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Paleoclimatic Significance of the Mineral Magnetic Record of the Chinese Loess and Paleosols

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The origins of the magnetic susceptibility variations of the Chinese loess and paleosols are explored by scanning and transmission electron microscopy of magnetic extracts, and by magnetic modeling of magnetic hysteresis data, to provide quantified estimates of the major magnetic components. Microscopy identifies several distinct size and shape characteristics in the magnetic carriers. Lithogenic magnetites, intact and abraded, dominate the coarse-grained magnetic fraction. The smallest of the coarse grains is ~2 μm. The remaining magnetic material is ultrafine in size, with two types of magnetite particles present. Type A particles strongly resemble soil magnetites produced by inorganic precipitation. Type B particles, which occur rarely, are probably bacterial in origin. Quantitative modeling of these magnetic assemblages shows that over 90% of the susceptibility variations is accounted for by the superparamagnetic magnetite component. Compared to the loess units, the paleosols are richer in magnetite, particularly of superparamagnetic size, and have a threefold higher ratio of magnetite to hematite. We identify pedogenic formation of magnetite as the major contributor to the loess magnetic record. Matching this record against other paleoclimatic records, we find an extremely high correlation with the standard ^{18}O record. The Chinese loess sequences record a very high resolution magnetic stratigraphy directly related to changing climate.

INTRODUCTION

Long sequences of loess are of great stratigraphic value as they provide some of the most complete continental records of climatic change during the Quaternary. They are probably the closest terrestrial analogue of deep-sea sediments, in that they result from semicontinuous deposition of fine-grained sediment (Begét *et al.*, 1990). Loess sequences are particularly extensive in north-central China, where they attain vertical thicknesses in excess of 150 m. Here, the fine-grained deposits of loess are interbedded with a series of buried soils, or paleosols.

Absolute dating of these sediments has recently become possible, with the establishment of a well-defined polarity reversal magnetostratigraphy (Heller and Liu, 1982), which extends back beyond the Olduvai subchron. Deposition of the Chinese loess is thus known to have begun about 2.4 myr ago, and to have reached its greatest spatial extent in the late Pleistocene.

Magnetic studies of loess, and other Quaternary sediments, are valuable not only for determining the geomagnetic information carried in their natural remanent magnetization. As in many earth surface materials, variations in the mineralogy, concentration, and grain size of their magnetic minerals can provide detailed information on their source and pathway of formation (Thompson and Oldfield, 1986; Maher and Taylor, 1988). Because the magnetic components of these sediments often occur in low concentrations (<1%) and as ultrafine grains (<0.1 μm), it is difficult to determine their properties by direct means (e.g., using optical microscopy or X-ray diffraction). However, stratigraphic fluctuations in magnetic mineralogy are readily detectable by measurements of magnetic hysteresis parameters. One such magnetic measurement, namely, magnetic susceptibility, has

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been applied recently to the Chinese loess sequences (Heller and Liu, 1984; Kukla *et al.*, 1988). These authors found consistently higher susceptibility values in the paleosol horizons and lower values in the loess. They also reported a striking correlation between the magnetic susceptibility signal and the deep-sea oxygen isotope record. Links between mineral magnetic records and climatic variation over glacial and interglacial cycles have previously been reported by Thompson and Oldfield (1986) for crater lake sediments in monsoonal northeastern Australia. For oceanic environments, Kent (1982), Robinson (1986), and Bloemendal and de Menocal (1989) have demonstrated striking relationships between magnetic susceptibility and climate change at sites influenced by changes in aeolian sediment input.

Variations in the magnetic properties of sediments can be caused by changes in sediment source, weathering regime of the sediment source region, the concentration of aeolian or fluvial magnetic components, the level of dilution by nonmagnetic components, dissolution rates of magnetic crystals in unfavorable redox conditions, and rates of authigenic or pedogenic growth of secondary magnetic minerals. In the case of the Chinese loess, early models identified the changes in aeolian influx of magnetic material as the cause of the susceptibility variations (Kukla *et al.*, 1988). More recently, Maher and Thompson (1991) and Zhou *et al.* (1990) have suggested that pedogenic formation of magnetite contributes significantly to the loess magnetic record.

Here, we explore further the origins of the magnetic susceptibility variations in the Chinese loess and their importance as a proxy record of paleoclimate. We have (i) carried out scanning and transmission electron microscopy of magnetic extracts from the loess, and (ii) applied a new multiple regression modeling technique to a wide range of magnetic hysteresis parameters to determine the mixtures of magnetic minerals responsible for the observed magnetic variations of the loess and paleosol horizons. Finally, we consider these results in the wider context of other Quaternary magnetic records.

