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Magnetostratigraphic age and monsoonal evolution recorded by the thickest Quaternary loess deposit of the Lanzhou region, western Chinese Loess Plateau

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A B S T R A C T

The loess-paleosol sequences of the Chinese Loess Plateau (CLP) are major paleoclimatic archives which document the evolution of the East Asian Monsoon (EAM) and changes in the Northern Hemisphere ice sheets during the Quaternary glacial-interglacial cycles. However, the mechanisms regulating the trend of EAM variations on a tectonic scale are unclear. The loess deposits of the western CLP, which have a close relationship with tectonics and climate, are much better-suited to exploring these mechanisms than those of the central CLP. However, studies of long-term EAM evolution from the western CLP have been hindered by the lack of long, accurately-dated sequences with high sediment accumulation rates. Here, we address this problem via high resolution magnetostratigraphic, magnetic susceptibility and grain-size analyses of a 416.2 m-long drill core located at Xijin Village, near Lanzhou. Paleomagnetic dating indicates that the basal age of the Xijin loess is ~2.2 Ma. The χ and grain-size records reveal that the East Asian Summer Monsoon (EASM) and East Asian Winter Monsoon (EAWM) strengthened synchronously at ~1.24 Ma. Subsequently, during interglacial periods, the EASM began to penetrate, and then dominate, in the Lanzhou region. This was followed by two stepwise uptrends, commencing at ~0.87 and ~0.62 Ma, which resulted in an increasingly moist interglacial climate in the region. We suggest that the uplift of the Tibetan Plateau was largely responsible for these three stepwise enhancements of the EASM. Overall, however, the long-term trend of strengthening in EAWM in the area may have been primarily caused by long-term global cooling from the Late Pliocene onwards.

1. Introduction

The dust comprising the Quaternary loess deposits of northern China originated in the central Eurasian continent and north-western China and was transported to the Chinese Loess Plateau (CLP) by the East Asian winter monsoon (EAWM) and the northern hemisphere westerlies. Chinese loess deposits have been widely used to study the evolution and cyclicity of the East Asian Monsoon (EAM), which are characterized by alternating warm-wet and cold-dry cycles during the Pleistocene (Liu, 1985); the interrelationship between the EAM and global climate change (An et al., 1990; Liu and Ding, 1998; Ding et al., 2002; Sun et al., 2010); and the progressive intensification of aridification in the Asian interior during the Quaternary (Liu and Ding, 1998; An et al., 2001; Ding et al., 2002; Sun, 2002; Wu et al., 2007a; Lu et al., 2010) and the development of China's major deserts (Fang et al., 2002b; Ding et al., 2005; Deng et al., 2006; Yang et al., 2011).

Over the past thirty years, a consistent correlation between variations of the EAM on glacial/interglacial cycles and various proxies measured on loess-paleosol sequences has been established. In particular, the magnetic susceptibility (χ) and grain-size have been confirmed as effective proxies of the intensities of the East Asian summer monsoon (EASM) (Liu, 1985; Kukla et al., 1988; An et al., 1991a; An, 2000; Sun et al., 2006a) and

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EAWM (Ding et al., 1994; Porter and An, 1995; Lu and An, 1998; Prins et al., 2007), respectively. Global glacial/interglacial cycles have been clearly demarcated by both proxies and furthermore a strong EAM appears to be associated with an increased amplitude of the climatic cycles on an orbital scale in East Asia (An et al., 2001; Sun et al., 2010). The mechanism responsible for the strengthening of the EAM is considered to be the thermal contrast resulting from variations in solar insolation at 65°N and northern hemisphere ice volume (Liu and Ding, 1998; An, 2000; Ding et al., 2002; Sun et al., 2006b; An et al., 2015).

The paleoclimatic record of the central CLP since 2.6 Ma exhibits two significant shifts, at ~1.24 Ma and ~0.62 Ma (An et al., 1990; Xiao and An, 1999; Sun and Liu, 2000; Sun et al., 2006b, 2010; Song et al., 2010), with the dominant cyclicity changing from 41-kyr before 1.2 Ma to 100-kyr after 0.6 Ma (Liu et al., 1999; An et al., 2015). However, in the western CLP, to the west of the Liupan Mountains, the nature of climatic changes on an orbital scale during the entire Pleistocene remain unclear and this limits the spatial comparison of monsoonal evolution of the central and western CLP. The loess deposits of the western CLP are characterised by higher accumulation rates and consequently are significantly thicker than elsewhere in China; thus they potentially enable high resolution records of EAM evolution to be obtained (Fang et al., 1999; Sun et al., 2006a; Jiang et al., 2011; Shi et al., 2013). Moreover, since the western CLP borders the northeastern Tibetan Plateau (TP) the area is also well suited for studying the relationship between plateau uplift and monsoon evolution (Li et al., 1988; Molnar, 2005). However, there have only been a few paleoclimatic studies of loess-paleosol sequences in the western CLP, principally in the Xining, Jingyuan and Lanzhou districts. Recently, a magnetostratigraphic survey of the age of the oldest Quaternary loess in Xining increased its age from 1.2 Ma to 2.0 Ma (Lu et al., 2012). In addition, the magnetic susceptibility record indicates that the plateau monsoon underwent a significant shift at ~1.2–1.0 Ma, and that after 0.8 Ma it underwent at least seven distinct phases of strengthening (Lu et al., 2012). However, the climatic records of the Xining loess sequences do not correlate well with those from the central CLP (Lu et al., 2012), probably due to their lower sensitivity to the EAM. Paleoclimatic archives from L7 to S0 for the Jingyuan Section (~505-m-thick; basal age 1.4 Ma - Yue et al., 1991; Lei, 1995) were investigated to identify any regional differences other than to characterize orbital-scale changes in the EAM (Heslop et al., 1999; Chen et al., 1999a; Sun et al., 2006a; Sun et al., 2012; Shi et al., 2013). However, the paleoclimatic record of the region prior to L7 remains poorly understood.

