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Evolving sources of eolian detritus on the Chinese Loess Plateau since early Miocene: Tectonic and climatic controls

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ABSTRACT

The thick deposits of eolian dust on the Chinese Loess Plateau provide a rare opportunity to explore the past changes of surface processes in response to climatic and tectonic oscillations. Here we report a 22 Ma-long Nd and Sr isotopic records of the eolian sources. Decreasing ε_{Nd} values and increasing ^{86}Sr/^{87}Sr ratios of the eolian deposits has been observed from early Miocene to about 7 Ma, which indicates growing material contribution from Qilian Mountains relative to the Gobi Altay Mountains. The source shift during 22–7 Ma is interpreted to reflect the erosional response of the Qilian Mountains to its surface uplift. Between 7 Ma and 1.2 Ma, the results show relative constant Nd and Sr isotopic compositions of the eolian deposits, and thus suggest a constant source contribution between Qilian Mountains and Gobi Altay Mountains. Synchronized uplift of the two mountain ranges during this period may explain the constant ratio of source contribution. Since 1.2 Ma, Nd and Sr isotopic records indicate that the relative debris input from Qilian Mountains drops rapidly. As large-scale topographic changes would not be expected in such a short time period, the source shift since 1.2 Ma might be by the differing erosional responses in Qilian Mountains and Gobi Altay Mountains to the development of full glacial climate after the middle Pleistocene transition. This work shows that combined Nd and Sr isotopic signatures of the dust records are valuable proxies to monitoring past surface processes on the million years time scale.

1. Introduction

Deciphering the response of surface processes to tectonic and climatic changes is essential to understand operation of the Earth system (e.g., Molnar, 2004). One of the key regions that attracts much attention is the Chinese Loess Plateau (Fig. 1), where the eolian deposits have been affected by two of the most prominent exogenic processes of the late Cenozoic: Tibetan uplift and Northern Hemisphere glaciation (An et al., 2001; Ding et al., 2005).

The Chinese Loess Plateau receives massive atmospheric dust since at least the late Oligocene (Ge and Guo, 2010; Guo et al., 2002; Heller and Liu, 1982; Qiang et al., 2011; Sun et al., 1998). It has been shown that the onset and development of the eolian deposits may be related to the desertification of Asian Interior coupled with the later uplift phases of Tibetan Plateau or the ongoing global cooling (Guo et al., 2002; Sun and An, 2005). Both Tibetan uplift and Northern Hemisphere glaciation has shaped the monsoonal winds that transport the eolian dust (Sun and An, 2005). Debris eroded from Tibetan Plateau itself is also an important source of the eolian particles (Li et al., 2011).

A new opportunity to investigate the response of eolian processes on the Chinese Loess Plateau to the tectonic and climatic oscillations is to look into the changes of eolian source using radiogenic isotopic tracers such as Nd and Sr (Li et al., 2009). A large database has been established for Nd and Sr isotopic composition of the surface materials in the arid inlands of Asia (Chen et al., 2007). Using this database, it has been shown (Li et al., 2009) that the eolian dust on the Chinese Loess Plateau, at least for the last glacial–interglacial period, is mainly derived from the vast arid lands (Alxa arid lands here after) between Qilian Mountains and Gobi Altay Mountains through northwesterly winds (Fig. 1). The intensive erosion in the high mountains serves as an effective way to produce the massive amounts of silt particles that are available for eolian transport (Smalley, 1995; Sun, 2002). However, it is still not clear whether the detrital source of the eolian dust on the Chinese Loess Plateau has changed on orbital and tectonic time scales. Changes in Nd isotopic composition of about 1 ε_{Nd} unit have been observed for the eolian dust deposited during the last glacial–interglacial cycle and since ~7 Ma (Chen and Li, 2011; Sun, 2005). Such changes in Nd isotopic composition is very small compared to the external analytical error of about 0.5 ε_{Nd} unit.

