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A new record of late Pliocene-early Pleistocene aeolian loess–red clay deposits from the western Chinese Loess Plateau and its palaeoenvironmental implications

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ABSTRACT

The loess–red clay sequences in northern China provide high-resolution terrestrial records of Asian monsoon evolution and aridification of the Asian interior. To date, however, aeolian deposits of late Pliocene-early Pleistocene age (3.5–2.4 Ma) have only rarely been reported from the western Chinese Loess Plateau (CLP), which significantly hinders our understanding of the distribution of aeolian deposits and the palaeoenvironmental evolution of the region. Here, we present magnetostratigraphic, lithologic and magnetic susceptibility results for two recently-drilled boreholes from the north bank of Baxie River, central Linxia Basin, which are highly correlative with those of the loess–red clay deposits spanning the interval from 3.6 to 2.4 Ma in the eastern CLP. Our results provide the first direct evidence for the occurrence of late Pliocene-early Pleistocene aeolian deposits in the western CLP and provide new insights into the distribution of aeolian deposits in northern China. The spatial coherence of the magnetic susceptibility fluctuations further indicates that magnetic susceptibility is a powerful tool for stratigraphic correlation of late Pliocene aeolian deposits in the western CLP. In addition, our results demonstrate that erosional events may have occurred in the early or middle Pleistocene, and they may provide new insights into the reasons for the absence of loess–red clay deposits from 3.5 to 2.4 Ma in most parts of the western CLP.

1. Introduction

Continuous late Cenozoic loess–red clay sequences are widely distributed in northern China and these aeolian deposits are important terrestrial archives of both palaeomagnetic and palaeoclimatic information (Liu, 1985; Liu et al., 2015; Maher, 2016). They prove the longest and most detailed terrestrial records of changes in the Asian monsoon and of the aridification of the Asian interior (Liu, 1985; Sun et al., 1998a, b; Ding et al., 1998, 2001; An et al., 2001; Guo et al., 2002; Hao and Guo, 2004; Sun et al., 2006; Qiang et al., 2011; Han et al., 2011; Nie et al., 2014; Wang et al., 2015; Zhang et al., 2016; Song et al., 2017a, b). However, there is increasing evidence indicating that the age range and palaeoclimatic significance of the aeolian loess–red clay sequences to the west of the Liupan Mountains differ significantly from those in the eastern Chinese Loess Plateau (CLP) (Burbank and Li, 1985; Rolph et al., 1989; Hao and Guo, 2004; Zhang et al., 2016). In the eastern CLP, it has been suggested that aeolian red clay–loess deposits formed mainly since ~8-7 Ma (Sun et al., 1998a,b; Ding et al., 1998, 2001; An et al., 2001; Nie et al., 2014; Song et al., 2017a). Magnetic susceptibility and grain size can be used as indicators of the intensity of the East Asian summer and winter monsoons respectively (An et al., 2001; Sun et al., 2006; Nie et al., 2014). However, aeolian deposits of late Pliocene-early Pleistocene age (3.5–2.4 Ma) have only rarely been reported from the western CLP, although typical aeolian deposits have been dated to as early as 22–25 Ma (Guo et al., 2002; Qiang et al., 2011). Magnetic susceptibility measurements have proven useful for stratigraphic correlation in the eastern CLP; however, the magnetic susceptibility

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variations within coeval red clay sequences in the western CLP and the eastern CLP, which are divided by the Liupan Mountains (Fig. 1a), have not been correlated successfully during the interval from ~8 to 3.5 Ma (Hao and Guo, 2004). These observations raise the following questions: Are there continuous late Pliocene-early Pleistocene aeolian red clay-loess sequences in the western CLP? Why are they absent from most parts of the western CLP? Can the magnetic susceptibility record of the late Pliocene red clay from the western CLP be used for stratigraphic correlation, and is the record coherent with that of the eastern CLP? To address these questions, new late Pliocene aeolian sequences in the western CLP need to be investigated.

Thick red beds and subsequent aeolian deposits have accumulated in Linxia Basin since the late Cenozoic (Fig. 1a). Early studies demonstrated that the early Pleistocene *Equus* fauna (2.5–2.2 Ma), excavated from the Longdan section on the south bank of Baxie River (Fig. 1a), was very likely to have been derived from loess deposits (Qiu et al., 2004). However, recent lithological and magnetic susceptibility analyses have demonstrated that aeolian materials from the Longdan section have been subjected to significant post-depositional reworking by water (Zan et al., 2016). Nevertheless, it is possible that further investigations of the red beds overlying the uppermost conglomerate layer along Baxie River (Fig. 1b) could provide new insights into the aeolian deposits of late Pliocene-early Pleistocene age in the western CLP.

Here, we present magnetostratigraphic, lithologic and magnetic susceptibility results for two newly-drilled boreholes from the highest platform surface on the north bank of Baxie River. Our results suggest an aeolian origin of these late Pliocene sequences and provide an opportunity to address the research questions mentioned above.

