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Magnetic grain-size distribution of the enhanced component in the loess–palaeosol sequences in the western Loess Plateau of China

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SUMMARY

Rock magnetic measurements of Chinese loess–palaeosol samples from the Beiyuan section in Linxia City suggest the presence of two magnetic components: a background component and an enhanced component. The magnetic properties of the enhanced component suggest strong grain-size control, which is in contrast with variable grain-size distribution in loess–palaeosol from the central Loess Plateau. Chemically formed magnetic grains do not fulfil the requirements in the case of the western Loess Plateau because they may show shifts in the grain-size distribution. The difference in climate between the western and central Loess Plateau may lead to different origins and different preservation conditions of the pedogenic magnetite.

Key words: Chinese Loess Plateau, magnetite, palaeoclimate, Quaternary, rock magnetism.

1 INTRODUCTION

The Chinese loess–palaeosol is one of the representative Quaternary sediments that have recorded the palaeoclimatic changes in the continental area. Magnetic properties of the loess–palaeosol sequence have been considered as one of the best palaeoclimate proxies (Maher & Thompson 1999). Heller & Liu (1984, 1986) reported a good correlation between the low-field magnetic susceptibility of the loess–palaeosol sequence and the marine oxygen isotope record. Since their pioneer studies, the low-field magnetic susceptibility profile has been regarded extensively as a convenient proxy for palaeoclimate determination (Liu *et al.* 1992; Heller *et al.* 1993).

Several models to interpret magnetic enhancement of palaeosol have been proposed. Most researchers now accept the idea of a pedogenic origin for very fine magnetite/maghemite as the source of magnetic enhancement (e.g. Heller & Evans 1995; Maher & Thompson 1999).

Maher & Thompson (1992) observed magnetite particles with variable grain size distribution by means of electron microscopy and regarded them as the pedogenic component of the loess–palaeosol sediment from the central Loess Plateau. In contrast, we report magnetite with a restricted grain-size distribution as the pedogenic component of loess–palaeosol sediment in the western Loess Plateau, whose present climate is more arid and colder than that of the central Loess Plateau, based on two contrasting data sets reported in Mishima *et al.* (1999).

2 SAMPLING AND LABORATORY METHODS

Loess and palaeosol samples were taken from the Beiyuan section of Linxia City and the Shajinping section of Lanzhou City, Gansu Province, China (Fig. 1). The Beiyuan section is on the third terrace of the Daxia River (a tributary of the Yellow River) in Linxia City. This section is 38 m high and covers the last 140 kyr (Fang *et al.* 1994). It consists of Holocene palaeosol S0, Malan loess L1 and four embedded Sm palaeosols, and S1 palaeosols (Fig. 2a). The Shajinping section is on the second terrace of the Yellow River in Lanzhou City. This section is 22 m high and covers the last 60–75 kyr (Fang *et al.* 1999; Yamada *et al.* 1999). It consists of Holocene palaeosol (S0) at the top, Malan loess (L1) and weak embedded palaeosols (Sm series), and alluvial loess at the base, as shown in Fig. 3(a).

We collected samples using small plastic boxes at both sites. After removing weathered surfaces of the outcrops as deep as

