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Deciphering magnetoclimatological patterns of late Early to early Middle Pleistocene loess–paleosol sequences in the western Chinese Loess Plateau

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ABSTRACT

A detailed environmental magnetic investigation in conjunction with geochemical, bulk grain size and redness analyses of late Early to early Middle Pleistocene loess–paleosol sequences at the Jiuzhoutai and Caotan loess sections has been carried out, aimed to explore the reliability of magnetic parameters as paleoclimatic proxies in the western Chinese Loess Plateau (CLP). The results show that magnetic enhancement of early- to mid-Pleistocene loess–paleosol sequences at both sites is not solely due to the neoformation of ultrafine magnetic particles through pedogenesis, but in the case of several loess layers (e.g., L8 and L9) is more attributed to the significant input of coarse-grained magnetic minerals associated with the advance of desert margin and/or with significant changes in local sediment input. Since the magnetoclimatological signals studied here are obviously controlled by both pedogenesis and wind vigor, measurements of magnetic susceptibility (χ) and saturation isothermal remanent magnetization (SIRM), both of which are responsive to both ultrafine pedogenic magnetic particles and eolian coarse-grained pseudo-single domain/multi-domain magnetic particles, could not provide unambiguous interpretation of the magnetic response to the East Asian summer monsoon intensity. In contrast, anhysteretic remanent magnetization (ARM) and the percentage of frequency-dependent magnetic susceptibility (χ_{fd}%), which are notably responsive to ultrafine magnetic particles, can aptly trace changes in the concentration of pedogenic magnetic particles and can therefore be used as reliable proxies of pedogenic intensity. The magnetic grain size dependent proxies, e.g., ARM/χ and ARM/M_s (M_s, saturation magnetization), geochemical indices (e.g., chemical index of alteration, Zr/Rb and Al/Si ratios), and bulk grain size records all exhibit concordant variations and are more straightforward proxies for addressing the East Asian monsoon variability. Therefore the combination of multi-parameter mineral magnetic, geochemical and grain size analyses is very useful for distinguishing, delimiting and correlating loess sequences, and for accurately deciphering their paleoclimatic signals embedded in the weakly weathered loess. As the classical precipitation-driven pedogenic model for magnetic susceptibility enhancement is not entirely applicable to the early- to mid-Pleistocene loess developed in the semi-arid western CLP, considerable caution should also be warranted in using magnetic susceptibility measurements alone in the quantitative reconstruction of paleoprecipitation.

1. Introduction

Chinese loess deposits are probably the most detailed and complete terrestrial archives of late Cenozoic environmental change. In the immense Chinese Loess Plateau (CLP), magnetoclimatological approaches have played a crucial role in deciphering quasi-continuous paleoclimatic records and have also been successfully applied to reconstruct the variability of the East Asian monsoon (EAM) throughout the entire Quaternary and even the Neogene (e.g., Kukla et al., 1988; Maher and Thompson, 1992; Evans and Heller, 1994; Heller and Evans, 1995; Florindo et al., 1999; Evans and Heller, 2001; Guo et al., 2002; Bloemendal and Liu, 2005; Deng et al., 2005, 2006; Wang et al., 2006a; Hao et al., 2008, 2009, 2012). The current consensus is that the less-weathered loess mainly derives from dust deposits transported by the northwesterly winter monsoon, and the intervening paleosols formed under warm, moist summer monsoon conditions during interglacials are always magnetically enhanced due to soil production (pedogenesis) (Zhou et al., 1990; Hunt et al., 1995; Thompson and Maher, 1995; Liu et al., 2004b, 2005; Wang et al., 2010). Consequently, the magnetic susceptibility and bulk grain size signals of Chinese loess are extensively assigned as first-order land-based proxies for the East Asian summer monsoon and winter monsoon, respectively (Kukla et al., 1988; An et al., 1991; Ding et al., 1994; Lu et al., 1999; An, 2000; Heslop et al.,

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2000; Sun and Liu, 2000a; Ding et al., 2002; Sun et al., 2006). Cycle-to-cycle correlations between paleoclimatic proxies from the CLP (e.g., bulk grain size, detrital quartz composition, magnetic susceptibility, stable carbon isotope ratio, chemical weathering index, and carbonate content) and marine oxygen isotope stages (MIS) not only indicate a tightly-coupled relationship between the EAM and global ice volume (e.g., Shackleton et al., 1990; An et al., 1991; Heller and Evans, 1995; Porter and An, 1995; Xiao et al., 1995; Guo et al., 1998; Liu and Ding, 1998; Guo et al., 2000; Ding et al., 2002; Chen et al., 2006), but also provide reliable age estimates for individual loess/paleosol layers by tuning variations in land-based paleoclimatic proxies to time-series of orbitally tuned MIS records (e.g., Ding et al., 1994; Vandenberghe et al., 1997; Liu and Ding, 1998; Heslop et al., 2000; Ding et al., 2002; Wang et al., 2006b; Sun et al., 2010).

