Research article

Provenance of loess deposits and stepwise expansion of the desert environment in NE China since ~1.2 Ma: Evidence from Nd-Sr isotopic composition and grain-size record

Lin Zeng^{a,b,c,*}, Shuangwen Yi^{b,**}, Wenfang Zhang^d, Han Feng^b, Anqi Lv^b, Wancang Zhao^b, Yongming Luo^c, Qing Wang^a, Huayu Lu^b

^a School of Resources and Environmental Engineering, Ludong University, Yantai 264025, China

^b School of Geography and Ocean Science, Nanjing University, Nanjing 210023, China

^c Key Laboratory of Coastal Environmental Processes and Ecological Remediation, Yantai Institute of Coastal Zone Research, Chinese Academy of Sciences, Yantai 264003, China

^d State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

ARTICLE INFO

Keywords:

Eolian deposits
Loess provenance
Nd and Sr isotopes
Grain size
Desert expansion
Aridification

ABSTRACT

The Quaternary wind-blown Chinese loess-paleosol sequence, which developed as a product of the intensification of Northern Hemisphere glacial-interglacial cycles, is a major source of information on aridification of the Asian interior. In northeastern (NE) China, extensive loess deposits occur that have great potential for reconstructing the long-term paleoclimatic evolution of the region. Despite existing geochemical data indicate that the probable major source areas for these loess deposits were the nearby Horqin and Otindag deserts, it is still unclear that whether there was a long-term change in the detrital source of these loess deposits. In addition, the aridity history and long-term desert evolution of NE China are currently poorly understood. In the present study, we measured the silicate Nd and Sr isotopic composition of the 28–45 μm grain-size fraction from multiple loess sections (NYZG, SBH, and TDJZ). The results show that the loess deposits of the three sites were dominantly sourced from the Otindag sandy desert and that this source remained constant for the past 1.2 Ma. Notably, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are influenced mainly by variations in the content of clay-sized material present in the form of aggregates or adhering to the surface of coarser particles. Therefore, caution is needed in the use of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the 28–45 μm fraction as a tracer of eolian dust, when the clay minerals are not completely removed during the pretreatment process. The grain-size variability of the three sections indicates that stepwise enhancement of aridification in the Otindag sandy desert occurred at 1.2 Ma, 0.9 Ma, and 0.7 Ma, which coincided respectively with the beginning of the Mid-Pleistocene transition (MPT), an extremely cold event at ~0.9 Ma within the MPT, and the establishment of a full glacial climate at the termination of the MPT. This finding supports the hypothesis that the growth of high-latitude ice sheets was the major driver of the long-term aridification of Asian dust source areas.

1. Introduction

Loess is a terrestrial eolian silt deposit which typically forms under an arid or semi-arid climate. It is mainly composed of silt-sized particles, and has a loose and massive structure without sedimentary bedding, and usually contains interbedded paleosols, calcareous nodules and the fossils shells of terrestrial mollusks (Liu, 1985; Pye, 1995; Muhs, 2013). The Cenozoic loess deposits in China typically consist of a Red Clay sequence formed during the late Oligocene-Pliocene (Guo

et al., 2002; Lu et al., 2004, 2019; Qiang et al., 2011; Licht et al., 2014; Li et al., 2018), and a loess-paleosol sequence which formed during the Pleistocene (Liu, 1985; Kukla and An, 1989). Chinese loess deposits have been used to determine the timing of the onset and stages in the development of the aridification of the Asian interior (Guo et al., 2002; Ding et al., 2005; Lu et al., 2010), the evolution of the East Asian summer monsoon (EASM) system (An et al., 1990; An, 2000; Ding et al., 1995; Liu and Ding, 1998), and the phased uplift of the Qinghai-Tibetan Plateau (Li and Fang, 1999; An et al., 2001; Guo et al., 2002; Lu et al.,

* Corresponding author at: School of Resources and Environmental Engineering, Ludong University, Yantai 264025, China.

** Corresponding author.

E-mail addresses: zenglin@ldu.edu.cn (L. Zeng), ysw7563@nju.edu.cn (S. Yi).

Fig. 1. (a) Distribution of deserts and loess in China and the locations of the study area and the Luochuan (LC), Lingtai (LT) and Zhaojiachuan (ZJC) loess sections. The modern 400 mm annual average isohyet represents the approximate boundary between the arid zone and the East Asian monsoon zone. EASM: East Asian summer monsoon; EAWM: East Asian winter monsoon; ISM: Indian summer monsoon; CLP: Chinese Loess Plateau. (b) Topography of the study region and locations of the investigated sections, shown on the shaded relief map. (c) Spring (March–April–May, MAM) mean 850 hPa streamline and mean wind speed near the surface based on NCEP/NCAR Reanalysis for 1981–2010. (d) Nd-Sr isotopic regions of the Chinese arid zone (Chen et al., 2007; Li et al., 2009). NBC—deserts around the northern boundary of China; NMTP—deserts on the northern margin of Tibetan Plateau; OD—Ordos Desert.

2004; Fang et al., 2019). With the establishment of a stratigraphical and chronological framework of loess deposits on the Chinese Loess Plateau (CLP), together with the development of modern analytical methods, a substantial amount of research has been conducted on loess provenance (e.g. Stevens et al., 2010; Stevens et al., 2013; Chen and Li, 2011; Nie et al., 2015; Zhang et al., 2015) and on paleoclimatic reconstruction (e.g. Da et al., 2015; Zhou et al., 2014; Yang et al., 2015; Li et al., 2017; Meng et al., 2018).

Northeastern (NE) China is an integral part of the East Asian monsoon region, and it contains extensive and thick loess deposits which represent deposition at the eastern end of the Eurasian loess belt (Fig. 1a) (Zeng et al., 2017). Long and continuous paleoclimatic records from these deposits are extremely scarce, yet there are several reasons why such records would be of high scientific value. First, the loess deposits of NE China are typical ‘desert loess’ and are an important part of the Eurasian loess belt (Muhs, 2013), and therefore detailed investigations of their geochronology, stratigraphy, provenance and paleoclimatic record will extend the spatial coverage of global loess research. Second, the numerous paleoclimatic studies of CLP loess, lake sediments, marine sediments, and stalagmites indicate large spatio-temporal differences in the variability of the East Asian summer monsoon (EASM) (An et al., 2013; Wang et al., 2014). Therefore, the forcing mechanisms and processes of evolution of the EASM on an orbital scale

remain controversial and long paleoclimatic records from throughout the EASM region are needed to resolve these issues. Third, the loess deposits in NE China are located downwind of the Horqin, Otindag and Hulun Buir sandy deserts (Fig. 1a), and are therefore sensitive to changes in the source area and source area aridity. Thus, loess records from the region can potentially increase our understanding of the spatiotemporal evolution of the aridification of the Asian interior during the late Cenozoic (Ding et al., 2005; Lu et al., 2010).

Identifying loess provenance can help discriminate the sources and transport paths of dust storms in the past and provide a reference for sustainable environmental management. In addition, because many climate proxies available for loess deposits are sensitive to changes in source materials and the dust transport path, discriminating changes in provenance is crucial for their paleoclimatic interpretation (Chen and Li, 2011). Geochemical tracers are the most effective tools for tracing the material sources of loess. They include element composition (Hao et al., 2010; Peng et al., 2016); radiogenic isotopes such as Nd, Sr, Pb, Hf (Sun, 2005; Chen et al., 2007; Chen and Li, 2013; Zhao et al., 2014; Zhang et al., 2015); zircon age distribution (Stevens et al., 2010; Stevens et al., 2013; Chen and Li, 2013; Nie et al., 2014; Zhang et al., 2016); and oxygen isotopic composition of quartz grains (Rex et al., 1969; Yan et al., 2014). Among them, Nd-Sr isotopes are the most intensively studied source tracer of eolian dust, and a large amount of

data has been accumulated worldwide (e.g., Sun, 2005; Chen et al., 2007; Rao et al., 2011, 2014, 2015; Chen and Li, 2013; Ben-Israel et al., 2015; Zhang et al., 2015; Zhao et al., 2015; Kumar et al., 2018; van der Does et al., 2018; Yang et al., 2017). The results of the Nd-Sr isotopic composition of the $< 75 \mu\text{m}$ and $< 5 \mu\text{m}$ silicate fractions of Chinese desert deposits show that the Nd-Sr isotopic composition was controlled mainly by the tectonic setting of North China, and that materials from the deserts are derived from the erosion of the rocks of the surrounding mountains (Chen et al., 2007). Changes in the Sr, Nd, and Pb isotopic composition of the $< 20 \mu\text{m}$ silicate fraction at the boundary between the Red Clay and the loess-paleosol sequence on the CLP also indicate a significant shift in the dust source material at $\sim 2.58 \text{ Ma}$ (Sun, 2005). However, the Sr isotopic composition can also be affected by the highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the clay mineral component (mostly $< 2 \mu\text{m}$), via the processes of eolian sorting and chemical weathering (Grousset and Biscaye, 2005; Yang et al., 2005). Chen and Li (2011) suggested that the use of the silicate Sr isotopic composition of a specific grain-size fraction ($28\text{--}45 \mu\text{m}$) could minimize grain-size effects on Sr isotopic composition, enabling it to be used as sensitive provenance tracer. Preliminary provenance studies based on bulk silicate Nd-Sr isotopic composition (Li et al., 2009; Chen and Li, 2011) and zircon U-Pb age spectrum analysis (Xie et al., 2012) demonstrate that the probable major source areas for these loess deposits in NE China were the nearby Horqin and Otindag deserts. However, the number of samples used in these previous studies was small and mainly confined to the top of the section. Thus, these previous researches are unable to demonstrate the possible occurrence of changes in sediment source in parallel with glacial-interglacial cycles and whether there was a long-term change in source, as was the case for the CLP (Chen and Li, 2013; Zhang et al., 2015). Zeng et al. (2011, 2016) conducted a high-resolution magnetostratigraphic and pedostratigraphic study of three loess-paleosol sections (NYZG, SBH, and TDJZ) in the Chifeng region of Inner Mongolia (Fig. 1b, Fig. 2). The results showed that the deposits date back to 1.2 Ma, and they have preserved a complete loess-paleosol sequence (L1-L14) since the late Early Pleistocene, comprising the equivalent of the Malan Formation (L1), the Upper Lishi Formation (S1-L5) and the Lower Lishi Formation (S5-L15) of the CLP. Yi et al. (2015,