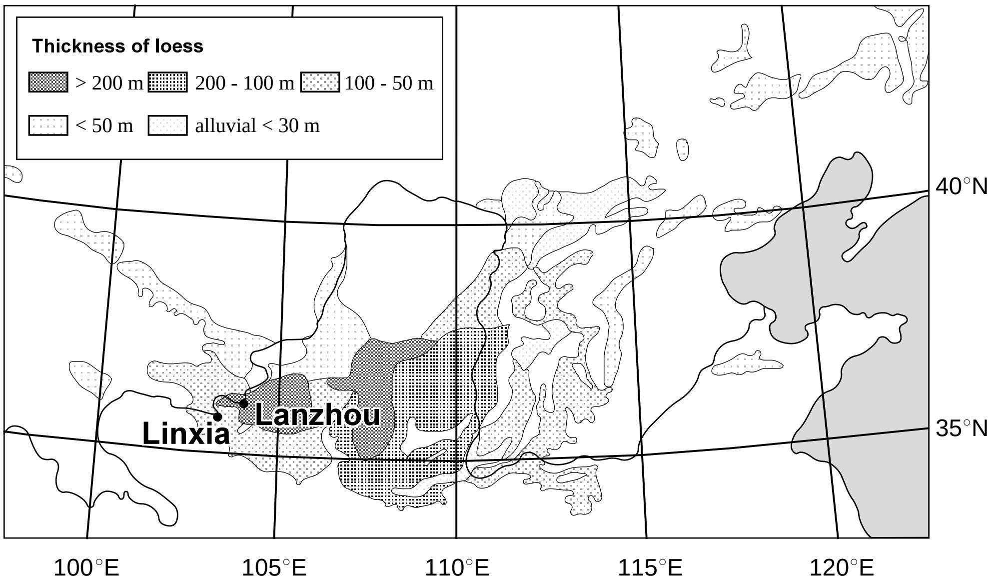

Figure 1. The locations of the sampling sites. Hatched areas show the distribution and thickness of loess–palaeosol sequences in the Chinese Loess Plateau (simplified after Wang *et al.* 1984).

10 cm, cubic plastic boxes (7 cm^3) were pressed down into the outcrop at 5 cm intervals and then recovered. At the Shajinping section, some samples were collected at much smaller intervals of $1.7 \sim 2.5$ cm.

Low-field magnetic susceptibility (χ) was measured with a Kappabridge KLY3 susceptometer and normalized to mass of the sample. High-field slope correction for paramagnetic and antiferromagnetic contributions was not adopted. Anhysteretic remanent magnetization (ARM) was acquired in a peak alternating field of 100 mT and a steady field of 0.1 mT using a 2G Enterprises model 600 degausser. ARM was measured using an ScT C-112 cryogenic magnetometer and converted into ARM susceptibility (χ_{ARM}). Isothermal remanent magnetization (IRM) was acquired at 1.2 T using an electromagnet. Some samples were not completely saturated in magnetic fields up to 1.8 T. As Chinese loess–palaeosol contains antiferromagnetic minerals such as haematite and goethite (Eyre & Dickson 1995), it is difficult to saturate samples completely. In this study, IRM acquired at 1.2 T is defined as 'saturated' IRM (SIRM). This means that the magnetic grains with high coercivity are ignored.

Thermal demagnetization of low-temperature remanence was carried out with a Quantum Design's Magnetic Properties Measurement System (MPMS). SIRM was acquired after 'zero-field cooling' (cooling from room temperature to 10 K in 0 T) and then the decay of SIRM was measured during the heating of the sample up to 300 K.

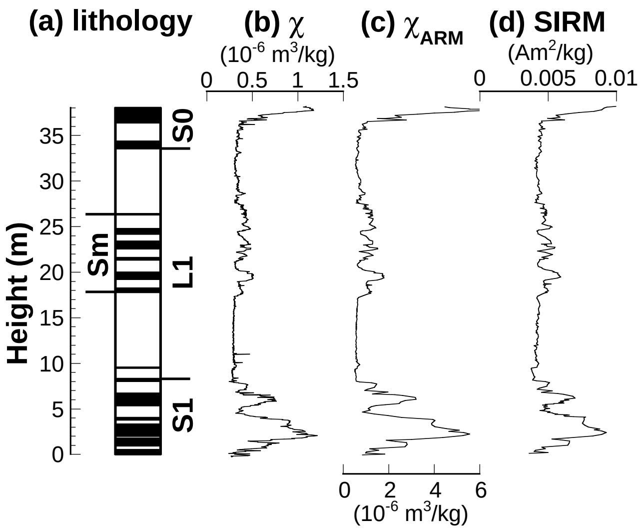

Figure 2. The lithology and magnetic profiles of the Beiyuan section, Linxia. (a) Lithology (white: loess; black: palaeosol); (b) low-field magnetic susceptibility; (c) ARM susceptibility; (d) SIRM (modified after Mishima *et al.* 1999).

