Quaternary Research 79 (2013) 465–470

Contents lists available at SciVerse ScienceDirect

Quaternary Research

journal homepage: www.elsevier.com/locate/yqres

Six million years of magnetic grain-size records reveal that temperature and precipitation were decoupled on the Chinese Loess Plateau during ~4.5–2.6 Ma

Junsheng Nie [a,b,c,d,*], Yougui Song [b], John W. King [c], Rui Zhang [a], Xiaomin Fang [d]

[a] Key Laboratory of Western China's Environment System, Ministry of Education, Lanzhou University, Lanzhou, Gansu 730000, China
[b] State Key Laboratory of Loess and Quaternary Geology, Institute of Earth Environment, Chinese Academy of Sciences, Xi'an, P.O. Box 17, 710075, China
[c] Graduate School of Oceanography, University of Rhode Island, South Ferry Road, Narragansett, RI 02882, USA
[d] Institute of Tibetan Plateau Research, Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, China

ARTICLE INFO

Article history:
Received 17 May 2012
Available online 14 February 2013

Keywords:
Loess
Red clay
Chinese Loess Plateau
Pliocene
Quaternary
Rock magnetism

ABSTRACT

Magnetic grain-size variations have been used as sensitive paleoclimate proxies to investigate the evolution of the East Asian summer monsoon, but their relationship with temperature and precipitation is not entirely clear. Here we find that two magnetic grain-size proxy records (χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM, where χ_{ARM}, χ_{LF} and SIRM are anhysteretic remanent magnetization susceptibility, magnetic susceptibility measured at 470 Hz and saturation isothermal remanent magnetization, respectively) of Chinese loess and red-clay sediments co-vary during the last 6 Ma, except between ~4.5 and 2.6 Ma, when these two records had opposite trends. We attribute this disparate behavior to the different responses of χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM to temperature and precipitation during ~4.5–2.6 Ma, when temperature and precipitation on the Chinese Loess Plateau were decoupled. A comparison of the loess and red-clay χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM records with the global ice-volume proxy records reveals that χ_{ARM}/χ_{LF} is more sensitive to temperature variations than χ_{ARM}/SIRM. The results suggest that temperature on the Chinese Loess Plateau had a cooling trend from ~4.5 to ~2.6 Ma, whereas rainfall tended to increase. Our studies demonstrate that joint analysis of loess χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM records can reveal paleoclimatic information that cannot be revealed by a single parameter.

Introduction

Rock magnetic proxies are widely used in extracting the history of the East Asia summer monsoon (EASM) from the Chinese Loess Plateau (CLP) (Heller et al., 1993; Maher et al., 1994; Florindo et al., 1999; An et al., 2001; Deng et al., 2005; Liu et al., 2007; Hao et al., 2008; Zhang et al., 2010; Han et al., 2012). Calibration from surface soils across the CLP demonstrates that magnetic susceptibility (χ; unit as $m^3\ kg^{-1}$) measured at 470 Hz (low-frequency susceptibility, or χ_{LF}) and pedogenic χ (defined as the difference in χ between soil B and C horizons) are strongly correlated with annual mean precipitation and thus χ can be used to study the paleo-precipitation history on the CLP (Heller et al., 1993; Maher et al., 1994). Southern sites on the CLP might be an exception to this relationship between χ and precipitation because precipitation exceeded a critical threshold that resulted in water-logged soil conditions and consequent alteration of the magnetic minerals contained in the soils that are responsible for magnetic enhancement (magnetite and maghemite) (Lu et al., 1994; Guo et al., 2001; Bloemendal and Liu, 2005). Data reported for the central CLP, in contrast, suggest that χ for profiles there reflects precipitation from the EASM, at least qualitatively (Guo et al., 2001; Bloemendal and Liu, 2005). One challenge to this argument is that χ of surface soils across the CLP is also strongly correlated with grain size, suggesting that enhancement of χ is caused by variation of the dust accumulation rate; a higher dust accumulation rate dilutes magnetic minerals and causes lower χ (Porter et al., 2001). However, a high-resolution geochronological and paleoclimatic study (Maher and Hu, 2006) from the western CLP reveals that higher (lower) χ values correspond to higher (lower) dust accumulation rates during the late (early) Holocene, and provides evidence against the hypothesis of dust dilution as the main cause for enhancement of loess χ (Porter et al., 2001). Although annual mean precipitation is well correlated with loess χ on the CLP, it either has no, or an inverse, relationship with loess χ in other parts of the world, such as Siberia and Argentina (Liu et al., 2001; Heil et al., 2010). Some authors have proposed a more universal model for explaining χ variations of loess in these areas (Orgeira et al., 2011). They propose that it is not precipitation, rather it is the soil-moisture condition controlled by the difference between precipitation and evapotranspiration that controls variations of χ. In semi-arid areas like the CLP, the evapotranspiration potential is much greater than the available precipitation and thus there is no potential for persistent reducing conditions in soils. In this case, the intermittent wetting and drying cycles associated with precipitation promote magnetic enhancement.

