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# Impacts of grain size sorting and chemical weathering on the geochemistry of Jingyuan loess in the northwestern Chinese Loess Plateau

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A B S T R A C T

Major and trace elemental compositions of loess samples collected from the Jingyuan section in the northwestern Chinese Loess Plateau (CLP) were analyzed to investigate the potential impacts of grain size sorting and chemical weathering on the loess geochemistry and to extract appropriate geochemical indices for better evaluating the East Asian monsoon variability. Based on variations of major and trace elements in different grain size fractions, seventeen elements were classified into three types: (1) Si and Na display higher contents with the increased particle sizes; (2) Al, Fe, Mg, K, Mn, Zn, Rb, Cr, V are mainly enriched in fine size fractions; (3) Ti, Ba, Zr, P, Ca and Sr show irregular variations among different size fractions. Comparison of Al-normalized elemental ratios with Zr/Rb and Rb/Sr ratios (two commonly employed indicators for grain size sorting and pedogenic weathering) indicates that Si/Al, Zr/Al, Ti/Al variations match well with Zr/Rb and grain size results, whilst Ca/Al, Sr/Al, P/Al ratios display similar variability as that of Rb/Sr ratio. Comparison of loess based proxies (e.g., elemental ratios, magnetic susceptibility, grain size) of Jingyuan section with speleothem and ice-core records confirms that elemental ratios of high-resolution loess sequences developed in the northwestern CLP can be employed to address fluctuations of the winter monsoon-induced grain size sorting and summer monsoon-related weathering and pedogenesis at glacial–interglacial and millennial timescales.



## 1. Introduction

The extensive and continuous loess-paleosol sequences in northern China are important markers of continental-scale climatic and environmental evolution during the Quaternary (last 2.6 Myr) (An et al., 1990, 1991a; Kukla et al., 1990; Porter and An, 1995; Ding et al., 1999; Nugteren and Vandenberghe, 2004). In the past three decades, numerous physical, geochemical and biological environmental proxies were extracted from Chinese loess-paleosol sequences. For instance, various grain size parameters (e.g., median grain size, mean grain size, coarse fraction content, U-ratio) and Zr/Rb ratio have been used as proxy indicators of East Asian winter monsoon strength, the main driver of dust transportation and loess deposition (An et al., 1991a; Porter and An, 1995; Xiao et al., 1995; Vandenberghe et al., 1997; Chen et al., 2006; Sun et al., 2006), whereas magnetic susceptibility, carbon isotope ratio, organic carbon content, Rb/Sr ratio, $Fe_{(free)}/Fe_{(total)}$, and chemical index of alteration have been employed as proxies of summer monsoon intensity which is responsible for the paleosol formation (An et al., 1990a,b; Jia et al., 1997; Chen et al., 1999a,b; Guo et al., 2000; Ding et al., 2001; Jahn et al., 2001; Bloemendal et al., 2008; Liu et al., 2011).

The geochemical compositions of loess sediments are mainly controlled by three factors: geochemistry of dust originated from different sources, grain size sorting during the transportation, and post-depositional weathering (Gallet et al., 1996; Bauluz et al., 2000; Chen et al., 1999a, 2006). The geochemical composition of loess sediment in source area is mainly influenced by the original material composition and weathering in source area (Chen et al., 2001). Many geochemical proxies have been developed to distinguish the provenance of Chinese loess, such as Fe/Al, Mg/Al and Sc/Al ratios (Zhang et al., 1996), Ba/Sr, Rb/Sr, Zr/Hf, U/Pb and Th/Pb ratios (Sun, 2002), providing important information on the provenance compositions from different source regions. Moreover, the Rare Earth Elements (REE) patterns were also utilized to address the loess provenance, implying the homogeneity and eolian origin of Chinese loess (Gallet et al., 1996). Notably, although the contents of most elements vary greatly in different host rocks, the major and minor elements are generally well mixed after

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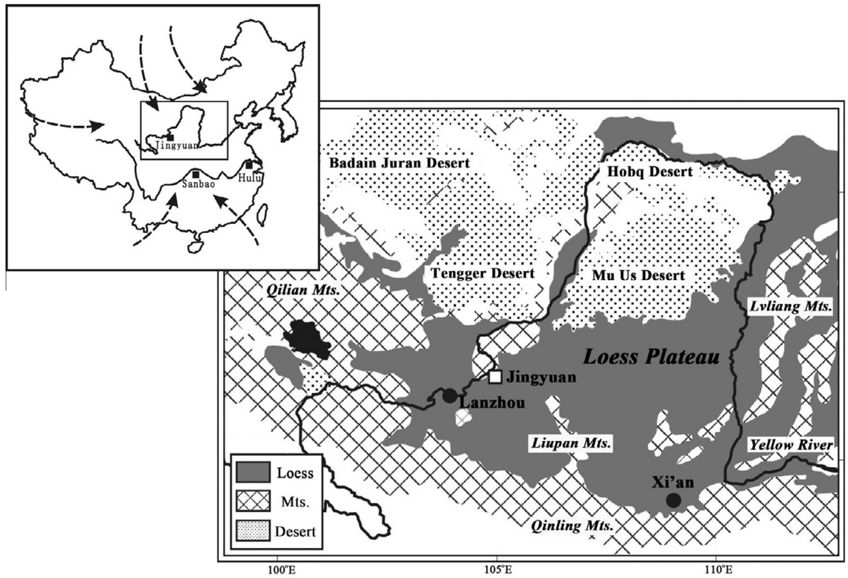


**Fig. 1.** Location of the Jingyuan section in the northwestern Loess Plateau.

numerous cycles of upper-crustal processes including transportation and weathering, and difficult to distinguish the subtle difference among the possible source areas (Chen and Li, 2011; Jeong et al., 2011).

