Magnetic properties of loess deposits on the northeastern Qinghai-Tibetan Plateau: palaeoclimatic implications for the Late Pleistocene

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SUMMARY

The loess–palaeosol deposit on the northeastern Qinghai-Tibetan Plateau is sensitive to environmental changes, thus providing a good opportunity to investigate regional palaeoenvironmental evolution and its relationship with global climatic changes. Detailed rock magnetic investigations and grain-size determination were carried out on a 35-m-thick loess–palaeosol sequence at Dongchuan, the northeastern Qinghai-Tibetan Plateau. The principal ferrimagnetic minerals in both the loess and palaeosol units are large pseudo-single domain magnetite/maghemite. Palaeosol units are generally enriched in ultrafine-grained magnetite/maghemite of pedogenic origin. Variations of low-field magnetic susceptibility and frequency-dependent susceptibility in the loess and palaeosols can mainly be attributed to changes in the concentration of these minerals. Higher values of frequency-dependent susceptibility occur in the palaeosol horizons except for the weakly developed palaeosol, suggesting that higher concentrations of ultrafine magnetite/maghemite particles occur in palaeosol units due to *in situ* pedogenesis. The frequency-dependent susceptibility of the loess units is very low and uniform, indicating absence of the super-paramagnetic grains and negligible pedogenically induced enhancement of magnetic susceptibility. Generally, magnetic susceptibility combined with the frequency-dependent susceptibility of the loess–palaeosol sequences reflect the glacial-interglacial changes, thus can be employed as a proxy measure of palaeoclimate in this region. However, the low-field magnetic susceptibility record does not consistently correlate to the variations in stratigraphy of the Dongchuan loess–palaeosol sequence. It is thus suggested that multiparameter rock magnetic investigations combined with non-magnetic measurements, such as grain-size analysis, represent a more powerful approach for palaeoclimatic research into the complex loess–palaeosol record in the Qinghai-Tibetan Plateau.

Key words: loess, northeastern Qinghai-Tibetan Plateau, palaeosol, rock magnetism.

1 INTRODUCTION

Windblown dust deposits on the Chinese Loess Plateau potentially constitute natural archives of palaeoclimatic changes in mid-continental regions during the Late Cenozoic era. Heller & Liu (1984, 1986) firstly suggested a link between variations in the loess–palaeosol magnetic susceptibility records and oxygen isotope records from deep-sea sediments, which paved the way for using rock magnetic properties of the Chinese loess–palaeosol sequence as a robust proxy for global climate variations (Kukla *et al.* 1988; Hunt *et al.* 1995; Bloemendal & Liu 2005; Liu *et al.* 2005a; Deng *et al.* 2005, 2006).

Variations in concentration and grain size of the magnetic minerals in these aeolian sediments control the magnetic susceptibility changes across the Loess Plateau (Hus & Han 1992; Hunt *et al.* 1995; Florindo *et al.* 1999; Deng *et al.* 2004). As a useful proxy in palaeoclimatic studies, magnetic susceptibility has been extensively investigated (Kukla *et al.* 1988; Verosub *et al.* 1993; Maher & Thompson 1995; Maher *et al.* 2003). Rock-magnetic, geochemical and microscopy data from the loess–palaeosol sequence across the

Loess Plateau indicate that the origin of the magnetic/climatic coupling is the pedogenic formation of ultrafine (<0.1 μm), superparamagnetic (SP) and single domain (SD) grains of the magnetic iron oxide, that is, magnetite and/or maghemite (Zhou *et al.* 1990; Maher & Thompson 1991; Verosub *et al.* 1993; Hus & Bai 1993; Maher & Thompson 1994; Liu *et al.* 2004a; Deng *et al.* 2004, 2005). However, the precise relationship between palaeoclimate changes and the magnetic intensification, as well as the mechanisms involved in the natural remnant magnetization acquisition remain unclear. For sediments, variations in magnetic properties can reflect changes in any of the following: allogenic inputs, authigenic inputs, and post depositional diagenesis (Maher & Taylor 1988). Thus, the nature of causal links between climate and magnetic properties are likely to change from site to site. In the Chinese loess sequences, the palaeosols usually have higher susceptibilities than the less-weathered loess. In Europe, Alaska and Siberia, many loessic soils show magnetic enhancement in soil horizons, but some palaeosols show a depletion of pedogenic ferrimagnetic magnetic minerals due to waterlogging (Nawroki 1992; Oches & Banerjee 1996; Vlag *et al.* 1999; Zhu *et al.* 2003). Therefore, it is necessary to establish the nature of the soil-magnetic signal for a given region before any attempts at palaeoclimatic reconstruction (Geiss *et al.* 2004).

Loess–palaeosol deposits in the northeastern Qinghai-Tibetan Plateau area are partly different to those to the east of Liupan Mountains on the Chinese Loess Plateau in terms of dust sources, sedimentary conditions, and climate environments (Wang *et al.* 2003; Lu *et al.* 2001, 2004a,b). Located on the margins of the semi-humid, semiarid and the high-cold zones, the loess–palaeosol sequence is very sensitive to environmental changes, and thus provides a good opportunity to investigate the regional palaeoenvironmental evolution and its relationship with global environment changes (Fig. 1). Several authors (Chen *et al.* 1997, 1999; Fang *et al.* 2003; Lu *et al.* 2001, 2004a,b) have preliminarily investigated the palaeoclimate and geomorphologic features of the loess deposits in the northeast Qinghai-Tibetan Plateau. There were few investigations (Zhu *et al.* 1994; Maher *et al.* 2003; Wang *et al.* 2003) have been made on the