* Corresponding author at: Key Laboratory of Western China's Environment System, Ministry of Education, Lanzhou University, Lanzhou, Gansu 730000, China.
E-mail addresses: jnie@lzu.edu.cn, niejunsheng@yahoo.com.cn (J. Nie).

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http://dx.doi.org/10.1016/j.yqres.2013.01.002

In contrast, in areas where the evapotranspiration potential is smaller than the available precipitation, persistent reducing conditions are common. In regions with this characteristic, more precipitation often causes magnetic grains to be either chemically altered to less magnetic and non-magnetic minerals, or dissolved and thus precipitation has an inverse or no relationship with loess χ in these areas. It is also noteworthy that although loess χ on the CLP is strongly correlated with annual mean precipitation, it is also correlated with annual mean temperature, although the correlation is not as good as with precipitation (Maher et al., 1994; Nie et al., 2010). Therefore, developing an approach to separating the temperature from the precipitation signal in loess χ remains a challenge. Despite these complications, most authors agree that superparamagnetic (SP) grains having very high χ but lacking stable magnetic remanence, which are produced via the numerous intermittent wetting (reduction) and drying (oxidation) cycles associated with monsoon climate during soil formation, are responsible for magnetic enhancement in paleosol layers (Zhou et al., 1990; Heller et al., 1993; Maher et al., 1994; Liu et al., 2007; Nie et al., 2007).

These same cycles also produce large amounts of fine stable single-domain (SSD) and small pseudo single-domain (PSD) magnetic grains (see Appendix A for corresponding grain-size range) having high anhysteretic remanent magnetization susceptibility (χ_{ARM}) but low χ_{LF} (Liu et al., 2007). Inter-parameter proxies for magnetic grain-size variations, such as χ_{ARM}/χ_{LF} (dimensionless) and χ_{ARM}/SIRM (unit: m A^{-1}), where SIRM represents saturation isothermal remanent magnetization (A m^2 kg^{-1}), are thus controlled by climate variation (Verosub and Roberts, 1995).

Few studies (Orgeira et al., 2011) have explored the relationship between magnetic grain-size proxies and climatic parameters. In this paper, we compare published χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM data on the CLP for the past 6 Ma and explore their paleoclimatic implications. Our previous studies based on magnetic paleoclimatic records during 8.1–1.2 Ma from Chaona on the central CLP focused on the enhancement mechanism of χ, its temporal variation, and relationship to orbital and tectonic forcing (Nie et al., 2007, 2008a,b,c). Temporal variations in magnetic grain-size records from Chaona and their relationship to external forcing have never been explored.

