the last climatic cycle shows that SiO_2/Al_2O_3 is in good agreement with median grain size (Md) in the loess units. On the contrary, SiO_2/Al_2O_3 has documented a series of fluctuations in the soil units that are not clearly indicated by the grain-size changes of bulk samples.

Keywords: SiO_2/Al_2O_3 ratio, grain size, loess-paleosol sequence, winter monsoon.

Grain size of eolian dust in terrestrial and marine sediments has been widely used to reconstruct the history of paleoclimatic evolution[1—8]. Grain-size records of the loess-paleosol sequences from the Chinese Loess Plateau are commonly regarded as an index of the strength of the East Asian winter monsoon or that of the desert evolution[3—8]. However, post-depositional weathering processes have significantly changed the size of original particles, such that the grain size of bulk samples is only approximately significant to the strength of the winter monsoon. It is therefore necessary to find a suitable indicator able to reflect the original eolian grain-size.

Since quartz is among the most resistant minerals to alter in the Loess Plateau, some authors have used the grain size of quartz to reflect the changes of original eolian particles[9]. However, the analytical procedures are quite complex and difficult to be applied on samples of quantity. Moreover, a multi-proxy approach is still highly necessary to address the behavior of the winter monsoon. Earlier studies[3,10—12] on loess geochemistry show that the chemical composition of loess is largely dependent on the source materials of eolian deposits, the intensity of chemical weathering and grain-size sorting. Different grain-size fractions consequently contain different mineralogy assemblages and chemical composition. Liu et al.[13] used the molecular ratio of SiO_2/TiO_2 as a winter monsoon index (WMI), because of the immobility of these two elements during weathering processes and the higher quartz content in the coarser fractions. This has shown a great potential in using geochemical parameters related to stable elements to reflect the original eolian grain size. This paper aims at developing a geochemical indicator of original eolian grain size based on the chemical composition of different grain-size fractions of nonweathering loess samples. The obtained index is then applied to two loess sections to compare with the grain-size changes of bulk loess samples.

1 Materials and methods

The Changwu section is located in the central Loess Plateau, where the Quaternary loess-soil sequences have been objective of a number of studies[14]. We have chosen two loess units L_1 and L_4, which are among the less weathered loess units. The two samples analyzed were selected from the positions, corresponding to the lowest magnetic susceptibility values in L_1 and L_4. Micromorphological investigations show that the contents of detrital carbonate of the samples are high (>10%). Loess at these parts has massive microstructure, indicating weak biological activities. The minerals, such as biotite, remain fresh. To ensure the dispersion of particles, the samples were dissolved in distilled water and ultrasonic pretreatment with addition of 20% $(NaPO_3)_6$ solution was performed and lasted for 2 min. Then, the samples were separated into eight grain-size fractions (>100, 100—75, 75—50, 50—25, 25—10, 10—5, 5—2 and <2 μm, respectively). The fraction >50 μm was obtained by sieving and the other fractions were obtained by the precipitation method following the Stokes law. The obtained samples were then condensed using a centrifuge and air-dried in the natural condition. The samples were analyzed by X-ray fluorescence using a Philips PW-1400 spectrometer to determine the major elemental abundances. To test the proxy in the loess-paleosol sequences, loess samples were taken at 10 cm intervals at Weinan and Luochuan, and then chemical compositions were also determined. Replicating analyses showed an analytical uncertainty of ±2% for all the major elements except for P_2O_5 and MnO (up to ±10%).

2 Results and discussion

2.1 Relations between grain size and chemical composition

The grain-size distribution and the weight proportions of each grain-size fraction in the two loess samples are shown in fig. 1. The fractions >50 μm represent only a proportion of less than 2%, indicating that the grain-size pattern of loess samples mainly depends on the fractions <50 μm. Examination on the relationship between grain-size and chemical elemental abundances shows that SiO_2/Al_2O_3 and SiO_2/TiO_2 (molecular ratio) are closely related with grain size. Fig. 2 indicates that in the two samples, similar SiO_2/Al_2O_3 and SiO_2/TiO_2 values have been obtained in the same grain-size fraction of the two samples, suggesting that the ratios are highly dependent on grain size. For each sample, the SiO_2/Al_2O_3 ratio shows two trends: for the fractions <50 μm,

SiO_2/Al_2O_3 is in positive proportion with grain size while an inversed pattern is obtained for the fractions > 50 μm. The SiO_2/TiO_2 ratio for the fraction from 5 to 50 μm is in the positive linear relation with grain size while the relation is inversed for the other fractions. This suggests that the SiO_2/Al_2O_3 ratio is better than the SiO_2/TiO_2 ratio for reflecting grain size. This is also supported by the better correlation pattern between SiO_2/Al_2O_3 and grain size for the fractions < 50 μm (fig. 2). Since the contents of the fractions >50 μm represent only a proportion of less than 2% of the bulk samples, the SiO_2/Al_2O_3 ratio can be fairly used as a proxy of grain size.