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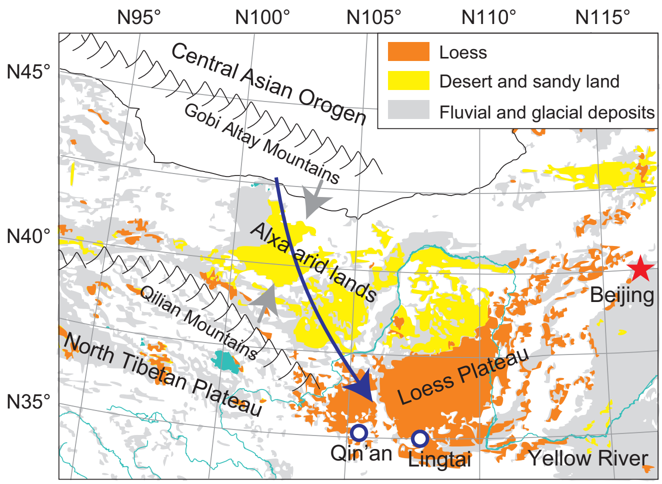

Fig. 1. Map showing geographical setting of Chinese Loess Plateau and the sampling sites at Qin'an and Lingtai. Blue arrow indicates transportation of eolian dust by northwesterly winds. Grey arrows indicate input of terrigenous material to the Alxa arid lands from Qilian Mountains and Gobi Altay Mountains.

Thus, no conclusive link has yet been established between the climatic or tectonic variations and the Nd isotopic compositions of the eolian dust (Chen and Li, 2011; Sun, 2005). Variations in strontium isotopic composition of the eolian deposits on the Chinese Loess Plateau is much larger than the analytical error, which show systematical correlation with glacial–interglacial climate changes and the long-term Quaternary climate shift (Chen and Li, 2011; Sun, 2005). However, the highly radiogenic $^{87}Sr/^{86}Sr$ ratio of the clay minerals (mostly in <2 μm grain size range) implies possible control of eolian sorting on the Sr isotopic ratios other than the source changes (Yang et al., 2005).

Here we investigate the long-term Nd and Sr isotopic evolution of the eolian dust on the Chinese Loess Plateau since early Miocene. A change in Nd isotopic composition of ~2 ε_{Nd} units is expected according to the records of the same period in North Pacific (Li et al., 2011; Pettke et al., 2002). In addition to bulk (all grain size range) silicate fraction, a very restricted grain size range (28–45 μm) of the silicate fraction is also used. The usage of 28–45 μm grain size fraction is design to exclude possible influence of eolian sorting, i.e., the content of fine clay minerals, on strontium isotopic composition. Hf isotopic compositions of the 28–45 μm grain size fractions are also measured to access the effect of eolian sorting on Sr isotopic composition. Because of the high density of zircon and the highly enrichment of Hf in zircon, it has been shown that the Hf isotopic composition of the eolian deposits is largely controlled by zircon effect that is very susceptible to eolian sorting (Chen et al., 2013). Our data demonstrates that the usage of 28–45 μm grain size fractions could largely eliminate the effect of eolian sorting on the isotopic composition of strontium. Combined Nd and Sr isotopic signatures of the dust records show long-term evolution of eolian sources that are tightly coupled with tectonic and climatic changes.

2. Samples and method

Samples of eolian deposits were collected from the Lingtai (35.06°N, 107.65°E) and Qin'an (105.46°E, 35.02°N) sites on the Chinese Loess Plateau (Fig. 1). Eolian deposits at the Lingtai site consist of tens of loess and paleosol alternations deposited over the past 2.6 Ma and the red-clay formation aged between 7 Ma and 2.6 Ma (Ding et al., 1999). The Qin'an site is recognized for its Miocene loess and red clay aged from about 6.2 Ma to 22 Ma (Guo et al., 2002). The age models of Lingtai and Qin'an sections have been well constrained by magnetostratigraphy (Ding et al., 2005; Guo et al., 2002). The position of the collected samples with respect to the magnetostratigraphic scale is shown in supplementary Fig. S1.