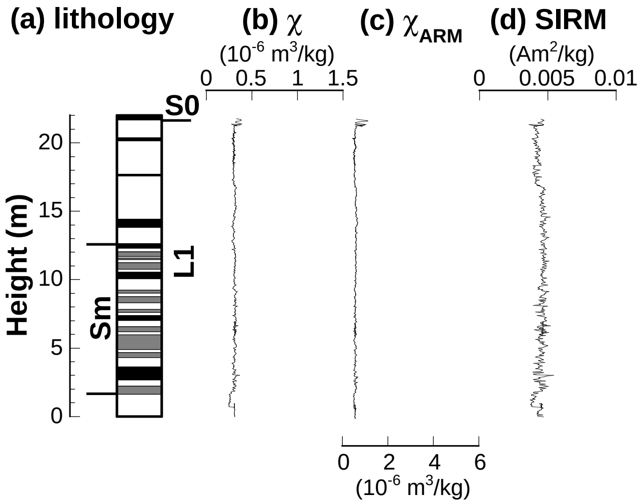

Figure 3. The lithology and magnetic profiles of the Shajinping section, Lanzhou. (a) Lithology (white: loess; black and grey: palaeosol); (b) low-field magnetic susceptibility; (c) ARM susceptibility; (d) SIRM. Note that horizontal scales are the same as Fig. 2. (Modified after Mishima *et al.* 1999.)

Magnetic hysteresis measurements were performed with a MicroMag alternating gradient force magnetometer. Saturation magnetization (M_s) and saturation remanence (M_{rs}) were calculated from each hysteresis loop with a maximum field of 1 T. Remanent coercivity (B_{cr}) and coercivity (B_c) were calculated from the stepwise demagnetization curve of IRM acquired at 1 T.

3 RESULTS

In this section, we briefly summarize the results of a previous study (Mishima *et al.* 1999). In the Beiyuan section, χ, χ_{ARM} and SIRM show stable low values in most of the L1 loess and elevated values in the palaeosols (Fig. 2). An excellent correlation among χ, χ_{ARM} and SIRM was found. Such a correlation can be explained by the mixing of two magnetic components, that is, the background and enhanced components. The idea of two-component mixing is analogous to that deployed by Forster *et al.* (1994) and Forster & Heller (1997) to explain the correlation between χ, χ_{FD} (the frequency dependence of magnetic susceptibility) and SIRM. The background component is located on the lower end of the regression line, and the enhanced component is determined from the slope of the regression line (Fig. 4).

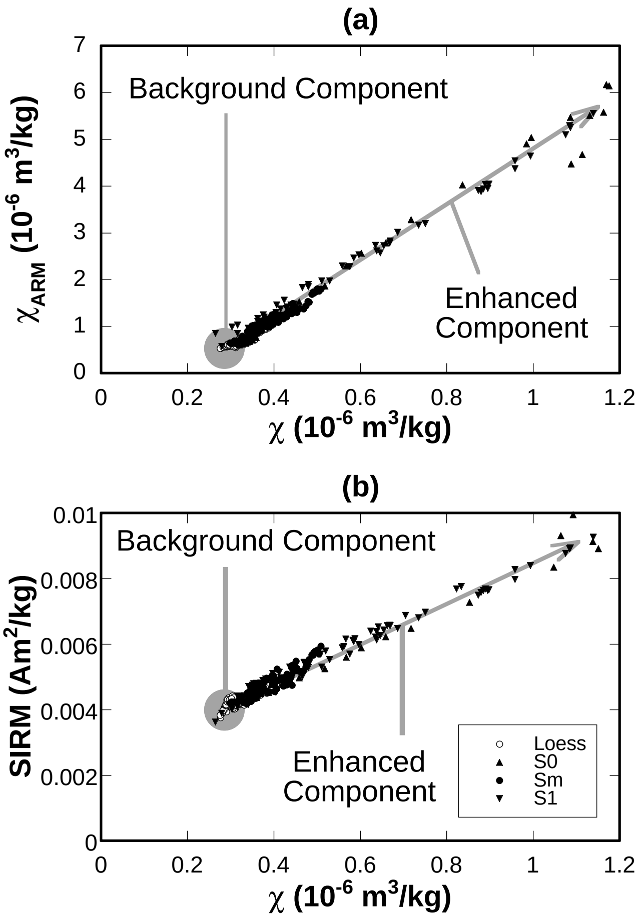

Figure 4. (a) Low-field magnetic susceptibility versus ARM susceptibility. (b) Low-field magnetic susceptibility versus SIRM. Two components can be inferred as sources of magnetization. (Modified after Mishima *et al.* 1999.)