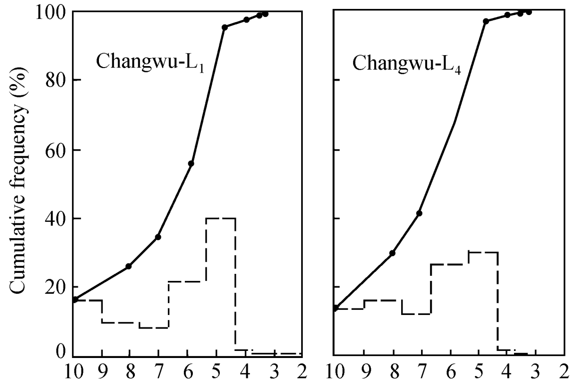

Fig. 1. Frequency cumulative curves (continuous lines) and weight percentage of different grain-size fractions in bulk samples (dashed lines) from L_1 and L_4 at Changwu.

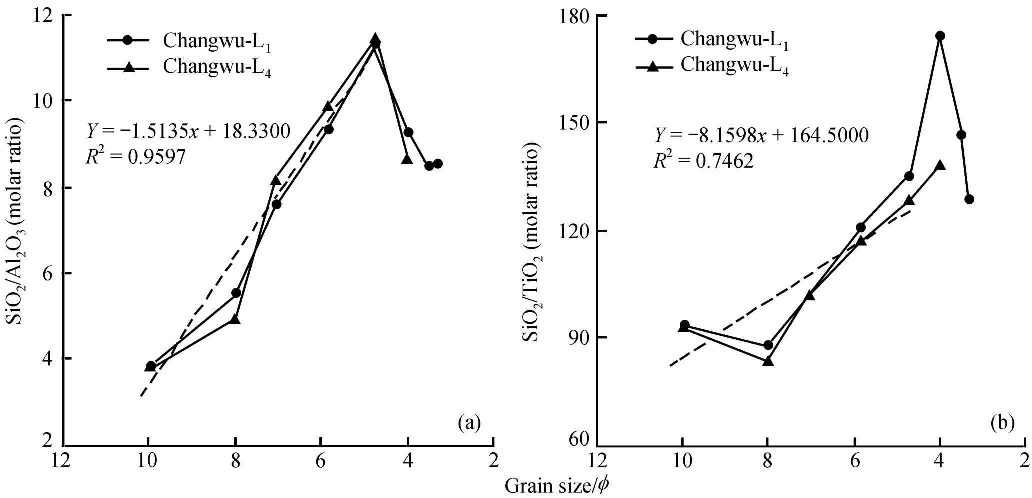

Fig. 2. SiO_2/Al_2O_3 and SiO_2/TiO_2 ratios in different grain-size fractions (dashed lines represent the linear correlations between the chemical indicators and grain size).

In loess, quartz represents more than half of the detrital minerals, which is resistant to weathering[12]. Since coarser fractions contain more quartz, the contents of SiO_2 are higher in coarse fractions. This may explain why higher SiO_2/Al_2O_3 values correspond to coarser grain size. Because SiO_2 and Al_2O_3 are among the most stable elements in a wide range of climatic conditions[12,15,16], their contents in loess or paleosols mainly depend on the composition of eolian dust, rather than post-depositional weathering. The close relationship between the SiO_2/Al_2O_3 ratio and grain size shows that the SiO_2/Al_2O_3 ratio can be used to reflect the size of the original eolian dust.

Previous studies[3] have proven that the loess in northern China is mainly transported from the deserts in the north and northwest by the Asian winter monsoon winds. Stronger winter monsoon intensity leads to coarser eolian dust. Consequently, the SiO_2/Al_2O_3 ratio can be used as an index of the strength of the Asian winter monsoon.

2.2 Variations of grain size over the last climatic cycle

The variations of SiO_2/Al_2O_3 and median grain size (Md) of Weinan[1)] and Luochuan[17] are shown in fig. 3, which shows that the SiO_2/Al_2O_3 ratio is in general agreement with Md at glacial-interglacial timescales. However, they have clear dissimilarities in the relative amplitudes of the fluctuations at shorter scales. The weaker contrast of SiO_2/Al_2O_3 ratio between loess and soil units compared to Md indicates that interglacial weathering has significantly changed the eolian grain size in paleosols. This suggests that the grain-size data of bulk samples bear indeed a large part of the information on soil weathering intensity, which is closely related to the strength of the summer monsoon. For loess units (Weinan L_{1-1},L_{1-3} and L_{1-5}; Luochuan L_{1-1} and L_{1-3}), the SiO_2/Al_2O_3 ratio and Md in the same section show a high similarity, indicating that the grain size of loess is much less affected by weathering. The consistency between the two proxies in non-weathering loess confirms the reliability of using SiO_2/Al_2O_3 as an index of original eolian grain size. On the contrary, the SiO_2/Al_2O_3 ratio in soil units (S_0, S_1, L_{1-2} and L_{1-4} at Weinan and L_{1-2} at Luochuan) differs significantly from Md. SiO_2/Al_2O_3 shows a series of secondary oscillations whereas these signals are not necessarily recorded by Md. The differences between the