The grain size distribution of the samples was determined using a laser particle sizer after removal of organic matter and carbonate using H_2O_2 and HCl, respectively (Lu and An, 1997), and dispersion by ultrasonification with 10% $(NaPO_3)_6$ solution. Replicate analyses indicate that the mean grain size has an analytical error of $<2\%$.

Silicate fractions of the samples were extracted by dissolving the samples in diluted acetic acid (0.5 mol/L) after Chen et al. (2007). Leaching by diluted acetic acid could remove all of the carbonate minerals while keeping the silicate minerals nearly unreacted (Chen et al., 2007). A subset of the extracted silicate fraction is then sieved to obtain the 28–45 μm grain size fractions. Nd and Sr isotopic ratios of bulk silicate and Nd, Sr and Hf isotopic ratios of 28–45 μm grain size fractions of the silicate were determined on a Neptune plus Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS). Purification of Nd, Sr and Hf are based on ion exchange techniques after digestion of the samples in a mixture of HNO_3+HF solution. Instrumental bias was corrected to $^{86}Sr/^{88}Sr$ of 0.1194, $^{146}Nd/^{144}Nd$ of 0.7219 and $^{179}Hf/^{177}Hf$ of 0.7325, respectively, applying an exponential mass fractionation law. Sr standard SRM987, Nd standard JMC Nd_2O_3, and Hf standard JMC-475 were periodically measured to check the reproducibility and accuracy of isotopic analyses with mean $^{87}Sr/^{86}Sr$ ratio of 0.710238 ± 42 (external standard deviation, $n=10$), mean $^{143}Nd/^{144}Nd$ ratio of 0.512099 ± 15 (external standard deviation, $n=7$), and mean $^{176}Hf/^{177}Hf$ ratio of 0.282162 ± 4 (external standard deviation, $n=9$), respectively. Epsilon Hf and Nd values (ε_{Nd} and ε_{Hf}) were calculated using chondritic values of $^{143}Nd/^{144}Nd=0.512638$ (Jacobsen and Wasserburg, 1980) and $^{176}Hf/^{177}Hf=0.282769$ (Nowell et al., 1998). The analytical results are listed in Supplementary Table S1.

3. Results

The Nd and Sr isotopic records of the eolian deposits show good coherence between the Qin'an and Lingtai sites during the overlapping time period around 6–7 Ma (Fig. 2). Combining the records from Qin'an and Lingtai sites indicates three stages of Nd and Sr isotopic evolution over the past 22 Ma (Fig. 2). From 22 Ma to 7 Ma, the $^{87}Sr/^{86}Sr$ ratio gradually increases by about 0.004 for both the bulk silicate and 28–45 μm silicate fractions of the eolian deposits, while the ε_{Nd} values deceases gradually from −9 to −11. The Nd and Sr isotopic compositions of the eolian deposits keep relatively constant during 7–1.2 Ma. After ~1.2 Ma, the trend of Nd and Sr isotopic evolution reverse rapidly towards the values of early Miocene. The similar evolutional trends of Nd and Sr isotopic compositions are also evident from the negative correlation between the ε_{Nd} value and the $^{87}Sr/^{86}Sr$ ratio (Fig. 3).

The $^{87}Sr/^{86}Sr$ ratios of bulk silicate are systematically higher than that of the 28–45 μm grain size fractions of silicate with a correlation slop of about 1:1 (Fig. 4a). Instead, the ε_{Nd} values of the 28–45 μm grain size fractions of silicate cannot be discriminated from those of bulk silicate considering an external analytical error of about 0.5 (Fig. 2a). The Nd and Hf isotopic compositions of the 28–45 μm grain size fractions of silicate distribute between the crustal Nd–Hf isotopic array and the fine fraction of the desert sand and loess in North China (Fig. 4b). Deviation of Hf isotopic composition from the crustal Nd–Hf isotopic array could be defined by $\Delta\varepsilon_{Hf}$ using the crustal array of Vervoort et al. (2011):

$$\Delta\varepsilon_{Hf} = \varepsilon_{Hf} - (1.55 \times \varepsilon_{Nd} + 1.21) \qquad (1)$$