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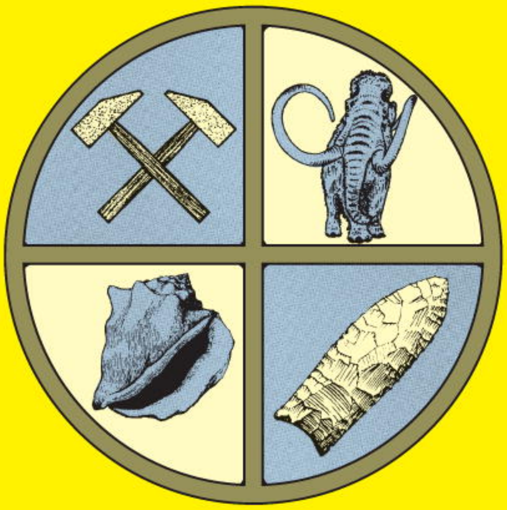

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Review of recent developments in mineral magnetism of the Chinese loess

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Abstract

Mineral magnetism of the Chinese loess has been investigated for more than 20 years. Although there is a consensus that the neoformation of fine-grained maghemite particles in the superparamagnetic (SP) and single-domain (SD) grain size regions accounts for the magnetic enhancement in the Chinese paleosols, quantitative retrieval of paleoclimatic signals in terms of rock magnetic proxies is still a subject of debate. The ambiguities arise from the inherent complexities of magnetic proxies as well as the multiple factors that control the pedogenic processes. Therefore, a better description of the magnetic assemblage (including its mineralogy, grain size distribution and stoichiometry) of two distinct origins (pedogenic and eolian) can help us better understand mechanisms behind variations in magnetic proxies at different timescales, in order to link them to the paleoclimatic processes. This review focuses on recent developments in loess magnetism, and carefully evaluates merits and limitations of rock magnetic proxies. Furthermore, several currently unsolved problems are addressed.

1. Introduction

The vast expanses ($\sim 5\times10^5\,km^2$) of ancient wind-blown dust (loess) preserved in northwest and north China ($\sim$100–300 m thick) (Fig. 1) are good archives for paleoclimate (Liu, 1985; Heller and Evans, 1995; Liu and Ding, 1998; Maher, 1998; An, 2000; Porter, 2001; Tang et al., 2003; Sun and Wang, 2005; Wang et al., 2005) and paleomagnetic variations over the last 2.5 million years (see reviews by Heller and Evans, 1995; Evans and Heller, 2001) and even considerably earlier (Guo et al., 2002). The dust from the Gobi and deserts in the north and northwest China began to accumulate in response to the major uplift of the Tibetan Plateau, and the associated change in Asian atmospheric circulation patterns (Li and Fang, 1999; An et al., 2001; Guo et al., 2002; Sun, 2002). Magnetostratigraphy (Heller and Liu, 1982, 1984, 1986) and detailed rock magnetic studies (Zhou et al., 1990; Heller et al., 1991; Maher and Thompson, 1991; Banerjee and Hunt, 1993; Hunt et al., 1995a; Evans and Heller, 1994; van Velzen and Dekkers, 1999a, b; Liu, 2004; Liu et al., 2003a, 2003b, 2004c; Deng et al., 2005, 2006) have been well documented over the last 20 years or so. As a result of these efforts, reliable records of paleomagnetic variations, which include major geomagnetic chrons (Heller and Liu, 1982) and geomagnetic excursions (Zhu et al., 1994b, 1999; Zheng et al., 1995; Fang et al., 1997; Pan et al., 2002), and paleoclimate changes, which include long-term climate variability (Heller and Liu, 1984, 1986; Kukla et al., 1988; Hovan et al., 1989; Ding et al., 2002; Deng et al., 2005, 2006) and short-term climate instability (Porter and An, 1995; Guo et al., 1996; Zhu et al., 2004; Liu et al., 2005a), have been successfully extracted for the last 2.5 Ma from Chinese loess/paleosol sequences.

Rapid progress in the study of Chinese loess was not made until the early 1980s. Heller and Liu (1984, 1986) firstly recognized that low-field magnetic susceptibility variations of the Chinese loess/paleosols correlated with deep-sea oxygen isotope records. This idea was further supported by the subsequent work by Liu (1985), Kukla et al. (1988), Hovan et al. (1989), Bloemendal et al. (1995),

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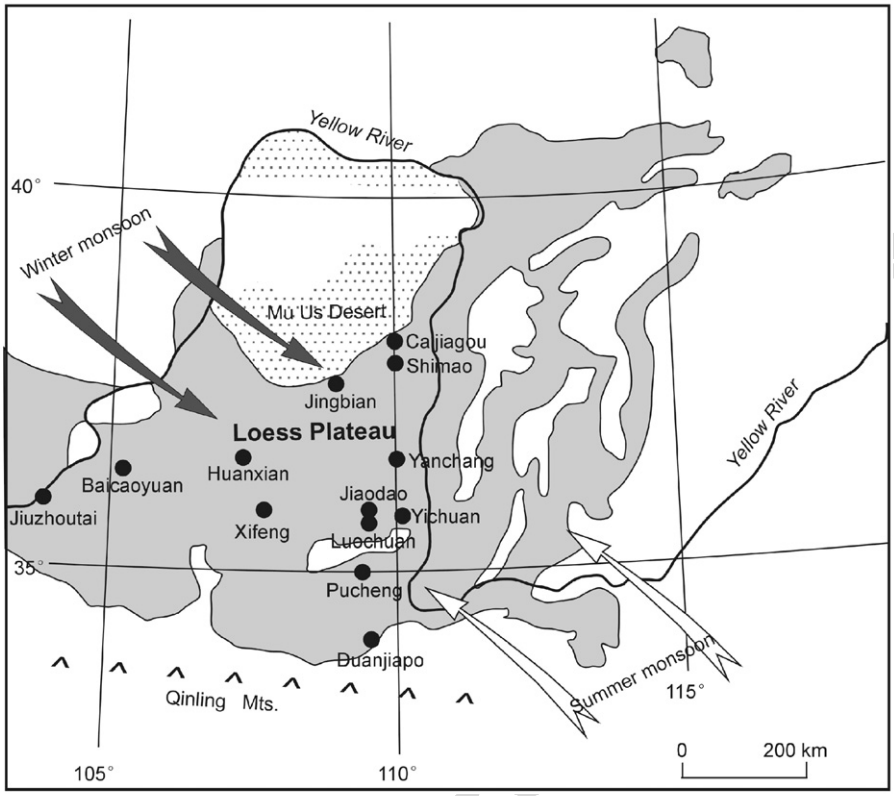

Fig. 1. Summary of the location of loess profiles discussed in this study. The Yellow River is the major river system in north China. The east–west trending Qinling Mountains are the traditional dividing line between temperate northern China and subtropical southern China. Solid and open arrows show the directions of winter and summer monsoons, respectively.

Heslop et al. (2000), Ding et al. (2002), Balsam et al. (2005), Deng et al. (2006) and Sun et al. (2006). Even though understanding of the dynamic links between variations in the local climate of the Chinese Loess Plateau and the global climate represented by the marine isotope records is still incomplete, evolution of the monsoonal climates of eastern Asia has been well determined, and is summarized by Liu and Ding (1998) and An (2000). For more general reviews of paleoclimatic indications of the Chinese loess/paleosol sequences, we refer the readers to Heller and Evans (1995), Liu and Ding (1998), Porter (2001) and Tang et al. (2003).

Mineral magnetism of Chinese loess/paleosol sequences, which provides important insights into climate change in the Plio-Pleistocene, and the history of the mechanism of remanence acquisition are two intensively investigated, and also hotly debated issues in loess magnetism. This review focuses more on the recent developments of the loess magnetism. Firstly, we address the magnetic assemblage (including mineralogy, stoichiometry, concentration, and grain size), which can be further decomposed into eolian and pedogenic fractions since the accurate determination of magnetic assemblages in sediments is a key issue in enviromagnetic and paleomagnetic study. Secondly, we discuss some widely employed mineral magnetic parameters and their magnetoclimatologic and paleomagnetic significance. Finally, we summarize several promising topics in both loess environmental magnetism and paleomagnetism, which may significantly constrain the problems mentioned above.

2. Magnetic assemblages in the Chinese loess

The key issue in environmental magnetism and paleomagnetism is to accurately determine the magnetic assemblage (including mineralogy, stoichiometry, concentration, and grain size) in samples. For the Chinese loess, we need to further decompose the magnetic assemblage into eolian and pedogenic fractions.

2.1. Ferrimagnetic phases

The ferrimagnetic (FM) assemblage in the Chinese loess consists of a mixture of eolian coarse-grained magnetite and low-Ti titanomagnetite (Maher and Thompson, 1992), and pedogenic fine-grained FM minerals (Zhou et al., 1990; Maher and Thompson, 1991, 1992; Verosub et al., 1993). The grain size of the fine-grained particles is mainly located in the superparamagnetic (SP) + single-domain (SD) region, and the corresponding magnetic phase is maghemite (Fine et al., 1993; Verosub et al., 1993; Heller and Evans, 1995; Deng et al., 2000, 2001; Liu et al., 2003a; Chen et al., 2005) rather than magnetite because these pedogenic FM particles with high surface to volume ratios are eventually oxidized into maghemite regardless of their initial states (magnetite or maghemite) (van Velzen and Dekkers, 1999a; Liu et al., 2003a, 2004c)

Initially, the enhanced susceptibility of paleosols was attributed to the ultrafine SP (<20−25 nm) maghemite (e.g., Zhou et al., 1990). However, subsequent results revealed that SD maghemite particles may play a dominant role in controlling the magnetic enhancement because they comprise a much higher volume fraction than the SP fraction although both of them co-vary with the degree of pedogenesis (Eyre and Shaw, 1994; Florindo et al., 1999; Deng et al., 2004; Liu et al., 2004c). Liu et al. (2004c) estimated that SD particles contribute more than half of the enhanced magnetic susceptibility of paleosols.

The grain size distribution (GSD) of the pedogenic SP + SD particles is fairly uniform (Forster et al., 1994; Forster and Heller, 1997; Maher et al., 2003b; Liu et al., 2004e, 2005c), and appears almost independent of the degree of pedogenesis (Fig. 2) (Liu et al., 2004e, 2005c). On the basis of the Neél theory, Liu et al. (2005c) constructed a more quantitative GSD model for the pedogenic particles in the Chinese paleosols. Their results confirmed a continuous GSD of the pedogenic particles with a maximum concentrated just above the SP/SD threshold (~22.5–25 nm for maghemite) (Fig. 2d). Note that the GSD above this threshold is extended by assuming a log-normal distribution of pedogenic magnetic particles. Therefore, the magnetic enhancement of paleosols is mainly determined by changes in the concentration instead of the grain size of the pedogenic particles. Because the dominant grain size of pedogenic particles is just above the SP/SD threshold, thermal agitation has efficiently decreased their room-temperature coercivity forces. Therefore, the more pedogenically altered units have relatively lower bulk coercivity values (Heller and Evans, 1995; Fukuma and Torri, 1998; Maher and Thompson, 1999; Evans and Heller, 2001; Deng et al., 2005).

Because the GSD of pedogenic particles is fairly consistent, the conventional grain size proxy, e.g., the ratio of ARM/SIRM (ARM, anhysteretic remanent magnetization; SIRM, saturation isothermal remanent magnetization) mainly reflects the changes in the concentration of these pedogenic SD particles, instead of changes in the GSD. With an increasing degree of pedogenesis, the

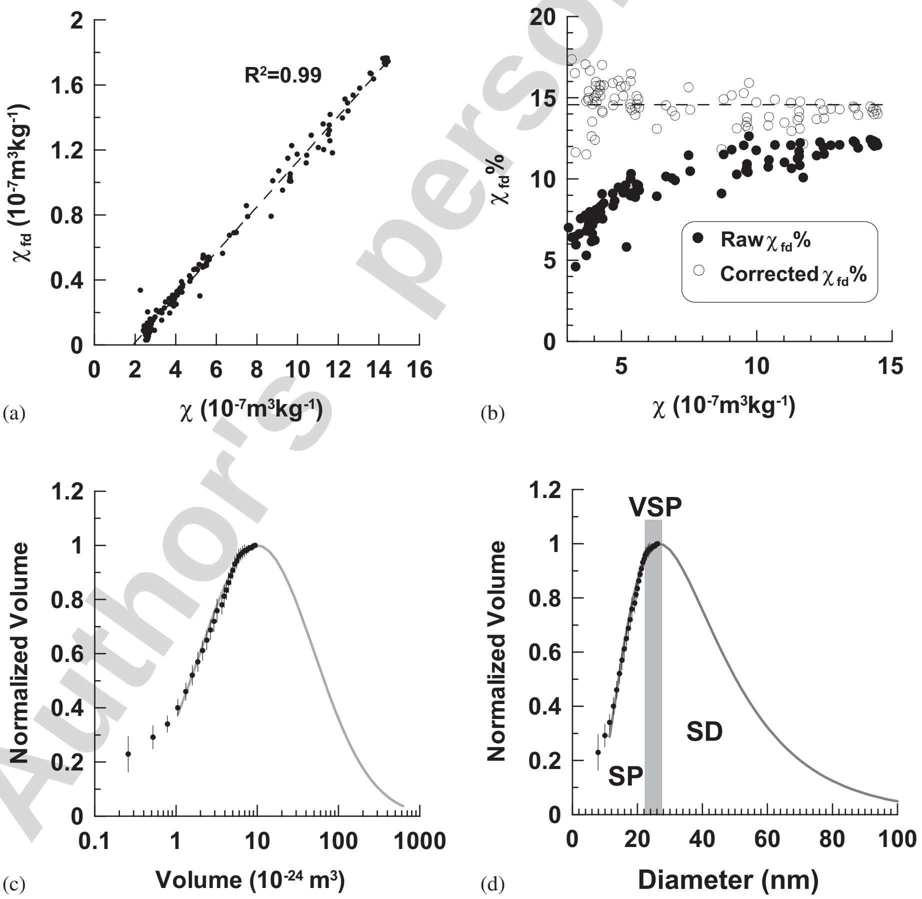

Fig. 2. Plots of χ_{fd} (a) and χ_{fd}% (b) versus χ (Liu et al., 2004e). Grain size distribution of pedogenic SP particles in volume (c) and diameter (d) (Liu et al., 2005c). The dashed line in (a) is the linear trend with $R^2 = 0.99$. The solid and open circles in (b) represent the raw χ_{fd}% and the corrected χ_{fd}%, respectively. The corrected χ_{fd}% is calculated by removing the effects of the eolian inputs defined by χ_0. The vertical bars in (c) and (d) show the error bar of the volume estimation calculated from six representative paleosol samples. The gray bar in (d) marks the viscous SP (VSP) grain size region around 22.5 nm for maghemite. Above and below VSP are the stable SD and 'true' SP grain size regions. The measured data is fitted by a log-normal distribution and is extended into the SD grain size region.

concentration of SD particles increases, and thus the overall grain size of the mixture of pedogenic SD particles and the eolian coarse-grained pseudo-single domain/multi-domain (PSD/MD) magnetic particles become finer, resulting in an increase of ARM/SIRM. This conclusion can be further supported by the linear correlation between ARM and SIRM in the Chinese loess/paleosols (Liu et al., 2004d; Deng et al., 2005).

