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Lack of correlation between paleoprecipitation and magnetic susceptibility of Chinese loess/paleosol sequences

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Abstract. We have conducted a detailed mineral magnetic study of loess unit 8 (L8) and paleosol unit 8 (S8) from three localities (Jingbian, Yichuan, and Duanjiapo) along a N-S transect in the Chinese loess plateau. As expected, the low-field magnetic susceptibility (χ) has higher values in S8 and lower values in L8. Similarly, superparamagnetic particle concentrations increase in S8 with increasingly humid climates along the N-S transect, which suggests that pedogenic magnetic enhancement is related to climate. However, in S8 at Duanjiapo, χ is so low that there is no correlation between χ and the degree of pedogenesis in this loess-paleosol cycle. It therefore appears that χ is not consistently the most suitable indicator of paleoclimate in Chinese loess-paleosol sequences. Our results indicate that there are complexities in the mineral magnetic response to pedogenesis, which could invalidate interpretation of the χ record of Chinese loess-paleosol sequences in terms of paleoprecipitation.

1. Introduction

On the Chinese loess plateau, loesses, which have low magnetic susceptibility (χ), accumulated under cold and dry conditions during glacial periods, whereas paleosols, which have relatively high χ, accumulated and developed on the top of loesses during warmer, more humid interglacial periods [*Liu et al.*, 1985]. Many explanations have been suggested for the magnetic enhancement of the paleosols. *Kukla et al.* [1988] proposed that the χ variation in loess-paleosol sequences is due to depositional dilution of a constant rain-out of ultra-fine magnetic particles from the troposphere during glacial and interglacial periods. Other interpretations include enrichment of magnetic minerals in paleosols due to decalcification and soil compaction [*Heller and Liu*, 1984], and the heating of loess by frequent natural fires [*Kletetschka and Banerjee*, 1995]. The prevailing hypothesis for enhancement of χ in paleosols is post-depositional weathering and/or formation of magnetic phases by pedogenic processes [*Zhou et al.*, 1990 ; *Maher and Thompson*, 1991]. Using a calibration between the pedogenic contribution to χ and rainfall from modern soils, the χ of loess and paleosol units has been used to estimate paleoprecipitation across the Chinese loess plateau [e.g. *Maher and Thompson*, 1995]. Recently, several researchers have challenged the pedogenic hypothesis and pointed out that enhancement of χ in paleosols may be due to the variety of dust sources rather than to pedogenesis [*Meng et al.*, 1997]. *Sun and Liu* [2000] proposed that χ enhancement in paleosols has multiple origins. In this paper, we attempt to clarify the relationship between the magnetic properties and other factors such as paleo-temperature and rainfall.

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2. Geological setting and sampling

We selected three sections in order to study the relationship between local paleoclimatic factors and the magnetic properties of loess sediments at different sites on the Chinese loess plateau. Currently, there exists a striking climatic contrast among the selected sections. We have studied the Matuyama/Brunhes geomagnetic reversal, which is recorded in loess unit 8 (L8), in all three sections. We therefore selected a loess/ paleosol cycle, comprising L8 and S8, as the target for this study.

The Duanjiapo loess section (34.2°N,109.2°E) is located in the southernmost part of the Chinese loess plateau. It consists of a sequence of 33 loess-paleosol units with a total thickness of about 133.5 m [*Zheng et al.*, 1992]. The Yichuan loess section (36.1°N, 110.1°E) is located in the central part of the loess plateau. The Jingbian section (37.5°N, 108.8°E) is located at the northern margin of the loess plateau, near the Mu Us Desert. At each location, we cleaned the outcrop surface to a depth of over 50cm to remove the effects of surface weathering, then continuously sampled oriented loess blocks from the top of L8 to the bottom of S8.

3. Experiments and Results

3.1 Magnetic susceptibility

A Bartington Instruments magnetic susceptibility meter with a MS-2B sensor was used to measure χ for all samples. χ varies between 21 and 90×10^{-8} m^3/kg in the Jingbian section, between 31 and 139×10^{-8} m^3/kg in the Yichuan section, and between 20 and 52×10^{-8} m^3/kg in the Duanji-

