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Spatial variations in paleowind direction during the last glacial period in north China reconstructed from variations in the anisotropy of magnetic susceptibility of loess deposits

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ABSTRACT

Anisotropy of magnetic susceptibility (AMS) of Chinese loess is considered to be an effective tool for determining paleowind direction. However, the relationship between AMS and the paleowind direction is still a matter of debate. This study reports the results of AMS measurements of Chinese loess deposited during the last glacial period on slopes of varying slope angles and orientations. The sites are located on the Chinese Loess Plateau, in West Qinling, and on the eastern margin of Qilian Mountain. The results show that within the same region, magnetic lineations are clustered along similar orientations despite differences in slope exposure and slope angle, but that different regions exhibit different directions of magnetic lineation. These results suggest that the alignment of the magnetic grains during deposition of the eolian deposits was determined by air circulation rather than by water flow on the surface of the slopes, and therefore that the AMS of Chinese loess can be used to determine paleowind directions. In addition, our results indicate that the AMS of Chinese loess is determined mainly by the patterns of regional surface wind flow that occurred during dust accumulation rather than by the uniform pattern of large-scale atmospheric circulation. In addition, since wind direction is influenced significantly by regional topography, the AMS of Chinese loess may have the potential to detect significant changes in past regional topography.

1. Introduction

The spatially correlative Quaternary loess–soil sequences in the Chinese Loess Plateau, characterized by alternations of loess and paleosol layers, have long been considered to preserve some of the most detailed long-term records of changes in East Asian monsoon climate during the Quaternary (Liu, 1985). Moreover, the oldest loess–soil sequences have been dated back to the early Miocene or late Oligocene (Guo et al., 2002; Qiang et al, 2011). Generally, during cold/dry glacial periods, eolian dust was transported from northern source areas by the winter monsoon and deposited on the Chinese Loess Plateau, while during warm/humid interglacial periods eolian inputs decreased dramatically and paleosol formation was promoted by the increased precipitation generated by an enhanced summer monsoon (An et al., 1990; Liu, 1985). Given its relationship with patterns of monsoonal air circulation, the Chinese loess is also regarded as having the potential to provide records of paleowind direction on the Chinese Loess Plateau (e.g. An et al., 1991; Ding et al., 1995; Guo et al., 2000; Liu and Ding, 1998).

The anisotropy of the low-field magnetic susceptibility (AMS) is a rapid and precise tool for determining the fabric of rocks and sediments by quantifying the average preferred crystallographic and dimensional (or shape) orientations of magnetic grains (e.g. Tarling and Hrouda, 1993). Since loess deposits are accumulations of windblown dust, the AMS of loess is a sensitive indicator of the texture of the magnetic fabric generated by patterns of wind flow, and thus wind directions can potentially be inferred from AMS measurements.

The first AMS study on Chinese loess was done by Heller et al. (1987), and demonstrated that loess at the Luochuan section exhibited a uniform magnetic fabric and sedimentation rate through time. Later, Liu et al. (1988) suggested that AMS parameters could be used to evaluate the re-working of wind-blown sediments by water. Subsequently,

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Thistlewood and Sun (1991) revealed that the maximum axes of the AMS ellipsoids in both loess and paleosol samples from a cross section in loess near Xi'an were uniformly distributed along the WNW–ESE direction, and they suggested that AMS of loess may indicate the direction of the prevailing paleowind near ground level. This relationship between wind direction and the orientation of K_{max} (where K_{max} and K_{min} are the maximum and minimum principal axes of the AMS ellipsoid, respectively) was later confirmed by wind-tunnel experiments, which demonstrated a strong correlation with deviations less than 20° (Wu et al., 1998). Subsequent AMS studies on loess sequences in central Alaska (Lagroix and Banerjee, 2002, 2004), Poland and Ukraine (Nawrocki et al., 2006), Hungary (Bradák, 2009) and China (Huang and Sun, 2005; Liu et al., 2008; Sun et al., 1995; Wang et al., 2007) confirmed this correlation. For example, the AMS of the Alaskan loess faithfully records eolian transportation directions, which are associated with major paleoclimatic changes over the Alaskan region: the recorded wind direction shifted from a NW–SE to N–S direction from glacial to interglacial periods, respectively (Lagroix and Banerjee, 2002).

However, despite the foregoing there are still areas of disagreement about the relationship between AMS and the paleowind direction. For example, the work of Zhu et al. (2007) indicated that K_{max} is chaotically distributed and cannot be used to determine paleowind directions at three loess profiles on the Chinese Loess Plateau; and similar phenomena were observed in loess–soil sequences at Kurtak in Siberia (Zhu, 2000), and at Luochuan in the Chinese Loess Plateau (Liu and Sun, 2012). In addition, in the case of the youngest loess deposits in Poland and Ukraine, it was concluded that the orientation of K_{max} did not reflect the prevailing paleowind directions (Nawrocki et al., 2006). Therefore these results seem to cast doubt on the fidelity of the AMS of loess as an indicator of paleowind direction.