Based on geochemical behavior discrepancies of individual elements in different geological processes, previous studies suggested that grain size sorting and chemical weathering have great influence on the loess geochemistry and proposed numerous geochemical ratios to infer the intensities of winter and summer monsoons (Gallet et al., 1996; Zhang et al., 1996; Ding et al., 2001; Jahn et al., 2001). For example, $SiO_2/TiO_2$ and Zr/Rb ratios, which are hardly affected by pedogenesis but influenced by grain size sorting, could be used to monitor wind strength of the East Asian winter monsoon (Peng and Guo, 2001; Liu et al., 2004; Chen et al., 2006). In contrast, Rb/Sr, $Fe_{(free)}/Fe_{(total)}$, and Ba/Sr ratios were employed to address the relative weathering and pedogenic intensity which is a function of precipitation, temperature and time for weathering reactions, and hence to infer the intensity of the East Asian summer monsoon (Gallet et al., 1996; Chen et al., 1999a, 1999b; Chen et al., 2001; Yang and Ding, 2001; Pang et al., 2007). However, most previous geochemical studies focused on the loess-paleosol sequences developed in the central Chinese Loess Plateau (CLP), whether these elemental ratios are sensitive to grain size sorting and chemical weathering in the northwestern CLP remains unclear.

Loess deposits in the northwestern part of CLP are characterized by high sedimentation rates and weak pedogenesis due to the relatively short distance from the source area and limited precipitation (Burbank and Li, 1985; Chen et al., 2003; Sun et al., 2006). Therefore, high-resolution climatic records can be obtained from loess-paleosol sequences in this area (Sun et al., 2010, 2012). Loess grain size, which is related to the strength of winter monsoon, displays distinct glacial–interglacial and millennial-scale variability in this region (Wu et al., 2006; Mirjam, 2007; Sun et al., 2012). However, the magnetic susceptibility signal that is commonly used as a proxy of rainfall and an indicator of summer monsoon intensity, is relatively low with minor variation in the $L_1$ loess layer of the sections (Lu et al., 2004; Sun et al., 2006, 2010), due to the low sensitivity to the weak summer monsoon changes. However, carbon isotope of carbonate in Jingyuan loess section revealed significant paleovegetation changes associated with the East Asian summer monsoon during the last glaciation (Liu et al., 2011). Therefore, extensive geochemical investigation of the Jingyuan loess would benefit to looking for new elemental ratios sensitive to summer monsoon variation in this region, and permit a better understanding of the winter and summer monsoon variability on glacial–interglacial and millennial timescales.

In this study, we conduct a systematic geochemical analysis of the Jingyuan loess sequence. The objectives are (1) to understand the distribution patterns of the major and trace elements in different size fractions; (2) to evaluate the sensitivity of different elemental ratios to grain size sorting and chemical weathering; and (3) to address the broad implications of loess geochemistry on the East Asian monsoon variability by comparison with speleothem and ice-core records.

## 2. Materials and methods

The Jingyuan loess section (36°34′N, 104°41′E, 2120 m above sea level) is situated at the northwestern CLP (Fig. 1). In this region, the mean annual temperature and precipitation are 8.3 °C and 233 mm, respectively. A 20 m pit was dug at Jingyuan for collecting powder samples at 2 cm intervals in 2008. Magnetic susceptibility of all powder samples were measured by using a Bartington MS2 meter at the Institute of Earth Environment, Chinese Academy of Sciences. Prior to grain size measurements, all samples were pretreated by removal of organic matter and carbonate using 10 ml, 10% $H_2O_2$ and 10 ml, 10% HCl, respectively (Lu and An, 1998), and then dispersed by ultrasonification with 10 ml, 10% $(NaPO_3)_6$ solution. The grain size distribution was determined using a Malvern 2000 laser instrument at the Institute of Earth Environment, Chinese Academy of Sciences. Meanwhile, carbonate contents of all size-separated and bulk samples were measured using volume method for calculating carbonate-free basis (cfb) concentrations of elements.

Samples for optically stimulated luminescence (OSL) dating were collected in stainless tubes hammered into a freshly-cleaned section face, and then wrapped in aluminum foil until processed under subdued red light in the luminescence dating laboratory of the Institute of Earth Environment, Chinese Academy of Sciences. All OSL measurements were performed using a Daybreak 2200 automated OSL reader equipped with a combined blue (470 ± 5 nm) and infrared (880 ± 80 nm) LED OSL unit, and a $^{90}Sr/^{90}Y$ beta source (0.107 Gy/s) for irradiations. All luminescence measurements were made at 125 °C for 200 s with both IR and blue