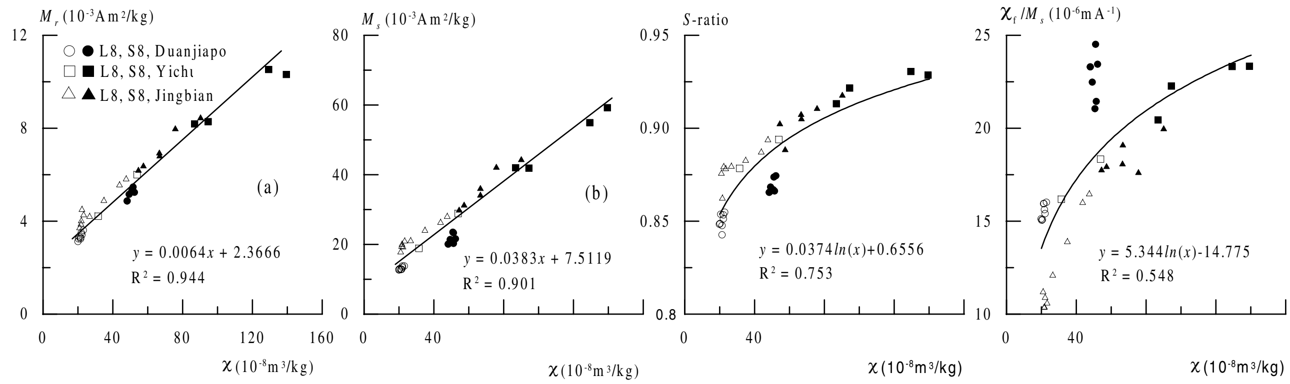

Figure 1. Variation of (a) saturation remanence (M_r) with χ, (b) saturation magnetization (M_s) with χ, (c) S-ratio with χ, and (d) χ_f/M_s with χ. Open/ solid circles, triangles, and squares represent L8 and S8 samples in the Duanjiapo, Jingbian and Yichuan sections, respectively.

apo section (Figure 1). The maximum and minimum values of χ occur within S8 and L8, respectively. χ is almost the same for L8 at all three sections. In S8, χ is highest in the Yichuan section, and lowest in the Duanjiapo section.

The high-field magnetic susceptibility (χ_h) was determined at high fields from the gradient, $\mathrm{d}M/\mathrm{d}H$, of hysteresis loops, which reflects the paramagnetic contribution to the susceptibility. χ_h varies between 7.27 and 11.97×10^{-8} m^3/kg in Jingbian, between 7.61 and 12.35×10^{-8} m^3/kg in Yichuan, and between 7.42 to 13.5×10^{-8} m^3/kg in Duanjiapo. χ_h is nearly the same for L8 at the three sites (as is χ), which suggests that the magnetic properties of the loess were nearly constant over the loess plateau during glacial periods. In contrast, χ_h of S8 seems to show an increase from the northern to the southern part of the loess plateau, which probably reflects enhancement of paramagnetic minerals related to pedogenesis [*Florindo et al.*, 1999].

3.2 Temperature-dependence of magnetic susceptibility

The temperature-dependence of χ was measured to maximum temperatures of 700°C. The temperature-dependence of χ was measured to maximum temperatures of 700°C using a furnace-equipped Kappabridge KLY-3 system. An argon atmosphere was used to minimize oxidation of the samples. Three samples were analysed from each L8 unit, along with three samples from each S8 unit. The heating curves for L8 samples have similar shape, with χ decreasing sharply near 580°C, which suggests that magnetite dominates the magnetic properties of the loess samples (Figure 2a-d). All samples also show a broad hump on heating between 150°C and 300°C, followed by a distinct decrease in χ. The broad hump probably indicates the transition of paramagnetic Fe-oxyhydroxides (e.g. lepidocrocite) to maghemite (γFeOOH$\longrightarrow\gamma Fe_2O_3$) [*Özdemir and Dunlop*, 1993]. The decrease in χ between 300°C and 550°C is probably the result of the thermally-induced transformation of metastable maghemite to hematite(α-Fe_2O_3) due to the lack of the decrease in χ between room temperature and 150°C [*Florindo et al.*, 1999]. Normalized heating curves (Figure 2d) indicate a similar magnetic mineral composition in L8 in all three sections. Between 300°C and 550°C, the heating curve from Duanjiapo shows more loss than that from Yichuan, whereas the loss of χ for loess samples from Jingbian is relatively low. If the loss of χ between 300°C and 550°C is a result of the thermally-induced transformation of maghemite to hematite [*Liu et al.*, 1999], it appears that the relative maghemite content decreases from south to north for L8 in the Chinese loess plateau. The broad hump between 150°C and 300°C nearly overlaps in the normalized heating curves of loess samples from the three sections. It probably, therefore, originates near the eolian source region rather than having a pedogenic origin at the three sites during this glacial period.

As observed in the loess samples, the heating curves for all S8 samples show a small increase in χ below 250°C, a decrease in χ between 250°C and 500°C, and a sharp decrease in χ near 580°C (Figure 2e-g). Normalized heating curves for the three sections (Figure 2h) indicate that the loss in χ between 250°C and 500°C is greatest at Jingbian, intermediate at Yichuan and least at Duanjiapo. Again, if this loss is the result of the thermally-induced transformation of maghemite to hematite, it reverses the geographic trend observed for L8, and indicates that the relative maghemite content increases from south to north for S8 in the Chinese loess plateau. If this observation for the L8-S8 cycle is true for the Chinese loess sequences in general, it means that the content of maghemite is not positively correlated to the degree of pedogenesis. As pedogenesis progresses, some threshold may be reached beyond which maghemite formation is less favoured [*Liu et al.*, 1999].