2016) conducted high-resolution OSL and post-IR IRSL dating of the S1-L1 sequence of the NYZG and SBH profiles, respectively. These researches provide a chronological framework for further paleoclimatic and provenance studies of loess. Moreover, Zeng et al. (2017) demonstrated that the grain-size variability of the NYZG section was characterized by a long-term coarsening upward trend since 1.0 Ma, punctuated by two significant abrupt coarsening events, at $\sim 0.65 \text{ Ma}$ and $\sim 0.3 \text{ Ma}$. This grain-size variability could be the result of either a dust provenance shift, climate change, or the combination of both. Thus, identification of provenance changes is a critical step in paleoclimatic reconstruction using loess deposits in NE China.

In this study, we analyzed the silicate Nd and Sr isotopic composition of the $28\text{--}45 \mu\text{m}$ grain-size fraction from multiple loess sections (NYZG, SBH, and TDJZ) in NE China. The $28\text{--}45 \mu\text{m}$ fraction was used to try to minimize the effects of the previously observed significant grain-size variations of the loess deposits in NE China (Zeng et al., 2017). Thus, we hoped that high stratigraphic-resolution Nd and Sr isotopic records of the $28\text{--}45 \mu\text{m}$ fraction would enable the determination of possible changes in provenance and its paleoclimatic implications since 1.2 Ma. In addition, we use a new high-resolution grain-size record of the SBH and TDJZ sections with a refined chronology, combined with the previously reported NYZG record (Zeng et al., 2017), to produce a continuous composite record since 1.2 Ma. Finally, we compare the new grain-size record from NE China with other paleoclimatic records in order to discuss the processes and forcing mechanisms responsible for the evolution of the Otindag sandy desert during the Mid-Pleistocene climate transition (MPT).

2. Sampling and methods

2.1. Environmental setting and sampling

The thickest and most representative eolian loess deposits in NE China are distributed in the Chifeng region, in southeastern Inner Mongolia (Fig. 1a). The present climate is semi-arid and controlled mainly by the dynamics of the East Asian Monsoon circulation, characterized by cold/dry winters and warm/wet summers. In winter the

Fig. 2. Correlation of pedostratigraphy, magnetic susceptibility (MS) and magnetostratigraphy of the SBH, TDJZ and NYZG sections (modified from Zeng et al. (2016)). Black (white) shading in the polarity column denotes normal (reversed) polarity. The red solid dots show the locations of samples used for Nd-Sr isotopic measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

prevailing wind direction is northwesterly, generated by the Siberian–Mongolian high-pressure zone; while in summer the dominant direction is southeasterly, driven by the pressure gradient between the Subtropical High and the Asian Continental Low. The mean annual precipitation ranges from 600 mm in the southeast to 200 mm in the northwest, and most of the precipitation falls during the boreal summer. As illustrated in Fig. 1c, the Horqin and Otindag sandy desert are located to the north and west of the Chifeng region, respectively.

Previous studies (Zeng et al., 2011, 2016; Yi et al., 2015, 2016) have reported the results of investigations of magnetostratigraphy (Fig. 2), magnetic susceptibility (MS), pedostratigraphy, and optically stimulated luminescence (OSL) dating of three sections from the Chifeng region: NYZG (41°55'N, 118°43'E, 774 m.a.s.l.), SBH (42°18' N, 118°41'E, 677 m.a.s.l) and TDJZ (42°7' N, 119°0' E, 666 m.a.s.l.). In addition, the results of grain-size analysis of the NYZG section are given in Zeng et al. (2017). These sections are located in the southwestern part of the Chifeng area (Fig. 1c), in a landscape characterized by hills composed of bedrock and valleys mantled by eolian loess deposits. The NYZG and SBH sections consist of a brickyard exposure and an underlying excavated pit, while the TDJZ section is a natural outcrop in a loess gully. The lithology of these sections can be roughly divided into two parts: an upper part consisting mainly of light brown sandy-silt loess layers interbedded with light reddish-brown paleosols or weakly-developed paleosols; and a lower part which exhibits stronger pedogenesis, with both the colour of the loess and paleosol layers becoming progressively redder with depth and with the colour contrast between them becoming weaker (Fig. 2). In addition, the texture of the lower part becomes a more homogeneous silt.

In this study, a total of 1895 bulk samples were taken at 5-cm intervals from the SBH and TDJZ sections for grain-size measurements. In addition, 23 samples were collected from the NYZG section, 15 samples from the TDJZ section, and 6 samples from the SBH section, which were used for Nd–Sr isotopic measurements of the 28–45 µm silicate fraction; the sampling was based on the loess and paleosol unit alternations (Fig. 2). It was hoped that this sampling strategy would identify possible changes in eolian dust sources on both the glacial-interglacial scale, as well as a possible long-term source shift over the last 1.2 Ma. In addition, in order to assess possible grain-size effects on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the 28–45 µm silicate fraction, this fraction was also used for grain-size and microscopic analysis.

2.2. Extraction of silicate fractions and Nd–Sr isotopic measurements

Primary soil/paleosol particles generally occur as bonded aggregates, and organic matter and secondary carbonates are two important non-silicate types of cement that form soil aggregates. Thus, in order to obtain dispersed mineral particles, the organic matter and carbonate content of samples was removed using 10% H_2O_2 and diluted acetic acid (0.5 mol/L), respectively (Chen et al., 2007). After treatment with an ultrasonic vibrator for about 10 min to further disperse the particles, the samples were sieved to isolate the 28–45 µm grain-size fraction with MilliQ deionized-water. The samples were concentrated by centrifugation and then dried at a temperature below 40 °C.

About 100 mg of the extracted 28–45 µm silicate fraction was digested in a mixture of HNO_3 (1 ml) + HF (1 ml) in tightly sealed Teflon vials at 120 °C for 36 h. Sr and Nd elements in the resulting solution were then purified using standard ion-exchange techniques (Zhang et al., 2015). Sr was separated using Sr-Spec resin, and Nd was separated using Ln-Spec resin following the enrichment of REEs using Tru-Spec resin (Aciego et al., 2009). Sr and Nd isotopes were measured in a Thermo Fisher Scientific Neptune plus Multi-Collector Inductively Coupled Plasma Mass Spectrometer (MC-ICP-MS) at the MOE Key Laboratory of Surficial Geochemistry, Nanjing University. Instrumental bias was corrected to $^{86}\text{Sr}/^{88}\text{Sr}$ of 0.1194 and $^{146}\text{Nd}/^{144}\text{Nd}$ of 0.7219, applying an exponential mass fractionation law. The analytical blank was < 1 ng for Sr and < 60 pg for Nd. Sr standard SRM987 and Nd

standard JMCNd₂O₃ were periodically measured to check the reproducibility and accuracy of isotopic analyses, with a mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.710239 ± 4 (2σ external standard deviation, $n = 10$) and mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512100 ± 2 (2σ external standard deviation, $n = 10$). Epsilon Nd values (ϵ_{Nd}) were calculated using chondritic values of $(^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} = 0.512638$ (Jacobsen and Wasserburg, 1980) and the equation $\epsilon_{\text{Nd}} = [(^{143}\text{Nd}/^{144}\text{Nd})_{\text{sample}} / (^{143}\text{Nd}/^{144}\text{Nd})_{\text{CHUR}} - 1] \times 10,000$. BCR-2 was used as a standard material to test for possible effects of the chemical procedures. Analyses repeated 10 times yielded a mean $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.705020 ± 7 (2σ external standard deviation, $n = 10$) and a mean $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.512626 ± 22 (2σ external standard deviation, $n = 10$). Analytical results and sample information are listed in Table S1.

2.3. Grain size and microscopic analysis

Grain-size distributions were measured with a Malvern Mastersizer 2000 laser particle-size analyzer with a measurement range of 0.02–2000 µm and a relative error of < 2%. The pre-treatment procedure consisted of the removal of organic matter and carbonates by the addition of 10% H_2O_2 and 10% HCl, respectively, followed by dispersal with 10 ml of 0.05 mol/L $(\text{NaPO}_3)_6$ and treatment in an ultrasonic vibrator for 10 min (Lu and An, 1997).

