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Out-of-phase evolution between summer and winter East Asian monsoons during the Holocene as recorded by Chinese loess deposits

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ABSTRACT

We analyzed climate proxies from loessic-soil sections of the southern Chinese Loess Plateau. The early Holocene paleosol, S0, is 3.2 m thick and contains six sub-soil units. Co-eval soils from the central Loess Plateau are thinner (~1 m). Consequently higher-resolution stratigraphic analyses can be made on our new sections and provide more insight into Holocene temporal variation of the East Asian monsoon. Both summer and winter monsoon evolution signals are recorded in the same sections, enabling the study of phase relationships between the signals. Our analyses consist of (i) measurements of magnetic properties sensitive to the production of fine-grained magnetic minerals which reflect precipitation intensity and summer monsoon strength; and (ii) grain-size analyses which reflect winter monsoon strength. Our results indicate that the Holocene precipitation maximum occurred in the mid-Holocene, ~7.8–3.5 cal ka BP, with an arid interval at 6.3–5.3 cal ka BP. The winter monsoon intensity declined to a minimum during 5.0–3.4 cal ka BP. These results suggest that the East Asian summer and winter monsoons were out of phase during the Holocene, possibly due to their different sensitivities to ice and snow coverage at high latitudes and to sea-surface temperature at low latitudes.

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Introduction

The summer and winter monsoon circulations in East Asia appear to have varied in an anti-phased manner during the Quaternary Period, as indicated by a large number of geological records (e.g. Ding et al., 1995). During interglacial periods, the summer monsoon extended much further to the northwest (Chen et al., 1999) and provided more precipitation (Wang et al., 2005), while simultaneously the winter monsoon weakened and retreated (Ding et al., 1995). During glacial stages, this climatic pattern was reversed. However, several authors have observed an asynchronous evolution between the summer and winter monsoons, or even a positive co-variation, on various time scales. For example, an out-of-phase pattern of variation was observed during the marine oxygen isotope stage (MIS) 11/10 (Hao et al., 2012), MIS 6/5 (Chen et al., 2003), and MIS 2/1 boundaries (Rao et al., 2013), when changes in the summer monsoon lagged changes in the winter monsoon by 4–5 ka or longer. In addition, in the eastern Tibetan Plateau, the summer and winter monsoons both weakened during the interval 5.9–4.1 ka cal BP (Yu et al., 2006) and in southern China, the summer and winter monsoons were almost in-phase during the Holocene (Wang et al., 2011).

However, these findings have not been fully confirmed, partly because of uncertainties both in the climate proxies used and in the sediment chronologies. Chinese loess deposits are one of the most useful deposits for climatic reconstruction, providing records of high temporal resolution (Li et al., 1992; Ding et al., 1995, 2002; Kravchinsky et al., 2008; Sun et al., 2010). In addition, the signals of both the Asian summer and winter monsoons are faithfully recorded and easily recovered. Therefore, Chinese loess deposits are well-suited for studying the phase relationship between the summer and winter monsoons, and any changes thereof. In the present study, a loess/paleosol sequence collected at Yaoxian (YX) was used to determine the relationship between the East Asian summer and winter monsoons during the Holocene.

Regional setting

YX section (34°53′ N, 108°45′ E) is located in the north of Guanzhong basin, about 120 km north of Xi'an city (Fig. 1). The present climate is semi-humid and modulated by the East Asian Monsoon. Typically, in winter and spring a cold and dry winter monsoon impinges on the area from the northwest, and in summer and autumn a warm and humid summer monsoon arrives from the southeast. The mean annual temperature and precipitation are 13°C and 554 mm, respectively, and more than 60% of the annual precipitation falls during July–September. In spring, the winter monsoon generates frequent dust storms which are regarded as the source of loess on the Loess Plateau (Sun, 2002). The dominant vegetation is currently semi-humid grassland.

Lithology and chronology

YX section can be divided into three lithological units (Fig. 2) based on texture, color and structure (Table 1). The three units comprise: modern soil (Ms), Holocene paleosol (S_0) and Malan loess (L_1). S0 is further divided into five sub-units: S0S1, S0L1, S0S2, S0L2, and S0S3, on the

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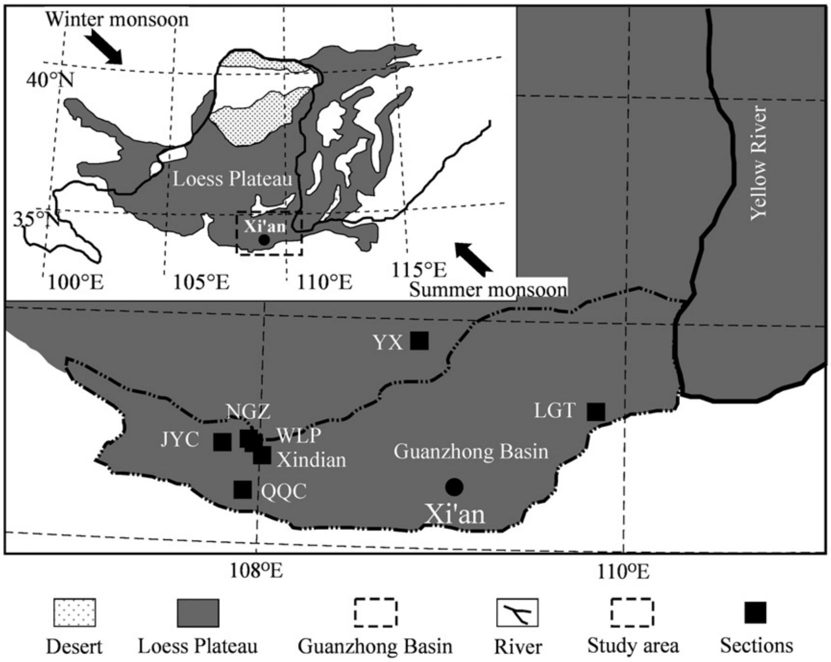