Even in those studies in which consistent K_{max} orientations are observed there has still been debate about their interpretation. According to AMS studies on the loess in China (Huang and Sun, 2005; Liu et al., 2008; Sun et al., 1995; Wang et al., 2007), Alaska (Lagroix and Banerjee, 2002, 2004) and Hungary (Bradák, 2009), the orientation of K_{max} mainly reflects the transportation direction of eolian dust. Therefore in China the East Asian winter monsoon, which transports dust from northwestern desert areas, was considered to be responsible for the development of magnetic fabric in loess sequences. However Zhu et al. (2004) demonstrated that in the area southeast of the Liupan Mountains, the K_{max} of AMS is orientated in the NE–SW and NW–SE directions during glacial and interglacial intervals, respectively. The authors interpreted these results in terms of dust transport by the NE winter monsoon and moisture transport by the SE summer monsoon. Recently, Zhang et al. (2010) examined the AMS of three loess sections along an east–west transect in the Chinese Loess Plateau, and their results suggested that the East Asian summer monsoon, rather than the winter monsoon, played the dominant role in generating the imbrication of the magnetic grains and thus the development of the AMS.

In the present study, we firstly made AMS measurements of loess deposited during the last glacial period at six sections near Luochuan, central Chinese Loess Plateau. Samples were obtained from paleo-slopes with different slope azimuths and dip angles in order to test the ability of the AMS of the loess consistently to reflect the paleowind direction within a particular area. Subsequently we studied an additional four loess sections from various regions, including those on the Chinese Loess Plateau, in the West Qinling, and on the eastern margin of Qilian Mountain, and compared the results with those of previous studies, in order to provide additional insights into the climatic implications of the AMS of the Chinese loess.

2. Sampling and methods

The Chinese loess unit of the last glacial, L_1, is the eolian deposit most widely distributed in north China. It is yellowish in color and massive in structure, and can generally be subdivided into five sub-units, termed $L_{1\text{-}1}$, $L_{1\text{-}2}$, $L_{1\text{-}3}$, $L_{1\text{-}4}$ and $L_{1\text{-}5}$. $L_{1\text{-}2}$ and $L_{1\text{-}4}$ are weakly developed soils, and the others are typical loess horizons. Previous studies (Ding et al., 2002; Kukla, 1987; Lu et al., 2007) have shown that $L_{1\text{-}1}$ is correlated with MIS 2, $L_{1\text{-}5}$ with MIS 4 and $L_{1\text{-}2}$, $L_{1\text{-}3}$ and $L_{1\text{-}4}$ collectively with MIS 3. The L_1 loess is generally overlain by the Holocene soil, S_0, which is dark in color because of its relatively high organic matter content. Due to its rapid accumulation rate, the Chinese loess of the last glacial can be observed mantling deposits of differing ages and deposited on different geomorphological units, including the Chinese Loess Plateau and its surrounding mountains, and some alluvial flood plains. In addition, because the Holocene soil S_0 has typically been disturbed by agricultural activity, the last glacial loess is frequently exposed and constitutes most of the ground surface across the Chinese Loess Plateau and can be easily recognized in the field.

In this study, 10 loess sections of the last glacial on different paleo-slopes at different sites were studied (Fig. 1), including sites on the Chinese Loess Plateau, in the West Qinling, and on the eastern margin of Qilian Mountain. A total of 1107 block samples, oriented by magnetic compass in the field, were collected. The azimuths and dip angles of these paleo-slopes, where the loess was deposited during the last glacial period, as observed within the Luochuan (LC1, LC2, LC3, LC4) and Tongchuan (TC1) sections, can be defined by the underlying paleosol layers the parent material of which was usually formed by depositional processes and controlled by the local paleotopography. These angles are 115°∠14°, 140°∠30°, 60°∠24°, 40°∠20° and 240°∠13°, respectively; and those of the other sections, including Xihe, Dongwan, Xining and Tianzhu, are horizontal. In the laboratory, cubic specimens of 2-cm edge length were cut for AMS measurements.

Various techniques were used to determine the magnetic mineralogy of representative samples from these sections. Hysteresis loops were measured using a Princeton MicroMag 3900 Vibrating Sample Magnetometer (VSM) with a maximum magnetic field of 1 T. Saturation magnetization (M_s), saturation remanence (M_{rs}) and coercivity (B_c) were determined after correction for the paramagnetic contribution. Samples were then demagnetized in alternating fields (AFs) up to 500 mT and isothermal remanent magnetizations (IRMs) were imparted from 0 to 1.0 T, also using the MicroMag 3900 VSM. Subsequently, the saturation isothermal remanent magnetization (SIRM) (the IRM acquired at the maximum field of 1.0 T) was demagnetized in a stepwise direct current backfield in order to obtain the coercivity of remanence (B_{cr}).

The AMS of each sample was measured using a KLY-3S Kappabridge (Agico Ltd., Brno) with an automated sample handling system. Each sample was rotated through three orthogonal planes. The susceptibility ellipsoid was calculated using the least-squares method, and the anisotropy parameters of lineation (L), foliation (F), degree of anisotropy (P), and shape factor (T) (Jelinek, 1981) were obtained with Anisoft software using the statistical method of Constable and Tauxe (1990). All the experiments were performed in the Paleomagnetism and Geochronology Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences.

3. Results

3.1. Magnetic properties

After the removal of the paramagnetic contribution, hysteresis loops for most of the samples are almost closed above 0.3 T (Fig. 2a–f), which is consistent with the presence of a dominant ferrimagnetic phase (e.g., magnetite, maghemite). The IRM curves for most of the samples rise rapidly below 0.1 T and reach approximate saturation at about 0.3 T (Fig. 2g), which confirms the abundance of low-coercivity ferrimagnetic minerals such as magnetite and/or maghemite. The stepwise demagnetization of SIRM using a DC backfield also shows a moderately low coercivity of remanence (B_{cr}) for all samples, consistent with ferrimagnetic carriers (Fig. 2h). In the Day plot (Day et al., 1977), all samples