3.3 High-field magnetic properties

Hysteresis loops were measured using a Molspin vibrating sample magnetometer. At high fields (>400 mT), the ascending and descending branches are indistinguishable and are dominated by paramagnetic behaviour. The saturation magnetization (M_s), saturation remanence (M_r), coercivity (H_c) and coercivity of remanence (H_{cr}) were calculated after removal of the paramagnetic contribution, which is determined by the slope of the loop at high fields. Both M_r and M_s (Figure 1a, b) are well correlated with χ (R^2=0.944 and 0.901, respectively). These data suggest that the enhanced χ in S8 is mainly controlled by ferrimagnetic concentration [*Forster and Heller*, 1997; *Florindo et al.*, 1999].

The S-ratio [IRM(-0.3T)/IRM(1T)] is a measure of the contribution of remanence-carrying low coercivity versus high coercivity minerals. In this study, increased concentra-

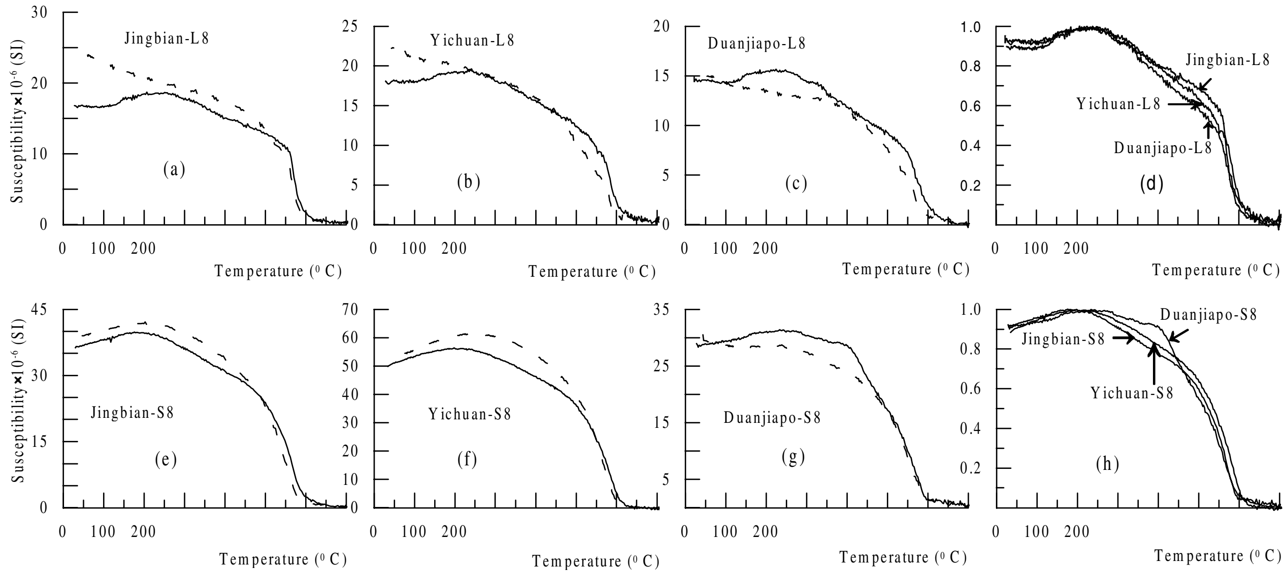

Figure 2. Temperature-dependence of magnetic susceptibility for (a) Jingbian-L8, (b) Yichuan-L8, (c) Duanjiapo-L8, (d) normalized heating curves of L8 samples for all three sections, (e) Jingbian-S8, (f) Yichuan-S8, (g) Duanjiapo-S8, and (f) normalized heating curves of S8 samples for all three sections. Solid/dashed lines indicate heating/cooling curves.

tions of low coercivity minerals (e.g. magnetite, maghemite) become more important than high coercivity minerals (e.g. hematite) in high χ samples from S8 (Figure 1c), even though this paleosol has a redder color than L8. Superparamagnetic (SP) fractions are calculated with the ratio of ferrimagnetic susceptibility (χ_f=χ-χ_h) and M_s [*Hunt et al.*, 1995], which represents a useful estimate of the concentration-independent variation of the SP magnetite and maghemite fraction and may be used as a measure of pedogenesis. Increasing χ_f/M_s with χ (Figure 1d) indicates that the SP fraction is higher in samples with high χ. However, χ_f/M_s is relatively high for S8 in the Duanjiapo section and departs from the trend line. Although χ is low for S8 at Duanjiapo, the relatively strong pedogenesis has led to high χ_f/M_s. It therefore appears that χ_f/M_s is a better proxy for pedogenesis in this case.