Figure 1. Chinese Loess Plateau and directions of the East Asian summer and winter monsoonal air flows (arrows; inset); and location of the seven Holocene loess sections (filled squares) referenced in this paper.

basis of variations in the intensity of soil development. The upper 60 cm of soil has been disturbed by human activity, and thus sampling was confined to the remainder of the section, from 60 to 400 cm depth. This interval was sampled every 2 cm for magnetic measurements and grain-size analyses.

The chronological framework for the typical Holocene loess/paleosol sequences in the southern part of the Loess Plateau was established in JYC, NGZ, WLP, and Xindian sections by Huang et al. (2000, 2002a, 2002b, 2002c, 2003, 2006) and Shang and Li (2010) and is shown in Figure 3 and summarized in Table 1. The boundaries S0S1/S0L1, S0L1/S0S2, S0S2/S0L2, S0L2/S0S3 and S0S3/L1 have been dated at 2.2 ^{14}C ka BP, 3.1 ^{14}C ka BP, 5.0 ^{14}C ka BP, 6.0 ^{14}C ka BP and 8.5 ^{14}C ka BP (Huang et al., 2000), respectively. Jia et al. (2008) dated these same horizons using optically stimulated luminescence (OSL) and their results are similar to the ^{14}C dates. The chronology of the YX section is based on the results of the investigations described above (Fig. 3, Table 1).

Methods

Low- (470 Hz) and high- (4700 Hz) frequency magnetic susceptibilities, χ_{lf} and χ_{hf} respectively, were measured using a Bartington Instruments MS2B sensor. Subsequently, mass-specific frequency-dependent susceptibility (χ_{fd}) was calculated as the difference between χ_{lf} and χ_{hf}; in addition, percentage frequency-dependent susceptibility was calculated as $\chi_{fd\%} = 100 \times \chi_{fd} / \chi_{lf}$ (Thompson and Oldfield, 1986). Anhysteretic Remanent Magnetization (ARM) was obtained using a DTECH AF demagnetizer with a peak AF field of 100 mT and a DC bias field of 0.05 mT. Saturation Isothermal

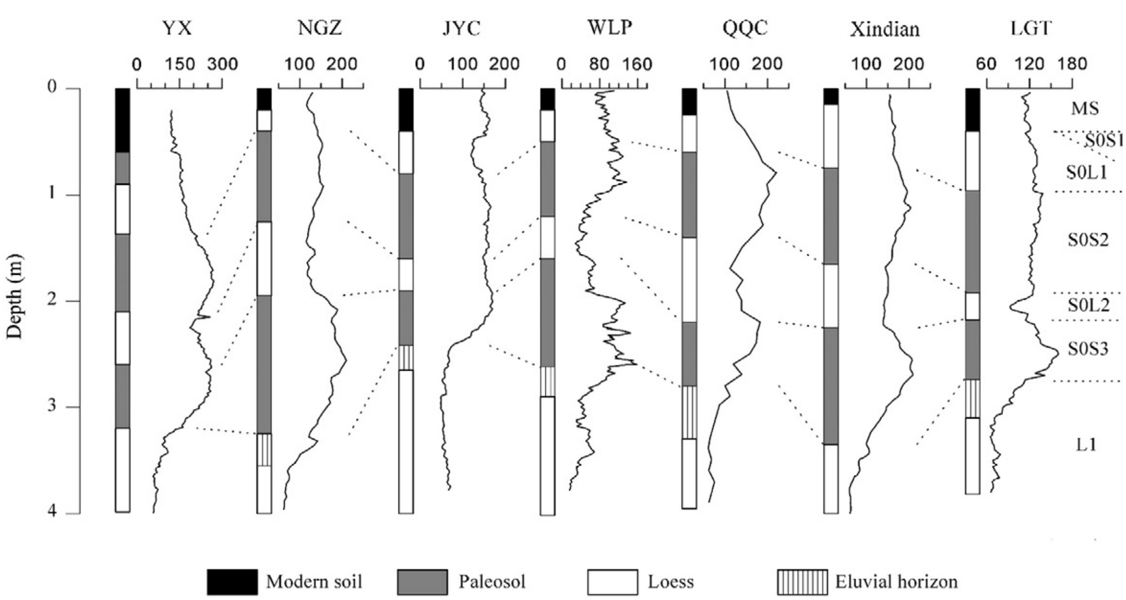

Figure 2. Comparison of the lithology and magnetic susceptibility (10^{-8} m^3 kg^{-1}) of typical loess/paleosol sequences in the southern Chinese Loess Plateau. NGZ, JYC, WLP, and QGC are from Huang et al. (2002c, 2002b, 2003, 1997), respectively; Xindian is from Jia et al. (2008); LGT is from Shang and Li (2010).

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