The background component is constant regardless of the degree of magnetic enhancement. The magnetic parameter of the background component is $\chi = 2.7 \times 10^{-7}$ m^3 kg^{-1}, $\chi_{ARM}/\chi = 1.7$ and SIRM/$\chi = 1.5 \times 10^4$ A m^{-1}. The enhanced component has specific values of χ_{ARM}/χ and SIRM/χ, and the concentration of magnetic minerals increases with the magnetic enhancement. The χ_{ARM}/χ and SIRM/χ values of the enhanced component are 5.9 and 6.1×10^3 A m^{-1}, respectively. S0, Sm and S1 palaeosols have identical enhanced components because the data from the three palaeosols fall on a consistent regression line in Fig. 4. Larger χ_{ARM}/χ values and smaller SIRM/χ values in the enhanced component suggest the dominance of finer-grained magnetic grains in the enhanced component. The dominance of fine-grained magnetic grains is also implied by high M_{rs}/M_s, low B_{cr}, and the B_c of high-χ samples (Fig. 5). Fukuma & Torii (1998) showed the presence of a pristine loess component and an increase in pedogenic material in palaeosols on the basis of hysteresis curves.

The thermal unblocking curves of low-temperature IRM (Fig. 6a) are also explained by the combination of two components. The remanence at each temperature step is well correlated to χ (at room temperature) and the remanence at each temperature for the two components can be calculated from the regression line. For example, the correlation between χ and the remanence at 80 K (Fig. 6b) is explained by a mixture of the background component (5.1×10^{-3} A m^2 kg^{-1}) and the enhanced component (remanence/$\chi = 9.7 \times 10^3$ A m^{-1}). The unblocking curves for the two components are compilations of similar calculations at every 5 K (Fig. 6c). The curve for the enhanced component, which reflects the magnetic grain-size distribution of the enhanced component, is independent of the degree of soil formation.

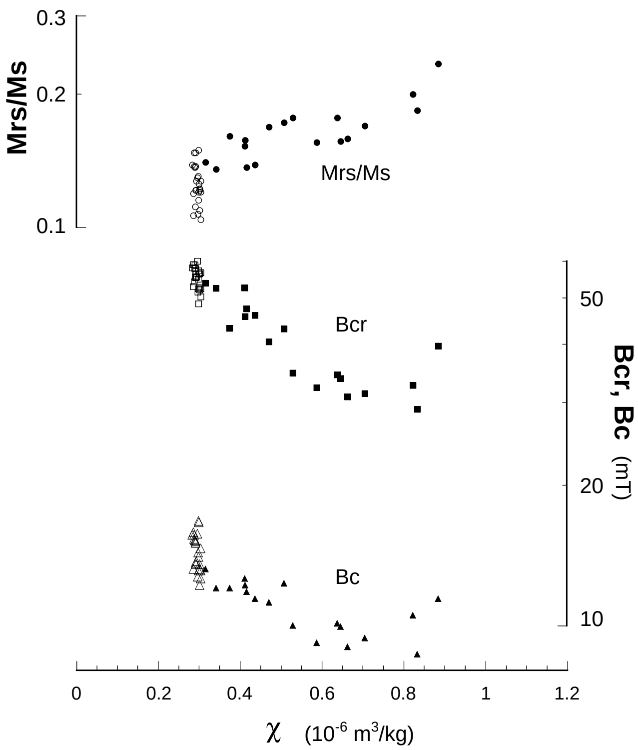

Figure 5. Magnetic hysteresis parameters. Circles: M_{rs}/M_s; squares: B_{cr}; triangles: B_c. Solid symbols: results from the Beiyuan section, Linxia; open symbols: results from the Shajinping section, Lanzhou.