Study sites, data and methods

All of the magnetic-grain concentration data and magnetic grain-size proxy data for the last 2.6 Ma used in this paper have been previously published. However, magnetic grain-size proxy data for 6–2.6 Ma were not previously calculated from published magnetic-grain concentration data. For 6–2.6 Ma, data are used from the Chaona section (107° 12′ E, 35° 6′ N) in Lingtai County (Nie et al., 2007) (Fig. 1). The Chaona section is about 300 m thick, with the upper 175 m comprising the loess–paleosol sequence and the underlying 125 m comprising the red-clay sequence. The age model of the Chaona section was established by Lü et al. (2001) based on ages for control point (the top and basal ages of astronomically tuned paleosols S1–S32 for the loess–paleosol sequence (Heslop et al., 2000) and paleomagnetic reversal ages (Cande and Kent, 1995) for the red-clay sequence). Recently, Han et al. (2012) tuned the Chaona χ_{LF} time series during 2.6–0.8 and 0.8–0 Ma to the obliquity data of Laskar et al. (2004) and the ODP Site 677 benthic oxygen isotope record, respectively. No χ_{ARM}/χ_{LF} and χ_{ARM}/SIRM data for the entire Quaternary Period have been generated from this section and there are several age models available (Lü et al., 2001; Han et al., 2012), making this section not ideal for studying Quaternary climate variabilities. Thus, data for the past 2.6 Ma are used from the Luochuan section (108° 23′ E, 35° 29′ N) (Bloemendal and Liu, 2005) (Fig. 1). This section is also from the central part of the CLP, but southeast of the Chaona section. The Luochuan loess–palaeosol sequence is ~135 m thick. It was one of the first CLP sites to be studied in detail and has been the subject of detailed stratigraphic studies using a variety of climate proxies (Verosub et al., 1993; Gallet et al., 1996; Wu et al., 1996). The age model for this section is based on orbital tuning (Bloemendal and Liu, 2005): χ data have been tuned to insolation (Laskar et al., 1993) for 65° N and to the marine oxygen-isotope record (Shackleton et al., 1990) from ODP Site 677. The current mean annual precipitation in Luochuan and Chaona is ~610 and ~600 mm and the mean annual temperature is ~9.5 and ~9°C, respectively (China Meteorological Data Sharing Service System: http://cdc.cma.gov.cn, in Chinese, last accessed 12 October 2012).

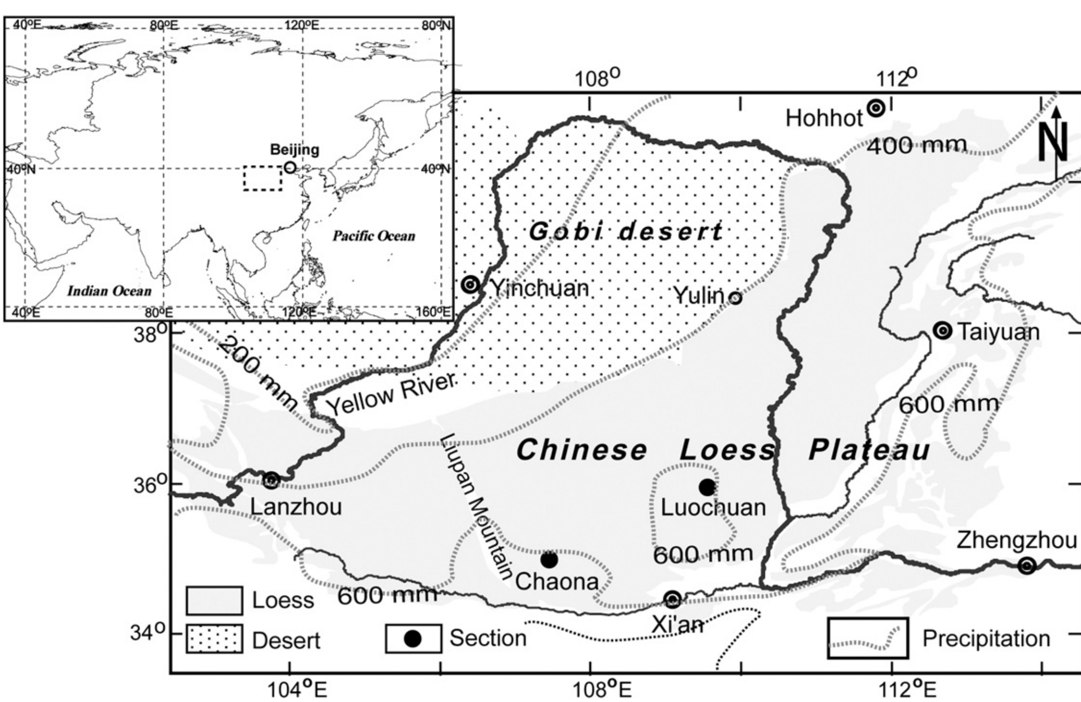

Figure 1. Map showing the Chinese Loess Plateau, Gobi desert, and location of the study sites. The main map corresponds to the area within the rectangle in the index map.