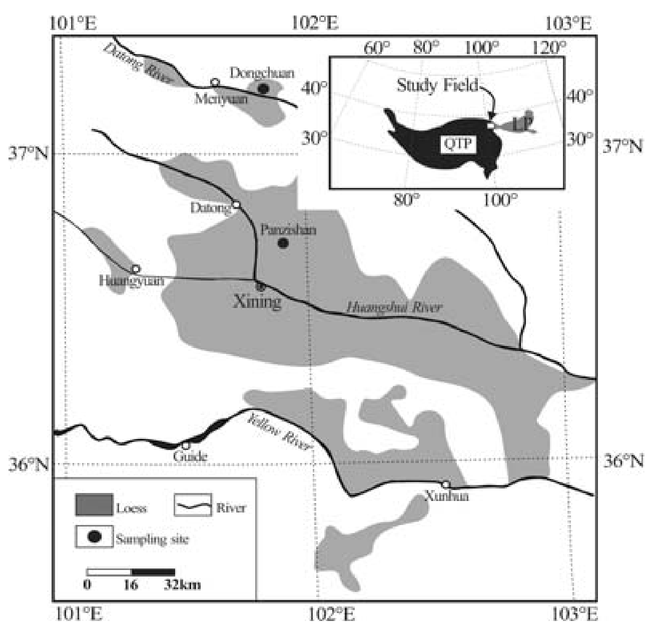

Figure 1. Schematic map showing the loess distribution in the northeastern Qinghai-Tibetan Plateau and sampling sites (Wang *et al.* 2003). QTP and LP represent the Qinghai-Tibetan Plateau and Loess Plateau, respectively.

magnetic properties of loess–palaeosol sequences in this area. In this study, detailed rock magnetic investigations combined with grain-size determination of loess and palaeosols in this area contribute to the understanding of the regional palaeoenvironmental evolution and its relationship with global environment changes for the Late Pleistocene.

The results of detailed rock magnetic investigations and grain-size analysis of a 35-m-thick loess profile on the northeastern Qinghai-Tibetan Plateau are given in order to address two questions: (1) do magnetic properties of the palaeosols, weakly developed palaeosols and loess on the northeastern Qinghai-Tibetan Plateau differ from those elsewhere, such as that on the Loess Plateau; and (2) is magnetic susceptibility a proxy measure of palaeoclimate in this region?

2 GENERAL SETTING AND SAMPLING

In this region, river terrace sequences and thick loess deposits are well developed. The loess deposits, with coarser particles and less compacted than that in the central Chinese Loess Plateau, mainly occur on river terraces (Lu *et al.* 2001, 2004a,b).

The loess–palaeosol sequence investigated in this study is visible in the Dongchuan section (latitude 37.2°N, longitude 101.8°E, elevation 3125 m above sea level), located on the second terrace of the Datong river in the northeastern margin of the Qinghai-Tibetan Plateau. The area is bordered by the Daban and Qilian mountains, in the South and the North, respectively. Present-day observations show that this region is characterized by warm-wet summer and cold-dry winter. The mean annual temperature is 0.6°C with a July average of 12°C while the mean January temperature is -13.5°C. Mean annual precipitation is 520 mm, and about 75 per cent of the annual precipitation falls in June-September with a peak value of 109 mm in August (Bureau of Geology and Mineral Resources of Qinghai Province 1991).

The Dongchuan section (Fig. 2), a 35-m-thick loess/palaeosol sequence with modern cultivated soil in the top, contains four well-developed palaeosol units labelled S_a, S_b, S_c, and S_d. The palaeosols can be recognized by their dull-brown colour and massive structure. In contrast, the loess units, labelled L_a, L_b, L_c, L_d, are characterized by a light yellowish orange colour, and are loose and porous. A weakly developed, weak granular palaeosol of dull-orange colour (labelled L_bS) occurs in the light-coloured unit L_b. Five well developed sub-palaeosols in S_d are identified in the field in terms of their dull-brown colour, massive structure and finer particle size. Fresh samples were obtained after removing about 80 cm of surface material from the well-exposed outcrops in order to eliminate weathering effects. Unoriented loose samples were taken at 5 cm intervals over the whole section.

Optical stimulated luminescence methods (OSL) as well as field observations, are used to construct the chronological framework of Dongchuan profile. Three block samples were taken for OSL dating (Fig. 2). The ages of the OSL dates given may approach or even exceed the luminescence limit. However, they offer useful time control. On the basis of field geomorphologic investigation and absolute OSL dating, the Dongchuan loess–palaeosol deposits are judged to have been formed during the Late Pleistocene (Dr. Jan-Pieter Buylaert, personal communication, 2006).

The other loess–palaeosol sequence (Lu *et al.* 2004b) mentioned in this paper (Fig. 2), the Panzishan sequence (36.6°N, 101.9°E, elevation 2728 m above sea level), located on a high terrace of the Huangshui River in the northeastern margin of the Qinghai-Tibetan Plateau, and, this sequence was absolutely dated and the