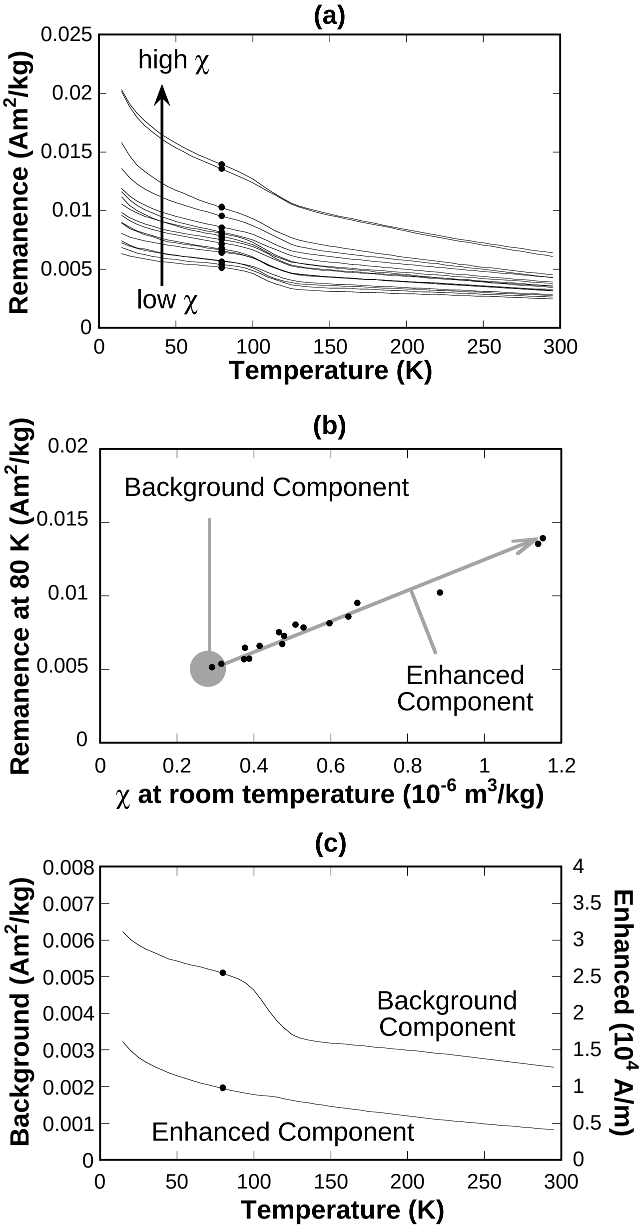

Figure 6. (a) Thermal unblocking curves of low-temperature IRM for samples from the Beiyuan section. (b) Low-field magnetic susceptibility versus the remanence at 80 K, i.e. the points on (a). (c) Calculated unblocking curves for the two magnetic components. The points show the two components in (b). (Modified after Mishima *et al.* 1999.)

In the Shajinping section, χ, χ_{ARM} and SIRM of the loess–palaeosol sequence are almost uniform and low (Fig. 3): $\chi = 2.7 \times 10^{-7}$ m^3 kg^{-1}, $\chi_{ARM} = 4 \sim 5 \times 10^{-7}$ m^3 kg^{-1} and SIRM $= 4 \times 10^{-3}$ A m^2 kg^{-1}. Such low values are in common with the background component of the Beiyuan section (Fig. 3). The existence of common background components in the two sections and the absence of the enhanced component can explain the magnetic properties in the Shajinping section. The identical background component from the two sections within a distance of 100 km would be expected if the grains of the background component were transported to these areas by wind and not influenced by soil formation.

4 DISCUSSION

One possible process of magnetic enhancement is the chemical formation of magnetic minerals. An example of this is biologically induced mineralization (Moskowitz *et al.* 1993), which is the chemical formation of magnetic grains under the extracellular environment of iron-reducing bacteria. It was proposed as the formation process of fine magnetite grains in topsoils from England (Dearing *et al.* 1996).

However, if the magnetic grains of the enhanced component were chemically produced, a shift of the grain-size distribution in proportion to the magnetic enhancement could occur. If we assume that the enhanced component is formed by oxidation of some source material, the sizes of oxidizable grains can vary according to environment. In another case, where fine magnetic grains act as nuclei and grow coarse, the shift in grain size may also occur. Such variable grain-size distributions have been reported from the central region of the Chinese Loess Plateau from electron microscopy (Maher & Thompson 1992).

The topsoils from England are variable in magnetic grain-size distribution because they are variable in χ_{FD} (Dearing *et al.* 1996). Forster & Heller (1997) and Jordanova & Petersen (1999) reported a change in magnetic grain size in the pedogenic fraction in palaeosols from a Bulgarian loess–palaeosol sequence. Inorganic formation of the magnetic minerals is a possible process for the magnetic enhancement in many sections. However, the size-controlled pedogenic fractions, such as the enhanced component of the Beiyuan section, may not be produced by an inorganic formation process.

One possible origin of the size-controlled magnetite grains is magnetosomes synthesized by magnetotactic bacteria. The existence of magnetosomes has been inferred in a previous study (Evans & Heller 1994). The magnetosomes are formed within cells of magnetotactic bacteria and feature well-controlled grain size bounded by cell dimensions. Magnetotactic bacteria are identified in sediments of various environments, including loess–palaeosol sediment in the central Loess Plateau (Jia *et al.* 1996) and soil in Southern Bavaria (Fassbinder *et al.* 1990). Thus, it is possible that magnetotactic bacteria once existed in ancient soil and produced magnetosomes in the western Loess Plateau.