The particle morphology of selected subsamples from the extracted 28–45 µm silicate fractions was observed using a Hitachi S-4800 Field Emission Scanning Electron Microscope (SEM) equipped with an EX-350 Energy Dispersive X-ray Microanalyzer (EDS), HORIBA EMAX Energy (Hitachi, Tokyo, Japan). Samples were dried at 40 °C and plated with Pt using a Hitachi E-1045 Ion Sputter prior to analysis. The SEM was operated at 3.0 kV electron accelerating voltage and images were obtained by secondary electrons in order to maximize the resolution.

2.4. Chronology of the sections

High-resolution magnetostratigraphic results suggest that the basal age of the NYZG section is ~1.02 Ma, the basal age of the SBH section is ~1.02 Ma, and the top and basal ages of the TDJZ loess sequence are ~0.63 and ~1.22 Ma, respectively (Zeng et al., 2016). The TDJZ section represents the oldest known loess deposits in NE China. The chronology of the NYZG section was reported by Zeng et al. (2017). In the present study, the chronology of the SBH and TDJZ sections were established using the same approach as for the NYZG section: the age control points were derived from the correlation of Chinese loess-paleosol sequences with the benthic $\delta^{18}\text{O}$ record (Ding et al., 1994; Lu et al., 1999; Heslop et al., 2000; Wu et al., 2005; Hao et al., 2012). The age control points the NYZG, SBH and TDJZ sections are shown in Fig. S1–S3. A grain-size sedimentation-rate age model was then used to interpolate the age at each sampling level between these age control points (Porter and An, 1995).

Fig. 3 shows that the MS time series for the three sections in NE China are consistently in-phase with the CLP records as well as with the benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005); in addition, the overall structures of the MS curves are well correlated on a glacial-interglacial timescale. This suggests that our chronology for these sections is valid on orbital timescales and that it can be used for comparison with other palaeoclimatic records.

3. Results and discussion

3.1. Constancy of the provenance of loess deposits from NE China since 1.2 Ma

A previous Nd–Sr isotopic investigation has been conducted of the < 75 µm silicate fraction of surface materials (including eolian and fluvial sand) from all the deserts in North China (Chen et al., 2007; Li et al., 2009). The results indicated that these deserts could be classified

Fig. 3. Correlation of the magnetic susceptibility (MS) records of the NYZG, SBH and TDJZ sections, plotted using a refined chronology, with the MS records of the LT and ZJC sections from the central Chinese Loess Plateau, and with the LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005). The locations of the LT and ZJC sections are shown in Fig. 1a; the chronologies of these sections was established by astronomical tuning (Sun et al., 2006). The MS features are generally consistent and in-phase on glacial-interglacial timescales. Light-green horizontal bars indicate major paleosol layers and corresponding marine isotope stages (MIS) of the LR04 benthic stack. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

into three isotopic regions (Fig. 1d, Fig. 4), which are controlled by the tectonic setting and the mountain ranges in North China (Chen et al., 2007). The regions are: (1) deserts around the northern boundary of China (NBC), which have the highest ϵ_{Nd} values and the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios; (2) deserts on the northern margin of the Tibetan Plateau (NMTP), with moderate ϵ_{Nd} values and the highest $^{87}\text{Sr}/^{86}\text{Sr}$ ratios; and (3) deserts on the Ordos Plateau (OD), with the lowest ϵ_{Nd} values and moderate $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. As shown in Fig. 4, the loess deposits (28–45- μm fraction) from the three sections in NE China have high ϵ_{Nd} values with the narrow range of -9.7 to -7.0 , which is consistent with the results of the bulk silicate fraction (Li et al., 2009). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios are relatively low, with a slightly larger range of variation (0.710–0.715) than the bulk silicate fraction (Li et al., 2009). In general, the Nd-Sr isotopic composition of our samples falls within the range of the isotope values characteristic of the NBC, which is distinctly different from that of the loess deposits of the CLP. It has been suggested that the Sr isotopic composition can be affected by the highly radiogenic $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the clay minerals (Yang et al., 2005). Thus, the Nd-Sr isotopic comparison between $< 75 \mu\text{m}$ silicate fraction of surface materials from all of the deserts in North China and the 28–45 μm fraction of loess 28–45 μm fraction from NE China could be potentially influenced by the difference of clay mineral content. However, it is noteworthy that the Nd-Sr isotopic comparison is not significantly influenced by the clay mineral content (Fig. 4). We infer that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the desert materials would have decreased after removal of the clay-sized component by the eolian sorting process, and therefore the loess samples still fall within the range of the isotopic region of the NBC. Part of the Nd-Sr isotopic distribution is located outside the range of the potential sources, possibly because of grain-size effects on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the loess samples used in this study, or because of the inadequate sample size used for classification of potential sources. Thus, the loess deposits from the three sections are

characterized by a high ϵ_{Nd} –low $^{87}\text{Sr}/^{86}\text{Sr}$ signature, indicating the dominant contribution of dust from the isotopic region of the NBC. The NBC consists of the Gurbantunggut, Hunlun Buir, Otindag, and Horqin sandy deserts, which are located in the Central Asian Orogenic Belt (CAOB), with the highest ϵ_{Nd} values resulting from the widely distributed paleo-ocean crust and basalts (Buchan et al., 2002). However, it is noteworthy that the ϵ_{Nd} values of the loess deposits in NE China are concentrated at the low-value end of the NBC distribution, and mainly fall within the range of the Otindag sandy desert (Fig. 4b). Detrital zircon U-Pb age spectra and Hf isotopic composition analysis indicated that the sand in the Otindag sandy desert was derived from both the CAOB and the mountains of the North China Craton (NCC) which have the lowest ϵ_{Nd} values (Xie et al., 2007). Thus, the ϵ_{Nd} values of sand in the Otindag and Horqin sandy desert are substantially lower than those of the Hulun Buir and Gurbantunggut sandy desert which are completely surrounded by the CAOB (Chen and Li, 2011). Therefore, it can be concluded that the loess deposits of the NYZG, SBH, and TDJZ sections are derived from the Otindag sandy desert, which is located a relatively short distance upwind. Moreover, the modern spring (March–April–May) mean 850 hPa streamlines and mean wind-speed distribution (Fig. 1b) also indicate that the prevailing wind direction in the Chifeng area is northwesterly, and that the Otindag sandy desert has one of the most vigorous wind regimes in China, which favors dust generation and transportation by spring dust storms. Thus, our results provide new evidence for the hypothesis that the Chinese loess deposits are mostly derived from the adjacent deserts on the upper wind direction with a short distance of transportation (Chen and Li, 2011).

The Nd-Sr isotopic compositions of the three sections, plotted on the refined timescale, are illustrated in Fig. 5. There is a negative correlation between ϵ_{Nd} and $^{87}\text{Sr}/^{86}\text{Sr}$ for the loess deposits of NE China; however, there is no significant correlation between variations in Nd-Sr isotopic composition and loess-paleosol alternations, which suggests

Fig. 4. (a) Comparison of the Nd-Sr isotopic composition of the NYZG, SBH and TDJZ sections with the isotopic ranges of potential sources, desert sand, loess deposits of the Chinese Loess Plateau (ZJC section) and sites from NE China analyzed in a previous study (a). NBC—deserts around the northern boundary of China; NMTP—deserts on the northern margin of the Tibetan Plateau; OD—Ordos Desert. (b) Comparison of the Nd-Sr isotopic composition of loess deposits from NE China and desert sand of the NBC (Gurbantunggut, Hunlun Buir, Otindag, and Horqin sandy deserts). The loess samples in this study are divided into two intervals based on the obvious differences of the grain-size variability before and after 700 ka, illustrated in Fig. 5. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 5. Magnetic susceptibility (MS), grain-size > 63 μm and Nd-Sr isotopic composition of the NYZG, SBH and TDJZ sections (using the refined chronology). Light-green horizontal bars indicate major paleosol layers. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that there are no significant shifts in dust source on a glacial-interglacial scale. Thus, we propose that the observed irregular fluctuations in Nd-Sr isotopic composition on the glacial-interglacial scale may reflect the heterogeneity of the source materials in the Otindag sandy desert rather than changes in dust source. In addition, the $^{87}\text{Sr}/^{86}\text{Sr}$ variability is characterized by a generally long-term decreasing trend since 1.2 Ma, with an abrupt decrease at 0.7 Ma, which is in accord with the grain-size analysis results of the loess deposits (Fig. 4b, Fig. 5). Unlike the Sr isotopes record, the ϵ_{Nd} record shows no obvious trend and abrupt decrease at 0.7 Ma (Fig. 4b, Fig. 5). It has been suggested that silicate Nd isotopes are a reliable source tracer which is little affected by grain-size sorting (Grousset and Biscaye, 2005). Thus, we raise a possibility that the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the 28–45 μm fraction might have been influenced by the grain-size sorting. This seems to be true, especially our Nd isotope results demonstrated that the dust source of the loess deposits in the Otindag sandy desert has remained constant since a least 1.2 Ma, implying that the prevailing wind direction and the tectonic-topographic pattern has remained unchanged in the Otindag sandy desert during this interval.