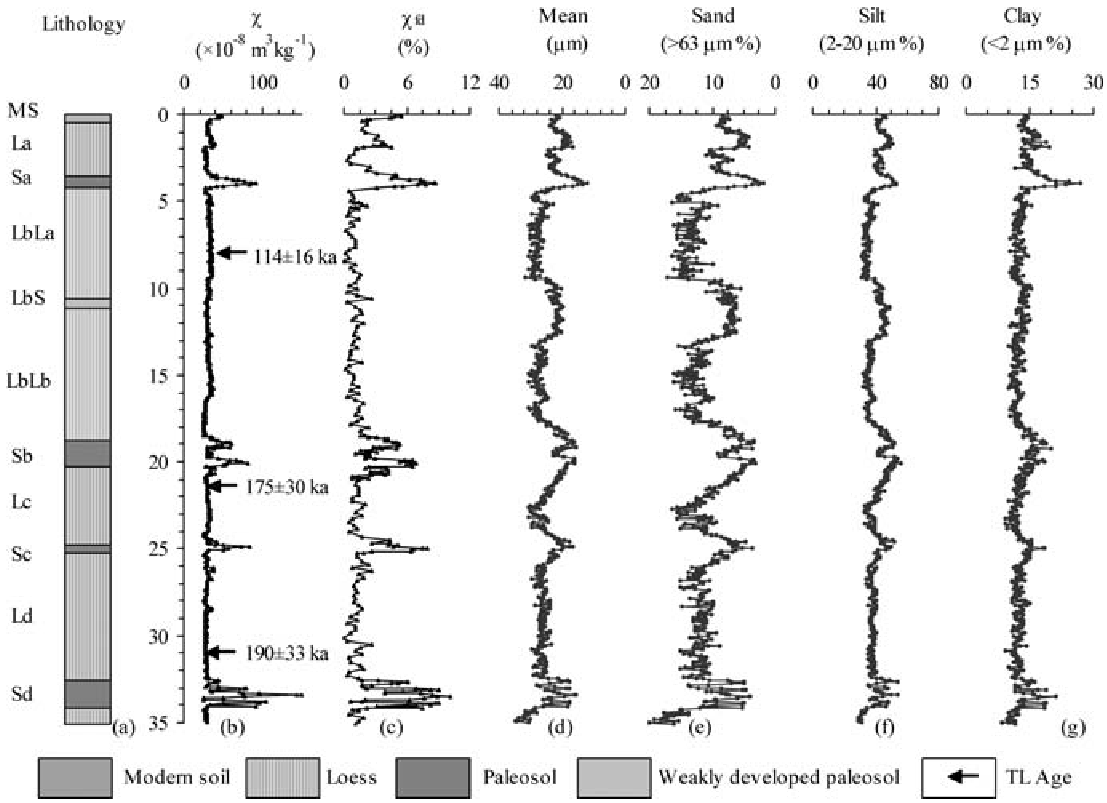

Figure 2. Depth versus of magnetic susceptibility (χ), frequency-dependent magnetic susceptibility (χ_{fd}) (Wang *et al.* 2003), mean grain size, sand fraction ratio, silt fraction ratio and clay fraction ratio within the Dongchuan Pedocomplex.

loess palaeosol deposit was formed during the last glacial and interglacial time, respectively. Present-day observations show that this region is characterized by warm-wet summer and cold-dry winter. The mean annual temperature is 5.7°C with a July average of 17.2°C while the mean January temperature is −8.4°C. Mean annual precipitation is 368 mm, and about 72 per cent of the annual precipitation falls in June–September with a peak value of 82 mm in August (Bureau of Geology and Mineral Resources of Qinghai Province 1991).

3 EXPERIMENTAL METHODS

3.1 Magnetic measurements

Low-field magnetic susceptibility (χ) was measured in a Bartington MS2 susceptibility meter at frequencies of 470 and 4700 Hz after drying the samples at 38°C for 48 hours. Frequency-dependent magnetic susceptibility, χ_{fd}, defined as $[(\chi_{470\,\mathrm{Hz}} - \chi_{4700\,\mathrm{Hz}})/\chi_{470\,\mathrm{Hz}} \times 100$ per cent], was determined from these measurements. High-temperature magnetic susceptibility curves ($\chi - T$) were obtained by measuring continuously from room temperature to 610°C and back to room temperature in a KLY-3 Kappabridge with a CS-3 high-temperature furnace (Agico Ltd., Brno, Czech Republic) in an argon atmosphere. The sample holder and thermocouple contributions to magnetic susceptibility were subtracted.

Hysteresis parameters of the loess and palaeosols were measured using a MicroMag 2900 Alternating Gradient Magnetometer (Princeton Measurements Corp., USA). A few milligrams of natural material were attached to the sample probe. The magnetic field was then cycled between ±1.5 T for each sample. Saturation magnetization (M_s), saturation remanence (M_{rs}), and coercivity (B_c) were determined after correction for the paramagnetic contribution identified from the slope at high fields. Samples were then demagnetized in alternating fields (AF) up to 150 mT, and an isothermal remanent magnetization (IRM) was imparted from 0 to 1.5 T in the MicroMag 2900 AGM. Subsequently the IRM at 1.5 T was demagnetized in a stepwise increasing backfield from 0 to −1.5 T to obtain the coercivity of remanence (B_{cr}). IRM was measured in a JR-5 spinner magnetometer after magnetization in a 2G-660 pulse magnetometer in a maximum applied field of 2.7 T.

3.2 Particle-size measurements

The samples were pre-treated with hydrogen peroxide (H_2O_2) to remove organic matter, with hydrochloric acid (HCl) to remove carbonates and finally with sodium hexametaphosphate ($(NaPO_3)_6$) to facilitate dispersion. The grain-size distribution was obtained in a Malvern Mastersizer 2000 particle analyser that automatically yields the percentages of the clay-, silt-, and sand-size fractions and the median grain-size diameter for a sample.

4 MAGNETIC PROPERTIES

4.1 Magnetic susceptibility (χ) and its frequency dependence (χ_{fd} per cent)

Magnetic susceptibility values (Figs 2a and b) range from (26–34) × 10^{-8} m^3 kg^{-1} in the loess units to a maximum of 143 × 10^{-8} m^3 kg^{-1} within the palaeosol units. The highest value was obtained for palaeosol unit S_d. Lower magnetic susceptibility values are found for the loess units compared to the interbedded palaeosol units. High and low magnetic susceptibility values, associated with palaeosols and loess, respectively, probably reflect the relative concentrations of magnetite and maghemite particles (An *et al.* 1991; Bloemendal *et al.* 1995). Values of the frequency-dependent susceptibility range from 0–3 per cent in the loess units, and rise to 4–11 per cent in the palaeosol samples. Higher frequency-dependent susceptibility occurs in the palaeosol layers, indicating the enrichment of SP grains occurred in the palaeosols due to *in situ* pedogenesis (Maher & Taylor 1988; Zhou *et al.* 1990; Evans & Heller 2001). However, the moderately weathered palaeosol unit L_bS in the depth interval 10.6–11.2 m shows uniform magnetic susceptibility and frequency-dependent susceptibility, not in contrast with the over and underlying loess units. The lower values of frequency-dependent susceptibility in loess and weakly developed palaeosol horizons suggest that less ultrafine ferrimagnetic grains were produced during the time when the loess and weakly developed palaeosol were formed. Higher susceptibility and frequency-dependent susceptibility also occur in the depth of 1.1–2.0 m, which indicate the existence of incipient soil, but it was not significant in the field because of farming.

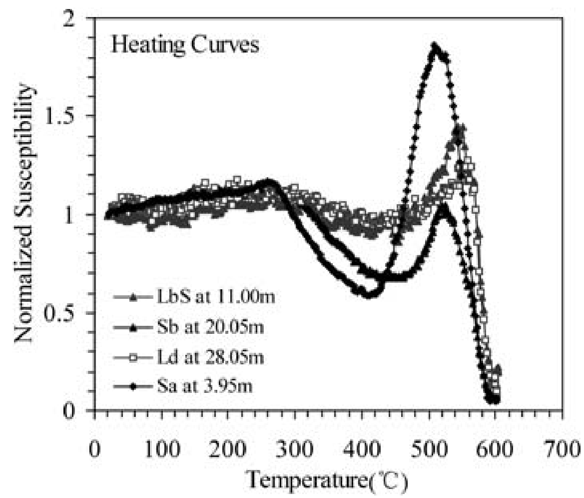

Figure 4. Heating curves of the loess, weakly developed palaeosol and palaeosol samples. For each sample, the susceptibility has been normalized by its room temperature susceptibility.