Although pedogenic processes involve multiple factors, e.g., temperature, precipitation, organic matter, Eh, pH, etc., the uniform GSD of SP particles in Chinese paleosols suggests that only one or a few of them controls the GSD of pedogenic magnetic particles. Orgeira et al. (2003) showed that the GSD of pedogenic SP particles in Argentina loess/soils seems also to be irrelevant to the degree of pedogenesis, but has a GSD different from that of the Chinese loess, indicating that the exact GSD in a certain region is indeed controlled by the environment. So far, no conclusions can be made about the precise factor controlling the GSD, and further comparison of the pedogenic environments between these two different regions could account for the corresponding big differences in GSD.

In contrast to the fine-grained pedogenic particles, the eolian coarse-grained magnetite/titanomagnetite has much higher coercivity values because of the high internal stress caused by the mismatch of the unit cell between the maghemite rim and the magnetite core (van Velzen and Dekkers, 1999a; Liu et al., 2003a, 2004c). This high internal stress can be released by thermal treatment and loess samples show a sharp decrease in coercivity at ~150 °C. Liu et al. (2004b) heated loess samples in an air environment to different temperatures. Even for the 700 °C thermal treatment, the sample still shows a detectable Verwey transition (Fig. 3a) and the dominant peak of the first-order derivative ($\mathrm{d}J/\mathrm{d}T$) occurs at about 120 K, corresponding to stoichiometric magnetite (Figs. 3b and c). Moreover, the absolute value of the derivative gradually decreases when the treatment temperature is above 300 °C (Fig. 3d), indicating that the size of the magnetite core is gradually diminished, but is always in a stoichiometric state.

The degree of low-temperature oxidation (LTO) is more controlled by both grain size and the depositional environment. For example, PSD magnetite particles have a higher degree of oxidation than MD particles, and pedogenic processes favor a higher degree of LTO (Liu et al., 2003a). Because of the distinctive coercivity spectrum, alternating field (AF) demagnetization has been proposed to clean the secondary chemical remanent

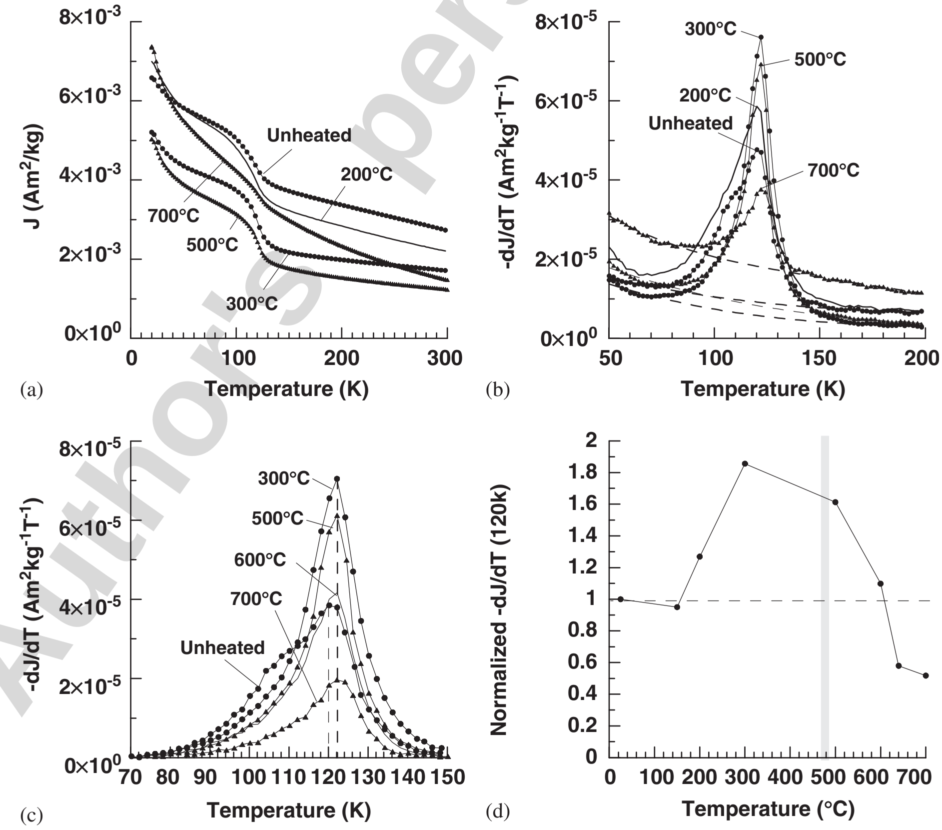

Fig. 3. Low-temperature measurements of a loess sample from S1L2 of the Jiuzhoutai section (after Liu et al., 2004b). (a) Low-temperature thermal demagnetization of SIRM, (b) first-order derivative of LTD-SIRM. Dashed lines are the third-order polynomial trends fitted to the data between 50–70 K and 150–300 K avoiding the effects of Verwey transitions, (c) background-corrected first-order derivative of LTD-SIRM and (d) The maximum derivatives in (c) of the thermal products at different elevated temperatures.

magnetization (CRM) carried by the pedogenic particles from the primary detrital remanent magnetization (DRM) carried by the eolian particles (Liu et al., 2005a).

2.2. Antiferromagnetic phases

The magnetic properties of antiferromagnetic (AFM) minerals (hematite and goethite) in the Chinese loess/paleosols have been less studied mainly because of their intrinsically weak magnetism, about two-orders of magnitude less than magnetite/maghemite. This obviously creates difficulties for their quantification by magnetic means.

The existence of hematite/goethite (Hm/Gt) has been proven in the Chinese loess by thermomagnetic techniques (Heller et al., 1991; Liu et al., 2004a), X-ray diffraction (XRD) (Zhu et al., 1994a, b; Deng et al., 2000; Liu et al., 2003a; Chen et al., 2005), and Mössbauer spectroscopy (Vandenberghe et al., 1992). Among the magnetic techniques, high-field isothermal remanent magnetization (HIRM) is the most common approach for detecting and estimating the AFM minerals. The HIRM parameter was defined as $0.5\times(\mathrm{SIRM}+\mathrm{IRM}_{-300\mathrm{mT}})$ (Thompson and Oldfield, 1986). The symbol $\mathrm{IRM}_{-300\mathrm{mT}}$ represents the remanent magnetization obtained by first saturating the sample in a field of 1.5 T, and then applying −300 mT field to reverse the SIRM contributed by magnetite/maghemite. However, this method is not always successful especially when the FM background is high. Liu et al. (2002) designed a new technique named M_{fr} to determine semi-quantitatively the variations in the absolute concentration of hematite and goethite. By applying this technique to a complete glacial/interglacial cycle (including S1L2, S1S3 and the upper part of L2, where L and S denote the standard stratigraphic nomenclatures for the loess and paleosol units, respectively, and numbers represent the corresponding stratigraphic sequence. For example, L2 and S1L2 represent the loess unit 2 and the sub-loess unit 2 within the paleosol unit 1, respectively (Kukla and An, 1989). Liu et al. (2002) showed that the concentration of AFM minerals is positively correlated to the degree of pedogenesis, on the basis that paleosols contain more hematite + goethite than loess. However, this method cannot distinguish contributions of hematite from those of goethite.

Recently, Ji et al. (2004) used first-derivative diffuse reflectance spectroscopy (DRS), a non-magnetic approach, to estimate the concentration of hematite + goethite from the Yanchang and Huanxian loess sections, in the central Chinese Loess Plateau. Their results further showed that the concentration of hematite + goethite was significantly enhanced in paleosols and that the Hm/Gt ratio was shown to be a good proxy for monitoring the long-term variations in the summer monsoon. Thus, paleosols in the north Loess Plateau area, e.g., at Huanxian and Yanchang (Ji et al., 2004), exhibit a Hm/Gt ratio lower than those in the central and south plateau, where paleotemperature and paleorainfall were higher than those of the regions to the north (Ji et al., 2001). A second-derivative DRS-chemical analysis study carried out on the Chinese loess by J. Torrent et al. (unpublished results) has shown substantially higher changes in the Hm/Gt ratio as a result of pedogenesis than those reported by Ji et al. (2004), probably because the latter authors used commercial pigment-grade Hm, which differs in reflectivity from most "soil hematites" (because of particle size and crystallinity). In contrast, the former authors used a wide range of natural soil samples and sediments, which contained goethite or goethite and hematite (estimated mainly by a combination of differential XRD and chemical analysis) to construct a calibration curve.

Liu (2004) constructed low-temperature dependence of HIRM curves for selected loess and paleosol samples to (semi-)quantitatively separate the contributions of hematite and goethite to the HIRM. The low-temperature behaviors of hematite and goethite differ. Goethite sharply increases its remanence (e.g., HIRM, SIRM) intensity by ~200–300% during cooling (e.g., France and Oldfield, 2000; Maher et al., 2004). In contrast, hematite decreases its remanence intensity because of the Morin transition. However, for natural hematite samples, the Morin transition is generally depressed due to the small grain size and substitution by foreign ions (Dunlop and Özdemir, 1997). Liu (2004) showed that the rate of increase of HIRM is higher for loess samples than for paleosol samples, indicating that in loess goethite contributes more to the 300 K HIRM than in paleosols. Assuming the Al-substitution of goethite in loess and paleosols is identical, for both loess and paleosol, hematite appears to be more abundant than goethite. In addition, loess units have a relatively higher goethite concentration than paleosols.

3. Understanding magnetic proxies

3.1. Frequency-dependent magnetic susceptibility

The magnetic susceptibility of SP particles in the transition zone from SP to SD is frequency-dependent on laboratory timescales (Stephenson, 1971; Mullins, 1977; Maher, 1986, 1988). For example, particles in the SP state can be blocked (in the SD state) at a higher frequency, resulting in lower susceptibility than when measured at a lower frequency. Thus, $\chi_{\mathrm{fd}}\%$, defined as $(\chi_{\mathrm{lf}}-\chi_{\mathrm{hf}})/\chi_{\mathrm{lf}}\times 100\%$ (where χ_{lf} and χ_{hf} are susceptibility measured at dual frequencies), can be used to characterize the contribution of SP particles (Maher, 1986; Heller et al., 1991). Note that in these references, this parameter has also been named as F-factor (Heller et al., 1991), FD% (Maher, 1986), χ_{fd}, and $\Delta\chi$ (Bloemendal and Liu, 2005). In this paper, χ_{fd} and $\chi_{\mathrm{fd}}\%$ represent the absolute ($\chi_{\mathrm{fd}}=\chi_{\mathrm{lf}}-\chi_{\mathrm{hf}}$) and relative behavior of frequency-dependent susceptibility, respectively.

Zhou et al. (1990) found that there is a positive correlation between χ and $\chi_{\mathrm{fd}}\%$, i.e. paleosols have higher

χ_{fd}% than loesses. Later, Heller et al. (1991) examined the long-term variations of χ_{fd}% over the last 2.5 Ma for Xifeng (central Loess Plateau with a higher degree of pedogenesis) and Baicaoyuan (western Loess Plateau with a lower degree of pedogenesis). Loess units have χ_{fd}% values of 0–4%. With increasing the bulk susceptibility, χ_{fd}% is positively correlated with bulk susceptibility and eventually saturates at ~10% when the bulk susceptibility is higher than 150×10^{-5} SI. Therefore, it seems that χ_{fd}% can be used as an index to reflect the formation of pedogenic particles only when its value is larger than ~5%, but less than ~10%, because χ_{fd}% is roughly linearly correlated to the bulk susceptibility. Below 5%, effects of the eolian background are significant, and above 10%, χ_{fd}% gradually saturates. On this basis, χ_{fd}% has been used as a proxy for the intensity of pedogenesis (Liu et al., 1990) and further used to determine long-term variations in the Asian summer monsoons (Chen et al., 1999; Deng et al., 2005).