3.2. Possible grain-size effect on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the extracted silicate fraction

Due to the extremely high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of clay minerals (which are enriched in the $< 2 \mu\text{m}$ fraction), it has been suggested that grain-size sorting is the dominant control on the $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios of loess deposits (Yang et al., 2005). Thus, the Sr isotopic composition of bulk silicate samples is mainly controlled by the size of the $< 2 \mu\text{m}$ fraction or by the proportion of clay minerals (Chen et al., 2007). Chen and Li (2013) suggested that measuring the silicate Sr isotopic composition of the 28–45 μm fraction of loess deposits can eliminate the influence of grain-size sorting. However, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of the 28–45 μm grain-size fraction in our study indicates a grain-size effect. As illustrated in Fig. 6, the Sr isotopic composition of the 28–45 μm fraction generally tracks the variations of the clay content of the 28–45 μm fraction extracted by wet sieving, and there is a strong positive correlation between them. The grain-size distribution curves also support the occurrence of clay-sized particles in the 28–45 μm fraction, indicated by the presence of peaks at the fine end of the curves (Fig. 6e). Thus, the presence of clay minerals within the 28–45 μm fraction is the likely primary cause of the observed grain-size effect on the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. SEM observations showed that clay-sized particles were present as aggregates or adhering to the surface of quartz and/or feldspar grains (Fig. 7). We therefore propose that pretreatment using an ultrasonic vibrator alone, without chemical dispersants such as $(\text{NaPO}_3)_6$, has failed to ensure the complete dispersion of the samples, due to flocculation and adhesion of clay-sized particles. Although a few samples contained only a few clay-sized particles after wet sieving, the clay content of the extracted 28–45 μm fraction is generally positively related to the clay-sized content of the bulk samples (Fig. 6f). In addition, it is noteworthy that the clay-sized content of several samples actually increased after wet sieving. Thus, a more effective approach for extracting the 28–45 μm fraction should be developed, and caution is needed in inferring source changes of loess deposits based on the Sr isotopic composition of the 28–45 μm fraction, in the absence of Nd isotopic evidence. However, although the Sr isotopic compositions in this study are affected by grain size, the range of Sr isotopic composition has not been significantly altered, most of which still lies within the isotopic ranges of the potential sources (Fig. 4).

3.3. Stepwise expansion of the Otindag sandy desert during the MPT and linkage to the growth of high-latitude ice sheets

3.3.1. Evidence for the desert migrations from the grain-size variability

As is evident in Fig. 5, the grain size ($\% > 63 \mu\text{m}$) of the NYZG, SBH and TDJZ sections is related to their distance from the Otindag sandy

desert: The SBH section is the closest to the southeastern margin of the Otindag sandy desert, and its grain size is the coarsest; and the TDJZ and NYZG sections are located to the southeast of the SBH section, and their grain size is similar during the interval of 1.0–0.7 Ma. The grain-size variability of both the SBH and NYZG sections exhibits a long-term coarsening trend with a substantial coarsening event at 0.7 Ma. In addition, the SBH section exhibits a less substantial coarsening event at 0.9 Ma. Previous research suggested that the variation of the sand fraction ($\% > 63 \mu\text{m}$) in loess deposits near the desert margin was sensitive to the expansion and contraction of areas of mobile sand dunes in northern China (Ding et al., 2005). Since our results of Nd-Sr isotopic composition demonstrate that the dust source of the loess deposits in the study area dominantly sourced from the Otindag sandy desert and that this source remained constant for the past 1.2 Ma. (see Section 3.1, above), implying that the sand-sized fraction in the loess deposits of NE China is a useful proxy of the migration of the desert margin and of wet-dry climatic oscillations in the Otindag sandy desert (Zeng et al., 2017). The grain-size variability of the three sections indicates that the stepwise enhancement of aridification in the Otindag sandy desert since 1.2 Ma can be divided into two major intervals: Interval I: 1.2–0.7 Ma, and Interval II: 0.7–0 Ma, which are separated by a substantial drying event at 0.7 Ma. Since the SBH section is much closer to the margin of the Otindag sandy desert, its grain-size should be more sensitive to the migration of the desert margin and therefore it is more likely to have recorded the low amplitude drying event at 0.9 Ma.

3.3.2. Possible causes of the stepwise expansion of the Otindag sandy during the MPT

The marine oxygen isotope record ($\delta^{18}\text{O}$) is a proxy for changes in global ice volume (Zachos et al., 2001). Spectral analysis of the marine $\delta^{18}\text{O}$ record suggests that global ice volume dynamics underwent a fundamental change between 1.25 and 0.7 Ma, namely the mid-Pleistocene transition (MPT), during which the dominant periodicity changed from 41 kyr to 100 kyr, and enhanced significantly after 0.7 Ma (Fig. 8a) (Ruddiman et al., 1986; Clark et al., 2006; Song et al., 2014; Chalk et al., 2017; Wang et al., 2017; Sun et al., 2019). Despite certain discrepancies occur particularly within some thin loess-paleosol units before 0.7 Ma, the grain-size time series ($\% > 63 \mu\text{m}$) of the NYZG, SBH and TDJZ sections for the major units are readily matched from one section to another at their overlapping parts (Fig. 5). Thus, in order to examine periodicities in the frequency domain of the loess record in NE China, it is crucial to stack a continuous and complete grain-size record since 1.2 Ma, owing to the different age of the three sections. The composite grain-size record was obtained following the procedures by Ding et al., (2002). Notably, both the rhythms and amplitude of stacked grain-size record are almost identical to the LR04 benthic $\delta^{18}\text{O}$ stack (Fig. 8c) (Lisiecki and Raymo, 2005). The wavelet transforms of grain-size record were performed using MATLAB software package to examine the variation of frequency space (Grinsted et al., 2004). The wavelet spectra of the stacked grain-size record and the LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005) are highly coherent, both displaying a mixing of 23-, 41- and 100- kyr cycles since 1.2 Ma, and exhibiting a continuous and significant 100- kyr periodicity after ~ 0.7 Ma. Notably, both frequency variability of the two records experienced a 100-kyr lull from ~ 1.0 Ma to ~ 0.7 Ma, which is a marked feature of the MPT (Clark et al., 2006). The oxygen isotope records from Chinese caves have demonstrated that the Asian monsoon over the past 0.64 Ma exhibited its dominant periodicity in precession cycles (23- kyr), which indicates that the insolation changes caused by the Earth's precession drove the low-latitude hydrological changes (Cheng et al., 2016). Thus, the timing and duration of the MPT are similar between grain-size record of the loess deposits in NE China and benthic $\delta^{18}\text{O}$ records, same transitions in the frequency domain point to unique mechanisms governing the desert migration in NE China responses to the ice forcing in high latitude, rather than the summer monsoon influenced by the low-latitude hydrological changes.

Fig. 6. (a) Comparison of the Nd isotopic composition and the clay content (< 2 μm) present within the 28–45 μm fraction, which was extracted by wet sieving. (b) Cross-plots of Nd isotopic composition and clay content (< 2 μm) of the extracted 28–45 μm fraction. (c) Comparison of the Sr isotopic composition and the clay content (< 2 μm) present in the 28–45 μm fraction, extracted by wet sieving. (d) Cross-plots of Sr isotopic composition and the clay content (< 2 μm) of the extracted 28–45 μm fraction. (e) Logarithmic frequency curves of the grain-size distribution of the extracted 28–45 μm fraction (f) Cross-plots of clay content (< 2 μm) of the extracted 28–45 μm fraction and the clay content of bulk samples.

Numerous studies (e.g., Clark et al., 2006; Sosdian and Hodell et al., 2008; Sosdian and Rosenthal, 2009) have shown that the MPT (1.25–0.7 Ma) experienced the most significant enhancement of the global ice volume, and the maximum volume of glaciations was established at the same time as the onset of the dominant 100-kyr cyclicity after the termination of the MPT at ~ 0.7 Ma. Moreover, the ice-rafted detritus (IRD) record (Fig. 9) of the North Atlantic indicates the volume of the Laurentide ice sheet exceeded a critical threshold with onset of the Heinrich events during MIS 16 (~ 0.64 Ma) (Hodell et al., 2008). Thus, the oldest loess deposits in NE China dated at ca. 1.22 Ma based on magnetostratigraphy of the TDJZ section was roughly coincident with the beginning of the MPT which corresponds to the onset of aridification in this region (Zeng et al., 2016), and the substantial drying event at 0.7 Ma of the NYZG and SBH section was synchronous

with end of the MPT (Fig. 5). In addition to the two major events of 1.25 Ma and 0.7 Ma, some paleoclimatic records suggest that 0.9 Ma within the MPT marked a major climatic event. The benthic $\delta^{18}\text{O}$ records (e.g., ODP 1123) of the Pacific indicate that the maximum ice sheet extent was established during MIS 22 (~ 0.9 Ma) (Fig. 9), which was mainly related to an abrupt increase in the extent of the Antarctic ice sheet (Elderfield et al., 2012). In addition, MIS 24–22 are characterized by an extreme cooling event in most SST records (McClymont et al., 2013). Thus, the low amplitude drying event of the SBH section at 0.9 Ma was well coincident with the abrupt increase in the Antarctic ice sheet during MIS 22. Moreover, it is noteworthy that the grain-size record of the loess deposits in NE China generally exhibits a drying trend during MPT, which coincided with increased ice volume in the benthic $\delta^{18}\text{O}$ record (Fig. 9). Thus, the abrupt drying events and drying

Fig. 7. Scanning Electron Microscope (SEM) images showing aggregations of clay-sized particles (a, b) and clay-sized particles adhering to the surface of quartz or feldspar grains (c, d) of the extracted 28–45 μm fraction. The sample names denote the sampling depth of the sections (in cm).