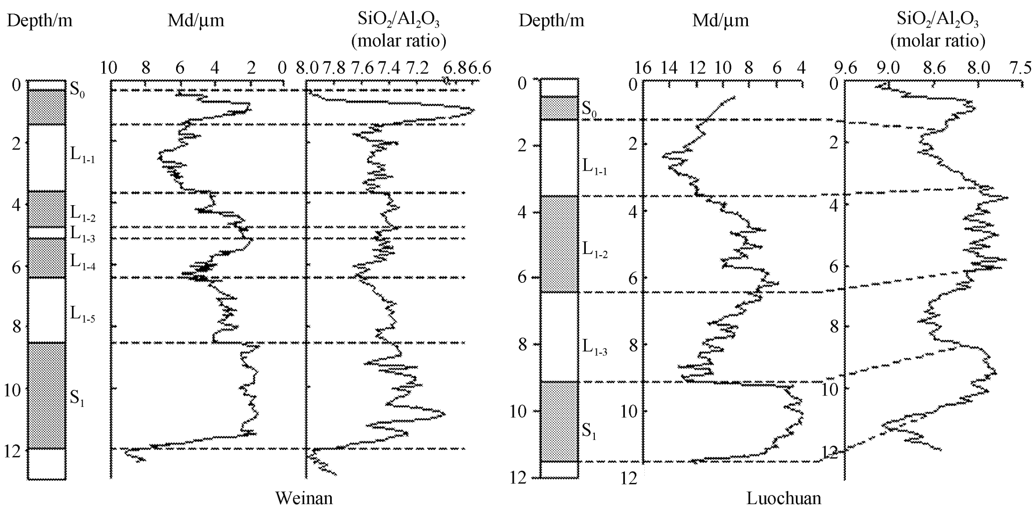

Fig. 3. Variations of SiO_2/Al_2O_3 and median grain size (Md) in the Weinan[1)] and Luochuan [17] loess-paleosol sequences of the last climatic cycle. The median grain-size data for Luochuan is from the Heimugou section and samples for geochemical analyses were taken from the Potou section. Stratigraphic correlation between Heimugou and Potou is based on the variations of magnetic susceptibility.

1) Song, C. Y., The paleoclimatic time series over the last 15 ka at Weinan, Shaanxi Province, Master Dissertation, Institute of Geology, CAS, 1994.

SiO_2/Al_2O_3 ratio and Md are undoubtedly attributable to post-depositional weathering in the soil units. For example, in these paleosol S_1 at Weinan, SiO_2/Al_2O_3 shows a series of fluctuations, which is consistent with field and microscopic observations[18,19]. Comparison between the SiO_2/Al_2O_3 ratio and median grain size (Md) for the two loess sections therefore indicates that our new proxy is better reflective to original eolian grain size.

In comparison with Weinan, better agreement is observed for Luochuan between SiO_2/Al_2O_3 and median grain size. This is attributable to weaker weathering of the paleosols in Luochuan than in Weinan[19]. It should be noted that the glacial-interglacial contrast of eolian grain size, as reflected by the SiO_2/Al_2O_3 ratio, is significantly weaker in Weinan than in Luochuan. This is explainable by the closer distance of Luochuan from the source areas. It was shown that closer sites to the source areas exhibit greater variability of grain size [20].

3 Conclusions

In the loess-paleosol sequences in China, grain size is usually used as a proxy of the Asian winter monsoon. However, post-depositional weathering has significantly affected the eolian grain size, especially in paleosols units, so that the grain size of bulk samples indeed results from the mixed effects of both the summer and winter monsoons.

Based on the chemical composition of different grain-size fractions of typical loess samples, we show that the SiO_2/Al_2O_3 ratio is in close relationship with grain size. Because Si and Al are among the most stable elements during chemical weathering, this proxy can be used as a suitable index in reconstructing the variations of original eolian grain size. It is thus better than the grain size of bulk loess samples for addressing the strength of the East Asian winter monsoon. These are supported by the application of this new proxy on the Weinan and Luochuan loess sections of the last climatic cycle. In loess units, variations of SiO_2/Al_2O_3 are highly consistent with those of the median grain size of bulk samples. On the contrary, SiO_2/Al_2O_3 has documented a series of grain-size changes in the paleosols that are not clearly expressed in median grain size of bulk samples.