However, more fundamental studies on the physical mechanism of χ_{fd}% showed that χ_{fd}% is controlled by both the GSD of SP+SD particles (Worm, 1998; Worm and Jackson, 1999), and by the relative concentration of SP+SD and PSD/MD particles (Liu et al., 2003a). For example, without the effects of PSD/MD particles, χ_{fd}% values are inversely related to the width of the GSD (Worm, 1998; Worm and Jackson, 1999). For SP+SD grains with a fixed GSD, χ_{fd}% is positively correlated to the concentration of SP+SD particles.

On the basis of the Neél theory and low-temperature variations of χ_{fd}%, Liu et al. (2005c) confirmed that pedogenesis produces an almost constant GSD for pedogenic particles and the GSD is irrelevant to the degree of pedogenesis. Therefore, the saturation χ_{fd}% for mature paleosols just simply indicates that the GSD of pedogenic particles is a constant. The positive correlation between χ_{fd}% and χ_{fd} for the intermediate paleosols reflects the fact that the susceptibility enhancement is caused by the increase of SP+SD particles, but not by the changes in the GSD of these fine-grained particles (Liu et al., 2004e). After removing the background susceptibility (~$2 \times 10^{-7}\,m^3\,kg^{-1}$) carried by eolian input prior to the pedogenic alterations, Liu et al. (2004e) showed that the corrected χ_{fd}% without the effects of eolian inputs is indeed a constant.

In summary, χ_{fd}% is not a direct proxy for the intensity of pedogenesis, especially in the case of paleosols in the central and eastern Loess Plateau which are characterized by a high degree of pedogenesis. In contrast, the absolute χ_{fd} is a faithful proxy for the concentration of viscous SP particles (in the SP/SD transition zone) and can be used to trace changes in the concentration of total pedogenic particles including both SP and SD particles if the GSD of pedogenic particles is a continuous distribution, as revealed by Liu et al. (2005c).

3.2. Magnetic susceptibility

Low-field magnetic susceptibility (χ) has been extensively used as a proxy of Asian summer monsoons recorded by the Chinese loess (Heller and Liu, 1984, 1986; Kukla et al., 1988; Heller et al., 1991) because it is fast, cheap and non-destructive. For standard Chinese loess profiles, paleosols always have higher χ than loesses. Overall, χ increases from northwest to southeast across the Loess Plateau, which is consistent with the pattern of increased reddening together with a decrease in the thickness of individual stratigraphic units and grain sizes (Ding et al., 2002). Moreover, changes in χ of the Chinese loess/paleosol sequences correlate well with variations in marine oxygen-isotope records (Heller and Liu, 1984, 1986; Kukla et al., 1988; Heslop et al., 2000; Balsam et al., 2005). This strongly indicates that paleoclimatic fluctuations have been reflected by χ, although with a non-linear or rather complicated relationship. In addition, χ has been used to quantitatively determine variations in the amount of paleorainfall (Heller et al., 1993; Maher and Thompson, 1994, 1995; Han et al., 1996).

Heller et al. (1991) first systematically investigated the carrier of magnetic susceptibility of the Chinese loess/paleosols. They confirmed the idea of Zhou et al. (1990) that the enhancement of χ is due to the neoformation of fine-grained ferrimagnetic particles through pedogenesis, and thus the total susceptibility is carried by both detrital and pedogenic magnetic components (Liu et al., 1990; Zhou et al., 1990).

To quantify contributions to susceptibility from eolian and pedogenic sources, Heller et al. (1993) combined the ^{10}Be concentration and χ from the Luochuan profile for the last 130 ka and estimated that ~45% and 75% of the magnetic susceptibility flux are produced by pedogenesis for S0 and S1, respectively. However, Maher et al. (1994) argued that both magnetic susceptibility enhancement and ^{10}Be retention in the Chinese loess/paleosol sequences are controlled by pedogenesis. Therefore, their estimations of the susceptibility flux by pedogenesis may be biased.

Unlike Heller et al., (1993) approach, the citrate-bicarbonate-dithionite (CBD) technique is a powerful method to dissolve the pedogenic fine-grained magnetic particles (Verosub et al., 1993; Sun et al., 1995b; Vidic et al., 2000, 2004; Deng et al., 2005). Verosub et al. (1993) argued that the bulk magnetic susceptibility of both paleosols and loesses is predominantly controlled by pedogenic components. However, this conclusion is true only for representative paleosols and the pedogenic susceptibility could have been overestimated because the CBD treatment can also dissolve small amounts of lithogenic magnetite particles with sizes larger than 1 μm (Hunt et al., 1995b). Nevertheless, the post-CBD susceptibility yields a good estimation of the lithogenic susceptibility, which is about $(1–2.5) \times 10^{-7}\,m^3\,kg^{-1}$ for the whole loess/paleosol sequence and decreases with depth (Verosub et al., 1993; Vidic et al., 2000, 2004; Deng et al., 2005). This value is consistent with the studies by Sun et al. (1995b),

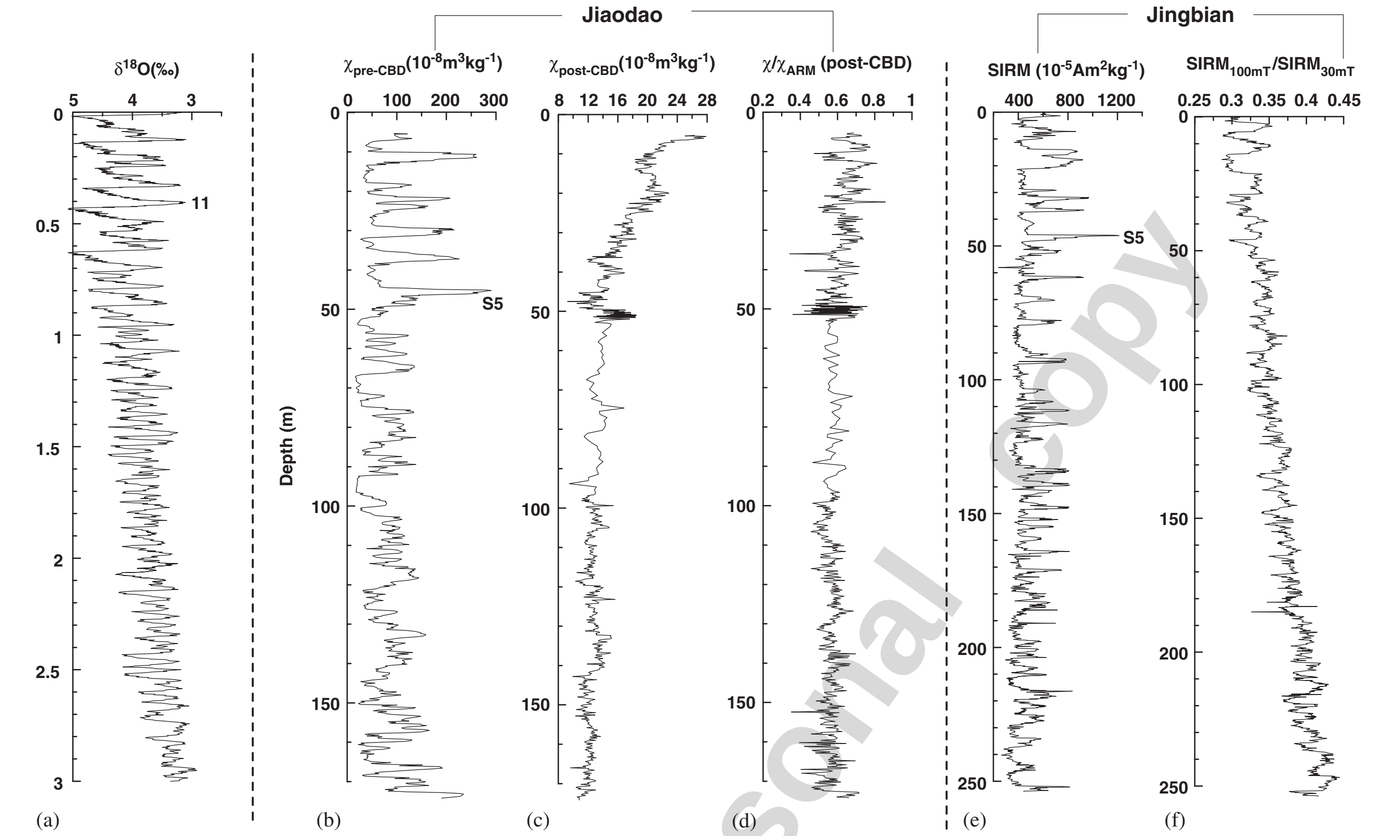

Fig. 4. Correlation of magnetic properties of the Jingbian and Jiaodao loess/paleosol sequence with the marine oxygen isotope record. (a) Stacked $\delta^{18}O$ record (Lisiecki and Raymo, 2005), (b) $\chi_{pre-CBD}$ of Jiaodao, (c) $\chi_{post-CBD}$ of Jiaodao, (d) post-CBD χ/χ_{ARM} of Jiaodao, (e) χ of Jingbian and (f) $SIRM_{100mT}$/ $SIRM_{30mT}$. Data in (b) and (d) are from Deng et al. (2005), and data in (e) and (f) are from Deng et al. (2006).

Hunt et al. (1995b), and Liu et al. (2004e). Vidic et al. (2000) put forward the view that the long-term down-section decrease in lithogenic susceptibility was caused by more intense or prolonged periods of weathering associated with the formation of the older paleosols. However, recent studies by Deng et al. (2005) showed that this down-section decrease in post-CBD susceptibility (Fig. 4c), a proxy for eolian signals, is accompanied by the down-core decrease in the grain size of eolian coarse-grained magnetite as indicated by decreases in χ/χ_{ARM} (Fig. 4d). Therefore, it may reflect changes in the strength of the eastern Asian winter monsoon. If so, higher lithogenic susceptibility is carried by coarse-grained eolian magnetite, which corresponds to a higher strength of the winter monsoon. The long-term increase in the source aridity is reflected by the ratio $SIRM_{100\,mT}/SIRM_{30\,mT}$ (Fig. 4f) (Deng et al., 2006). $SIRM_{100\,mT}$ and $SIRM_{30\,mT}$ are the residual remanence of SIRM after AF demagnetization at fields of 100 and 30 mT, and they are interpreted to be sensitive to the contributions of hematite and eolian coarse-grained partially oxidized magnetite, respectively. This ratio is more reliable for loess units because of the minor effects of pedogenesis. Clearly, the long-term decrease in $SIRM_{100\,mT}/SIRM_{30\,mT}$, particularly for loess units (Fig. 4f), coincides with the increase of marine $\delta^{18}O$ values (a cooling trend, Fig. 4a). This is probably due to the reduced formation of hematite at the source region due to colder climate.

It has been shown that the susceptibility enhancements are controlled more by the amount of paleorainfall than by paleotemperature (Heller et al., 1993; Maher et al., 1994; Han et al., 1996; Liu et al., 2005a), but this is probably valid more for spatial patterns than for the temporal patterns. By combining ^{10}Be and susceptibility measurements, Heller et al. (1993) deduced high rainfall values around 25 and 55 ka and a reduced rainfall of ~530 mm/yr in the interglacial period relative to the modern value of ~630 mm/yr for the Luochuan profile at the center of the Loess Plateau. Maher et al. (1994) constructed a transformation function directly between paleoprecipitation and the logarithm of χ for modern soils and then applied it to older units. To remove the effects of the lithologic components, Maher et al. (1994) simply used the difference in susceptibility of the B (χ_B, subsoil) and C (parent material, e.g., $\chi_C = \sim 2.5\times10^{-7}\,m^3\,kg^{-1}$ for the least pedogenically altered loess unit) horizons, and yielded the following climofunction:

$$P(mm/yr) = 222 + 199\log_{10}(\chi_B - \chi_C 10^{-8}\,m^3\,kg^{-1}).$$

Based on this equation, Maher et al. (1994) suggested the opposite to that pattern of Heller et al. (1993) in that the amount of paleorainfall during the last interglacial was much higher than the present value. Han et al. (1996) examined other 63 topsoil samples across the Loess Plateau and confirmed Maher et al. (1994) model. The positive correlation between magnetic susceptibility and rainfall has been further attested by the global data set in the temperate and warm temperate climate zones without preferential selection (Maher and Thompson, 1995) and data from the modern soils across the Russian Steppe (Maher et al., 2003a). Moreover, the Russian Steppe susceptibility/rainfall relationship matches that for the Chinese Loess Plateau, indicating a possibly consistent pedogenic model for these very different regions where rainfall controls the pedogenic processes.