Fig. 8. Wavelet power spectra (Grinsted et al., 2004). (a) LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005); (b) stacked grain-size record of the loess deposits in NE China; (c) time series of the two signals (each normalized to the interval of [0 1]) over the past 1.2 Ma. The thick black contour designates the 5% significance level against red noise, and the cones of influence (COI) that are influenced by edge effects are shown as lighter shading at the beginning and end of the frequency-time plane. The grain-size records of the NYZG, SBH and TDJZ sections were stacked according to the procedures of Ding et al. (2002). The black dashed line indicates the onset of dominant 100-kyr cycles at 0.7 Ma. MPT: mid-Pleistocene transition (1.25–0.7 Ma). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Fig. 9. Comparison of grain-size records from loess deposits in NE China with other loess records of the Jingbian section (Ding et al., 2005), Fanshan section (Xiong et al., 2001), Shagou section (Wu et al., 2005), Hetian section (Zan et al., 2013), and Chashmanigar section (Ding et al., 2002). Also shown are the LR04 benthic $\delta^{18}\text{O}$ stack (Lisiecki and Raymo, 2005), the ice-rafted debris (IRD) record from IODP Site 303-U1308 in the North Atlantic (Hodell et al., 2008) and the ODP 1123 benthic $\delta^{18}\text{O}$ record in the Pacific (Elderfield et al., 2012). All records are shown on their published age models, except for the Fanshan section which was refined by Zeng et al. (2017). Blue (green) shaded bars indicate the abrupt drying event occurred at 900 ka (700 ka). The red arrow indicates an increased drying trend in NE China during MPT (1.25–0.7 Ma). The dashed lines in the records of LR04 and ODP1123 indicate the significant enhancement of the global ice volume at ~0.9 Ma and ~0.7 Ma, respectively. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

trend recorded in the loess deposits of NE China are both well correlated with the increase in high-latitude ice volume during the MPT (Fig. 9), which is consistent with the hypothesis that cooling and ice volume expansion at high latitudes was the driver of long-term stepwise aridification of the Asian interior during the late Cenozoic (Ding et al., 2005; Lu et al., 2010; Lu and Guo, 2014; Zeng et al., 2017). The numerical simulations have provided insight into the forcing mechanism of the enhanced aridity in Northern China linkage to the growth of high-latitude ice sheets. The latest experiments using the Community Atmosphere Model version (CAM4) have confirmed that global cooling and ice sheet expansion can reduce annual precipitation in Northern China, resulting in enhanced aridity (Zhang et al., 2017). More specifically, the expansion of North American and European ice sheets can change the existing trough and ridge system in the Northern Hemisphere, leading to anomalous cyclone to the south of the European ice sheet in winter, which could result in strengthened westerly and northwesterly winds over inland China in winter (Zhang et al., 2017). As a result, the aridification and stronger winds could cause the large-scale expansion of desert and eventually entrain more and coarser dust particles which were deposited downwind (Ding et al., 2005; Lu et al., 2010; Zeng et al., 2017).

In summary, the large expansion of the Eurasian loess belt at ~1.2 Ma coincided with the beginning of the MPT (Zeng et al., 2017), during which global cooling and the growth of high-latitude ice sheets may have caused the aridification of the Asian interior to exceed a critical threshold, and promoted the extension of the desert belt to NE China. Thus, the Otindag sandy desert probably formed during this interval, leading eventually to loess accumulation downwind. The extreme cold event at ~0.9 Ma within the MPT caused the abrupt coarsening of the grain size evident in the SBH section, and the concurrent formation of ‘sandy loess’ marker bed L9 in the loess deposits of the CLP (Kukla and An, 1989). After the maximum volume of glaciations was established at ~0.7 Ma, loess layers L6–L1 of the SBH and NYZG sections in NE China, corresponding to the last six glacial-interglacial cycles, generally have a coarser grain-size during glacials; this phenomenon is also evident in loess sections located near deserts (Fig. 9), such as the Jingbian section in the northern CLP (Ding et al., 2005), Fanshan section near Beijing (Xiong et al., 2001), Shagou section on the northern slopes of the Qilian Mountains (Wu et al., 2005), Hetian section on the

northern slopes of the West Kunlun Mountains (Zan et al., 2013), and Chashmanigar section in Tajikistan (Ding et al., 2002). In conclusion, the grain-size characteristics of the loess sections in NE China, and of other sections from the Eurasian loess belt, indicate that global cooling, the growth of high-latitude ice sheets, and prolonged glacials strongly affected the aridification process of the Asian interior since the MPT.

4. Conclusions

- (1) The silicate Nd and Sr isotopic composition of the 28–45 μm grain-size fraction of the NYZG, TDJZ and SBH loess sections in NE China reveals that the sediments are derived directly from the Otindag sandy desert located a short distance upwind. In addition, the source of the loess deposits in NE China has remained constant since 1.2 Ma, and the prevailing wind direction and the tectonic-topographic configuration of the Otindag sandy desert during the past 1.2 Ma were unchanged.
- (2) Unexpectedly, the $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the 28–45 μm fraction are influenced by a grain-size effect, and clay particles present as aggregates or adhering to the surface of larger particles are likely the main cause. This finding shows that caution is needed when using $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of the 28–45 μm fraction to trace the source of loess deposits.
- (3) The grain-size records of the three loess sections in NE China reveal the stepwise enhancement of aridification in the Otindag sandy desert at 1.2 Ma, 0.9 Ma, and 0.7 Ma. The drying trend and abrupt drying events recorded in the loess deposits of NE China are strikingly correlated to high-latitude ice volume increases during the MPT, which supports the hypothesis that cooling and ice volume expansion in high latitudes during the late Cenozoic were the major drivers of the long-term stepwise aridification of the Asian interior. The stepwise expansion of the Otindag sandy desert at ~1.2 Ma, 0.9 Ma and 0.7 Ma coincided with the beginning of the MPT, an extremely cold event at ~0.9 Ma within the MPT, and the establishment of a full glacial climate at the termination of the MPT.

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.gloplacha.2019.103087>.

Declaration of Competing Interest

The authors declared that they have no conflicts of interest to this work.

Acknowledgments

We sincerely appreciate the constructive comments and suggestions from two anonymous reviewers that have greatly improved the manuscript. We thank Zhimin Qiu, Zhiwei Xu, Haixin Zhuo, Wenchao Zhang, Kaifeng Yu, Zhimin Jiao, Tao Li, Yang Yang, Qian Zhou, Yuan Li and Chuancheng Fu for their help with field sampling and with the laboratory measurements. Xianyan Wang, Xiaoyong Wang, Xuefeng Sun and Hongyan Zhang provided helpful advice. This work was funded by the National Natural Science Foundation of China (grants 41807418, 41877451, 41690111), the Global Change Program of Ministry of Science and Technology of China (grant 2016YFA0600503), the National Science Foundation of China-Shandong United fund (grant U1706220), Shandong Key Laboratory of Coastal Environmental Processes, YICCAS (grant 2019SDHADKFJJ13).

