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Geochemical evidence of windblown origin of the Late Cenozoic lacustrine sediments in Beijing and implications for weathering and climate change

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ABSTRACT

The origin of lacustrine sediments in the middle latitudes of Asia remains controversial. In this study, we conducted major and trace element analyses on 86 lacustrine samples from the X5 core in Beijing to determine their origin and provenance. The results indicate that their abundances all varied in relatively narrow ranges, similar to those of the samples in the Chinese Loess Plateau (CLP). A high correlation of major and trace element abundances exists between our lacustrine samples and the CLP samples. UCC-normalized major and trace element abundances also have a similar pattern between the lacustrine and the CLP samples, with the exception of a few elements with high solubility, such as Mg. In the ternary diagrams of A–CN–K, La–Th–Sc and Zr/10–Th–Sc, and the correlation maps of major/trace elements and their ratios, four groups of the X5 lacustrine samples with different sedimentation stages (3.16–2.7 Ma, 2.7–1.8 Ma, 1.8–0.9 Ma and 0.9–0 Ma) overlap well with each other and with the CLP samples, indicating that the X5 lacustrine samples are likely of windblown origin and possibly shared common, unchanged dust source regions with the CLP since the Late Pliocene. This interpretation is supported by the overlap of the lacustrine samples from Beijing with the CLP samples in the correlation maps of Ms vs. sorting, Ms vs. skewness, Ms vs. kurtosis, and kurtosis vs. skewness. Analysis of the frequency and cumulative frequency curves indicates that the X5 lacustrine sediments were dominantly transported by the winter monsoon and the westerly circulation. Given more scattered distributions of different elemental ratios and grain size parameters of the X5 core lacustrine sediments compared to those of the CLP samples, local dust particles must have contributed occasionally, which deserves further investigation in the future. Several chemical ratios, such as Rb/Sr, Na_2O/Al_2O_3, CaO/Al_2O_3, and chemical index of alteration (CIA), were calculated for the lacustrine samples in Beijing. Comparison of these ratios' variations with those of the sea level of the South China Sea and the global benthic $\delta^{18}O$ record indicates that Na_2O/Al_2O_3 and CIA can be regarded as sensitive indicators of chemical weathering of lacustrine dust sediments in the mid-latitudes of Northern Hemisphere.

1. Introduction

Windblown loess and loess-like deposits are widely distributed in North China where the Chinese Loess Plateau (CLP) covers an area of ~640,000 km^2 (Liu, 1985). These loess deposits record abundant information on regional climatic and environmental changes. Accompanying these dust accumulation, lots of lacustrine sediments developed in North China and are commonly studied in more detail because they are more continuous than the loess-soil sequences in the CLP.

A number of proxies are often used to reconstruct paleoclimatic and paleoenvironmental evolution of a region from sedimentary records, such as grain size (e.g. Jiang and Ding, 2010; An et al., 2012a, 2012b; Tian et al., 2013), redness (e.g. Ji et al., 2005; Jiang et al., 2007), pollen (e.g. Jiang and Ding, 2008, 2009; Xu et al., 2010; Wen et al., 2010; Tian et al., 2013), total organic carbon (TOC, Xiao et al., 2006; An et al., 2012b; Tian et al., 2013), geochemical element ratios, chemical index of alteration (CIA), chemical weathering intensity (CWI) (e.g. Sun et al., 2010a; Cai et al., 2014), and $\delta^{18}O$ of lacustrine carbonate (e.g. Zheng et al., 2007; Fan et al., 2014). Reliable interpretation of these proxies generally requires knowledge of the origin of lacustrine sediments. To date, the origin of the lacustrine sediments in the middle latitudes of Asia remains controversial. One view states that lacustrine

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sediments were derived from the upstream catchments and transported by rivers and streams into the lakes (e.g. Wang et al., 1990; Peng et al., 2005). In this case, an increase in the coarse-grained fraction of lacustrine sediments reflects an increase in transport dynamics and then precipitation intensification (e.g. Wang et al., 1990; Peng et al., 2005; Li et al., 2009; Zhong et al., 2010; Cai et al., 2014). On the other hand, an alternative view suggests that eolian dust input is likely to compose most of the non-organic lacustrine sediments due to the strong winter monsoon and westerly circulations (e.g. Jiang et al., 2004; Zhai et al., 2006; Yin et al., 2011; Tian et al., 2013). Under these different assumptions, an increase in the coarse-grained lacustrine sediments might reveal an enhancement of the winter monsoon as transport dynamics and even of dust storms instead of precipitation intensification (e.g. Jiang and Ding, 2010; Yin et al., 2011; An et al., 2012a). Thus, provenance studies on lacustrine sediments in North China are necessary before multi-proxy interpretation can be conducted.

Major and trace element compositions are often used to trace the provenance of various deposits (e.g. Liu et al., 1993; Ding et al., 2001; Liang et al., 2009; Hao et al., 2010; Liang and Jiang, 2016) and to reconstruct the paleoclimatic history (e.g. Gallet et al., 1996; Gu et al., 1996; Yang et al., 2006; Xiong et al., 2010). In this study, Late Cenozoic lacustrine sediments were uncovered in the Beijing region through a core known as X5. We compared the geochemical compositions of fine-grained sediments from the depth of 0–314 m with those of loess-soil samples from the CLP. The main objectives are: (1) to characterize the elemental geochemistry of the X5 core lacustrine sediments in North China; (2) to discuss their origin and determine if the provenance changed with time; and (3) to interpret their chemical weathering and paleoclimatic significance.