4. Discussion

4.1 Magnetic enhancement

The view that magnetic enhancement is caused by the pedogenic formation of SP grains is widely accepted [*Zhou et al.*, 1990; *Maher and Thompson*, 1991]. χ data have therefore been used as a semi-quantitative measure of pedogenic magnetic enhancement and paleoprecipitation across the Chinese Loess Plateau [e.g. *Maher and Thompson*, 1995]. The Jingbian, Yichuan and Duanjiapo sections have strong differences in their present-day climate. The annual rainfall at the three sites is 395 mm, 577 mm and 720 mm, respectively [*Wang et al.*, 1997]. In addition, χ_f/M_s increases from north to south, reflecting enhanced pedogenesis from north to south. If the paleoclimate contrast between the three sites during deposition of S8 and L8 was similar to the present-day climatic contrast, the highest χ would be expected from S8 in the Duanjiapo section. However, it is not observed from the experimental data (Figure 1), which suggests that χ is not consistently the suitable proxy for Quaternary paleoclimate in the Chinese loess plateau. This observation is supported by a recent investigation of the petromagnetic history of the last interglacial portion of Chinese loess/paleosol sequences [*Evans and Rokosh*, 2000]. A similar case was also reported by *Guo et al.* [2000]. In both sections investigated by *Guo et al.* [2000], soils S1, S4, S5-1 and S5-3 are the most developed soils in terms of morphological features, and the ratio of the citrate-bicarbonate-dithionite extractable free Fe_2O_3 versus the total Fe_2O_3 available, while χ is not higher for S1, S4 and S5-3 than for the other soil units. On the other hand, the colour, composition and structure of S8 at Duanjiapo indicate that it underwent the strongest pedogenesis of the three sections that we have investigated (*Guo Z. T.*, personal communication). The low χ probably, therefore, reflects a pedogenic environment in which magnetite and maghemite production and preservation are not favoured [*Liu et al.*, 1999]. Recent investigations of the χ of modern soils indicate that χ increases with enhanced pedogenesis, but that there exists some threshold beyond which χ decreases [*Lü et al.*, 1994].

4.2 Estimation of maghemite content and the effects of pedogenesis

Magnetite, maghemite and hematite are the main magnetic minerals in the Chinese loess sequences [*Heller and Evans*, 1995], however, the contribution of maghemite to χ, and the origin of any maghemite, remains unclear. *Verosub et al.* [1993] proposed, on the basis of citrate-bicarbonate-dithionite analyses, that most of the χ enhancement is contributed by pedogenic maghemite. In contrast, *Liu et al.* [1999] computed the maghemite component based on the loss of magnetization between heating and cooling curves at room temperature and concluded that, because the relative contribution of maghemite is higher in loess units, much of the maghemite originates in the eolian source area.

In our study, the heating curves of samples from L8 in all three studied sections showed a loss of χ between 300°C and 500°C due to maghemite. This χ loss increases from

N to S in L8 and is highest in our southernmost sites with the most humid climate, which suggests that the maghemite has a pedogenic origin. However, for S8, maghemite content is not positively correlated with the degree of pedogenesis. Thus, although recent research into modern loess provides evidence for maghemite formation during pedogenesis [*Deng et al.*, 2000], our results indicate that the relationship between maghemite content and degree of pedogenesis is not always straightforward for the Chinese loess-paleosol.

5. Conclusions

Our results for three sections along a N-S transect on the Chinese loess plateau indicate that the maghemite content increases in L8 from N to S, which indicates an increase in pedogenesis at localities with more humid climate. Similarly, for S8, the SP particle content, as indicated by χ_f/M_s, increases from N to S. This indicates that pedogenic enhancement of SP particles also increases with increasingly humid climate in S8 along our transect. The above interpretations are consistent with field-based pedological observations, which indicate that the degree of pedogenesis increases from N to S. Despite this trend, the maghemite content and χ, both of which are commonly used as indicators of pedogenesis, do not increase from N to S in S8. It therefore appears that χ is not consistently the most suitable indicator of paleoclimate in Chinese loess-paleosol sequences, and that, in this case, χ_f/M_s is a more useful indicator. Also, maghemite content increases with pedogenesis in L8, but in S8 there appears to be a threshold beyond which maghemite formation is not favoured. These observations indicate that there are complexities in the magnetic mineral response to pedogenesis that require caution in interpreting the χ record of Chinese loess-paleosol sequences in terms of paleoprecipitation.

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