4.2 Thermomagnetic analysis

Temperature-dependent susceptibility is highly sensitive to mineralogical changes during thermal treatment, which can provide useful information about magnetic mineral composition (Hunt *et al.* 1995; Deng *et al.* 2001, 2004; Liu *et al.* 2005b). The heating curves of both the loess samples and the palaeosol samples decrease sharply near 580°C, which suggests that magnetite makes dominant contributions to the magnetic susceptibility (Fig. 3).

The heating curves also display a gradual increase from room temperature to about 250°C. This steady (but nearly reversible) increase of susceptibility may be ascribed to the gradual unblocking of fine-grained (near the SP/SD boundary) ferrimagnetic particles (Deng *et al.* 2005). This magnetic susceptibility maximum is followed by a steady decrease between 300°C and 450°C, which is much more pronounced in palaeosol samples than in loess samples and weakly developed palaeosol samples (Figs 3 and 4). This decrease can be interpreted in terms of a thermally induced conversion from metastable ferrimagnetic maghemite (γ-Fe_2O_3) to weakly magnetic haematite (α-Fe_2O_3), as seen in the eastern Chinese Loess Plateau and Siberian loess deposits (Oches & Banerjee 1996; Florindo *et al.* 1999; Deng *et al.* 2000, 2001; Zhu *et al.* 2003). It appears that the relative maghemite content in the palaeosol is much higher than that in the loess units. It is interesting to note that the heating curves of all samples from the northeastern Qinghai-Tibetan Plateau display a susceptibility maximum above 500°C, which may arise from the transformation from iron-containing silicates/clay to magnetite during heating (Deng *et al.* 2001, 2004; Zhu *et al.* 2001). In addition, all samples display cooling curves that are far above the heating curves (Fig. 3), suggesting thermally induced conversion from iron-containing silicates/clay minerals to new magnetite.

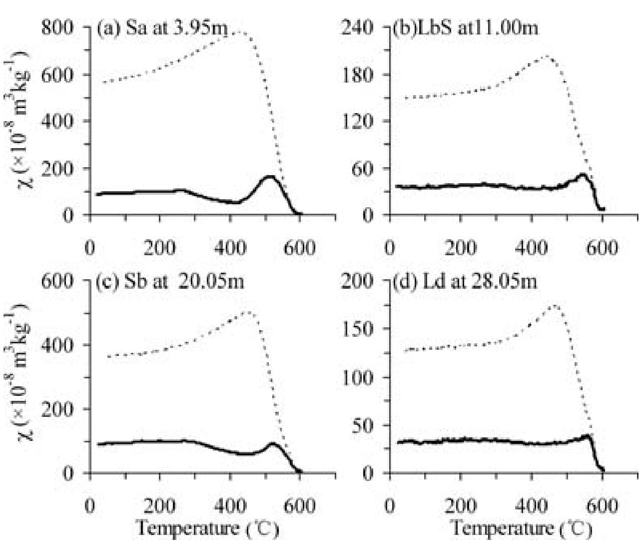

Figure 3. High-temperature magnetic susceptibility analysis for palaeosol (a, c), weakly developed palaeosol (LbS) in Lb, and loess (d) samples. Solid and dotted lines indicate heating and cooling cycles, respectively.

4.3 Hysteresis loops

Hysteresis loops provide information about the coercivity spectrum and domain state of ferrimagnetic materials (Dunlop & Özdemir 1997). All the samples display a significant paramagnetic contribution. After removal of the paramagnetic signal, the loess and palaeosol samples exhibit different hysteresis behaviour as shown in Fig. 5. The hysteresis loops are closed above about 300 mT for the palaeosol samples (Figs 5b and d), which is consistent with the presence of a dominant ferrimagnetic phase. The loops of the loess sample and weakly developed palaeosol samples (Figs 5a and c) close at a higher field than those of the palaeosol samples. The high coercivities in the loess samples may result from the combined effects of antiferromagnetic phases (e.g. haematite and/or goethite) and low-temperature oxidized coarse-grained magnetite (Liu *et al.* 2003; Deng *et al.* 2005, 2006). Moreover, loess and weakly weathered soil samples with low χ have wide hysteresis loops, while palaeosol samples with high χ display narrow hysteresis loops.

In a day diagram, or M_{rs}/M_s versus B_{cr}/B_c plot (Day *et al.* 1977), magnetic grain size of the loess and palaeosol samples falls in the coarser end of the pseudo-single domain (PSD) window (Fig. 6). Since the primary magnetic carrier is probably magnetite/maghemite, this diagram can be used to infer that the average magnetic grain size falls in the larger PSD range for both loess and palaeosols. Furthermore, the data points for loess and weakly developed palaeosols are near the right limit of the PSD field. This