Acknowledgements Thanks are extended to Wei Lanying, Hao Qingzhen, Wu Haibin, Yao Xiaofeng, Wei Jianjing, Qiao Yansong and Zhang Lianbing for their assistance. This work was supported by the National Basic Research Project (Grant No. 1998040800), the National Natural Science Foundation of China (Grant Nos. 49725206, 49894170-06 and 40024202) and the Chinese Academy of Sciences (Grant No. KZCX2-108).

References

1. Rea, D. K., Snoeckx, H., Joseph, L. H., Late Cenozoic eolian deposition in the North Pacific: Asian drying, Tibetan uplift, and cooling of the Northern Hemisphere, Paleoceanography, 1999, 13(3): 215—224.
2. Hovan, S. A., Rea, D. K., Pisias, N. G., Late Pleistocene continental climate and Oceanic variability recorded in Northwest Pacific sediments, Paleoceanography, 1991, 6(3): 349—370.
3. Liu, T. S., Loess and Environment (in Chinese), Beijing: China Ocean Press, 1985, 1—251.
4. An, Z. S., Kukla, G., Porter, S. C. et al., Late Quaternary dust flow on the Chinese Loess Plateau, Catena, 1991, 18: 125—132.
5. Ding, Z. L., Liu, T. S., Rutter, N. W. et al., Ice-volume forcing of East Asian winter monsoon variations in the past

800, 000years, Quaternary Research, 1995, 44: 149—159.
6. Lu, H. Y., An, Z. S., Paleoclimatic significance of grain size of loess-paleosol deposit in Chinese Loess Plateau, Science in China, Ser. D, 1998, 41(6): 626—631.
7. Guo, Z. T., Peng, S. Z., Hao, Q .Z. et al., Late Tertiary development of aridification in Northwestern China: Link with the arctic ice-sheet formation and Tibetan uplifts, Quaternary Sciences (in Chinese), 1999, (6): 556—567.
8. Chen, F. H., Feng, Z. D., Zhang, J. W., Loess particle size date indicative of stable winter monsoons during the last interglacial in the western part of the Chinese Loess Plateau, Catena, 2000, 39: 233—244.
9. Xiao, J. L., Porter, S. C., An, Z. S. et al., Grain size of quartz as a indicator winter monsoon strength on the Loess Plateau of central China during the last 130,000 yr, Quaternary Research, 1995, 43: 22—29.
10. Gallet, S., Jahn, B. M., Lanoë, B. V. L. et al., Loess geochemistry and implications for particle origin and composition of the upper continental crust, Earth and Planetary Science Letters, 1998, 156: 157—172.
11. Wen, Q. Z., Geochemistry of the Chinese Loess (in Chinese), Beijing: Science Press, 1989, 36—63.
12. Liu, T. S., Composition and Texture of Loess (in Chinese), Beijing: Science Press, 1966, 46—56.
13. Liu, T. S., Guo, Z. T., Liu, J. Q. et al., Variation of Eastern Asian monsoon over the last 140,000 years, Bulletin de la Société Geologique de France, 1995, 166: 221—229.
14. Guo, Z. T., Liu, T. S., Fedoroff, N. et al., Climate extremes in loess of China coupled with the strength of deep-water formation in the North Atlantic, Global and Planetary Changes, 1998, 18: 113—128.
15. Chen, J., Ji, J. F., Qiu, G. et al., Geochemical studies on the intensity of the chemical weathering in Luochuan loess-paleosol sequence, China, Science in China, Ser. D, 1998, 41(3): 235—241.
16. Gu, Z. Y., Lal, D., Liu, T. S. et al., Weathering histories of Chinese loess deposits based on uranium and thorium series nuclides and cosmogenic ^{10}Be, Geochemica et Cosmochimica Acta, 1997, 61: 5221—5231.
17. Xiao, J. L., Zheng, H. B., Zhao, H. et al., Variation of winter monsoon intensity on the Chinese Loess Plateau, central China during the last 130,000 years: Evidence from grain size distribution, Quaternary Research, 1992, 31: 13—19.
18. Guo, Z. T., Liu, T. S., An, Z. S., Paleosols of the last 0.15 Ma in the Weinan loess section and their paleoenvironments, Quaternary Sciences (in Chinese) 1994, (3): 256—269.
19. An, Z. S., Kukla, G. J., Porter, S. C. et al., Magnetic susceptibility evidence of monsoon variation on the Loess Plateau of central China during the last 130,000 years, Quaternary Research, 1991, 36: 29—36.
20. Ding, Z. L., Yang, S. L., Sun, J. M. et al., Re-organization of atmospheric circulation at about 2.6 Ma over Northern China, Quaternary Sciences (in Chinese), 1999, (3): 277—281.