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East Asian monsoon evolution during the Eemian, as recorded in the western Chinese Loess Plateau

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A B S T R A C T

We present a high resolution environmental magnetic record of the East Asian summer monsoon spanning paleosol S1, corresponding to Marine Oxygen Isotope (MIS) 5, from the Jiuzhoutai (JZT) loess section in Lanzhou, on the northwestern edge of the Chinese Loess Plateau. We use a chronology based on a sediment grain-size age model frequently used for Chinese loess. The Eemian is dated to 127.37 – 121.31 ka BP and can be divided into three sub-stages based on variations in summer monsoon intensity: early Eemian (127.37 – 125.67 ka BP) with an intermediate summer monsoon intensity; mid Eemian (125.67 – 124.24 ka BP) with weakest summer monsoon intensity, and late Eemian (124.24 – 121.31 ka BP) with the strongest summer monsoon intensity. Contrasting, the winter monsoon weakened at the beginning of MIS5e, reached its weakest intensity during the late Eemian (~121 ka BP), and then commenced an irreversible strengthening trend. Furthermore, the Eemian exhibits a similar climatic trend to the Holocene optimum, since both are divided into two parts by an intervening arid interval and the most humid period occurs in the secondary pedogenic stage. Therefore we suggest that the climate evolution during Eemian and later may provide useful information about climate forecast in the future.

1. Introduction

The Eemian is regarded as an archetypal interglacial event characterized by a high eustatic sea level, high sea surface temperatures, minimum extent of global ice-sheets, and biotic assemblages which closely resemble those of the Holocene (Turner, 2002). However, although numerous studies have focused on the Eemian, a significant degree of uncertainty remains regarding its climatic characteristics. The Asian monsoonal circulation system is one of key atmospheric systems that control a broad region of northern hemispheric climate change. The complex Asian Monsoon system is the subject of many studies, especially of the East Asian monsoon (An et al., 2000; He et al., 2004; Tian et al., 2005; Maher and Hu, 2006; Liu and Shi, 2009; Wang, 2009). The observed asynchronous behavior of the summer and winter components of the East Asian monsoon presents a rather confusing picture (An et al., 2000; He et al., 2004).

The loess deposits of the Chinese Loess Plateau (CLP) are regarded as one of the best continental geological archives, preserving a continuous high-resolution record of environmental change for the Quaternary and earlier (Heller and Liu, 1982, 1984; Kukla et al., 1988; Zhou et al., 1990; Maher and Thompson, 1991; Deng et al., 2005; Liu et al., 2007). In addition, loess/paleosol sequences in the western part of the CLP exhibit a significantly higher resolution stratigraphy and more obvious stratigraphic divisions (Chen et al., 1999, 2000, 2003a) than in the central CLP where most previous studies have been conducted (An et al., 1991; Porter and An, 1995; Guo et al., 1996; An and Porter, 1997). Furthermore, because of the high rate of sediment accumulation and the relatively cool, dry climate, the loess deposits of the western part of the CLP are less subject to the over-printing effect whereby the contemporary weathering regime is superimposed on previously accumulated loess (Feng and Wang, 2006). Based on analysis of reliable climate proxies measured at high resolution, here we try to address three issues: whether the Eemian as recorded in Chinese loess deposits is equivalent to MIS5e as recognised on a global basis; whether or not the climate of the Eemian was stable; and whether or not it exhibits similar climatic characteristics to the Holocene climatic optimum. With regard to the first question, research on deep sea sediments (Shackleton, 1967), polar ice cores (Delmonte et al., 2004; North Greenland Ice Core Project members, 2006), stalagmites (Wang et al., 2008) and even on some loess/

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paleosol sequences in the central CLP (An et al., 1991; Porter and An, 1995; Guo et al., 1996; An and Porter, 1997) tends to support the equivalence of the Eemian and MIS5e; however, this conclusion is opposed by some palynologists (Shackleton et al., 2003). With regard to the second question $\delta^{18}O$ isotopic data from the GRIP ice core depict a significantly fluctuating climate during MIS5e; however, this had been negated by subsequent research (GRIP Members, 1993). More recently, an increasing number of high-resolution geological records display a cooling and (or) drying episode in the mid-Eemian (Linsley, 1996; Bardají et al., 2009), but this phenomenon has not been observed in data from polar ice cores and stalagmites (Delmonte et al., 2004; North Greenland Ice Core Project members, 2006; Wang et al., 2008). Clearly, determining whether or not this cooling and (or) drying signals are of regional or global extent requires more case studies. The last question, the possible climatic equivalence of the Eemian and the Holocene, has rarely been addressed.