In summary, susceptibility enhancements over the Chinese Loess Plateau and the Russian Steppe undoubtedly correlate with the amount of rainfall and can be a reliable paleoclimatic proxy. However, ambiguities arise when considering the long-term paleoclimatic variations due to the inherent complexities of magnetic susceptibility. Based on Maher et al., (1994) model, the amount of paleorainfall is the highest for S5S1. However, an inverse pattern has been proposed by Balsam et al. (2004). They documented a continuous decrease of hematite concentrations above S5, indicating an enhancement of precipitation. Therefore, the precipitation during S5 has to be lower than the modern value of about 620–650 mm/yr, and the possible amount is 350–450 mm/yr. The mass accumulation rate (MAR) recorded in deep-sea sediment core V21-146 by Hovan et al. (1989) seems to contradict Balsam et al., (2004) model. Hovan et al. (1989) reported an increasing trend of MAR since S5, reflecting "a trend toward greater aridity of the climate system in eastern Asia during the late Pleistocene epoch". More recently, Deng et al. (2006) also confirmed a trend of increasing aridity after 2.6 Ma, which indicates a drier process in the interior Asia over the entire Quaternary.

Such a discrepancy is caused by the non-unique relationship between magnetic susceptibility and the amount rainfall. Sun and Liu (2000) showed that there is no simple positive correlation between magnetic susceptibility and the degree of pedogenesis for the Cajiagou, Shimao and Pucheng loess profiles. By examining the paleosol unit 8 (S8) from three localities (Jingbian, Yichuan, and Duanjiapo) along a N–S transect in the Chinese Loess Plateau, Guo et al. (2001) found that the magnetic susceptibility in S8 at Duanjiapo is too low to sensitively reflect the degree of pedogenesis in this paleosol unit, and thus magnetic susceptibility alone is not suitable for paleoclimate reconstruction in Chinese loess/paleosol sequences, specifically for these units older than S5.

A model of Balsam et al. (2004) showed that the formation of hematite and ferrimagnets is not always in phase (Fig. 5). When the amount of rainfall exceeds a threshold, say, ~600–650 mm/yr, the concentration of hematite and goethite will be significantly reduced at a rate faster than that of ferrimagnets. This corresponds to the condition of loess/paleosols above S5 where there is higher susceptibility but a lower concentration of hematite and goethite. In contrast, when the amount of rainfall is below this threshold, an inverse pattern is observed. This could explain why loess/paleosols below S5 have higher concentrations of Hm/Gt, but lower susceptibility. Paleosol S5S1 thus corresponds to a special condition where the concentration of both Hm/Gt and ferrimagnets reach a maximum with the amount of rainfall about 600 mm/yr.

If Balsam et al's, (2004) conceptual model is correct, the paleosol unit S5S1 should be very sensitive to subtle changes in paleorainfall because slight fluctuations in paleorainfall could significantly change the soil-forming conditions. Therefore, it might be useful to investigate the magnetic properties of S5S1 along a NW–SE transect corresponding to a rainfall gradient. However, this is not supported by the spatial distribution of magnetic susceptibility for S5S1 constructed by Hao and Guo (2005). Their results show the S5S1 and S4 have very similar spatial distribution patterns of magnetic susceptibility.

We should note that the absolute value of χ of Chinese loess/paleosol sequences could also be affected by the initial eolian inputs and climatic factors in the depositional regions. For a relatively shorter period, e.g., during the Holocene or since the last glacial, the eolian inputs can be regarded as a constant, and thus susceptibility changes mainly reflect paleoclimatic fluctuations. However, for even longer periods, the effects of the eolian inputs are significant and cannot be neglected. For example, Vidic et al. (2000) and Deng et al. (2005) revealed a down-section decrease in the post-CBD magnetic susceptibility (an indicator of the lithogenic contribution). This trend is

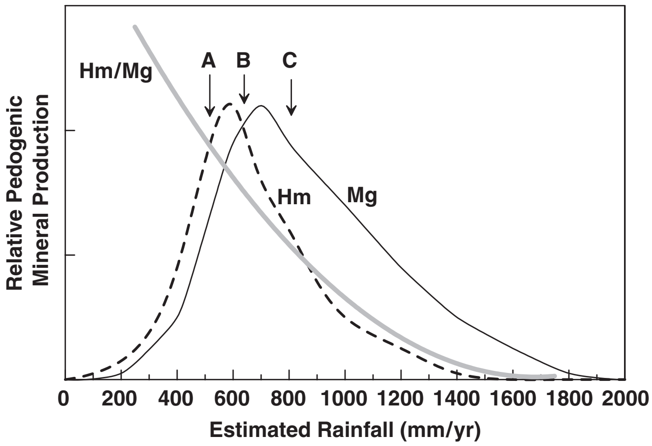

Fig. 5. A conceptual model showing the correlation between the relative pedogenic mineral production and the amount of rainfall (modified from Balsam et al., 2004). Hm and Mg represent hematite and magnetite, respectively. Arrow A points to the condition for units below S5 when rainfall is high enough to produce more hematite than magnetite. Arrow B represents the conditions for the peak S5, which is characterized by high concentrations of both hematite and pedogenic magnetite. Arrow C marks the condition for deposits above S5 when a sufficient amount of rainfall is available to significantly reduce the amount of hematite. The gray curve is the correlation between Hm/Mg and rainfall. Based on this model, Hm/Mg should be an excellent proxy to indicate the amount of rainfall. Further studies on modern soils are essential to test this relationship.

partially compatible with the trend for the maximum magnetic susceptibility above S5 to be much higher than below although the degree of pedogenesis is comparable for units just below and above S5, as revealed by measurement of Rb/Sr ratios (Ji et al., 2001).

Naturally, the maximum amount of pedogenic maghemite is determined by the total available iron in the eolian input, and prior to the saturation of pedogenesis, the observed amount of fine-grained maghemite is proportional to the degree of pedogenesis. Thus for constructing long-term paleoclimatic changes, a normalized parameter such as χ/χ_{eolian} (where χ_{eolian} is the susceptibility carried by eolian material prior to pedogenic alterations) will be possibly more suitable than χ alone (see section 4 for details).

In summary, the mechanism of the low susceptibility values of loess/paleosol units below S5 is not fully understood. Further studies combining both rock magnetic and geochemical proxies along a systematic NW–SE transect would be helpful.

3.3. Anisotropy of magnetic susceptibility (AMS)

AMS is a powerful tool for quantitatively determining the preferred average mineral orientation. Heller et al. (1987) evaluated the uniformity of the loess deposition rate at Luochuan in terms of AMS. More detailed studies by Clarke (1995) revealed four types of magnetic fabrics associated with alluvial reworking, the influence of a paleoslope, wind-deposited with no preferential wind direction, and wind deposited with a preferential wind direction. Later studies showed that the maximum principal axis of the loess AMS ellipsoids (K_{max}) can be used to determine the paleowind direction (Sun et al., 1995a; Thistlewood and Sun, 1995; Zhu et al., 2004). In addition, AMS parameters, specifically the inclination of K_{max}, can be used to evaluate the fidelity of the natural remanent magnetization (NRM) (Fang et al., 1997; Zhu et al., 2000).

The loess AMS is rather weak. To test the significance of such a weak AMS, Liu et al. (2005d) examined the field-impressed AMS behavior of representative loess/paleosol samples from the last interglacial and the penultimate glacial periods. Their results showed that the loess/paleosol samples initially have an oblate foliation and a weak magnetic lineation. The coincidence between the declination of K_{max} and the angle of the AF for the maximum lineation unambiguously demonstrates that the K_{max}-Dec record reflects the statistical distribution of the long-axis of the eolian coarse-grained magnetites, and thus the paleowind direction.

Loess and paleosol units were deposited during cold periods and were formed when summer monsoons prevailed over the Loess Plateau, respectively. Zhu et al. (2004) showed that temporal changes in the K_{max}-Dec can be directly teleconnected with paleoclimatic fluctuations over the North Atlantic and sub-polar regions during the last glacial–interglacial cycle. They further proposed that the paleowind direction during cold and warm periods defined by K_{max}-Dec clustered along NE-SW and NW-SE axes, respectively. Unlike K_{max}, K_{min} is more controlled by pedogenic fine-grained particles because the long-axis of these particles also align within the horizontal bedding plane and yield an "inverted" fabric (Liu et al., 2005d).

3.4. Hysteresis measurements

Hysteresis measurements provide information on magnetic mineralogy, grain size and the concentration of magnetic minerals, as well as the paramagnetic minerals in samples (Day et al., 1977; Roberts et al., 1995; Dunlop, 2002a, b). The shape of magnetic hysteresis loops of the Chinese loess/paleosols has been systematically examined by Fukuma and Torri (1998). For the loess and incipient paleosol samples with relatively low susceptibility and high ratios of AFM/FM, the broad loop is controlled by both AFM and FM minerals. With a further increase in pedogenic components, SP/SD maghemite particles gradually dominate the bulk magnetic properties, yielding much narrower loops. Therefore, the shape of hysteresis loops could also be an indicator of the degree of pedogenesis.

Correlations between different hysteresis parameters reveal different magnetic enhancement pathways for loess sediments from Tajikistan, Hungary and China (e.g., Forster and Heller, 1997; Maher and Thompson, 1999). Such differences are most probably caused by the mixing of the relative amounts of the original eolian mixture and pedogenic fine-grained magnetic particles.

The high-field susceptibility (χ_h) generally represents the susceptibility of paramagnetic minerals (χ_{para}). For standard Chinese loess/paleosol sequences, χ_h is also enhanced by an increasing degree of pedogenesis. Forster and Heller (1997) revealed a positive correlation between χ_h and the grain size fraction $<2\,\mu m$, and concluded that χ_h is controlled by the amount of clay minerals. However, AFM minerals (hematite and goethite) can also contribute to χ_h because of their high saturation fields. The enhancement of AFM minerals in paleosols has been confirmed by color studies (Ji et al., 2001; Vidic et al., 2004) and rock magnetic studies (Liu et al., 2004a; Bloemendal and Liu, 2005).

Another useful application of hysteresis parameters is to construct a Day plot (Day et al., 1977; Dunlop, 2002a, b) for inferring the domain states, and in turn estimating the average grain-size of magnetic minerals in a bulk sample. Overall, the magnetic assemblage in both loess and paleosols is located in the PSD grain size region, and is well clustered but slightly spread along the B_{cr}/B_c axis (Fukuma and Torri, 1998). The overall grain size of loess samples indicated by the Day-plot is somewhat coarser than that of paleosols. Liu et al. (2004b) found that LTO can significantly affect the coercivity of the coarse-grained eolian magnetite, and thus shifts the points of Day-plot right-upwards. Thus, caution is needed when interpreting the Day-plots of Chinese loess.

3.5. Temperature-dependent magnetic measurements

3.5.1. High-temperature magnetic measurements

Thermomagnetic measurements ($M_s \sim T$ and $\chi \sim T$) are conventional techniques for determining the magnetic mineralogy in terms of Curie temperature (T_c). $M_s \sim T$ has a simpler interpretation than $\chi \sim T$ because M_s is independent of grain size. Early studies showed that all loess/paleosol samples have a T_c of ~580 °C, indicating that the dominant mineral is stoichiometric magnetite (Heller et al., 1991; Liu et al., 1999; Maher et al., 1994; Zhu et al., 1994a, b, 1999). However, ambiguities apply to such conclusions because (1) the T_c of 580 °C does not guarantee that magnetite is the dominant phase; (2) magnetites revealed by the warming curves could either be of primary origin or be due to neoformation during heating. These ambiguities can be partly solved by stepwise cycle thermomagnetic analysis, which is also a useful approach for revealing mineralogical transformations during heating (Mullender et al., 1993; Deng et al., 2001).

Liu et al. (2005b) systematically investigated the mineral transformation during heating in an argon environment. They confirmed that susceptibility reductions between 300 and 350 °C are due to the transformation from fine-grained maghemite to hematite. However, the maghemite in loesses formed by the LTO has a much higher mineral inversion point at about 550 °C (Liu et al., 2003a), indicating that the eolian maghemite has a coarser size. de Boer and Dekkers (1996) found that the fractional decrease of M_{rs} after heating to 600 °C for natural maghemite is negatively correlated with grain size. Calibrated by their synthetic curve, the grain size of the eolian maghemite is about 200 nm.

3.5.2. Low-temperature magnetic experiments

Banerjee and Hunt (1993) proposed a low-temperature technique for quantifying the full SP contribution by utilizing the different thermal behavior of ferrimagnetic particles of different grain sizes. First, the sample was cooled in a zero field (ZFC) and acquired a 2.5 T IRM imparted at 10 K, then the sample was warmed up to 300 K also in a zero field. During such a process, PSD/MD magnetites sharply lose the majority of their remanences around the Verwey transition (~120 K). SP particles also lose their remanences but follow a more continuous trend when heating to 300 K due to a gradual unblocking process. In contrast, SD particles are almost temperature-independent. Thus the contribution of different grain size portions can be graphically separated. Later, Liu et al. (1995) revealed a positive correlation between the full SP magnetizations with the modern precipitation at six sites over the Loess Plateau with $R^2 = 0.9$.

However, several problems exist for this method. First, Liu et al. (2003a) argued that the gradual decay of remanence between 50 and 300 K reflects the unblocking of SP particles as well as the smoothly decreasing magnetic moments of maghemite and goethite. Therefore, the "full SP" magnetizations overestimate the true SP contributions. Second, the SP magnetization is determined by the choice of initial low-T IRM. For example, the initial remanence was imparted at 10 K with an applied field of 2.5 T by Banerjee and Hunt (1993) and at 77 K with an applied field of 0.3 T by Liu et al. (1995), respectively. Different experimental settings will yield different estimates although they may be positively correlated. Third, for PSD/MD magnetites in paleosols, the Verwey transition occurs in a wide temperature interval of 100–120 K (Liu et al., 2003a). Therefore, Liu et al. (1995) had underestimated the PSD/MD contributions and thus overestimated the SP contributions to the total magnetization. This is particularly important for samples, which have experienced a relatively low degree of pedogenesis. For example, the first two samples (in Fig. 3 by Liu et al., 1995) lay well below the linear regression line, supporting the idea that their SP magnetizations are overestimated.