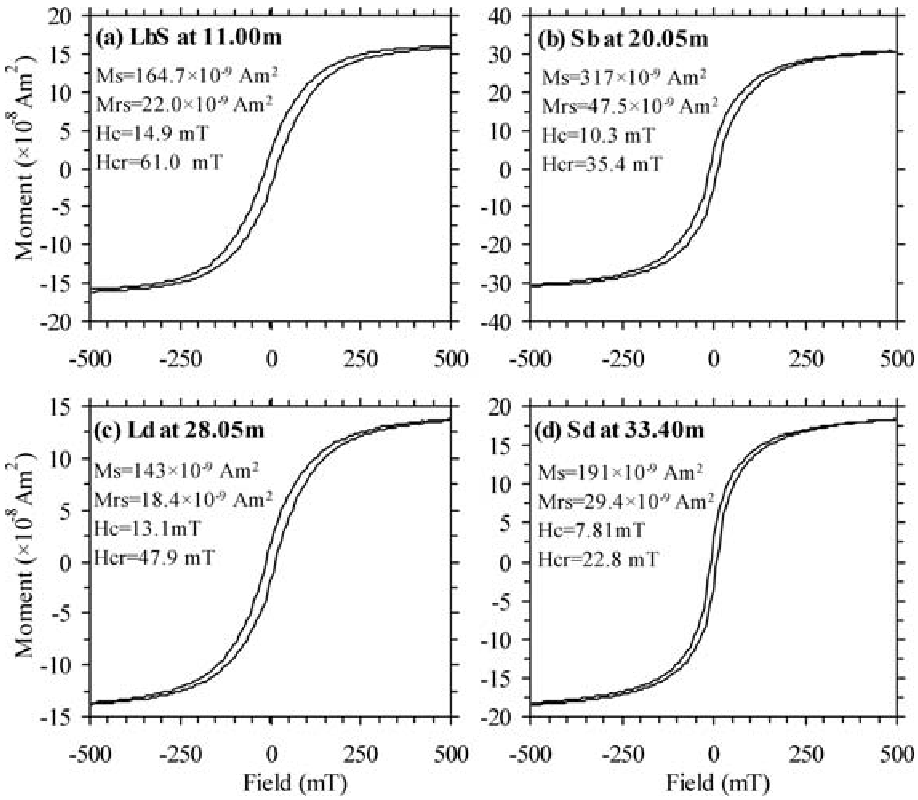

Figure 5. Hysteresis loops for representative weakly developed palaeosol (a), palaeosol (b, d) and loess (c) samples. Paramagnetic contributions were subtracted. The hysteresis loops were obtained by cycling the field between +1.5 T and −1.5 T but that the graphs are given up to 300 mT for clarity.

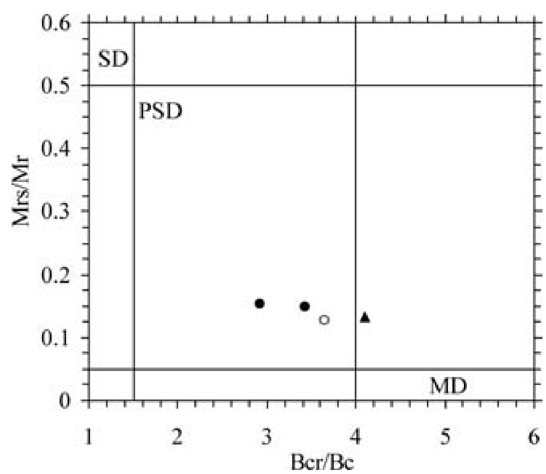

Figure 6. Hysteresis ratios plotted on a Day diagram (Day *et al.* 1977) of the Dongchan samples of loess (open circle), palaeosols (solid circles) and weakly developed palaeosol (solid triangle). SD, single domain; PSD, pseudo-single domain; MD, multidomain.

is caused by relatively larger B_{cr}/B_c values and is probably interpreted to be the effect of a bimodal grain-size distribution such as SD + multidomain or SD + SP grains (Torii *et al.* 2001).

4.4 Isothermal remanent magnetization

IRM acquisition experiments were carried out to further characterise the ferrimagnetic phases. The loess and palaeosol samples from the Dongchuan section yield different IRM acquisition curves (Fig. 7b). For palaeosol samples, the more rapid rise below 100 mT indicates a higher contribution of magnetically soft components. More than 85 per cent of the SIRM is acquired below an inducing field of 300 mT for both palaeosol and loess samples. The IRM acquisition curves are typical for sediments where low coercivity phases (magnetite/maghemite) dominate. The remanence continues to be acquired above 300 mT (not shown here), which is generally considered to be the theoretical maximum coercivity for magnetite grains. Therefore, approximately 10 per cent of this remanence is apparently carried by haematite and/or goethite. The coercivity of remanence values (B_{cr}) are used to further identify the magnetic mineralogy. The progressive removal of the SIRM by applying back fields yields a B_{cr} value of 61 ± 5 mT for the loess samples, and 40 ± 10 mT for the buried soils (Figs 7a and 8f). Therefore, it can be concluded that the magnetic mineralogy in the investigated samples is dominated by magnetite/maghemite. The higher coercivities of the loess can be attributed to the partially oxidized coarse-grained magnetite grains and/or antiferromagnetic phases.

SIRM and back-field IRM values yield useful parameters for estimating the enrichment of low coercivity or high coercivity minerals in the samples. SIRM is a concentration-dependent parameter. It is high if the amount of ferrimagnetic material present is high and *vice versa* (Akram *et al.* 1998). The SIRM intensity of the palaeosol samples varies within (7.2–12.1) × 10^{-3} Am^2 kg^{-1} except for the weakly developed palaeosol sample, which has a value of 5.2 × 10^{-3} Am^2 kg^{-1} (Fig. 8d). The loess samples display relatively lower SIRM values ranging between (4.4–5.7) × 10^{-3} Am^2 kg^{-1}. The enhanced SIRM in the palaeosol horizons is mainly resulted from higher concentrations of ferrimagnetic phases (e.g. magnetite and maghemite) due to *in situ* pedogenesis.

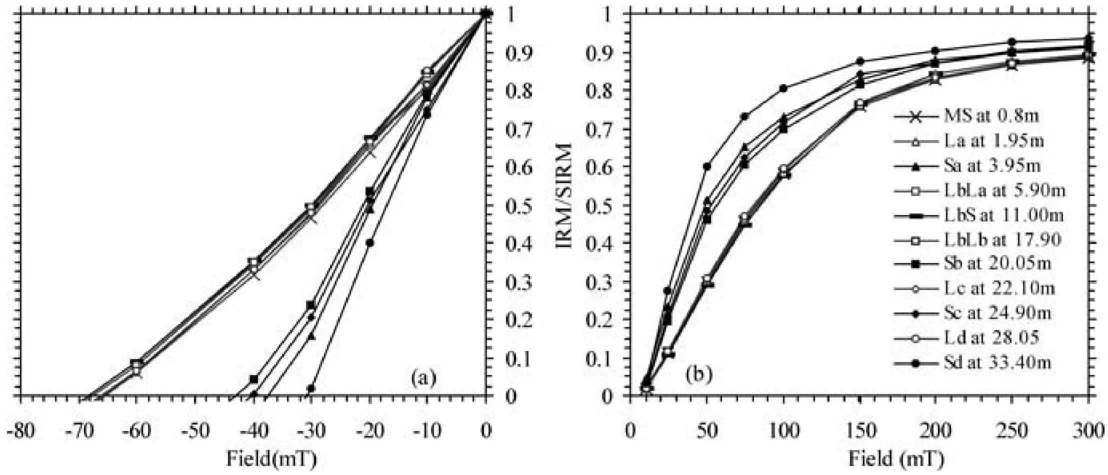

Figure 7. Acquisition (right) of IRM and demagnetization (left) of IRM for selected samples of the Dongchuan section. The IRM curves were obtained in applied field up to 2.7 T and given up to 300 mT for reasons of clarity.