The majority of previous magnetoclimatological studies were conducted in the hinterland of the CLP, where all of the loess profiles exhibit marked magnetic enhancement of the paleosols and the linkages among mineral magnetic parameters and monsoonal fluctuations are relatively straightforward (e.g., Zhou et al., 1990; Maher and Thompson, 1992; Evans and Heller, 2001; Liu et al., 2004a; Wang et al., 2010). In contrast to the plethora of magnetoclimatological data from the hinterland of the CLP, there is a dearth of systematic magnetoclimatological investigations of the weakly weathered loess–paleosol couplets developed in the semi-arid western CLP. Here, the strong East Asian winter monsoon resulted in rapid accumulation of loess, yielding thick loess profiles (Burbank and Li, 1985; Ding et al., 1990; Jahn et al., 2001; Sun et al., 2006; Deng, 2008; Chen et al., 2014; Wang et al., 2014). However, weak pedogenesis due to limited monsoon precipitation has limited the application of magnetic parameters, especially those that are sensitive to the East Asian summer monsoon (e.g., magnetic susceptibility). In addition, probable spatial and temporal variations in loess provenance further complicate the interpretation of linkages of magnetic signals to long-term monsoonal fluctuations. Therefore it is critical to apply multi-parameter magnetic approaches to effectively discriminate magnetic contributions from ultrafine magnetic particles, formed during pedogenesis, and from coarse-grained ferrimagnetic particles related to climate-dependent variations in eolian flux and sources, both of which may result in magnetic enhancement of the high-accumulation-rate loess in the western CLP.

Relying on a chronological framework provided by a magnetostratigrahic study of early-to-mid Pleistocene loess–paleosol sequences from Jiuzhoutai and Caotan (Wang et al., 2014), we performed a multi-parameter mineral magnetic study combined with analyses of bulk grain size, redness, and geochemistry. The main purposes of this study are (1) to assess whether or not the prevailing pedogenic model for the origin of magnetic signal is applicable to high-accumulation-rate loess with weak pedogenesis; (2) to explore reliable paleoclimatic proxies for faithfully resolving high-resolution fluctuations of the EAM in the semi-arid western CLP; and (3) to help improve inter-profile comparisons of lithostratigraphic and paleoclimatic records from sections in the high accumulation rate western CLP with those in the hinterland of the CLP.

2. Study sites and sampling

Both Jiuzhoutai (36°05′50″N, 103°47′14″E) and Caotan (36°18′N, 105°6′E) lie to the west of the Liupan Mountain in the far west of the CLP, proximal to the eolian dust provenance (Fig. 1). The region, which is located in the northwestern front of the summer monsoon circulation, has a mean annual temperature of 8 °C–9 °C and mean annual precipitation of 280–320 mm. The dust accumulation rate is three to four times higher than in the central CLP (Burbank and Li, 1985; Ding et al., 1990; Sun et al., 2006; Deng, 2008). Jiuzhoutai is one of the thickest loess profiles in the world with a total thickness of ca. 330 m. The Baicaoyuan loess at Caotan, ~150 km northeast of Lanzhou, has a total thickness of over 220 m, comprising at least 20 soil-forming intervals (Ding et al., 1990).

Due to low precipitation and resulting weak soil development, the loess–paleosol layers and the exact stratigraphic boundaries in both sections are not readily recognizable from variations in either soil color or structure. After removal of the surface 2–3 m of sediments to eliminate possible physical disturbance and surface weathering effects, bulk samples from Jiuzhoutai were collected every 10 cm from the depth interval 170–191 m (shown in Fig. 2), within which a 7.5-m-thick polarity transitional zone has been recognized, and which was provisionally assigned to the Matuyama/Brunhes (M/B) geomagnetic reversal (Wang et al., 2014). At Caotan, an exceptionally coarse-grained 14-m-thick loess layer in the middle–lower portion of the section was identified in the field as a stratigraphic marker layer, which we assume represents 'the upper sandy loess layer' (L9), and a total of 343 bulk samples spanning the whole of L9 and several adjacent loess–paleosol units were taken at 20-cm intervals (Fig. 2).

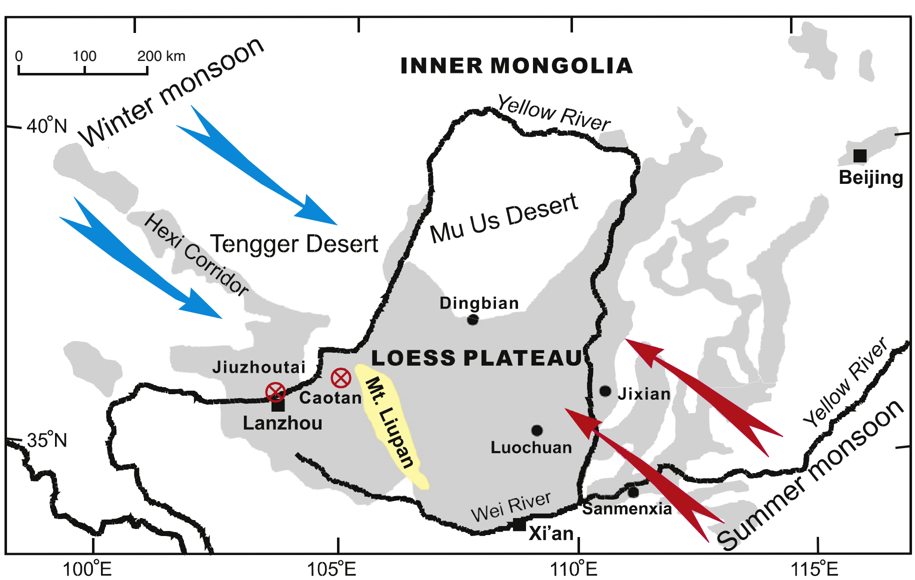

Fig. 1. Schematic map showing the distribution of Chinese loess (gray shaded area) and the locations of the studied loess sections. The blue and red arrows denote the directions of the winter and summer monsoons, respectively. Liupan Mountain is indicated by the yellow shaded zone.