In the Lanzhou region, Burbank and Li (1985) first reported the paleomagnetic age of the loess-paleosol sequence of the Jiuzhoutai section in Lanzhou, dating the base of the 330-m-thick sequence to ~1.3 Ma. Further magnetostratigraphic work together with fission track dating extended the basal age to ~1.4–1.5 Ma (Cao et al., 1988; Chen et al., 1991; Yue et al., 1992). Furthermore, magnetostratigraphic results from several loess sections deposited on higher terrace surfaces around Lanzhou city gave ages for the onset of loess deposition of 1.7–1.84 Ma (Zhu et al., 1996; Li et al., 1999; Zhang et al., 2001). These sections are mainly located north of the Yellow River in Lanzhou; however, less attention has been paid to the thickest loess deposits which are present on or close to the river's southern bank. Bai and Zhu (1986) reported a magnetostratigraphic age of a drill core from the Xijin loess (409.93 m in length), from the southern bank, of 2.09 Ma; however, the sampling resolution was low and moreover there were analytical errors (Bai and Zhu, 1986). Nevertheless, the Xijin loess warrants more detailed study since the combination of its relatively high accumulation rate and old basal age makes it one of the most potentially valuable sequences in the western CLP for paleoclimatic reconstruction. To date, only a few high-resolution studies of the paleoclimatic record of the loess deposits in the Lanzhou area have been conducted, and they have almost always focussed on the last glacial/interglacial cycle (Chen et al., 1997, 1999a; Fang et al., 1999).

Here, we present the results of a magnetostratigraphic, magnetic susceptibility and grain-size study of a drill core from the thickest Xijin loess in the Lanzhou area. Since the Lanzhou region closely abuts the TP, it was hoped that any paleoclimatic information retrieved would also contribute to our understanding of the uplift process of the TP, its effect on the evolution of the EAM and global cooling, and on the expansion of ice sheets during the Pleistocene.

2. Geological and geographical background

Tectonically, the Lanzhou Basin is divided into two sub-basins, one to the east, and the other to the west; the Xijin area on the southern bank of the Yellow River lies in the depocenter of the rhomboidal west basin, and is demarcated by the Leitanhe Fault to the east, the Huangyu Fault to the south, the Shengou Fault to the west and the Jinchengguan Fault to the north (Fig. 1; Yuan et al., 2008). The 200–300 m thickness (272 m under Xijin Village) of the Wuquan Conglomerate Formation in the Basin is affected by strong post-depositional tectonic deformation (Gansu BGMR, 1988).

Lanzhou is located in the geometric centre of China, at the junction of the area impacted by the EAM, the TP and arid northwestern China; consequently its loess sequences respond sensitively to climate change (Li et al., 1988) (Fig. 1). The modern climate is temperate semi-arid–the mean annual precipitation for Lanzhou is ~310 mm, the mean annual temperature is ~10 °C, and the natural vegetation of the area is grassland (EBCPG, 1985; CMA, 2015). The climate of the region is closely related to the weather system of the Lanzhou Small High. This anticyclone is the product of dynamic atmospheric circulation caused by the TP (Xu and Zhang, 1983; Li et al., 2006). The western CLP, including the Lanzhou area, is separated from the central CLP by the Liupan Mountains. It is relatively close to the dust source areas and for this reason the loess accumulation rate is significantly higher than in the central CLP. In addition, a high dust flux may be promoted by both topographical factors and the Lanzhou Small High atmospheric circulatory system (Chen and Zhang, 1993).

Xijin Village is located on a remnant loess tableland, at an altitude of ~1900 m asl. The coring site (N36°1″1.1″, E103°44′50.8″, altitude ~1908 m asl) is located in the middle of Xijin Village in Lanzhou (Fig. 1). The drilling was performed from July to August 2012, and the hole penetrated the entire Quaternary loess-paleosol and entered the underlying conglomerate beds. The total drilled depth of loess strata was 416.2 m, with an underlying siltstone and breccia-gravel bed 8.35 m thick. A 401-m-long loess core was obtained, with an average recovery rate of 96.35%. The Quaternary loess-paleosol sequence consists of alternating yellowish-brown silts and more weathered light-brown argillaceous silts, corresponding to cyclical climatic variations. Occasional granular structures, grey-white fine carbonate nodules or pseudomycelia, brown-black ferromanganese dots and micro-sand wedges occur in the loess layers; and numerous plant roots or worm holes, white leached and cracked gypsum, and some discontinuous crack-filling clays with a spherulite structure occur in the paleosol layers. Small animal fossils, such as snail and rodent fossils occur sporadically.