References

- Aciego, S.M., Bourdon, B., Lupker, M., Rickli, J., 2009. A new procedure for separating and measuring radiogenic isotopes (U, Th, Pa, Ra, Sr, Nd, Hf) in ice cores. *Chem. Geol.* 266, 194–204. <https://doi.org/10.1016/j.chemgeo.2009.06.003>.
- An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. *Quat. Sci. Rev.* 19, 171–187. [https://doi.org/10.1016/S0277-3791\(99\)00060-8](https://doi.org/10.1016/S0277-3791(99)00060-8).
- An, Z.S., Liu, T.S., Lu, Y.C., Porter, S., Kukla, G., Wu, X.H., Hua, Y.M., 1990. The long-term paleomonsoon variation recorded by the loess-paleosol sequence in Central China. *Quat. Int.* 7/8, 91–95. [https://doi.org/10.1016/1040-6182\(90\)90042-3](https://doi.org/10.1016/1040-6182(90)90042-3).
- An, Z.S., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalayan Tibetan plateau since late Miocene times. *Nature* 411, 62–66.
- An, Z., Wu, G., Li, J., Sun, Y., Liu, Y., Zhou, W., Cai, Y., Duan, A., Li, L., Mao, J., Cheng, H., Shi, Z., Tan, L., Yan, H., Ao, H., Chang, H., Feng, J., 2013. Global monsoon dynamics and climate change. *Annu. Rev. Earth Pl. Sc.* 43, 1–49.
- Ben-Israel, M., Enzel, Y., Amit, R., Erel, Y., 2015. Provenance of the various grain-size fractions in the negev loess and potential changes in major dust sources to the Eastern Mediterranean. *Quat. Res.* 83, 105–115. <https://doi.org/10.1016/j.yqres.2014.08.001>.
- Buchan, C., Pfänder, J., Kröner, A., Brewer, T.S., Tomurtogoo, O., Tomurhuu, D., Cunningham, D., Windley, B.F., 2002. Timing of accretion and collisional deformation in the Central Asian orogenic belt: implications of granite geochronology in the Bayankhongor Ophiolite Zone. *Chem. Geol.* 192, 23–45. [https://doi.org/10.1016/S0009-2541\(02\)00138-9](https://doi.org/10.1016/S0009-2541(02)00138-9).
- Chalk, T.B., Hain, M.P., Foster, G.L., Rohling, E.J., Sexton, P.F., Badger, M.P.S., Cherry, S.G., Hasenfratz, A.P., Haug, G.H., Jaccard, S.L., Martínez-García, A., Pälike, H., Pancost, R.D., Wilson, P.A., 2017. Causes of ice age intensification across the Mid-Pleistocene transition. *P. Natl. Acad. Sci.* 114, 13114–13119. <https://doi.org/10.1073/pnas.1702143114>.
- Che, X.D., Li, G.J., 2013. Binary sources of loess on the Chinese Loess Plateau revealed by U-Pb ages of zircon. *Quat. Res.* 80, 545–551. <https://doi.org/10.1016/j.yqres.2013.05.007>.
- Chen, J., Li, G., 2011. Geochemical studies on the source region of Asian dust. *Sci. China Earth Sci.* 54, 1279–1301.
- Chen, Z., Li, G.J., 2013. Evolving sources of eolian detritus on the Chinese Loess Plateau since early Miocene: tectonic and climatic controls. *Earth Planet. Sc. Lett.* 371, 220–225. <https://doi.org/10.1016/j.epsl.2013.03.044>.
- Chen, J., Li, G.J., Yang, J.D., Rao, W.B., Lu, H.Y., Balsam, W., Sun, Y.B., Ji, J.F., 2007. Nd and Sr isotopic characteristics of Chinese deserts: implications for the provenances of Asian dust. *Geochim. Cosmochim. Ac.* 71, 3904–3914. <https://doi.org/10.1016/j.gca.2007.04.033>.
- Cheng, H., Edwards, R.L., Sinha, A., Spötl, C., Yi, L., Chen, S., Kelly, M., Kathayat, G., Wang, X., Li, X., Kong, X., Wang, Y., Ning, Y., Zhang, H., 2016. The Asian monsoon over the past 640,000 years and ice age terminations. *Nature* 534, 640–646. <https://doi.org/10.1038/nature18591>.
- Clark, P.U., Archer, D., Pollard, D., Blum, J.D., Rial, J.A., Brovkin, V., Mix, A.C., Pisias, N.G., Roy, M., 2006. The middle Pleistocene transition: characteristics, mechanisms, and implications for long-term changes in atmospheric pCO₂. *Quat. Sci. Rev.* 25, 3150–3184. <https://doi.org/10.1016/j.quascirev.2006.07.008>.
- Da, J., Zhang, Y.G., Wang, H., Balsam, W., Ji, J., 2015. An early Pleistocene atmospheric CO₂ record based on pedogenic carbonate from the Chinese loess deposits. *Earth Planet. Sc. Lett.* 426, 69–75. <https://doi.org/10.1016/j.epsl.2015.05.053>.
- Ding, Z.L., Yu, Z., Rutter, N.W., Liu, T.S., 1994. Towards an orbital time-scale for Chinese Loess deposits. *Quat. Sci. Rev.* 13, 39–70. [https://doi.org/10.1016/0277-3791\(94\)90124-4](https://doi.org/10.1016/0277-3791(94)90124-4).
- Ding, Z.L., Liu, T.S., Rutter, N.W., Yu, Z.W., Guo, Z.T., Zhu, R.X., 1995. Ice-volume forcing of east-asian winter monsoon variations in the past 800,000 years. *Quat. Res.* 44, 149–159. <https://doi.org/10.1006/qres.1995.1059>.
- Ding, Z.L., Ranov, V., Yang, S.L., Finaev, A., Han, J.M., Wang, G.A., 2002. The loess record in southern Tajikistan and correlation with Chinese loess. *Earth Planet. Sci. Lett.* 200, 387–400. [https://doi.org/10.1016/S0012-821X\(02\)00637-4](https://doi.org/10.1016/S0012-821X(02)00637-4).
- Ding, Z.L., Derbyshire, E., Yang, S.L., Yu, Z.W., Liu, T.S., 2005. Stepwise expansion of desert environment across northern China in the past 3.5 Ma and implications for monsoon evolution. *Earth Planet. Sci. Lett.* 237, 45–55. <https://doi.org/10.1016/j.epsl.2005.06.036>.
- Elderfield, H., Ferretti, P., Greaves, M., Crowhurst, S., McCave, I.N., Hodel, D., Piotrowski, A.M., 2012. Evolution of ocean temperature and ice volume through the Mid-Pleistocene climate transition. *Science* 337, 704–709. <https://doi.org/10.1126/science.1221294>.
- Fang, X., Fang, Y., Zan, J., Zhang, W., Song, C., Appel, E., Meng, Q., Miao, Y., Dai, S., Lu, Y., Zhang, T., 2019. Cenozoic magnetostratigraphy of the Xining Basin, NE Tibetan Plateau, and its constraints on paleontological, sedimentological and tectonomorphological evolution. *Earth-Sci. Rev.* 190, 460–485. <https://doi.org/10.1016/j.earscirev.2019.01.021>.
- Grinsted, A., Moor, J.C., Jevrejeva, S., 2004. Application of the cross wavelet transform and wavelet coherence to geophysical time series. *Nonlinear Process. Geophys.* 11, 561–566. <https://doi.org/10.5194/npg-11-561-2004>.
- Grousset, F.E., Biscaye, P.E., 2005. Tracing dust sources and transport patterns using Sr, Nd and Pb isotopes. *Chem. Geol.* 222, 149–167. <https://doi.org/10.1016/j.chemgeo.2005.05.006>.
- Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. *Nature* 416, 159–163.
- Hao, Q., Guo, Z., Qiao, Y., Xu, B., Oldfield, F., 2010. Geochemical evidence for the provenance of middle Pleistocene loess deposits in southern China. *Quat. Sci. Rev.* 29, 3317–3326. <https://doi.org/10.1016/j.quascirev.2010.08.004>.
- Hao, Q.Z., Wang, L., Oldfield, F., Peng, S.Z., Qin, L., Song, Y., Xu, B., Qiao, Y.S., Bloemendal, J., Guo, Z.T., 2012. Delayed build-up of Arctic ice sheets during 400,000-year minima in insolation variability. *Nature* 490, 393–396.
- Heslop, D., Langereis, C.G., Dekkers, M.J., 2000. A new astronomical timescale for the loess deposits of Northern China. *Earth Planet. Sci. Lett.* 184, 125–139. [https://doi.org/10.1016/S0012-821X\(00\)00324-1](https://doi.org/10.1016/S0012-821X(00)00324-1).
- Hodell, D.A., Channell, J.E., Curtis, J.H., Romero, O.E., Röhl, U., 2008. Onset of "Hudson Strait" Heinrich events in the eastern North Atlantic at the end of the middle Pleistocene transition (~640 ka)? *Paleoceanography* 23. <https://doi.org/10.1029/2008PA001591>. PA4218.
- Jacobsen, S.B., Wasserburg, G.J., 1980. Sm-Nd isotopic evolution of chondrites. *Earth Planet. Sc. Lett.* 50, 139–155. [https://doi.org/10.1016/0012-821X\(80\)90125-9](https://doi.org/10.1016/0012-821X(80)90125-9).
- Kukla, G., An, Z.S., 1989. Loess stratigraphy in Central China. *Palaeogeogr. Palaeoclimatol.* 72, 203–225. [https://doi.org/10.1016/0277-3791\(87\)90004-7](https://doi.org/10.1016/0277-3791(87)90004-7).
- Kumar, A., Abouchami, W., Galer, S.J.G., Singh, S.P., Fomfo, K.W., Prospero, J.M., Andreae, M.O., 2018. Seasonal radiogenic isotopic variability of the African dust outflow to the tropical Atlantic Ocean and across to the Caribbean. *Earth Planet. Sc. Lett.* 487, 94–105. <https://doi.org/10.1016/j.epsl.2018.01.025>.
- Li, J.J., Fang, X.M., 1999. Uplift of the Tibetan Plateau and environmental changes. *Chin. Sci. Bull.* 44, 2117–2124. <https://doi.org/10.1007/BF03182692>.
- Li, G., Chen, J., Ji, J., Yang, J., Conway, T.M., 2009. Natural and anthropogenic sources of East Asian dust. *Geology* 37, 727. <https://doi.org/10.1130/G30031A.1>.
- Li, T., Liu, F., Abels, H.A., You, C., Zhang, Z., Chen, J., Ji, J., Li, L., Li, L., Liu, H., Ren, C., Xia, R., Zhao, L., Zhang, W., Li, G., 2017. Continued obliquity pacing of East Asian summer precipitation after the mid-Pleistocene transition. *Earth Planet. Sc. Lett.* 457, 181–190. <https://doi.org/10.1016/j.epsl.2016.09.045>.
- Li, J.X., Yue, L.P., Roberts, A.P., Hirt, A.M., Pan, F., Guo, L., Xu, Y., Xi, R.G., Guo, L., Qiang, X.K., Gai, C.C., Jiang, Z.X., Sun, Z.M., Liu, Q.S., 2018. Global cooling and enhanced Eocene Asian mid-latitude interior aridity. *Nat. Commun.* 9. <https://doi.org/10.1038/s41467-018-05415-x>.
- Licht, A., van Cappelle, M., Abels, H.A., Ladant, J.B., Trabucho-Alexandre, J., France-Lanord, C., Donnadieu, Y., Vandenbergh, J., Rigaudier, T., Lécuyer, C., Terry Jr., D., Adriaens, R., Boura, A., Guo, Z., Soe, A.N., Quade, J., Dupont-Nivet, G., Jaeger, J.J., 2014. Asian monsoons in a late Eocene greenhouse world. *Nature* 513, 501–506.
- Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ¹⁸O records. *Paleoceanography* 20. <https://doi.org/10.1029/2004PA001071>. PA1003.
- Liu, T.S., 1985. *Loess and the Environment*. China Ocean Press, Beijing.
- Liu, T.S., Ding, Z.L., 1998. Chinese loess and the paleomonsoon. *Annu. Rev. Earth Pl. Sc.* 26, 111–145.
- Lu, H.Y., An, Z.S., 1997. Pretreated methods on loess-paleosol samples granulometry. *Chin. Sci. Bull.* 43, 237–240.
- Lu, H.Y., Guo, Z.T., 2014. Evolution of the monsoon and dry climate in East Asia during late Cenozoic: a review. *Sci. China Earth Sci.* 57, 70–79.
- Lu, H., Liu, X., Zhang, F., An, Z., Dodson, J., 1999. Astronomical calibration of loess-paleosol deposits at Luochuan, central Chinese Loess Plateau. *Palaeogeogr. Palaeoclimatol.* 154, 237–246. [https://doi.org/10.1016/S0031-0182\(99\)00113-3](https://doi.org/10.1016/S0031-0182(99)00113-3).
- Lu, H., Wang, X., An, Z., Miao, X., Zhu, R., Ma, H., Li, Z., Tan, H., Wang, X., 2004. Geomorphologic evidence of phased uplift of the northeastern Qinghai-Tibet Plateau since 14 million years ago. *Sci. China Ser. D* 47, 822. <https://doi.org/10.1360/03yd0315>.
- Lu, H., Wang, X., Li, L., 2010. Aeolian sediment evidence that global cooling has driven late Cenozoic stepwise aridification in Central Asia. *Geol. Soc. Lond., Spec. Publ.* 342, 29–44. <https://doi.org/10.1144/SP342.4>.
- Lu, H., Wang, X., Wang, X., Chang, X., Zhang, H., Xu, Z., Zhang, W., Wei, H., Zhang, X., Yi, S., Zhang, W., Feng, H., Wang, Y., Wang, Y., Han, Z., 2019. Formation and evolution of Gobi Desert in central and eastern Asia. *Earth-Sci. Rev.* 194, 251–263. <https://doi.org/10.1016/j.earscirev.2019.01.021>.