Rather than using the graphical method, Liu et al. (2004a) mathematically separated the PSD/MD magnetization (named ΔJ_{TV}) from the SP background. (1) the first derivatives of the mass-normalized intensity of LT-SIRM were calculated to enhance the features of the Verwey transition; (2) the background was removed by subtracting the third-order polynomial fit between 50–70 K and 145–300 K to avoid the effects of the Verwey transitions. ΔJ_{TV} is caused by the eolian coarse-grained magnetite, which is very sensitive to the changes in the intensity of the winter monsoon. By applying this method to an interval including the top of L2, S1S3 and S1L2, Liu et al. (2004a) clearly revealed a downward propagating process of pedogenesis and then were also reliable to determine the authentic glacial/interglacial boundary, which has been obscured by the susceptibility boundary.

The maximum of the first-order derivative of low-temperature thermal demagnetization of the SIRM curve (LT-SIRM) can also be used to accurately determine the Verwey transition. Kletetschka and Banerjee (1995) showed that paleosols have a higher T_v than loesses, indicating magnetites in paleosols are more stoichiometric than in loesses. Based on this model, they further suggested that wild fires could have been a major factor for enhancing the magnetic susceptibility. However, Liu et al. (2003a) found that the apparent shifting of T_v to higher temperatures for magnetite in paleosols is caused by the suppression of the intensity at relatively lower temperatures. Liu et al. (2004b) further examined the changes in the Verwey transition by heating samples in an air atmosphere and confirmed that the magnetite core and the maghemite rim behave independently. Thus, for the natural samples, the highly suppressed but nearly stoichiometric Verwey transition (~120 K), is masked by a strong maghemite and SP background, indicating a high degree of LTO. In contrast, the broad Verwey transition peak and relatively large intensity drop for the loess indicates a lower degree of LTO.

More recently, Liu et al. (2005c) designed a low-temperature technique to quantify the exact GSD of the Chinese loess/paleosols by using the temperature dependency of χ_{fd} (defined as χ_{1Hz}–χ_{10Hz}, where χ_{1Hz} and χ_{10Hz} are AC magnetic susceptibility measured at 1 and 10 Hz, respectively). Assuming that shape anisotropy is dominant for the pedogenic maghemite, Liu et al. (2005c) showed that the dominant pedogenic magnetic grain sizes are just above the SP/SD threshold (~20–25 nm). Moreover, the GSD is almost independent of the degree of pedogenesis.

4. Factors controlling the long-term magnetoclimatology

The amount of pedogenic ferrimagnets depends on the amount of weatherable Fe-bearing minerals and the integral through time of temperature and moisture plus the combination of hydrological regime and temperature that determines the formation and dissolution of ferrihydrite, goethite, hematite, magnetite, and maghemite. To the first-order, the significant relationship between ferrimagnetic content and rainfall in the Chinese loess/paleosols is probably because the eolian inputs of loesses are relative uniform, and rainfall and temperature covary in this monsoonal region.

Maher et al. (2003b) examined the relationship between the degree of pedogenesis and the accumulation rate for a Holocene loess profile at the western edge of the Chinese Loess Plateau. With accurate OSL age controls, they found that the sedimentation rate is almost irrelevant to the degree of pedogenesis, and thus the development of soils seemingly correlates more to the availability of moisture at this region. However, this conclusion does not hold for the older paleosols. Vidic et al. (2004) tried to quantify effects of the degree of pedogenesis and the duration of pedogenesis. Their results show that the enhancement of magnetic susceptibility is at least partially controlled by the duration of pedogenesis for paleosols S1–S5, and thus is directly related to the sedimentation rate because higher sedimentation rate lowered the magnetic susceptibility.

Magnetic susceptibility can decline with time in a number of situations. Thus, Maher (1998) pointed out that soils can also lose iron during the weathering process or by subsequent reduction or chelation by organic compounds. Moreover, the neoformation of relatively large amounts of weakly magnetic minerals can also decrease the bulk susceptibility due to the dilution effect. By combining rock magnetism and geochemistry, Bloemendal and Liu (2005) revealed that the lowest part of S1 at Luochuan has suffered magnetic depletion because this layer has minima in Ca, Fe and all magnetic parameters, but a high Rb/Sr ratio, which is positively related to the degree of pedogenesis. By the same rationale, selective destruction of AFM minerals has also occurred within the uppermost part of S5 at both Duanjiapo and Luochuan. However, detailed comparison of the bulk susceptibility (dominated by pedogenic fine-grained maghemite) and HIRM (carried mostly by hematite and goethite) for paleosol unit S5 exhibits a complicated pattern (Figs. 6a

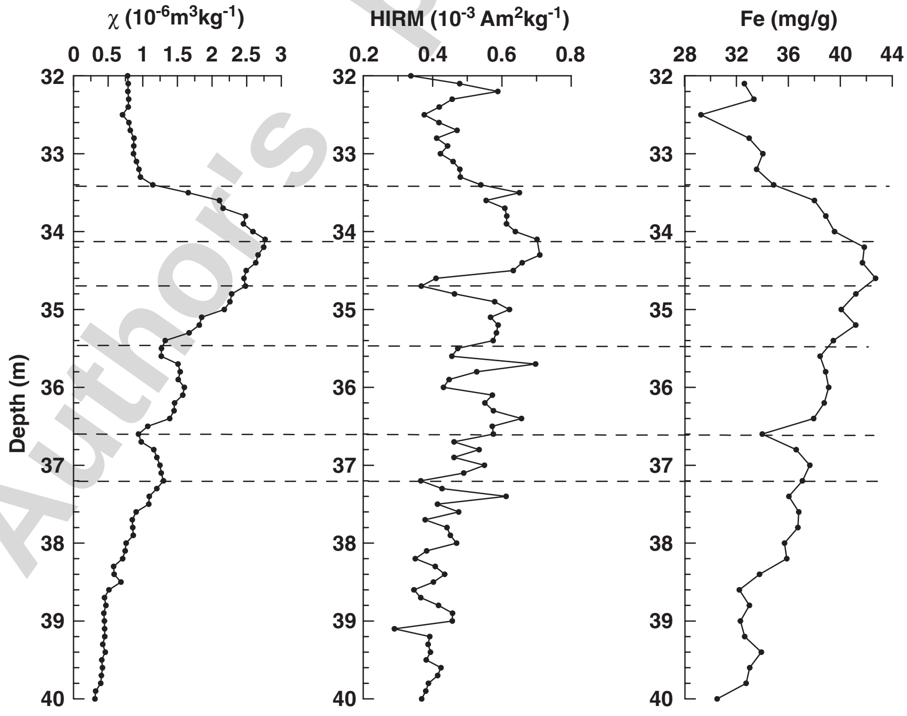

Fig. 6. Comparison of depth plots of χ (a), HIRM (b) and Fe (c) concentration for the paleosol unit S5 from Luochuan. Data from Bloemendal and Liu (2005). Note that the trend of HIRM resembles that of the bulk susceptibility, but is superimposed by high-frequency fluctuations.

and b). Therefore, caution is needed in establishing the exact transformation relationship between ferrimagnetic and AFM minerals in paleosols. The high-frequency fluctuations of HIRM could either reflect the paleoclimatic instability during S5 or be caused by the inherent limitations of HIRM (Liu et al., 2002). Instead, the bulk susceptibility seems to positively correlate to the iron concentration in samples (Fig. 6c).

The use of the Rb/Sr ratio as an indicator of the degree of pedogenesis has limitations, especially when $CaCO_3$ leaching-precipitation has occurred (personal communication with Z.T. Guo, 2005). Rb and Fe have geochemical behaviour similar, and are very stable in the pedogenic environment. However, $CaCO_3$ contains a significant amount of Sr, which can be translocated by water. Because soils were decalcified while loess was not, the fluctuations of Rb/Sr (if measured on bulk samples) in fact reflects, to a very large extent, the variations of $CaCO_3$ content, rather than chemical weathering (intensity of pedogenesis). Nevertheless, studies of Bloemendal and Liu (2005) provide hints that magnetic depletions may also be a significant factor in explaining the magnetic variations.

Another important factor that could strongly affect the magnetic properties of Chinese loess is the evolution of the source material. Ding et al. (1999a, 2005) suggested that temporal changes in grain sizes could be due to desert expansion and contraction. The uniform geochemical characteristics of the Chinese loess/paleosols are seemingly insensitive to this dynamic process, but the magnetic properties of the loess units and the iron budget available for the pedogenic process are strongly affected by it. Without strong pedogenic alteration in arid regions, e.g., in Alaska, the coarse-grained magnetite transported from the source area is the chief magnetic carrier in loess and paleosol (Beget et al., 1990). The weaker wind strength in interglacials leads to a lower concentration of coarse magnetite in poorly developed paleosols, and hence to magnetic depletion. In contrast, in humid regions, e.g., on the Chinese Loess Plateau, it is likely that a higher initial iron content could yield a higher concentration of maghemite particles, and thus a greater enhancement of the bulk magnetic susceptibility.

This idea is partially illustrated in Fig. 7. χ_0 represents an ideal state in which the eolian inputs have not been suffered

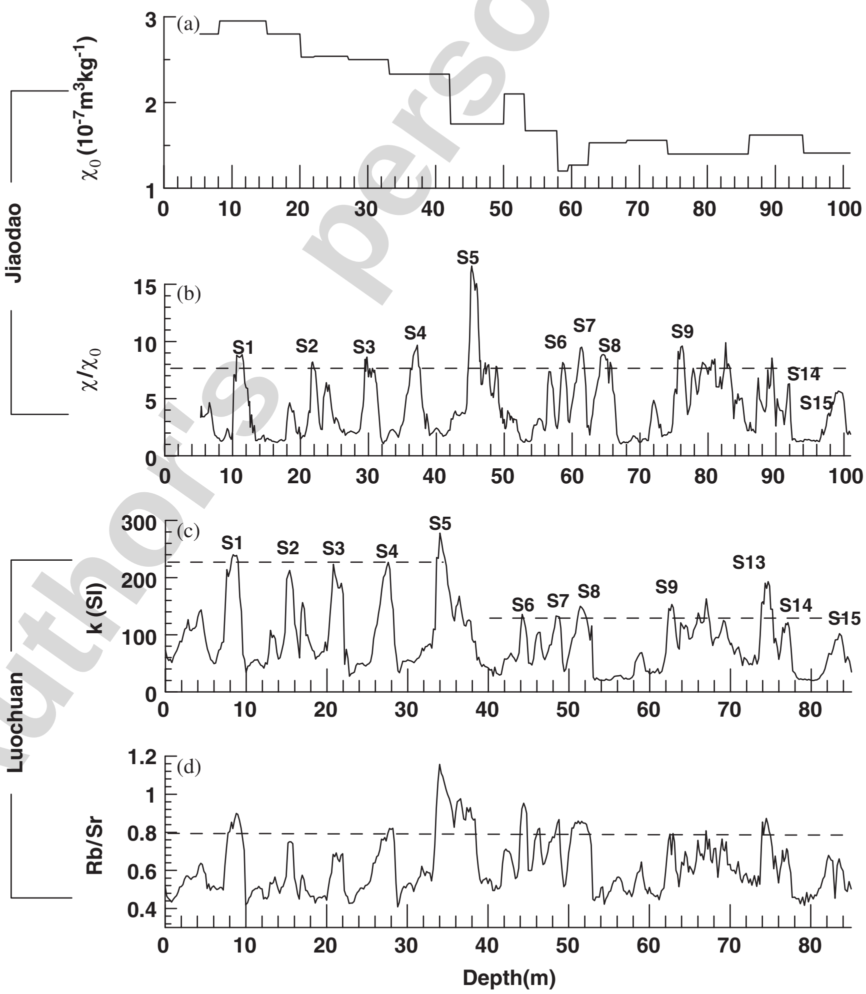

Fig. 7. Depth plots of (a) χ_0, (b) χ/χ_0, (c) χ, and (d) Rb/Sr. The data set in (c–d) is from Ji et al. (2001). χ_0 is calculated from the data set of Deng et al. (2005). The major paleosols have comparable χ/χ_0 (b) except for S5S1.

pedogenic alterations, and thus the corresponding χ_{fd} is zero. χ_0 includes contributions from paramagnetic minerals, eolian coarse-grained magnetite and hematite, and is irrelevant to pedogenic particles. Deng et al. (2005) systematically investigated the bulk susceptibility of the post-CBD residues ($\chi_{post\text{-}CBD}$). Because the CBD treatment can effectively remove the contributions of pedogenic components (Verosub et al., 1993; Vidic et al., 2000; Deng et al., 2005), $\chi_{post\text{-}CBD}$ reflects information solely about eolian inputs. Their results showed a long-term up-section increase, and consistent with the changes in χ_0. The normalized susceptibility, χ/χ_0 (Fig. 7b), shows that the peak values of these major paleosols are comparable with the exception of S5S1. The reason that S1S5 has the highest susceptibility but a moderate iron budget is unclear, and needs further study.