2. Geographical and geological settings

The Beijing Plain is located on the northwestern margin of the North China Plain (Fig. 1A). To the west and north, the Beijing Plain is surrounded by the Taihangshan Ranges and the Jundushan Mountains (also called as the Yanshan ranges), respectively. The southeastern part of the Beijing Plain is mainly sculptured by the alluvial–deluvial activity of several rivers, such as the Yongding, Chaobai, and Wenyu rivers (Fig. 1B).

This area is influenced by a monsoonal climate. Summer in Beijing is generally hot and wet while the winter is cold and dry. Spring and autumn are relatively short seasons. Mean annual temperature (MAT) from 1971 to 2000 was 12.3 °C, with a July average of 26.2 °C and a January average of −3.7 °C (Jiang et al., 2013). The mean annual precipitation (MAP) is 571.8 mm and ~74% of the precipitation falls between June and August, with peak mean rainfall of 185.2 mm in July.

At present, most of the study area is usually cultivated for agricultural production, with crops such as winter wheat, coarse grains, oil crops, cotton, and vegetables. Conifers are usually in the middle mountains above 1500 m a.s.l., while broadleaved deciduous forests dominate the valleys, hilly areas, and uplands above 100 m a.s.l. In contrast, shrubs and meadow usually occupy the flood plains and lowlands (Zhang et al., 2007). Recently, an Early Pleistocene pollen record of the X5 core indicates that shrub and herb taxa were dominant during most of 1.68–0.49 Ma, implying an overall arid–semiarid environment in the Beijing region during much of the Early Pleistocene (Jiang et al., 2013).

As described by Jiang et al. (2013), correlation of the magnetic polarity column of the upper 314.0 m of the X5 core (116°30′55.3″E, 39°57′04.3″N) to the Geomagnetic Polarity Timescale (Lourens et al., 2004) suggests that this sequence spans the past 3.16 Ma and is generally continuous (Cai et al., 2010). As for the lithological sequence, the lower part (314.0–271.75 m) is composed of light brownish clay interbedded with brownish silt, medium sand, and gravelly coarse sand. The middle part (271.75–60.56 m) is characterized by yellowish to brownish fine sediments dominated by clay and silt. For the upper section (60.56–0 m), coarse sand and gravelly coarse sand increases in content with well-developed horizontal bedding (Guo et al., 2013).

3. Field and laboratory methods

In total, eighty-six samples were collected at a sampling interval of 1.5–5.5 m, with variations in sample spacing due to lithologic variations. We used the magnetostratigraphic boundaries as age control to determine the age of each sample by linear interpolation (Jiang et al., 2013; Guo et al., 2013).

All samples were finely ground in agate mortar before acid dissolution. Major and trace elemental concentrations were determined by a Philips PW2404 X-ray Fluorescence Spectrometer and a Finnigan MAT HR-ICP-MS (Element I) instrument, respectively, at the Fujian Center of Geo-analysis in Fuzhou, Fujian Province. About 0.6 g of dry-ground samples was mixed with 6 g of $Li_2B_4O_7$–Li_2CO_3 fusion reagent in platinum crucibles, heated to 1100 °C in a furnace and finally cooled down to form a glass disk for the major element analysis. Analytical uncertainties are less than 3% for the major elements (SiO_2, Al_2O_3, CaO, $Fe_2O_{3(Total)}$, K_2O, TiO_2, Na_2O, P_2O_5 and MnO). Previous studies indicate that original totals for major element compositions and original loss on ignition (LOI) are very close to 100% in weight (e.g. Gallet et al., 1996; Ding et al., 2001). Constrained by deficiency in sample amounts and analytical costs, we obtained the LOI in this study by deducting the major element compositions from 100%.

The dry-ground samples for trace element analysis were weighed to 0.05 g in airtight Teflon vessels. The samples were wetted by a certain amount of water and shaken slightly to scatter them completely. 5 ml of HNO_3 was added to the bombs, and heated on a hot plate (200 °C) for dissolution. After the solution was dried, 3–5 ml of HNO_3 was added and the vessels were covered to maximize dissolution. The solution

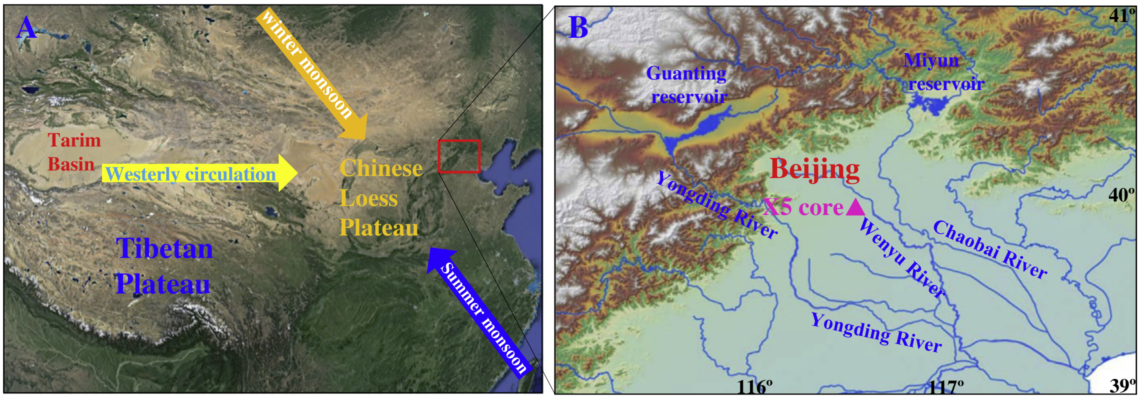

Fig. 1. Maps showing the climatic system in North China including the winter monsoon, the East Asian summer monsoon and the westerlies (A) and showing geomorphology and drainage system in the study region (B). Location of the X5 core is marked. The base map for panel A is from Google-Earth.