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Radiocarbon dating of the Pleistocene/Holocene climatic transition across the Chinese Loess Plateau

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ABSTRACT

The magnetic susceptibility (MS) of Chinese loess deposits is extensively used to reconstruct climate changes from centennial to earth orbital time scales. The approach assumes that the MS is sensitive to the variations of the Asian Summer Monsoon (ASM), and thus that changes in MS are synchronous across the Chinese Loess Plateau. However, this inference has not been fully confirmed due to the limitations of both chronological control of Chinese loess sequences and the climatic proxies of the ASM. Here, we present the results of radiocarbon dating of the shifts in the oxygen isotopic composition of fossil land snail shells ($\delta^{18}O_s$) and in MS during the Pleistocene/Holocene transition at various sites in Chinese Loess Plateau. The results show that the age of shift in MS at Pleistocene/Holocene transition at Mangshan, Heshui, and Huanxian sections is 10.43 ka, 8.55 ka, and 7.13 ka BP, respectively. Thus, the shift is time-transgressive with age decreasing from southeast to northwest across the plateau. However, the $\delta^{18}O_s$ record, which is directly related to the precipitation delivered by the ASM, is not significantly time-transgressive, indicating that the ASM strengthened almost simultaneously across the plateau. We suggest that the time-transgressive nature of the shifts in MS may result from the low amplitude of the ASM strengthening during the Pleistocene/Holocene transition. Overall, our results demonstrate a regional difference in the insensitivity of MS to low amplitude climatic changes, and they challenge the previously-held assumption that the ages of climatic boundary based on MS stratigraphy are time-equivalent in Chinese loess.

1. Introduction

The thick loess-paleosol sequences of the Chinese Loess Plateau (CLP) provide an unrivalled continuous terrestrial record of climatic change extending back to over 22.0 Ma (Guo et al., 2002). The records from climatic proxies, such as the magnetic susceptibility (MS) and the sediment grain-size distribution of Chinese loess, have been widely used to reconstruct and interpret the dynamics of global and regional climatic change (An, 2000; Balsam et al., 2005; Derbyshire et al., 1995; Ding et al., 1995; Guo et al., 1996; Hao et al., 2012; Porter and Zhisheng, 1995; Sun et al., 2006). Much or all of this work is based on the chronologies established by correlating the MS record or grain-size distributions of loess with the astronomically tuned oceanic $\delta^{18}O$ record (Imbrie et al., 1984; Martinson et al., 1987). The methods used include proxy-based (Kukla et al., 1988), statistical correlation to the $\delta^{18}O$ record (Bloemendal et al., 1995), independent astronomical tuning (Ding et al., 2002), and direct correlation to the $\delta^{18}O$ record (Balsam et al., 2005). These methods are based on two key assumptions: 1) the loess records are continuous and highly resolved, and the resolution of the climate signals has not been significantly impacted by post-depositional diagenesis; and 2) the major changes inferred from the proxy records (e.g. the MS) are synchronous not only within the CLP, but also with those of the marine oxygen isotope record. However, recent work, such as the chronological studies based on Optically Stimulated Luminescence (OSL), challenge the validity of these two assumptions (Lai and Wintle, 2006; Lu et al., 2006; Stevens et al., 2006), especially during the Pleistocene/Holocene transition.

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The results of OSL dating of loess sequences at Beiguoyaun, Xifeng, Shiguanzhi, and Huanxian sites indicate that sedimentation was episodic at suborbital time scales, and that unconformities, cessation of eolian deposition, and mixing of sediments are common (Lu et al., 2006; Stevens et al., 2006). Discontinuities within Chinese loess sequences are also evidenced by welding and truncations of paleosols, erosion surfaces (Derbyshire et al., 1997), and wind deflation (Zhengtang and Dongsheng, 1996). The OSL age of the S0/L1 boundary defined by the MS shift at Xifeng and Shiguanzhi (ca. 20 ka) indicates a significant pedogenic overprinting of the late glacial loess (Stevens et al., 2006). Similar post-depositional diagenesis has also been detected at the Beiguoyaun and Yuanbao sites (Lai and Wintle, 2006; Stevens et al., 2007). With regard to the second assumption, the Pleistocene/Holocene boundary defined by a rapid shift in MS is dated at around 10.5 ka, 8.5 ka and 7.5 ka in the Yaoxian, Jingchuan, and Huanxian sections, respectively, indicating that the boundary is time-transgressive across China (An et al., 2000; He et al., 2004). This evidence indicates that previous conclusions about the timing and nature of climatic and environmental changes during the Pleistocene/Holocene transition inferred from Chinese loess records need to be reassessed.

Given the discontinuous nature of loess sedimentation, it has been suggested that independent dating is the only means of obtaining an effective chronology for determining the history of depositions and for climatic reconstruction (Lu et al., 2006; Stevens et al., 2006). However, the occurrence of post-depositional diagenesis of loess indicates that the use of climatic proxies that are relatively unaffected by the vagaries of sedimentation and pedogenic diagenesis, is equally important. This is because it is difficult to separate the signals of spatially-synchronous pedogenic processes from those of long-term post-depositional diagenesis by absolute dating alone. The coupled radiocarbon dating and analysis of the oxygen isotopic composition of fossil land snails ($\delta^{18}O_s$) has significant potential for establishing an accurate chronology of loess accumulation and climate history, for two reasons: 1) $\delta^{18}O_s$ is often directly related to the regional precipitation during the interval when the snails are alive (Balakrishnan et al., 2005; Leng et al., 1998; Liu et al., 2006; Zanchetta et al., 2005); and 2) the combined radiocarbon and $\delta^{18}O$ analysis of land snails excludes the possibility of a phase difference between the dating material and the climate proxy. However, to the best of our knowledge, no previous study has used this approach to determine the timing of climatic changes during the Pleistocene/Holocene transition on the CLP.