The most straightforward evidence for the origin of the enhanced component is electron microscope photographs, which can clarify the identical shape and arrangement of fine magnetic minerals. However, such photographs are only taken from well-developed palaeosol samples from the central Loess Plateau. Electron microscopic photographs of palaeosol in the western Loess Plateau will reveal the origin of the enhanced component in this region.

In the Shajinping section in Lanzhou City, almost no magnetically enhanced component was found in the palaeosol horizons. However, 18 weakly to moderately developed palaeosol horizons have been identified (Fang *et al.* 1999). The colour reflectance data (Yamada *et al.* 1999) also indicate soil development. Such a situation may have occurred at some levels (e.g. $8 \sim 17$ and $28 \sim 35$ m) of the Beiyuan section. While the low-field magnetic susceptibility is almost constant, a narrow variation of colour reflectance is observed (Yamada *et al.* 1999). Moreover, stable low-field magnetic susceptibility in loess horizons is commonly observed at several sections in the western Loess Plateau, for example, at Xining (Hunt *et al.* 1995), Baicaoyuan (Evans & Heller 1994) and Huanxian (Zheng *et al.* 1995).

Such observations imply that weak soil development can occur without magnetic enhancement. The inadequate environment for the formation of magnetic grains with controlled grain-size distributions can be estimated.

In the same way, other possible processes for magnetic enhancement of soils may impose the conditions to work. Biologically induced mineralization is considered as the dominant process for magnetic enhancement in the central Loess Plateau (Maher & Thompson 1999), where the weather is more humid and warmer than in the western Loess Plateau. An assumption that the pedogenic condition in the western Loess Plateau is inadequate for such processes can explain the different grain-size distributions between the western and central Loess Plateau.

On the other hand, the climatic difference between the western and central regions of the Chinese Loess Plateau can also affect the preservation conditions of the pedogenic fine magnetite. In the Beiyuan section, the size-controlled magnetite grains could have undergone weathering and/or pedogenesis and oxidized to maghemite. However, the effect of weathering and/or pedogenesis is probably slight, because the grain-size distribution was maintained. In the case of the central Loess Plateau, strong alteration and/or dissolution may have transformed the original grain-size distribution even if magnetite with controlled grain-size distribution was once produced.

5 CONCLUSIONS

The confined magnetic grain-size distribution of the enhanced component in the Beiyuan section suggests that the strongly size-controlled formation of magnetic grains produced this component. It is not compatible with variable magnetic grain-size distributions reported in the central Loess Plateau. The different climatic conditions between the western and central Loess Plateau may have caused the different origin and preservation conditions and different grain-size distributions of the pedogenic magnetite.

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REFERENCES

Dearing, J.A., Hay, K.L., Baban, S.M.J., Huddleston, A.S., Wellington, E.M. & Loveland, P.J., 1996. Magnetic susceptibility of soil: an evaluation of conflicting theories using a national data set, *Geophys. J. Int.*, **127,** 728–734.

Evans, M.E. & Heller, F., 1994. Magnetic enhancement and palaeoclimate: study of a loess/paleosol couplet across the Loess Plateau of China, *Geophys. J. Int.*, **117,** 257–264.

Eyre, J.K. & Dickson, D.P.E., 1995. Mössbauer spectroscopy analysis of iron-containing minerals in the Chinese Loess, *J. geophys. Res.*, **100,** 17 925–17 930.

Fang, X.-M., Li, J.-J., Derbyshire, E., Fitzpatrick, E.A. & Kemp, R.A., 1994. Micromorphology of the Beiyuan loess-paleosol sequence in Gansu Province, China; geomorphological and paleoenvironmental significance, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **111,** 289–303.

Fang, X.M., *et al.*, 1999. Asian summer monsoon instability during the past 60,000 years: magnetic susceptibility and pedogenic evidence from the western Chinese Loess Plateau, *Earth planet. Sci. Lett.*, **168,** 219–232.

Fassbinder, J.W.E., Stanjek, H. & Vali, H., 1990. Occurrence of magnetic bacteria in soil, *Nature,* **343,** 161–163.