2. General setting

In 2015 two borehole cores, ~10 km apart, were successfully retrieved from Guonigou (GNG, 35°33′ N, 103°25′E) and Nalesi (NLS, 35°33′ N, 103°30′E) on the north bank of Baxie River (Fig. 1). The NLS and GNG boreholes were drilled to depths of 161 m and 99 m, respectively, and both penetrated the red beds and reached the upper part of the conglomerate layer (Fig. 1b). Based on colour and texture, the lithostratigraphy of both the GNG and NLS boreholes can be divided into five stratigraphic units (Fig. 2):

Unit I (156–161 m in NLS and 95–99 m in GNG) - thick conglomerate layer. The gravel clasts have subrounded to subangular shapes and are strongly carbonate-cemented; the lithology is mainly limestone and quartzite, but metasandstone and granite clasts are also present. Along Baxie River, the conglomerate layer is relatively thick (8–15 m) and widely and uniformly distributed.

Unit II (90–156 m in NLS and 45–95 m in GNG) - Red Clay. The sediments in this unit are reddish brown (5 YR - dry Munsell colour), uniform in composition, and have a moderate to strong subangular blocky structure with occasional clay and iron/manganese coatings. As in the case of the late Pliocene *Hipparion* Red Earth deposits from the eastern CLP, the loess and palaeosol layers could not be clearly distinguished. Small pebbles and numerous well-distributed calcareous concretions are present in the lowermost part of the unit.

Unit III (58–90 m in NLS and 23–45 m in GNG) - alternating reddish soils and yellow-brown loess horizons. The unit consists of clear alternations of five visually-distinct soil and loess layers ("S" and "L" designate palaeosol and loess layers, respectively). Loess layers are yellow-brown to reddish in colour (10 YR to 7.5 YR) and are well cemented and densely jointed. The intervening palaeosols are reddish (5 YR 5/6), characterized by strong clay illuviation and abundant iron/manganese coatings. These characteristics resemble those of the Wucheng loess-palaeosol sequences in the eastern CLP (Liu, 1985).

Unit IV (34–58 m in NLS and 18–23 m in GNG) - loess deposits reworked by water). The unit consists of loess deposits intercalated with thick bluish-gray or black-gray silt layers. The bluish-gray or black-gray silt layers contain abundant oxidation spots and are clearly and finely stratified, which was possibly caused by sheet-flow processes due to the undulating palaeotopography. The palaeosols are weakly developed. Lithofacies and sedimentary characteristics indicate that the stratigraphic contact between Units III and IV may be unconformable.

Unit V (0–34 m in NLS and 0–18 m in GNG) - Malan/Lishi loess deposits. This unit is gray or light grayish yellow in colour (10 YR 5/4), massive, with a uniform composition and loose texture. Many biochannels and carbonate coatings are present in the upper part. The paleosols are well developed in the intervals of 13–16 m in the GNG section and 21–27 m in the NLS section.

3. Materials and methods

A total of 560 and 270 block samples were taken at 25–40-cm intervals from the NLS and GNG borehole cores, respectively. The block samples were cut into 2-cm cubes and demagnetized in a MMTD80 thermal demagnetizer. Most of the samples were subjected to progressive thermal demagnetization in 20 steps, varying between 10 and 50 °C. To minimize possible phase transformations of magnetic minerals, samples from the black-gray or bluish-gray silt layers were subjected to stepwise alternating-field (AF) demagnetization at fields up to 140 mT at 5 or 10 mT increments. All measurements of the natural remanent magnetization were made using a 2G Enterprises Model 755 cryogenic magnetometer installed in a field-free space (<150 nT) at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences.

Low-field magnetic susceptibility was measured at frequencies of 470 and 4700 Hz using a Bartington Instruments meter and MS2B sensor. Frequency dependent susceptibility (χ_{fd}) was calculated as $\chi_{fd} = \chi_{470Hz} - \chi_{4700Hz}$. Low-field temperature-dependent magnetic susceptibility (κ-T) was measured on selected samples using a MFK1-FA Kappabridge equipped with a CS-4 high-temperature furnace (Agico Ltd., Brno, Czech Republic). The κ-T curves were measured from room temperature to 700 °C in an argon atmosphere to minimize oxidation. Grain-size analyses were conducted using a Mastersizer 3000 laser Particle Size Analyzer at the Institute of Tibetan Plateau Research, Chinese Academy of Sciences. Prior to grain-size measurements, organic matter and carbonates were removed using conventional pre-treatment procedures (Konert and Vandenberghe, 1997).

4. Results

The κ-T curves for the samples from the Nalesi (NLS) and Guonigou (GNG) boreholes all exhibit a rapid loss of susceptibility at about 585 °C (Fig. 3), indicating the presence of magnetite. For most of the selected samples, a dramatic loss of susceptibility occurs between 300 and 450 °C, which can be ascribed to the conversion of ferrimagnetic maghemite to weakly magnetic hematite. The loss of susceptibility between 300 and 450 °C in the κ-T curves is more significant in the palaeosol layers than that in the loess layers, suggesting that the soil samples were subjected to stronger pedogenesis and are enriched in fine-grained maghemite particles (Deng et al., 2000; Zan et al., 2017). A further minor fall in magnetic susceptibility between 585 °C and 680 °C (Fig. 3), evident in all the samples, indicates the presence of hematite. Most samples exhibit a clear 'hump' at ca. 520 °C in their heating curves, which can be ascribed either to the Hopkinson effect (Dunlop and Özdemir, 1997)