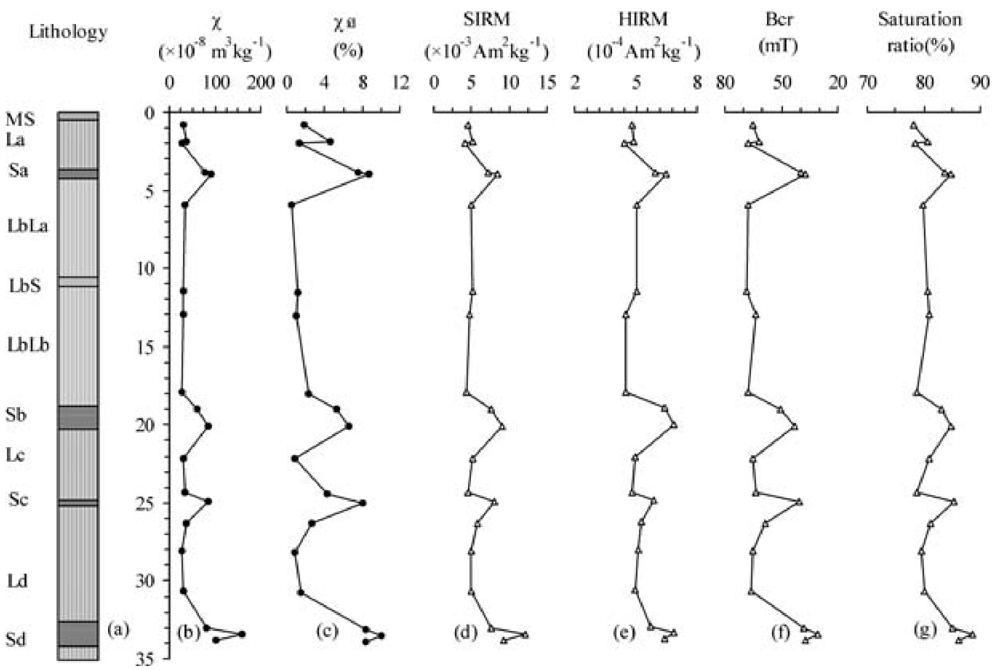

Figure 8. Variations of magnetic properties for representative samples. (a) stratigraphy, (b) magnetic susceptibility, (c) frequency-dependent magnetic susceptibility, (d) SIRM, (e) HIRM, (f) coercivity of remanence and (g) *S*-ratio.

The *S*-ratio ($S_{-0.3\,\mathrm{T}} = -\mathrm{IRM}_{-0.3\,\mathrm{T}}/\mathrm{SIRM}$) serves as a measure of the proportion of higher coercivity minerals (i.e. haematite and goethite) relative to lower coercivity minerals (i.e. magnetite and maghemite) in a sample (King & Channell 1991). The *S*-ratio is the absolute value of the IRM remaining after exposure to a reversed field of 0.3T divided by the SIRM acquired at 2.7 T. The 'Hard IRM' (HIRM) (Robinson 1986; Bloemendal *et al.* 1992), defined as $\mathrm{HIRM} = (\mathrm{IRM}_{-0.3\,\mathrm{T}} + \mathrm{SIRM})/2$ (Yoshida *et al.* 1994), is a measure of the concentration of high-coercivity minerals. The HIRM values become large if high coercivity minerals are relatively abundant (Akram *et al.* 1998). For most palaeosol samples, the *S* values are close to 90 per cent (Fig. 8g), suggesting a relatively higher proportion of low-coercivity ferrimagnetic minerals except for the weakly developed palaeosol samples which show similar *S* values to the loess samples. However, weakly enhanced loess samples are characterized by lower *S* values ranging from 78 to 83 per cent, which implies a significant contribution from high-coercivity antiferromagnetic minerals (haematite and/or goethite) and/or partially oxidized coarse-grained magnetite grain (Liu *et al.* 2003, 2005a; Deng *et al.* 2005, 2006). It is noteworthy that HIRM display higher values in palaeosol horizons except for the weakly developed palaeosol L_bS and lower values for loess samples (Fig. 8e). This may indicate higher absolute content of high-coercivity antiferromagnetic minerals (haematite and/or goethite) present in the palaeosols except for the weakly developed palaeosol L_bS than in the loess due to stronger *in situ* pedogenic process.

5 GRAIN-SIZE DISTRIBUTIONS

Grain-size distributions of the loess deposits are now generally accepted as a proxy measures of palaeowind strength (Lu *et al.*