Forster, T. & Heller, F., 1999. Magnetic enhancement paths in loess sediments from Tajikistan, China and Hungary, *Geophys. Res. Lett.*, **24,** 19–20.

Forster, T., Evans, M.E. & Heller, F., 1994. The frequency dependence of low field susceptibility in loess sediments, *Geophys. J. Int.*, **118,** 636–642.

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

Heller, F. & Evans, M.E., 1995. Loess magnetism, *Rev. Geophys.*, **33,** 211–240.

Heller, F. & Liu, T.-S., 1984. Magnetism of Chinese loess deposits, *Geophys. J. R. astr. Soc.*, **77,** 125–141.

Heller, F. & Liu, T.-S., 1986. Paleoclimatic and sedimentary history from magnetic susceptibility of loess in China, *Geophys. Res. Lett.*, **13,** 1169–1172.

Heller, F., Shen, C.D., Beer, J., Liu, X.M., Liu, T.S., Bronger, A., Suter, M. & Bonani, G., 1993. Quantitative estimates of pedogenic ferromagnetic mineral formation in Chinese loess and palaeoclimatic implications, *Earth planet. Sci. Lett.*, **114,** 385–390.

Hunt, C.P., Banerjee, S.K., Han, J.-M., Solheid, P.A., Oches, E., Sun, W. & Liu, T.-S., 1995. Rock-magnetic proxies of climate change in the loess–palaeosol sequences of the western Loess Plateau of China, *Geophys. J. Int.*, **123,** 232–244.

Jia, R.-F., Yan, B.-Z., Li, R.-S., Fan, G.-C. & Lin, B.-H., 1996. Characteristics of magnetotactic bacteria in Duanjiapo loess section, Shaanxi Province and their environmental significance, *Sci. China,* **39,** 478–485.

Jordanova, D. & Petersen, N., 1999. Palaeoclimatic record from a loess-soil profile in northeastern Bulgaria—I. Rock magnetic properties, *Geophys. J. Int.*, **138,** 520–532.

Liu, X.-M., Shaw, J., Liu, T.-S., Heller, F. & Yuan, B.-Y., 1992. Magnetic mineralogy of Chinese loess and its significance, *Geophys. J. Int.*, **108,** 301–308.

Maher, B.A. & Thompson, R., 1992. Paleoclimatic significance of the mineral magnetic record of the Chinese loess and paleosols, *Quat. Res.*, **37,** 155–170.

Maher, B.A. & Thompson, R., 1999. Palaeomonsoons I: the magnetic record of palaeoclimate in the terrestrial loess and palaeosol sequences, in *Quaternary Climates, Environments and Magnetism,* pp. 81–125, eds Maher, B.A. & Thompson, R., Cambridge University Press, Cambridge.

Mishima, T., *et al.*, 1999. Contrasting magnetic properties from two loess/paleosol sections in Gansu Province, west China, in *Climatic Change: Paleopedological and Soil Rock Magnetic Approaches,* eds Fang, X.-M. & Nettleton, D., *Chinese Sci. Bull.*, **44,** 181–188.

Moskowitz, B.M., Frankel, R.B. & Bazylinski, D.A., 1993. Rock magnetic criteria for the detection of biogenic magnetite, *Earth planet. Sci. Lett.*, **120,** 283–300.

Wang, Y.-Y., Sasajima, S., Teng, Z.-H., Lei, X.-Y. & Sun, W., 1984. Loess in China and its stratigraphic sequence, in *The Recent Research of Loess in China: Stratigraphy, Magnetostratigraphy,* *Chronology, Pedology, Paleontology and Paleoclimatology,* pp. 1–31, eds Sasajima, S. & Wang, Y.-Y., Kyoto Institute of Natural History, Kyoto.

Yamada, K., Fukusawa, H., Fang, X.-M., Pan, B.-T., Li, J.-J. & Iwata, S., 1999. High-resolution multi-proxy records of Asian monsoon activities from terrestrial sediments over the last 75,000 years, in *Climatic Change: Paleopedological and Soil Rock Magnetic Approaches,* eds Fang, X.-M. & Nettleton, D., *Chinese Sci. Bull.,* **44,** 223–229.

Zheng, H.-B., Rolph, T., Shaw, J. & An, Z.-S., 1995. A detailed paleomagnetic record for the last interglacial period, *Earth planet. Sci. Lett.,* **133,** 339–351.