Here, we present the results of the first coupled analysis of the radiocarbon and oxygen isotopic compositions of land snail shells collected from three loess sequences, spanning the main part of the CLP. Our main aims are to characterize and date the changes in the ASM across Pleistocene/Holocene transition, and to provide fresh insights into the nature of climate changes across Chinese Loess Plateau.

2. Materials and methods

The three study sites, Mangshan, Heshui, and Huanxian, are located along a southeast-northwest transect, which spans the steepest climatic gradient across the CLP, as well as significant differences in the distance to the moisture sources of the Asian Summer Monsoon (Fig. 1). The Mangshan section is located on Mangshan Yuan (34.9603 N, 113.2675 E, 255 m), north Henan Province. Mangshan Yuan is a small plateau consisting of eolian loess, which is presumed to have been the most southeastern part of the Loess Plateau before it was separated by the Yellow River (Jiang et al., 2007). The site has a mean annual temperature (MAT) of ~14.0 °C and a mean annual precipitation (MAP) of ~640 mm. The sampled part of the section is composed of the whole of the Black Loams (1.3 m thick) and the upper 3.1 m of the Malan Loess. The Heshui section (35.8618N, 107.8814E, 1171 m asl) is in northwestern Heshui county, Gansu Province. The MAT and MAP of the area are ~10 °C and ~570 mm, respectively. The samples from this section spanned the whole of Black Loam (1.5 m thick) and upper 1.0 m of the Malan Loess. The northernmost section, Huanxian (36.6233°N, 107.2861°E), is situated in the northernmost part of the Loess Plateau near the city of Huanxian in Gansu Province. The MAT of the area is ~8.3 °C and the MAP is ~350 mm. The studied part of the section includes the whole of the Black Loam (1.5 m thick) and the uppermost 1.2 m of Malan Loess.

A total 95 of samples were collected from the 3 sections at a 10-cm interval for MS measurements. At the same time, soil samples of more than 10 kg weight (range: 10–30 kg) were obtained at a 10-cm interval for collecting fossil land snails. After wet sieving, shells of *Cathaica*, which can provide accurate radiocarbon ages (Xu et al., 2010, 2011), were picked out for ^{14}C dating and oxygen isotope analysis. To reduce the possible influence of diagenesis, only well-preserved samples (whole shells) were collected. In addition, our previous studies showed that the measured oxygen isotopic composition of snail shells from the Chinese Loess Plateau attains a stable value with the analysis of an increasing number of individual shells (Liu et al., 2006). Therefore, only samples with more than 7 fossil shells were selected for the radiocarbon dating and stable oxygen isotope analysis. At the same time, a total of 15 samples of modern living snails, each of which consisted of more than 5 shells, were collected from the studied areas to establish a regional baseline value of modern $\delta^{18}O_s$.

The samples of both fossil and living snail shells were sonicated repeatedly until the water was clean. The shells were then viewed under an optical microscope to remove any remaining macroscopic contamination. Then, the samples were reacted with 6% NaOCl for 48–72 h to remove organic matter, washed repeatedly, and sonicated for 5–10 min to remove any remaining adhering material. The cleaned samples were then washed with 0.01 HCl to remove adhering carbonates, rinsed with distilled water, and dried in a vacuum oven overnight at 70 °C. Finally, the dried samples were ground into 150-mesh powder. To further assess the possible impact of post-depositional diagenesis, a portion of the fossil samples was used for mineral phase analysis by X-ray diffraction (XRD). Only samples without aragonite-calcite transformation, which indicates either no or negligible diagenetic effect (Xuefen et al., 2005), were used for radiocarbon dating and oxygen isotopic analysis. A total of 20 fossil samples were analyzed from the three sites (9 from Mangshan, 6 from Hesui, 5 from Huanxian).

Each powdered fossil snail sample was split into two portions. One portion was converted to CO_2 by combustion in vacuum and reduced to graphite at a temperature of 525 °C (Getachew et al., 2006), and then sent to the Accelerator Mass Spectrometry (AMS) facility of Peking University for ^{14}C analysis. The second portion of the fossil samples, as well as the powder of modern snail shells, was converted to CO_2 using 100% phosphoric acid in a vacuum and the oxygen isotopic composition measured using a MAT 252 mass spectrometer. The isotopic data are reported in the conventional notation as per mil (‰) deviations relative to the PDB standard with an uncertainty (1σ) of 0.02 (‰). The MS of the three sections was measured in the laboratory on air dried samples using a Bartington Instruments MS2 susceptibility meter following the procedures of Liu (1985) and Kukla et al. (1988).

3. Results

The land snails that graze or aestivate on limestone substrates may incorporate older carbon into their shells by ingestion or