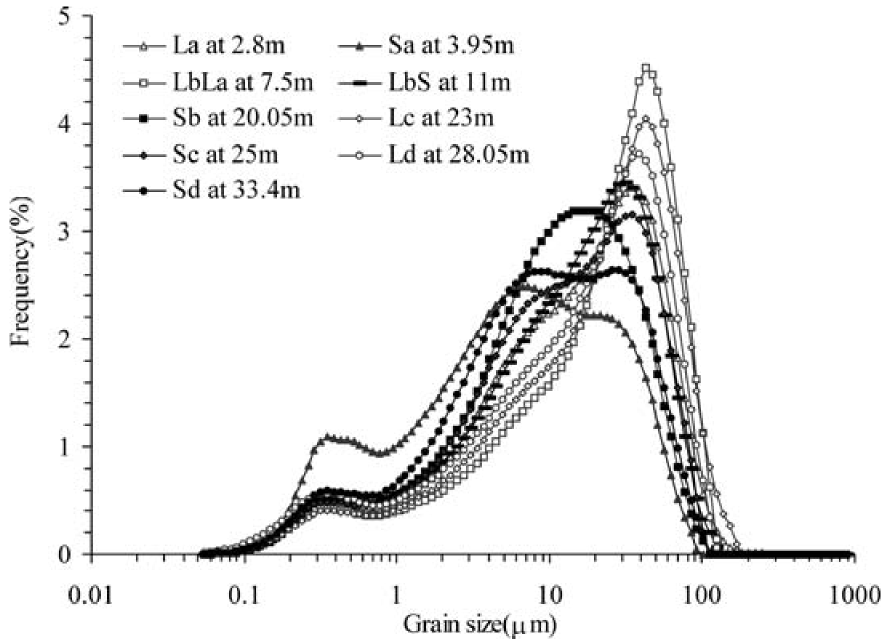

Figure 9. Grain-size distribution curves of loess, palaeosol, weakly developed palaeosol samples for the Dongchuan section. All loess samples display higher sand fraction content than that of the interbedded palaeosol and weakly developed palaeosol.

2004b,c). Fig. 2 shows the clay fraction (<2 μm), silt fraction (2–20 μm), sand fraction (>63 μm) and the mean grain-size variations within the Dongchuan section; variations are remarkably consistent with the loess–palaeosol stratigraphy identified in the field. Grain size of the weakly developed palaeosol is finer than of the loess but coarser than that of the well-developed palaeosols. The nearly stable mean grain sizes of the loess units suggest they suffered relatively weak post depositional weathering. Results of finer mean grain size, lower sand fraction as well as field observation of the palaeosol indicate relatively strong pedogenic process during the palaeosol formation periods.

Particle-size distributions of the Dongchuan section show that the loess units have mean grain sizes between 23 μm and 35 μm (Fig. 2d). The mean grain size for the weakly developed palaeosol units ranges from 20 μm to 24 μm. Generally, the mean grain size of the palaeosols is between 15 μm and 25 μm, which are much finer than the mean grain size of the loess units. Most of the grain-size distribution curves for loess samples show a predominantly bimodal character with a relatively higher sand fraction (>63 μm) (Fig. 9). On the other hand, the grain-size distribution curves of the palaeosols display a more complex and bimodal distribution indicating higher silt fractions. This may reflect their aeolian origin together with an *in situ* pedogenic processes. The weakly developed palaeosol samples also display a bimodal character but have a relatively lower sand content compared to the loess samples (Fig. 9). It is noteworthy that the weakly developed palaeosols display the very slight enhancement of the clay fraction (<2 μm) and a significant enhancement of silt fraction (2–20 μm) compared to loess. However, no significantly enhanced magnetic susceptibility, frequency-dependent magnetic susceptibility or SIRM occur in the weakly developed palaeosol horizons (Figs 8b–d). Obviously, the results indicate that no significant fine-grained (SP and SD) ferrimagnetic phases of magnetite and maghemite were formed by *in situ* pedogenic processes in the weakly developed palaeosol layers.

6 DISCUSSION

6.1 Magnetic mineralogy of the loess deposits on the northeastern Qinghai-Tibetan Plateau

The rock magnetic analysis suggests that the loess deposit in the Dongchuan on the northeastern Qinghai-Tibetan Plateau contains the same types of magnetic minerals as the loess deposits of the Loess Plateau (Zhou *et al.* 1990; Maher & Thompson 1992, 1994; Verosub *et al.* 1993; Hunt *et al.* 1995; Zhu *et al.* 2001; Liu *et al.* 2004b; Zhu *et al.* 2004), for example, the magnetically soft ferrimagnetic minerals magnetite and/or maghemite, and the magnetically hard minerals haematite and/or goethite. The major magnetic carrier in the Dongchuan section is magnetite/maghemite, and palaeosol units are generally enriched in magnetite/maghemite grains of pedogenic origin. The magnetic susceptibility enhancement in the palaeosol layers depends upon concentration, grain size, and mineralogy of the ferrimagnetic minerals present.

It is striking that there are almost no susceptibility variations in the weakly developed L_bS palaeosol (10.7–11.2 m) horizons characterized by moderate pedogenic process, dull-orange colour and relatively finer grain sizes. The frequency-dependent susceptibility also shows that there are no significant variations between the weakly developed palaeosol and the overlying and underlying loess units. However, the weakly developed palaeosol L_bS has a slightly higher clay fractions (<2 μm) than the loess units (Figs 2 and 9). As a high percentage (>6 per cent) of frequency-dependent susceptibility reflects the presence of significant numbers of SP grains with grain diameters < ∼20 nm (Dearing *et al.* 1996; Maher 1998). This may indicate that the principal carrier of the magnetic susceptibility is not ultrafine magnetic grains, but mainly coarse detrital grains larger than 2 μm. Such a similar disagreement between magnetic susceptibility and the grain-size distribution can also be observed between 15.7 and 16.7 m in the Panzishan section reported by Lu *et al.* (2004b) (Fig. 10). Unfortunately, we could not confirm weather