5. Future studies

5.1. The NRM acquisition history

In order to enhance the contribution of loess studies to both geodynamic and paleoclimatic modeling, we need to generate much more quantitative time series of both the paleomagnetic field and specific paleoclimatic parameters. However, there are some problems in obtaining this quantitative and accurate information. The most specific one has been the lack of precise understanding of the NRM acquisition process. What is the relationship between loess NRM, stratigraphy, and paleofield behavior? How has the field signal been smoothed, delayed or degraded? The recent ideas put forward by Zhou and Shackleton (1999) stress the importance of these questions even more. They pointed out that the location of Matuyama/Brunhes (M/B) geomagnetic reversal boundary recorded in the Chinese loess unit L8 (glacial deposits) disagrees with that in many deep-sea sediments records, in which the reversal occurs in interglacial sediments (Tauxe et al., 1996). Assuming a paleoclimatic consistency between the stratigraphy of loess and marine sediments, they proposed that the remanence-carrying grains did not block in the reversed polarity until some time after the reversal. Due to a slow NRM acquisition process, the NRM records in the Chinese loess may have a "lock-in" depth ranging from a few tens of cm to 300 cm, corresponding to a time delay of up to 30,000 years. Therefore, the NRM records in the Chinese loess may be unreliable (Zhou and Shackleton, 1999). However, we note that this interpretation is not based on a mathematical or physical model, as was the "lock-in" model put forward for marine sediments by Hyodo (1984). Zhu et al. (1998) argue that there may be a phase lag between the climate records in the loess and marine sediments caused by local climatic change. To test these hypotheses, we need to answer the following questions: (a) How can we characterize the types of NRM components and their sequence of occurrence in order to determine which mechanism of NRM acquisition is dominant in the Chinese loess/paleosols; and (b) what are the exact pathways of diagenesis that lead from detrital Fe-bearing silicates, and oxides to authigenic magnetic minerals in the Chinese loess/paleosols, and how can we quantify the diagenetic effects on NRM components?

The first question involves the origin of the NRM in the Chinese loess/paleosols. Two likely mechanisms of the NRM acquisition, CRM and DRM, correspond to diagenetic and depositional processes, respectively. The careful separation of CRM from DRM can help us to determine which kind of NRM is dominant in loess/paleosol units, and to provide constraints on the mechanism of NRM acquisition. A study of the Luochuan loess indicated that the contribution of CRM carried by hematite is dominant (Heller and Liu, 1984). In contrast, most studies suggested that the stable NRM has a detrital origin. To clarify and apply these results more generally, we should investigate two relevant aspects: (a) What is the contribution of CRM carried by hematite, goethite and other iron minerals; and (b) what is the potential contribution of DRM carried by coarse-grained eolian magnetite. To quantify their contributions to NRM, we should not only carefully separate the NRM carried by hematite from magnetite, but also systematically study the grain-size dependence of NRM carried by each of the magnetic mineral types. Detailed magnetic measurements and direct particle size analysis should be carried out from the SP to MD ($d > 10\,\mu m$) size ranges.

The second question concerns the climatic and environmental controls on diagenetic pathways and their effects on the NRM. The properties of magnetic minerals can be strongly influenced by soil-forming factors. Correct understanding of diagenetic pathways can provide insight into both the recording history of the NRM and paleoclimate. Singer et al. (1996) put forward a "conceptual" model for the enhancement of magnetic susceptibility at various sites. They concluded that preferential accumulation, transformation, lessivage, neoformation, and solubilization are all processes that convert the primary minerals inherited from loess parent material to the secondary pedogenic magnetic minerals. The model suggests a strong relationship between susceptibility variations and pathways of diagenetic processes. However, the relationships between diagenetic processes and NRM or specific environmental proxies have not been fully established in this conceptual model. To begin to understand how diagenesis affects the NRM acquisition, we need to address the following questions: (a) How is a primary DRM altered by pedogenic processes when a CRM is produced? (b) What are the possible movements (lessivage) of secondary magnetic minerals during the diagenetic processes? (c) What are the effects of such "overprints" on the underlying unit? The answers to these questions can also help us understand the basis for reconstruction of paleorainfall by means of susceptibility. The nature of the links between diagenesis and magnetic properties (susceptibility, NRM, and other laboratory-imparted remanences) is likely to be *site-specific* (Maher, 1998). Thus knowledge of the magnetic properties of modern soils undergoing alteration by pedogenesis, and their comparison with paleosols, is also essential for solving these problems.

5.2. Mechanism of the enhancement of the magnetic susceptibility

Maher (1998) showed that variations in susceptibility are in fact site-specific or paleoenvironmentally dependent. For example, the Chinese paleosols have higher susceptibility than the less-weathered loess counterparts (Heller and Liu, 1982, 1984, 1986), whereas, in Alaska (Beget et al., 1990; Lagroix and Banerjee, 2002), Argentina (Nabel, 1993; Orgeira et al., 2003), and Siberia (Chlachula et al., 1998; Matasova et al., 2001; Zhu et al., 2000, 2003), the paleosol units have a lower susceptibility. For the Chinese loess/paleosol sequences, several mechanisms have been proposed to explain the enhancement of magnetic susceptibility of paleosols, e.g., depositional dilution of a constant flux of tropospheric ultrafine magnetic particles during glacial periods (Kukla et al., 1988), physical enrichment of magnetic minerals in paleosols due to decalcification and soil compaction (Heller and Liu, 1984), and pedogenic production of SP($<$40 nm) particles (Zhou et al., 1990; Maher and Thompson, 1991; Banerjee and Hunt, 1993). Even though these earlier studies have provided a general framework for interpretation of susceptibility enhancement of the Chinese loess/paleosol sequences, efforts are still needed to determine whether or not there is a consistent model for the pedogenic pathways at different sites with different paleoenvironmental conditions, including China, Europe, Alaska, and Argentina.

5.3. Relative paleointensity

A first-order chronological framework was obtained by determining the stratigraphic location of the main geomagnetic reversals (e.g., Matuyama/Brunhés, Gauss/Matuyama, as well as the Jaramillo and Olduvai subchrons) (Heller and Liu, 1982, 1984, 1986; Zhu et al., 1994a; Ding et al., 1999b). Then the chronology was further refined by "indirect" orbital tuning and peak-matching between the loess paleoclimatic proxies (susceptibility and grain size) with the marine isotope record (Kukla et al., 1988; Heslop et al., 2000; Ding et al., 2002; Balsam et al., 2005). However, none of these methods can provide a consistent timescale throughout the whole loess/paleosol sequence.

Some problems for the current correlation between the Chinese loess and marine oxygen isotope records are: (1) S5 and MIS 11 requested the warmest periods for the loess and marine records, respectively. However, they are not correlated with each other in this model; (2) Two sub-peaks of S5 match with MIS13 and MIS15, respectively, resulting in the abrupt onset of an extremely low depositional rate for S5; (3) S6, S7 and S8 are not well characterized by the current paleoclimatic proxies compared to S1 to S5; (4) the discrepancy of the stratigraphic location for the M/B boundary could alternatively suggest incorrect peak-matching. There is only one major geomagnetic reversal, the M/B boundary, but the fluctuations in paleointensity could provide finer scale correlations.

Sedimentary (or relative) paleointensity (referred as to RPI) variations have been used for chronostratigraphy purposes (e.g. Guyodo and Valet, 1999, Stoner et al., 1998, 2002). RPI has a high potential for refining the chronology of Chinese loess profiles (Liu et al., 2005a). RPI is obtained from the NRM after normalizing by selected rock magnetic parameters, which are used to compensate for these non-field effects, especially variations in the concentration of the magnetic particles in samples (Tauxe, 1993; and references therein).

So far, only one investigation of the RPI has been conducted on the Chinese loess since the last glacial period ($<$70 ka) by Pan et al. (2001). This scarcity of data is due to difficulties in the construction and interpretation of the relative paleointensity record, and also due to the absence of firm theoretical framework for the method. For example, complexities apply to the nature of the NRM acquisition process as well as of the corresponding normalization parameters, which are affected by multiple factors, such as grain size, concentration, and mineralogy (Tauxe, 1993). So, Levi and Banerjee (1976) pointed out that, because magnetic susceptibility (χ) and saturation isothermal remanent magnetization (SIRM) could be highly distorted by SP ($<$20 nm) and MD$>$40 μm particles, they are not always suitable for intensity normalization. The problem becomes even more complex for the Chinese loess/paleosol sequences compared to the marine sediments because of potential pedogenic effects.

To reliably construct such a continuous paleomagnetic record (including both direction and intensity) for the Chinese loess, the following basic questions have to be fully answered: (1) What techniques (e.g., AF or thermal demagnetization) should be used to isolate the characteristic remanent magnetization (ChRM), representing the primary remanent magnetization, from the post-depositional overprints. (2) How do we select appropriate normalization parameters, which activate the same relative spectrum of magnetic particle sizes responsible for the ChRM? (3) How do we quantify post-depositional effects on the NRM acquisition history?

6. Conclusions

The bulk magnetic properties of the Chinese loess are determined by an assemblage of magnetic minerals of both eolian and pedogenic origins. For characteristic paleosols, the eolian contributions are masked by the pedogenic signals, thus the magnetic enhancements reflect changes mainly in the concentration of pedogenic components. Although the pedogenic processes are controlled by multiple factors, the almost constant GSD of pedogenically produced fine-grained maghemite particles strongly indicates that only a few factors (e.g., moisture, temperature) are dominant. Thus, it is feasible to quantify the degree of pedogenesis using pedogenesis-related magnetic properties, e.g., χ_{fd}. However, for the incipient paleosol or the least-altered loess units, contributions from the eolian components are relatively significant, resulting in ambiguous interpretation of the magnetic proxies, e.g., the bulk χ, χ_{fd}%, ARM, SIRM, HIRM, and all ratios. Suitable separation techniques (either chemical, e.g. the CBD treatment, or mathematical, e.g. the correction of χ_o) are needed to distinguish the eolian from the pedogenic signals. Similar to the bulk rock magnetic properties, the NRM carried by the Chinese loess/paleosol sequences is also the vector summation of the primary DRM (carried by the eolian partially oxidized coarse-grained magnetite) and CRM (carried by the pedogenically produced fine-grained maghemite). Studies on the long-term variations in the RPI could be useful to refine the chronological framework of the Chinese loess.

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References

An, Z.S., 2000. The history and variability of the East Asian paleomonsoon climate. Quaternary Science Reviews 19, 171–187.

An, Z.S., Kutzbach, J.E., Prell, W.L., Porter, S.C., 2001. Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan plateau since Late Miocene times. Nature 411, 62–66.

Balsam, W., Ji, J.F., Chen, J., 2004. Climatic interpretation of the Luochuan and Lingtai loess sections, China, based on changing iron oxide mineralogy and magnetic susceptibility. Earth and Planetary Science Letters 223, 335–348.

Balsam, W., Ellwood, B., Ji, J.F., 2005. Direct correlation of the marine oxygen isotope record with the Chinese Loess Plateau iron oxide and magnetic susceptibility records. Palaeogeography, Palaeoclimatology, Palaeoecology 221, 141–152.

Banerjee, S.K., Hunt, C.P., 1993. Separation of local signals from the regional paleomonsoon record of the Chinese Loess Plateau; a rock-magnetic approach. Geophysical Research Letters 20, 843–846.

Beget, J.E., Stone, D.B., Hawkins, D.B., 1990. Paleoclimatic forcing of magnetic susceptibility variations in Alaskan loess during the late Quaternary. Geology 18, 40–43.

Bloemendal, J., Liu, X.M., Rolph, T.C., 1995. Correlation of the magnetic susceptibility stratigraphy of Chinese loess and the marine oxygen isotope record: chronological and palaeoclimatic implications. Earth and Planetary Science Letters 131, 371–380.

Bloemendal, J., Liu, X.M., 2005. Rock magnetism and geochemistry of two plio-pleistocene Chinese loess–palaeosol sequences—implications for quantitative palaeoprecipitation reconstruction. Palaeogeography, Palaeoclimatology, Palaeoecology 226, 149–166.

Chen, F.H., Bloemendal, J., Feng, Z.D., Wang, J.M., Parker, E., Guo, Z.T., 1999. East Asian monsoon variations during Oxygen Isotope Stage 5: evidence from the northwestern margin of the Chinese loess plateau. Quaternary Science Reviews 18, 1127–1135.

Chen, T., Xu, H., Xie, Q., Chen, J., Ji, J., Lu, H., 2005. Characteristics and genesis of maghemite in Chinese loess and paleosols: mechanism for magnetic susceptibility enhancement in paleosols. Earth and Planetary Science Letters 240, 790–802.

Chlachula, J., Evans, M.E., Rutter, N.W., 1998. A magnetic investigation of a Late Quaternary loess/palaeosol record in Siberia. Geophysical Journal International 132, 128–132.

Clarke, M.L., 1995. A comparison of magnetic fabrics from loess silts across the Tibetan Front, Western China. Quaternary Proceedings, pp. 9–26.

Day, R., Fuller, M., Schmidt, V.A., 1977. Hysteresis properties of titanomagnetites: grain-size and compositional dependence. Physics of the Earth and Planetary Interiors 13, 260–267.

De Boer, C.B., Dekkers, M.J., 1996. Grain-size dependence of the rock magnetic properties for a natural maghemite. Geophysical Research Letters 23, 2815–2818.