- org/10.1016/j.earscirev.2019.04.014.
- McClymont, E.L., Soudan, S.M., Rosell-Melé, A., Rosenthal, Y., 2013. Pleistocene Sea-surface temperature evolution: early cooling, delayed glacial intensification, and implications for the mid-Pleistocene climate transition. *Earth-Sci. Rev.* 123, 173–193. <https://doi.org/10.1016/j.earscirev.2013.04.006>.
- Meng, X., Liu, L., Wang, X.T., Balsam, W., Chen, J., Ji, J., 2018. Mineralogical evidence of reduced East Asian summer monsoon rainfall on the Chinese loess plateau during the early Pleistocene interglacials. *Earth Planet. Sc. Lett.* 486, 61–69. <https://doi.org/10.1016/j.epsl.2017.12.048>.
- Muhs, D.R., 2013. The geologic records of dust in the quaternary. *Aeolian Res.* 9, 3–48. <https://doi.org/10.1016/j.aeolia.2012.08.001>.
- Nie, J., Peng, W., Möller, A., Song, Y., Stockli, D.F., Stevens, T., Horton, B.K., Liu, S., Bird, A., Oalman, J., Gong, H., Fang, X., 2014. Provenance of the upper Miocene–Pliocene red clay deposits of the Chinese loess plateau. *Earth Planet. Sc. Lett.* 407, 35–47. <https://doi.org/10.1016/j.epsl.2014.09.026>.
- Nie, J., Stevens, T., Rittner, M., Stockli, D., Garzanti, E., Limonta, M., Bird, A., Ando, S., Vermeesch, P., Saylor, J., Lu, H., Brecker, D., Hu, X., Liu, S., Resentini, A., Vezzoli, G., Peng, W., Carter, A., Ji, S., Pan, B., 2015. Loess Plateau storage of Northeastern Tibetan Plateau-derived Yellow River sediment. *Nat. Commun.* 6, 8511. <https://doi.org/10.1038/ncomms9511>.
- Peng, S., Hao, Q., Wang, L., Ding, M., Zhang, W., Wang, Y., Guo, Z., 2016. Geochemical and grain-size evidence for the provenance of loess deposits in the Central Shandong Mountains region, northern China. *Quat. Res.* 85, 290–298. <https://doi.org/10.1016/j.yqres.2016.01.005>.
- Porter, S.C., An, Z.S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation. *Nature* 375, 305–308.
- Pye, K., 1995. The nature, origin and accumulation of loess. *Quat. Sci. Rev.* 14, 653–667. [https://doi.org/10.1016/0277-3791\(95\)00047-X](https://doi.org/10.1016/0277-3791(95)00047-X).
- Qiang, X., An, Z., Song, Y., Chang, H., Sun, Y., Liu, W., Ao, H., Dong, J., Fu, C., Wu, F., Lu, F., Cai, Y., Zhou, W., Cao, J., Xu, X., Ai, L., 2011. New eolian red clay sequence on the western Chinese Loess Plateau linked to onset of Asian desertification about 25 Ma ago. *Sci. China Earth Sci.* 54, 136–144.
- Rao, W., Chen, J., Tan, H., Jiang, S., Su, J., 2011. Sr–Nd isotopic and REE geochemical constraints on the provenance of fine-grained sands in the Ordos deserts, North-Central China. *Geomorphology* 132 (3–4), 123–138. <https://doi.org/10.1016/j.geomorph.2011.05.003>.
- Rao, W., Chen, J., Tan, H., Weise, S.M., Wang, Y., 2014. Nd–Sr isotopic and REE geochemical compositions of late Quaternary deposits in the desert-loess transition, north-central China: Implications for their provenance and past wind systems. *Quat. Int.* 334–335, 197–212. <https://doi.org/10.1016/j.quaint.2013.06.009>.
- Rao, W., Tan, H., Chen, J., Ji, J., Chen, Y., Pan, Y., Zhang, W., 2015. Nd–Sr isotope geochemistry of fine-grained sands in the basin-type deserts, West China: Implications for the source mechanism and atmospheric transport. *Geomorphology* 246, 458–471. <https://doi.org/10.1016/j.geomorph.2015.06.043>.
- Rex, R.W., Syers, J.K., Jackson, M.L., Clayton, R.N., 1969. Eolian origin of quartz in soils of Hawaiian islands and in Pacific pelagic sediments. *Science* 163, 277–279. <https://doi.org/10.1126/science.163.3864.277>.
- Ruddiman, W.F., Raymo, M., McIntyre, A., 1986. Matuyama 41,000-year cycles: North Atlantic Ocean and northern hemisphere ice sheets. *Earth Planet. Sc. Lett.* 80, 117–129. [https://doi.org/10.1016/0012-821X\(86\)90024-5](https://doi.org/10.1016/0012-821X(86)90024-5).
- Song, Y.G., Fang, X.M., King, J.W., Li, J.J., Naoto, I., An, Z.S., 2014. Magnetic parameter variations in the Chaona loess/paleosol sequences in the central Chinese Loess Plateau, and their significance for the middle Pleistocene climate transition. *Quat. Res.* 81, 433–444. <https://doi.org/10.1016/j.yqres.2013.10.002>.
- Soudan, S., Rosenthal, Y., 2009. Deep-sea temperature and ice volume changes across the Pliocene–Pleistocene climate transitions. *Science* 325, 306–310. <https://doi.org/10.1126/science.1169938>.
- Stevens, T., Palk, C., Carter, A., Lu, H.Y., Clift, P.D., 2010. Assessing the provenance of loess and desert sediments in northern China using U–Pb dating and morphology of detrital zircons. *Geol. Soc. Am. Bull.* 122, 1331–1344. <https://doi.org/10.1130/B30102.1>.
- Stevens, T., Carter, A., Watson, T.P., Vermeesch, P., Ando, S., Bird, A.F., Lu, H., Garzanti, E., Cottam, M.A., Sevastjanova, I., 2013. Genetic linkage between the Yellow River, the Mu Us desert and the Chinese Loess Plateau. *Quat. Sci. Rev.* 78, 355–368. <https://doi.org/10.1016/j.quascirev.2012.11.032>.
- Sun, J., 2005. Nd and Sr isotopic variations in Chinese eolian deposits during the past 8 Ma: implications for provenance change. *Earth Planet. Sc. Lett.* 240, 454–466. <https://doi.org/10.1016/j.epsl.2005.09.019>.
- Sun, Y., Clemens, S.C., An, Z., Yu, Z., 2006. Astronomical timescale and palaeoclimatic implication of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau. *Quat. Sci. Rev.* 25, 33–48. <https://doi.org/10.1016/j.quascirev.2005.07.005>.
- Sun, Y., Yin, Q., Crucifix, M., Clemens, S.C., Araya-Melo, P., Liu, W., Qiang, X., Liu, Q., Zhao, H., Liang, L., Chen, H., Li, Y., Zhang, L., Dong, G., Li, M., Zhou, W., Berger, A., An, Z., 2019. Diverse manifestations of the mid-Pleistocene climate transition. *Nat. Commun.* 10, 352. <https://doi.org/10.1038/s41467-018-08257-9>.
- van der Does, M., Pourmand, A., Sharifi, A., Stuut, J.W., 2018. North African mineral dust across the tropical Atlantic Ocean: Insights from dust particle size, radiogenic Sr–Nd–Hf isotopes and rare earth elements (REE). *Aeolian Res.* 33, 106–116. <https://doi.org/10.1016/j.aeolia.2018.06.001>.