2. Site description

The Jiuzhoutai (JZT) section, a typical loess/paleosol sequence in the western part of the CLP (Fig. 1), is located on the sixth terrace of the Yellow River in Lanzhou (36°5′46″N, 103°47′15″E). Due to its high sedimentation rate and clear stratigraphic divisions it has been the subject of several high resolution paleoclimatic studies (e.g. Fang et al., 1997; Chen et al., 1999, 2000, 2003a; Liu et al., 2005). In the present study, paleosol unit S1 (≈MIS 5) is located between 29.7 and 36.15 m depth, which is slightly different to the depth recorded in Fang et al. (1997), who located it at 28.6–36 m depth. In fact, the loess sediment deposited during MIS5 is much thicker than paleosol S1 and is located between 28.5 and 37.35 m depth, as indicated by sediment granulometry (Fig. 2). Three sub-paleosol units and two sub-loess units are recognized and are labeled S1S1, S1L1, S1S2, S1L2 and S1S3, in sequence (Fig. 2). S1S1, S1S2 and S1S3 consist of entisol-like paleosols which are characterized by being more compacted, having observable granular structures and by a darker color with more rootlet canals than the intercalated loess units. According to field investigation, S1S3 is the most developed soil unit.

3. Sampling and laboratory methods

210 unoriented powder samples were collected at a 5 cm interval. After air-drying in the laboratory, 5.5 g of each sample were packed in a plastic box for the following series of magnetic measurements: Low field (470 Hz) and high field (4700 Hz) frequency magnetic susceptibility (χ_{lf} and χ_{hf}) were measured using the Bartington MS2 magnetic susceptibility meter and MS2B sensor. The difference between the measurements at the two frequencies was then used to calculate the frequency-dependent susceptibility (χ_{fd}) ($\chi_{fd} = \chi_{lf} - \chi_{hf}$). The percentage frequency-dependent magnetic susceptibility ($\chi_{fd}\%$), was calculated as: $\chi_{fd}\% = 100\% \times \chi_{fd}/\chi_{lf}$. Anhysteretic remanent magnetization (ARM) was imparted using a DTECH AF demagnetizer with a peak AF field of 50 mT and DC bias field of 0.05 mT. Here, ARM is expressed as an anhysteretic susceptibility, $\chi_{ARM,}$ by dividing it by the biasing field strength. We define the saturation isothermal remanent magnetization (SIRM) as the IRM imparted after exposure to a 1000 mT DC field. IRMs were imparted using an MMPM10 pulse magnetizer. All remanence measurements were made using a Minispin magnetometer. Saturation magnetization (Ms) was measured using a variable field translation balance (VFTB). X-ray diffraction (XRD) analyses were carried out using an X'Pert Pro MPD X-ray diffractometer with Cu–Kα radiation. Finally, the sediment grain size was measured using the methods of Lu and An (1997). The samples were pretreated in order to remove organic matter and carbonates by heating in H_2O_2 and HCl, respectively. $(NaPO_3)_6$ was added and the samples were ultrasonicated in order to aid dispersion of fine particles. The grain-size distributions were measured using a Mastersizer 2000 laser diffraction particle size analyzer. All experiments were conducted in the Key Laboratory of West China's Environmental Systems, Lanzhou University, China.

4. Climate proxies

4.1. Magnetic parameters as a summer monsoon proxy

Numerous studies have determined that the magnetic properties of loess deposits are dominated by a mixture of coarse-grained eolian magnetite and low-Ti titanomagnetite and fine-grained pedogenic ferrimagnetic minerals (magnetite and/or maghemite) (Deng et al., 2004, 2005; Liu et al., 2004a, b, c, 2005; 2007). Due to the similarity of their magnetic properties at room temperature, magnetite/titanomagnetite and maghemite are collectively labeled 'FM' in the present study.

Variations in the magnetic susceptibility of Chinese loess sequences typically correspond to the alternation of loess and paleosol units, with high magnetic susceptibility in the paleosols and low values in the loess (Deng et al., 2004, 2005; Liu et al., 2004a, b, c, 2005; 2007). Magnetic susceptibility enhancement results from

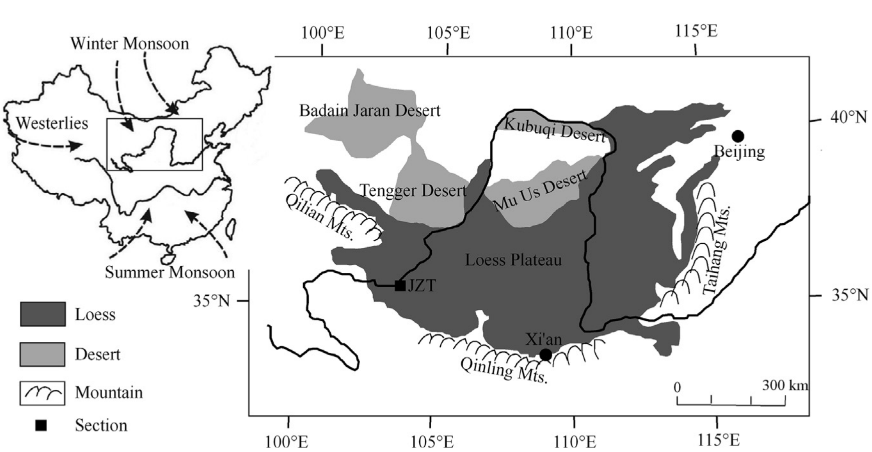

Fig. 1. Location of the Chinese Loess Plateau (CLP) in China, directions of major atmospheric circulation systems (modified from Sun et al., 2010), and location of the JZT study section within the CLP.