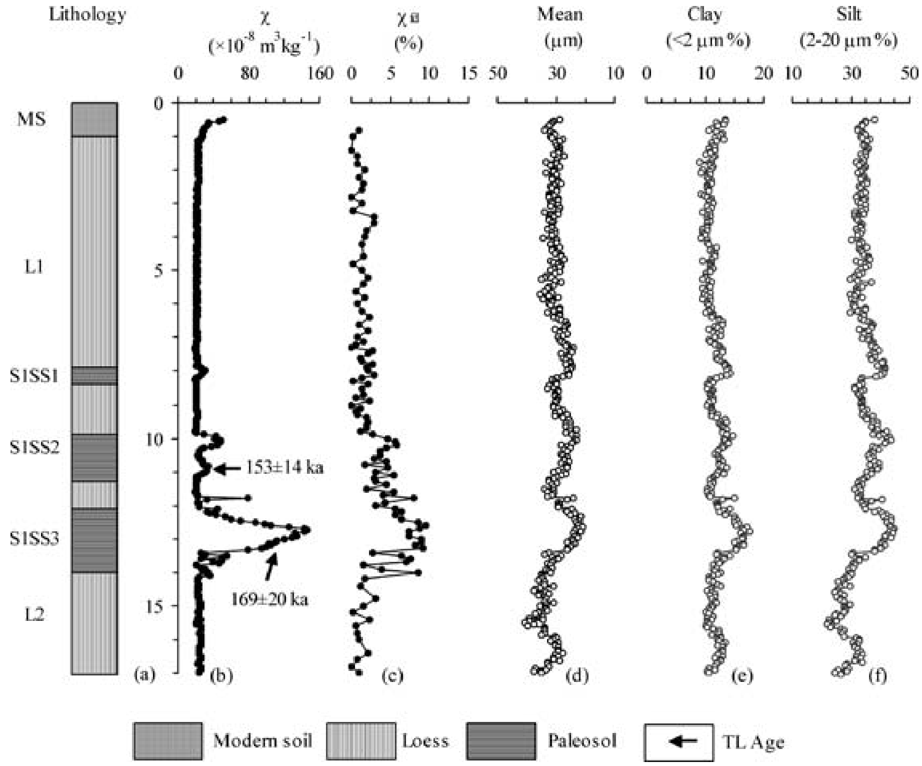

Figure 10. Depth functions of pedostratigraphy, magnetic susceptibility, frequency-dependent susceptibility, and grain-size variations within the Panzishan Pedocomplex (Lu *et al.* 2004b).

there exists a weakly developed palaeosol unit because of the sample was sampled in a manual well. Thus, it can be concluded that there is no significant magnetic susceptibility enhancement due to the pedogenic ultrafine magnetite/maghemite grains in the weakly developed palaeosol layers.

6.2 Can magnetic susceptibility serve as a proxy for palaeoclimate on the northeastern Qinghai-Tibetan Plateau?

Generally, magnetic susceptibility is consistent with the loess–palaeosol stratigraphy identified on the northeastern Qinghai-Tibetan Plateau (Fig. 2). Magnetic susceptibility combined with the frequency-dependent susceptibility of the loess–palaeosol sequences reflects the glacial-interglacial changes (Chen *et al.* 1997, 1999; Lu *et al.* 2001, 2004a,b). The highest magnetic susceptibility values are found for the palaeosols except for the weakly developed palaeosol horizons. Frequency-dependent magnetic susceptibility clearly indicates the presence of the pedogenic ferrimagnetic minerals (magnetite and/or maghemite). Additionally, total magnetic susceptibility enhancement increases as a soil matures. Thus, just as loess deposits at the loess–palaeosol sequence of the Chinese Loess Plateau (Zhou *et al.* 1990; Maher & Thompson 1991), magnetic susceptibility can be interpreted as a proxy of weathering degree or as a proxy of palaeoclimate on the northeastern Qinghai-Tibetan Plateau.

However, magnetic susceptibility variations of the Dongchuan section are not fully consistent with the pedogenic process. For example, the weakly developed palaeosol L_bS can be clearly distinguished in the field by its weakly granular structure, dull-orange colour and blurred boundary with the overlying and underlying loess units. However, this palaeosol unit displays magnetic susceptibility values comparable to the overlying and underlying loess layers (Fig. 2). As magnetite and maghemite are the principal ferrimagnetic phases in this palaeosol unit indicated from high-temperature magnetic susceptibility measurements (Figs 3 and 4), the presence of pedogenic ultrafine magnetite/maghemite grains in the weakly developed palaeosol is not significant because of its low value of frequency-dependent susceptibility. This may due to the complex loess origin when the weakly developed soil was formed. The Dongchuan and Panzishan sections are, respectively, located on the terrace of the Datong River and Huangshui River, suggesting that the loess deposits there have a rather complex origin than those in the Loess Plateau region. The riverbed silt of Datong river and Huangshui river, the moraine from the Qinghai-Tibetan Plateau and the dust from Qaidam desert all can serve as the origin of the loess deposits here, thus local climate changes may lead to changes in origins and preservation conditions of the pedogenic magnetite when weakly developed soil was formed. In addition, it is possible that during the formation of the weakly developed palaeosol the climate was not very humid and warm and so that pedogenic processes could not develop properly as a result or the low rainfall in this area during interstadials prevented pedogenesis. As a result, in this palaeosol magnetic susceptibility of *in situ* pedogenic origin can only partially account for the total susceptibility signals, and that other factors such as loess origin, time-dependent soil development, weathering and alternation afterwards may be involved in determining the strength of the magnetic susceptibility signal (Liu *et al.* 1999; Sun *et al.* 1999; Hus 2003). The balance between the pedogenic process and other processes probably controls the variation of the susceptibility across the loess deposits on the northeastern Qinghai-Tibetan Plateau.

Apparently, the ultrafine magnetite/maghemite grains were indeed formed during pedogenesis in most palaeosols. However, the low field magnetic susceptibility record does not consistently correlate to the variation in the stratigraphy of the Dongchuan sequence. Therefore, we need to be cautious when directly translating magnetic susceptibility changes into a proxy measure of palaeoclimate change because only pedogenic magnetic susceptibility is related to palaeoclimate. Our study suggests that multiparameter rock magnetic investigations combined with non-magnetic measurements, such as grain-size analysis, represent a more powerful approach for palaeoclimatic research into the complex loess–palaeosol sequences in the Qinghai-Tibetan Plateau region.

7 CONCLUSIONS

Detailed rock magnetic investigations on loess deposits on the northeastern Qinghai-Tibetan Plateau suggest that the predominant ferrimagnetic minerals in the Dongchuan section are large PSD grains of magnetite/maghemite. Ultrafine magnetite/maghemite of pedogenic origin plays an important role in enhancing the magnetic susceptibility of palaeosols.

The variation of magnetic susceptibility combined with the frequency-dependent susceptibility can be generally correlated with the intensity of the pedogenesis, thus can be employed as a useful proxy measure of palaeoclimate in the northeastern Qinghai-Tibetan Plateau region. However, it is suggested that multiparameter rock magnetic investigations combined with non-magnetic measurements, such as grain-size analysis, represent a more powerful approach for palaeoclimatic research into the complex loess–palaeosol sequences in the Qinghai-Tibetan Plateau region, especially for those weakly developed palaeosol layers.

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