Deng, C.L., Zhu, R.X., Verosub, K.L., Singer, M.J., Yuan, B.Y., 2000. Paleoclimatic significance of the temperature-dependent susceptibility of Holocene loess along a NW-SE transect in the Chinese loess plateau. Geophysical Research Letters 27, 3715–3718.

Deng, C., Zhu, R., Jackson, M.J., Verosub, K.L., Singer, M.J., 2001. Variability of the temperature-dependent susceptibility of the Holocene eolian deposits in the Chinese loess plateau: a pedogenesis indicator. Physics and Chemistry of the Earth, Part A 26, 873–878.

Deng, C.L., Zhu, R.X., Verosub, K.L., Singer, M.J., Vidic, N.J., 2004. Mineral magnetic properties of loess/paleosol couplets of the central loess plateau of China over the last 1.2 Myr. Journal of Geophysical Research 109, B01103.

Deng, C.L., Vidic, N.J., Verosub, K.L., Singer, M.J., Liu, Q.S., Shaw, J., Zhu, R.X., 2005. Mineral magnetic variation of the Jiaodao Chinese loess/paleosol sequence and its bearing on long-term climatic variability. Journal of Geophysical Research 110, B03103.

Deng, C.L., Shaw, J., Liu, Q.S., Pan, Y.X., Zhu, R.X., 2006. Mineral magnetic variation of the Jingbian loess/paleosol sequence in the Northern Loess Plateau of China: Implications for Quaternary development of Asian aridification and cooling. Earth and Planetary Science Letters 241, 248–259.

Ding, Z.L., Sun, J., Rutter, N.W., Rokosh, D., Liu, T., 1999a. Changes in the sand content of loess deposits along a north to south transect of the Chinese Loess Plateau and the implications for desert variations. Quaternary Research 52, 56–62.

Ding, Z.L., Xiong, S.F., Sun, J.M., Yang, S.L., Gu, Z.Y., Liu, T.S., 1999b. Pedostratigraphy and paleomagnetism of a ~7.0 Ma eolian loess–red clay sequence at Lingtai, Loess Plateau, north-central China and the implications for paleomonsoon evolution. Palaeogeography, Palaeoclimatology, Palaeoecology 152, 49–66.

Ding, Z.L., Derbyshire, E., Yang, S.L., Yu, Z.W., Xiong, S.F., Liu, T.S., 2002. Stacked 2.6-Ma grain size record from the Chinese loess based on five sections and correlation with the deep-sea $\delta^{18}O$ record. Paleoceanography 17, 1033.

Ding, Z.L., Derbyshire, E., Yang, S.L., Sun, J.M., Liu, T.S., 2005. Stepwise expansion of desert environment across northern China in the past 3.5 Ma and implications for monsoon evolution. Earth and Planetary Science Letters 237, 45–55.

Dunlop, D.J., 2002a. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc) 1. Theoretical curves and tests using titanomagnetite data. Journal of Geophysical Research 107 (B3), 2076.

Dunlop, D.J., 2002b. Theory and application of the Day plot (Mrs/Ms versus Hcr/Hc): 2. Application to data for rocks, sediments, and soils. Journal of Geophysical Research 107 (B3), 2057.

Dunlop, D.J., Özdemir, Ö., 1997. Rock Magnetism: Fundamentals and Frontiers. Cambridge University Press, New York (p. 573).

Evans, M.E., Heller, F., 1994. Magnetic enhancement and palaeoclimate: a study of a loess/palaeosol couplet across the Loess Plateau of China. Geophysical Journal International 117, 257–264.

Evans, M.E., Heller, F., 2001. Magnetism of loess/palaeosol sequences: recent developments. Earth-Science Reviews 54, 129–144.

Eyre, J.K., Shaw, J., 1994. Magnetic enhancement of Chinese loess—the role of γFe2O3? Geophysical Journal International 117, 265–271.

Fang, X.M., Li, J.J., Van der Voo, R., Niocaill, C.M., Dai, X.R., Kemp, R.A., Derbyshire, E., Cao, J.X., Wang, J.M., Wang, G., 1997. A record of the Blake Event during the last interglacial paleosol in the western Loess Plateau of China. Earth and Planetary Science Letters 146, 73–82.

Fine, P., Singer, M.J., Verosub, K.L., TenPas, J., 1993. New evidence for the origin of ferrimagnetic minerals in loess from China. Soil Science Society of America Journal 57, 1537–1542.

Florindo, F., Zhu, R.X., Guo, B., Yue, L.P., Pan, Y.X., Speranza, F., 1999. Magnetic proxy climate results from the Duanjiapo Loess section, southernmost extremity of the Chinese loess plateau. Journal of Geophysical Research 104, 645–659.

Forster, T., Heller, F., 1997. Magnetic enhancement paths in loess sediments from Tajikistan, China, and Hungary. Geophysical Research Letters 24, 17–20.

Forster, T., Evans, M.E., Heller, F., 1994. The frequency dependence of low field susceptibility in loess sediments. Geophysical Journal International 118, 636–642.

France, D.E., Oldfield, F., 2000. Identifying goethite and hematite from rock magnetic measurements of soils and sediments. Journal of Geophysical Research 105, 2781–2795.

Fukuma, K., Torri, M., 1998. Variable shape of magnetic hysteresis loops in the Chinese loess-paleosol sequence. Earth Planets Space 50, 9–14.

Guo, Z., Liu, T., Guiot, J., Wu, N., Lü, H., Han, J., Liu, J., Gu, Z., 1996. High frequency pulses of East Asian monsoon climate in the last two glaciations: link with the North Atlantic. Climate Dynamics 12, 701–709.

Guo, Z.T., Ruddiman, W.F., Hao, Q.Z., Wu, H.B., Qiao, Y.S., Zhu, R.X., Peng, S.Z., Wei, J.J., Yuan, B.Y., Liu, T.S., 2002. Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China. Nature 416, 159–163.

Guo, B., Zhu, R.X., Roberts, A.P., Florindo, F., 2001. Lack of correlation between paleoprecipitation and magnetic susceptibility of Chinese loess/paleosol sequences. Geophysical Research Letters 28, 4259–4562.

Guyodo, Y., Valet, J.P., 1999. Global changes in intensity of the Earth's magnetic field during the past 800 kyr. Nature 399, 249–252.

Han, J.M., Lu, H.Y., Wu, N.Q., Guo, Z.T., 1996. The magnetic susceptibility of modern soils in China and its paleoclimate reconstruction. Studia Geophysica et Geodaetica 40, 262–275.

Hao, Q.Z., Guo, Z.T., 2005. Spatial variations of magnetic susceptibility of Chinese loess for the last 600 kyr: implications for monsoon evolution. Journal of Geophysical Research 110, B12101.

Heller, F., Evans, M.E., 1995. Loess magnetism. Reviews of Geophysics 33, 211–240.

Heller, F., Liu, T.S., 1982. Magnetostratigraphical dating of loess deposits in China. Nature 300, 431–433.

Heller, F., Liu, T.S., 1984. Magnetism of Chinese loess deposits. Geophysical Journal of the Royal Astronomical Society 77, 125–141.

Heller, F., Liu, T.S., 1986. Palaeoclimatic and sedimentary history from magnetic susceptibility of loess in China. Geophysical Research Letters 13, 1169–1172.

Heller, F., Beat, M., Wang, J., Liu, H., Liu, T.S., 1987. Magnetization and sedimentary history of loess in the central Loess Plateau of China. In: Liu, T.S. (Ed.), Aspects of Loess Research. China Ocean Press, pp. 147–163.

Heller, F., Liu, X.M., Liu, T.S., Xu, T.C., 1991. Magnetic susceptibility of loess in China. Earth and Planetary Science Letters 103, 301–310.

Heller, F., Shen, C.D., Beer, J., Liu, X.M., Liu, T.S., Bronger, A., Suter, M., Bonani, G., 1993. Quantitative estimations of pedogenic ferrimagnetic formation in Chinese loess and palaeoclimatic implications. Earth and Planetary Science Letters 114, 385–390.

Heslop, D., Langereis, C.G., Dekkers, M.J., 2000. A new astronomical timescale for the loess deposits of Northern China. Earth and Planetary Science Letters 184, 125–139.

Hovan, S.A., Rea, D.K., Pisias, N.G., Shackleton, N.J., 1989. A direct link between the China loess and marine δ^{18}O records: aeolian flux to the north Pacific. Nature 340, 296–298.

Hyodo, M., 1984. Possibility of reconstruction of the past geomagnetic field from homogeneous sediments. Journal of Geomagnetism and Geoelectricity 36, 45–62.

Hunt, C.P., Banerjee, S.K., Han, J.M., Solheid, P.A., Oches, E., Sun, W.W., Liu, T.S., 1995a. Rock-magnetic proxies of climate change in the loess-paleosol sequences of the western loess plateau of China. Geophysical Journal International 123, 232–244.

Hunt, C.P., Singer, M.J., Kletetschka, G., TenPas, J., Verosub, K.L., 1995b. Effect of citrate-bicarbonate-dithionite treatment on fine-grained magnetite and maghemite. Earth and Planetary Science Letters 130, 87–94.

Ji, J.F., Balsam, W., Chen, J., 2001. Mineralogic and climatic interpretations of the Luochuan loess section (China) based on diffuse reflectance spectrophotometry. Quaternary Research 56, 23–30.

Ji, J., Chen, J., Balsam, W., Lu, H., Sun, Y., Xu, H., 2004. High resolution hematite/goethite records from Chinese loess sequences for the last glacial-interglacial cycle: rapid climatic response of the East Asian Monsoon to the tropical Pacific. Geophysical Research Letters 31, L03207.

Kletetschka, G., Banerjee, S.K., 1995. Magnetic stratigraphy of Chinese loess as a record of natural fires. Geophysical Research Letters 22, 1341–1343.

Kukla, G., Heller, F., Liu, X.M., Xu, T.C., Liu, T.S., An, Z.S., 1988. Pleistocene climates in China dated by magnetic susceptibility. Geology 16, 811–814.

Kukla, G., An, Z.S., 1989. Loess stratigraphy in central China. Palaeogeography, Palaeoclimatology, Palaeoecology 72, 203–225.

Lagroix, F., Banerjee, S.K., 2002. Paleowind directions from the magnetic fabric of loess profiles in central Alaska. Earth and Planetary Science Letters 195, 99–112.

Levi, S., Banerjee, S.K., 1976. On the possibility of obtaining relative paleointensities from lake sediments. Earth and Planetary Science Letters 29, 219–226.

Li, J.J., Fang, X.M., 1999. Uplift of the Tibetan Plateau and environmental changes. Chinese Science Bulletin 44, 2117–2124.

Lisiecki, L.E., Raymo, M.E., 2005. A Pliocene–Pleistocene stack of 57 globally distributed benthic δ18O records. Paleoceanography 20, PA1003.

Liu, Q., Banerjee, S.K., Jackson, M.J., Zhu, R., Pan, Y., 2002. A new method in mineral magnetism for the separation of weak antiferromagnetic signal from a strong ferrimagnetic background. Geophysical Research Letters 29 (12).

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Chen, F.H., Pan, Y.X., Zhu, R.X., 2003a. An integrated study of the grain-size-dependent magnetic mineralogy of the Chinese loess/paleosol and its environmental significance. Journal of Geophysical Research 108 (B9), 2437.

Liu, Q.S., Jackson, M.J., Banerjee, S.K., Zhu, R.X., Pan, Y.X., Chen, F.H., 2003b. Determination of magnetic carriers of the characteristic remanent magnetization of Chinese loess by low-temperature demagnetization. Earth and Planetary Science Letters 216, 175–186.

Liu, Q.S., 2004. Pedogenesis and its effects on the natural remanent magnetization acquisition history of the Chinese loess. Ph.D. thesis, Minneapolis, MN.

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Chen, F.H., Pan, Y.X., Zhu, R.X., 2004a. Determining the climatic boundary between the Chinese loess and palaeosol: evidence from aeolian coarse-grained magnetite. Geophysical Journal International 156, 267–274.

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Deng, C.L., Pan, Y.X., Zhu, R.X., 2004b. New insights into partial oxidation model of magnetites and thermal alteration of magnetic mineralogy of the Chinese loess in air. Geophysical Journal International 158, 506–514.

Liu, Q.S., Jackson, M.J., Banerjee, S.K., Maher, B.A., Deng, C.L., Pan, Y.X., Zhu, R.X., 2004c. Mechanism of the magnetic susceptibility enhancements of the Chinese loess. Journal of Geophysical Research 110.

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Maher, B.A., Pan, Y.X., Zhu, R.X., Deng, C.L., Chen, F.H., 2004d. Grain sizes of susceptibility and anhysteretic remanent magnetization carriers in Chinese loess/paleosol sequences. Journal of Geophysical Research 109, B03101.

Liu, Q.S., Jackson, M.J., Yu, Y.J., Chen, F.H., Deng, C.L., Zhu, R.X., 2004e. Grain size distribution of pedogenic magnetic particles in Chinese loess/paleosols. Geophysical Research Letters 31, L22603.

Liu, Q.S., Banerjee, S.K., Jackson, M.J., Deng, C.L., Pan, Y.X., Zhu, R.X., 2005a. Inter-profile correlation of the Chinese loess/paleosol sequences during Marine Oxygen Isotope Stage 5 and indications of pedogenesis. Quaternary Science Reviews 24, 195–210.