- Wang, P.X., Wang, B., Cheng, H., Fasullo, J., Guo, Z.T., Kiefer, T., Liu, Z.Y., 2014. The global monsoon across timescales: coherent variability of regional monsoons. *Clim. Past* 10, 2007–2052. <https://doi.org/10.5194/cp-10-2007-2014>.
- Wang, T., Sun, Y., Liu, X., 2017. Mid-Pleistocene climate transition: Characteristic, mechanism and perspective. *Chin. Sci. Bull.* 62, 3861–3872. (in Chinese with English abstract). <https://doi.org/10.1360/N972017-00427>.
- Wu, G., Pan, B., Guan, Q., Xia, D., 2005. Terminations and their correlation with solar insolation in the Northern Hemisphere: a record from a loess section in Northwest China. *Palaeogeogr. Palaeoclimatol.* 216, 267–277. <https://doi.org/10.1016/j.palaeo.2004.11.004>.
- Xie, J., Wu, F.Y., Ding, Z.L., 2007. Detrital zircon composition of U–Pb and Hf isotope of the Hunshandake sandland and implications for its provenance. *Acta Petrol. Sin.* 23, 523–528 (in Chinese with English abstract).
- Xie, J., Yang, S., Ding, Z., 2012. Methods and application of using detrital zircons to trace the provenance of loess. *Sci. China Earth Sci.* 55, 1837–1846.
- Xiong, S., Ding, Z., Liu, T., 2001. Climatic implications of loess deposits from the Beijing region. *J. Quat. Sci.* 16, 575–582. <https://doi.org/10.1002/jqs.618>.
- Yan, Y., Sun, Y., Chen, H., Ma, L., 2014. Oxygen isotope signatures of quartz from major Asian dust sources: Implications for changes in the provenance of Chinese loess. *Geochim. Cosmochim. Acta* 139, 399–410. <https://doi.org/10.1016/j.gca.2014.04.043>.
- Yang, J.D., Chen, J., Zhang, J.X., 2005. Variations in $^{87}\text{Sr}/^{86}\text{Sr}$ of the Huanxian profile, Loess Plateau of China from 40 ka B.P. to 10 ka B.P. and Heinrich events. *Geochim. J.* 39, 165–171. <https://doi.org/10.2343/geochimj.39.165>.
- Yang, S., Ding, Z., Li, Y., Wang, X., Jiang, W., Huang, X., 2015. Warming-induced northward migration of the East Asian monsoon rain belt from the last Glacial Maximum to the mid-Holocene. *P. Natl. Acad. Sci. USA* 112, 13178–13183. <https://doi.org/10.1073/pnas.1504688112>.
- Yang, Y., Mason, J.A., Zhang, H., Lu, H., Ji, J., Chen, J., Liu, L., 2017. Provenance of loess in the central Great Plains, U.S.A. based on Nd–Sr isotopic composition, and paleoenvironmental implications. *Quat. Sci. Rev.* 173, 114–123. <https://doi.org/10.1016/j.quascirev.2017.08.009>.
- Yi, S., Buylaert, J., Murray, A.S., Thiel, C., Zeng, L., Lu, H., 2015. High resolution OSL and post-IR IRSL dating of the last interglacial-glacial cycle at the Sanbahu loess site (northeastern China). *Quat. Geochronol.* 30, 200–206. <https://doi.org/10.1016/j.quageo.2015.02.013>.
- Yi, S., Buylaert, J., Murray, A.S., Lu, H., Thiel, C., Zeng, L., 2016. A detailed post-IR IRSL dating study of the Niuyangzigou loess site in northeastern China. *Boreas* 41, 435–451. <https://doi.org/10.1111/bor.12185>.
- Zachos, J., Pagani, M., Sloan, L., Thomas, E., Billups, K., 2001. Trends, rhythms, and aberrations in global climate 65 Ma to present. *Science* 292, 686–693. <https://doi.org/10.1126/science.1059412>.
- Zan, J., Fang, X., Yang, S., Yan, M., 2013. Evolution of the arid climate in High Asia since ~1 Ma: evidence from loess deposits on the surface and rims of the Tibetan Plateau. *Quat. Int.* 313, 210–217. <https://doi.org/10.1016/j.quaint.2013.03.012>.
- Zeng, L., Lu, H.Y., Yi, S.W., Xu, Z.W., Qiu, Z.M., Yang, Z.Y., Li, Y.X., 2011. Magnetostratigraphy of loess in northeastern China and paleoclimatic changes. *Chinese Sci. Bull. (Chinese Version)* 56, 2267–2275. (in Chinese with English abstract). <https://doi.org/10.1360/972011-311>.
- Zeng, L., Lu, H., Yi, S., Li, Y., Lv, A., Zhang, W., Xu, Z., Wu, H., Feng, H., Cui, M., 2016. New magnetostratigraphic and pedostratigraphic investigations of loess deposits in north-east China and their implications for regional environmental change during the Mid-Pleistocene climatic transition. *J. Quat. Sci.* 31, 20–32. <https://doi.org/10.1002/jqs.2829>.
- Zeng, L., Lu, H., Yi, S., Stevens, T., Xu, Z., Zhuo, H., Yu, K., Zhang, H., 2017. Long-term Pleistocene aridification and possible linkage to high-latitude forcing: new evidence from grain size and magnetic susceptibility proxies from loess-paleosol record in northeastern China. *Catena* 154, 21–32. <https://doi.org/10.1016/j.catena.2017.02.020>.
- Zhang, W., Chen, J., Li, G., 2015. Shifting material source of Chinese loess since ~2.7 Ma reflected by Sr isotopic composition. *Sci. Rep.-UK* 5, 10235. [https://doi.org/10.1016/S0277-3791\(99\)00060-8](https://doi.org/10.1016/S0277-3791(99)00060-8).
- Zhang, H., Lu, H., Xu, X., Liu, X., Yang, T., Stevens, T., Bird, A., Xu, Z., Zhang, T., Lei, F., Feng, H., 2016. Quantitative estimation of the contribution of dust sources to Chinese loess using detrital zircon U–Pb age patterns. *J. Geophys. Res.* -Earth 121, 2085–2099. <https://doi.org/10.1002/2016JF003936>.
- Zhang, Z., Yan, Q., Zhang, R., Li, X., Dai, G., Leng, S., Tian, Y., 2017. Teleconnection between northern hemisphere ice sheets and East Asian climate during quaternary. *Quat. Sci.* 37 (in Chinese with English abstract), 1009–1016. <https://doi.org/10.11928/j.issn.1001-7410.2017.05.08>.
- Zhao, W., Sun, Y., Balsam, W., Lu, H., Liu, L., Che, J., Ji, J., 2014. Hf–Nd isotopic variability in mineral dust from Chinese and Mongolian deserts: implications for sources and dispersal. *Sci. Rep.-UK* 4, 5837. <https://doi.org/10.1038/srep05837>.
- Zhao, W., Sun, Y., Balsam, W., Zeng, L., Lu, H., Otgonbayar, K., Ji, J., 2015. Clay-sized Hf–Nd–Sr isotopic composition of Mongolian dust as a fingerprint for regional to hemispherical transport. *Geophys. Res. Lett.* 42, 5661–5669. <https://doi.org/10.1002/2015GL064357>.
- Zhou, B., Shen, C., Sun, W., Bird, M., Ma, W., Taylor, D., Liu, W., Peterse, F., Yi, W., Zheng, H., 2014. Late Pliocene–Pleistocene expansion of C4 vegetation in semiarid East Asia linked to increased burning. *Geology* 42, 1067–1070. <https://doi.org/10.1130/G36110.1>.