Liu, Q.S., Deng, C.L., Yu, Y., Torrent, J., Jackson, M.J., Banerjee, S.K., Zhu, R.X., 2005b. Temperature dependence of magnetic susceptibility in argon environment: implications for pedogenesis of Chinese loess/palaeosols. Geophysical Journal International 161, 102–112.

Liu, Q.S., Torrent, J., Maher, B.A., Yu, Y., Deng, C.L., Zhu, R.X., Zhao, X.X., 2005c. Quantifying grain size distribution of pedogenic magnetic particles in Chinese loess and its significance for pedogenesis. Journal of Geophysical Research 110, B11102.

Liu, Q.S., Yu, Y.J., Deng, C.L., Pan, Y.X., Zhu, R.X., 2005d. Enhancing weak magnetic fabrics using field-impressed anisotropy: application to the Chinese loess. Geophysical Journal International 162, 381–389.

Liu, T.S., 1985. Loess and the Environment. China Ocean Press, Beijing (p. 251).

Liu, T.S., Ding, Z.L., 1998. Chinese loess and the paleomonsoon. Annual Review of Earth and Planetary Science 26, 111–145.

Liu, X.M., Liu, T.S., Heller, F., Xu, T.C., 1990. Frequency-dependent susceptibility of loess and Quaternary paleosol. Quaternary Science 1, 42–50 (in Chinese).

Liu, X.M., Rolph, T., Bloemendal, J., Shaw, J., Liu, T.S., 1995. Quantitative estimates of palaeoprecipitation at Xifeng, in the loess plateau of China. Palaeogeography, Palaeoclimatology, Palaeoecology 113, 243–248.

Liu, X.M., Hesse, P., Rolph, T., 1999. Origin of maghaemite in Chinese loess deposits: aeolian or pedogenic? Physics of the Earth and Planetary Interiors 112, 191–201.

Maher, B.A., 1986. Characterisation of soils by mineral magnetic measurements. Physics of the Earth and Planetary Interiors 42, 76–92.

Maher, B.A., 1988. Magnetic properties of some synthetic sub-micron magnetites. Journal of Geophysical Research 94, 83–96.

Maher, B.A., 1998. Magnetic properties of modern soils and Quaternary loessic paleosols: paleoclimatic implications. Palaeogeography, Palaeoclimatology, Palaeoecology 137, 25–54.

Maher, B.A., Thompson, R., 1991. Mineral magnetic record of the Chinese loess and paleosols. Geology 19, 3–6.

Maher, B.A., Thompson, R., 1992. Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols. Quaternary Research 37, 155–170.

Maher, B.A., Thompson, R., Zhou, L.P., 1994. Spatial and temporal reconstructions of changes in the Asian palaeomonsoon—a new mineral magnetic approach. Earth and Planetary Science Letters 125, 461–471.

Maher, B.A., Thompson, R., 1995. Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and paleosols. Quaternary Research 44, 383–391.

Maher, B.A., Thompson, R., 1999. Quaternary Climates, Environments and Magnetism. Cambridge University Press, Cambridge.

Maher, B.A., Alekseev, A., Alekseeva, T., 2003a. Magnetic mineralogy of soils across the Russian Steppe: climatic dependence of pedogenic magnetite formation. Palaeogeography, Palaeoclimatology, Palaeoecology 201, 321–341.

Maher, B.A., Hu, M.Y., Roberts, H.M., Wintle, A.G., 2003b. Holocene loess accumulation and soil development at the western edge of the Chinese Loess Plateau: implications for magnetic proxies of paleorainfall. Quaternary Science Reviews 22, 445–451.

Maher, B.A., Karloukovski, V.V., Mutch, T.J., 2004. High-field remanence properties of synthetic and natural submicrometer haematites and goethites: significance for environmental contexts. Earth and Planetary Science Letters 226, 491–505.

Matasova, G., Petrovsky, E., Jordanova, N., Zykina, V., Kapicka, A., 2001. Magnetic study of Late Pleistocene loess/palaeosol sections from Siberia: palaeoenvironmental implications. Geophysical Journal International 147, 367–380.

Mullender, T.A.T., van Velzen, A.J., Dekkers, M.J., 1993. Continuous drift correction and separate identification of ferrimagnetic and paramagnetic contributions in thermomagnetic runs. Geophysical Journal International 114, 663–672.

Mullins, C.E., 1977. Magnetic susceptibility of the soil and its significance in soil science: a review. Journal of Soil Science 28, 223–246.

Nabel, P., 1993. The Brunhes–Matuyama boundary in Pleistocene sediments of Buenos Aires Province, Argentina. Quaternary International 17, 79–85.

Orgeira, M.J., Walther, A.M., Tófalo, R.O., Vásquez, C., Berquó, T., Favier Dobois, C., Bohnel, H., 2003. Environmental magnetism in fluvial and loessic Holocene sediments and paleosols from the Champean plain (Argentina). Journal of South American Earth Sciences 16, 259–274.

Pan, Y.X., Zhu, R.X., Shaw, J., Liu, Q.S., Guo, B., 2001. Can relative paleointensities be determined from the normalized magnetization of the wind-blown loess of China? Journal of Geophysical Research 106, 19221–19232.

Pan, Y.X., Zhu, R.X., Liu, Q.S., Guo, B., Yue, L.P., Wu, H.N., 2002. Geomagnetic episodes of the last 1.2 Myr recorded in Chinese loess. Geophysical Research Letters 29, 1282.

Porter, S.C., An, Z.S., 1995. Correlation between climate events in the North Atlantic and China during the last glaciation. Nature 375, 305–308.

Porter, S.C., 2001. Chinese loess record of monsoon climate during the last glacial–interglacial cycle. Earth-Science Reviews 54, 115–128.

Roberts, A.P., Cui, Y., Verosub, K.L., 1995. Wasp-waisted hysteresis loops: mineral magnetic characteristics and discrimination of components in mixed magnetic systems. Journal of Geophysical Research 100, 17909–17924.

Singer, M.J., Verosub, K.L., Fine, P., TenPas, J., 1996. A conceptual model for the enhancement of magnetic susceptibility in soils. Quaternary International 24–36, 243–248.

Stephenson, A., 1971. Single domain grain distributions I. A method for the determination of single domain grain distributions. Physics of Earth and Planetary Interiors 4, 353–360.

Stoner, J.S., Channell, J.E.T., Hillaire-Marcel, C.A., 1998. A 200 ka chronostratigraphy for the Labrador Sea: Indirect correlation of the sediment record to SPECMAP. Earth and Planetary Science Letters 159, 165–181.

Stoner, J.S., Laj, C., Channell, J.E.T., Kissel, C., 2002. South Atlantic and North Atlantic geomagnetic paleointensity stacks (0–80 ka): implication for inter-hemispheric correlation. Quaternary Science Reviews 21, 1141–1151.

Sun, J.M., 2002. Provenance of loess material and formation of loess deposits on the Chinese Loess Plateau. Earth and Planetary Science Letters 203, 845–859.

Sun, J.M., Liu, T.S., 2000. Multiple origins and interpretations of the magnetic susceptibility signal in Chinese wind-blown sediments. Earth and Planetary Science Letters 180, 287–296.

Sun, J.M., Ding, Z.L., Liu, T.S., 1995a. Primary application of magnetic susceptibility mensuration of loess and paleosols for reconstruction of winter monsoon direction (in Chinese). Chinese Science Bulletin 40, 1976–1978.

Sun, W.W., Banerjee, S.K., Hunt, C.P., 1995b. The role of maghemite in the enhancement of magnetic signal in the Chinese loess–paleosol sequence: An extensive rock magnetic study combined with citrate-bicarbonate-dithionite treatment. Earth and Planetary Science Letters 133, 493–505.

Sun, X.J., Wang, P.X., 2005. How old is the Asian monsoon system?—Palaeobotanical records from China. Palaeogeography, Palaeoclimatology, Palaeoecology 222, 181–222.

Sun, Y.B., Clemens, S.C., An, Z.S., Yu, Z.W., 2006. Astronomical timescale and palaeoclimatic implication of stacked 3.6-Myr monsoon records from the Chinese Loess Plateau. Quaternary Science Reviews 25, 33–48.

Tang, Y.J., Jia, J.Y., Xie, X.D., 2003. Records of magnetic properties in Quaternary loess and its paleoclimatic significance: a brief review. Quaternary International 108, 33–50.

Tauxe, L., 1993. Sedimentary records of relative paleointensity of the geomagnetic field: theory and practice. Reviews of Geophysics 31, 319–354.

Tauxe, L., Herbert, T., Shackleton, N.J., Kok, Y.S., 1996. Astronomical calibration of the Matuyama–Brunhes boundary consequences for magnetic remanence acquisition in marine carbonates and the Asian loess sequences. Earth and Planetary Science Letters 140, 133–146.

Thistlewood, L., Sun, J., 1995. A paleomagnetic and mineral magnetic study of the loess sequence at Liujiapo, Xian, China. Journal of Quaternary Science 6, 13–26.

Thompson, R., Oldfield, F., 1986. Environmental Magnetism. Allen and Union, London (p. 229).

van Velzen, A.J., Dekkers, M.J., 1999a. Low-temperature oxidation of magnetite in loess-paleosol sequences: a correction of rock magnetic parameters. Studia Geophysica et Geodaetica 43, 357–375.

van Velzen, A.J., Dekkers, M.J., 1999b. The incorporation of thermal methods in mineral magnetism of loess-paleosol sequences: a brief overview. Chinese Science Bulletin 44 (Suppl. 1), 53–63.

Vandenberghe, R.E., de Grave, E., Hus, J.J., Han, J., 1992. Characterization of Chinese loess and associated palaeosol by Mössbauer spectroscopy. Hyperfine Interactions 70, 977–980.

Verosub, K.L., Fine, P., Singer, M.J., TenPas, J., 1993. Pedogenesis and paleoclimate: Interpretation of the magnetic susceptibility record of Chinese loess–paleosol sequences. Geology 21, 1011–1014.

Vidic, N.J., TenPas, J.D., Verosub, K.L., Singer, M.J., 2000. Separation of pedogenic and lithogenic components of magnetic susceptibility in the Chinese loess/palaeosol sequence as determined by the CBD procedure and a mixing analysis. Geophysical Journal International 142, 551–562.

Vidic, N.J., Singer, M.J., Verosub, K.L., 2004. Duration dependence of magnetic susceptibility enhancement in the Chinese loess–palaeosols of the past 620 ky. Palaeogeography, Palaeoclimatology, Palaeoecology 211, 271–288.

Wang, P.X., Clemens, S., Beaufort, L., Braconnot, P., Ganssen, G., Jian, Z.M., Kershaw, P., Sarnthein, M., 2005. Evolution and variability of the Asian monsoon system: state of the art and outstanding issues. Quaternary Science Reviews 24, 595–629.

Worm, H.-U., 1998. On the superparamagnetic-stable single domain transition for magnetite, and frequency dependency of susceptibility. Geophysical Journal International 133, 201–206.

Worm, H.-U., Jackson, M., 1999. The superparamagnetism of Yucca Mountain Tuff. Journal of Geophysical Research 104, 25415–25425.

Zheng, H.B., Rolph, T.C., Shaw, J., An, Z.S., 1995. A detailed palaeomagnetic record for the last interglacial period. Earth and Planetary Science Letters 133, 339–351.

Zhou, L.P., Oldfield, F., Wintle, A.G., Robinson, S.G., Wang, J.T., 1990. Partly pedogenic origin of magnetic variations in Chinese loess. Nature 346, 737–739.

Zhou, L.P., Shackleton, N.J., 1999. Misleading positions of geomagnetic reversal boundaries in Eurasian loess and implications for correlation between continental and marine sedimentary sequences. Earth and Planetary Science Letters 168, 117–130.

Zhu, R.X., Laj, C., Mazaud, A., 1994a. The Matuyama–Brunhes and Upper Jaramillo transitions recorded in a loess section at Weinan, north-central China. Earth and Planetary Science Letters 125, 143–158.

Zhu, R.X., Zhou, L.P., Laj, C., Mazaud, A., Ding, Z.L., 1994b. The Blake geomagnetic polarity episode recorded in Chinese loess. Geophysical Research Letters 21, 697–700.

Zhu, R.X., Pan, Y.X., Guo, B., Liu, Q.S., 1998. A recording phase lag between ocean and continent climate changes: constrained by the Matuyama/Brunhes polarity boundary. Chinese Science Bulletin 43, 1593–1598.

Zhu, R.X., Pan, Y.X., Liu, Q.S., 1999. Geomagnetic excursions recorded in Chinese loess in the last 70,000 years. Geophysical Research Letters 26, 505–508.

Zhu, R.X., Kazansky, A., Matasova, G., Guo, B., Zykina, V., Petrovsky, E., Jordanova, N., 2000. Rock-magnetic investigation of Siberia loess and its implication. Chinese Science Bulletin 45, 2192–2197.

Zhu, R.X., Matasova, G., Kazansky, A., Zykina, V., Sun, J.M., 2003. Rock magnetic record of the last glacial-interglacial cycle from the Kurtak loess section, southern Siberia. Geophysical Journal International 152, 335–343.

Zhu, R.X., Liu, Q.S., Jackson, M.J., 2004. Paleoenvironmental significance of the magnetic fabrics in Chinese loess–paleosols since the last interglacial (< 130 ka). Earth and Planetary Science Letters 221, 55–69.