ANALYSIS OF MAGNETIC MINERALS IN THE LOESS BY SCANNING AND TRANSMISSION ELECTRON MICROSCOPY (STEM)

The magnetic minerals present in the Chinese loess and paleosols have been identified using a range of analytical techniques, including rock magnetic methods (Maher and Thompson, 1991; Zhou *et al.*, 1990; Heller *et al.*, 1991), optical microscopy, and X-ray diffraction (Kukla *et al.*, 1988). Magnetite and maghemite, both strongly magnetic (ferrimagnetic) minerals, occur, as does hematite, which is much more weakly magnetic (as it is an imperfect canted antiferromagnetic mineral). In a number of the paleosols, magnetite rather than maghemite is the dominant ferrimagnet, as shown by thermomagnetic analysis of magnetic extracts (Fig. 1). Typically, these curves are slightly inflected between 300° and 400°C, and show an irreversible loss in magnetization on cooling. These features are probably due to conversion, at high temperature, of maghemite to hematite. However, the dominant Curie temperature is just below 600°C, indicating the more significant contribution of magnetite.

Maher and Thompson (1991) and Zhou *et al.* (1990) have shown that compared with the loess units, the paleosols contain a higher proportion of ultrafine-grained magnetite, of single domain (~0.05–0.02 μm) and superparamagnetic (<ca. 0.02 μm) dimensions. Magnetite of this distinctive, ultrafine grain size range has been shown to form organically (e.g., by magnetotactic bacteria; Blakemore, 1982) and through bacterial-induced chemical reactions (Lovley *et al.*, 1987), and also inorganically, through low-temperature chemical reactions (Maher and Taylor, 1988; Taylor *et al.*, 1988). To identify the source of the ul-

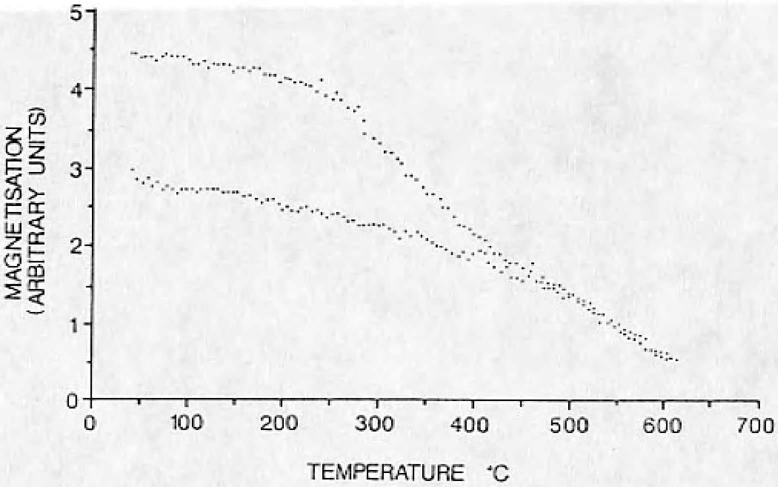

FIG. 1. Thermomagnetic curve for magnetic extract from L2.SS1, Luochuan.

trafine magnetite, the magnetic constituents of samples of loess and soil from Luochuan, in the central Loess Plateau of China, were extracted magnetically and examined under scanning and transmission electron microscopy. This enabled (a) direct identification of the shape and size of the magnetite grains, and (b) elemental analysis by dispersive X-ray.

The high-gradient magnetic extraction procedure of Petersen *et al.* (1986) was used to collect the coarse magnetite, which was then dispersed in acetone, mounted on a glass-topped stub, carbon coated, and examined using a Hitachi S450 scanning electron microscope. Images of the coarse-grained fraction were obtained at magnifications between 5000 and 15,000 (Fig. 2).

Figure 2 illustrates the major types of coarse magnetic particles, obtained from loess unit L2.SS1 Luochuan. A number of these coarse grains appear euhedral, with little sign of transport erosion (Fig. 2b). Some are damaged, however, like the titanomagnetite grain shown in Figure 2c, and display fractured edges and corners. These geometric crystals, whether damaged or intact, constitute the major proportion of the coarse magnetic fraction. From their size and shape, it is clear that they are lithogenic in origin. Their composition is variable, and includes both titanium-rich and titanium-free grains (Figs. 3a and 3b). Albeit at very low concentrations, another distinctive particle type was also found within the coarse fraction, namely, magnetic spherules. These spherules are variable in morphology, some appearing smooth and glassy, and others having irregular surfaces of fused platelets (Fig. 2d). They closely resemble spherules described by Freeman (1986), which are cosmic in origin and deposited at the earth's surface as micrometeorites. Such magnetic particles have long been known (e.g., Murray, 1876) to occur in deep-sea sediments.

The extraction procedure was then used to collect the ultrafine-grained magnetite fraction from paleosols S1 and S4. After dispersion, this material was placed on a copper grid, carbon coated, and examined using JEOL 100CX and 300CX transmission electron microscopes. The micrographs in Figure 4 show grains from the ultrafine magnetic fraction at magnifications up to 250,000×. Two distinct categories of magnetite can be identified. The first, dominant category (Type A) is represented by the crystals shown in Figures 4a–4c. These are all submicron in size, but vary continuously from smaller than 0.01 to ~0.1 μm in diameter and display more or less geometric morphologies, typically hexagonal or cubic. The size distribution and morphology of these magnetites are characteristic of low-temperature magnetites formed either from (a) the oxidation of ferrous iron, the source of the soil magnetites described

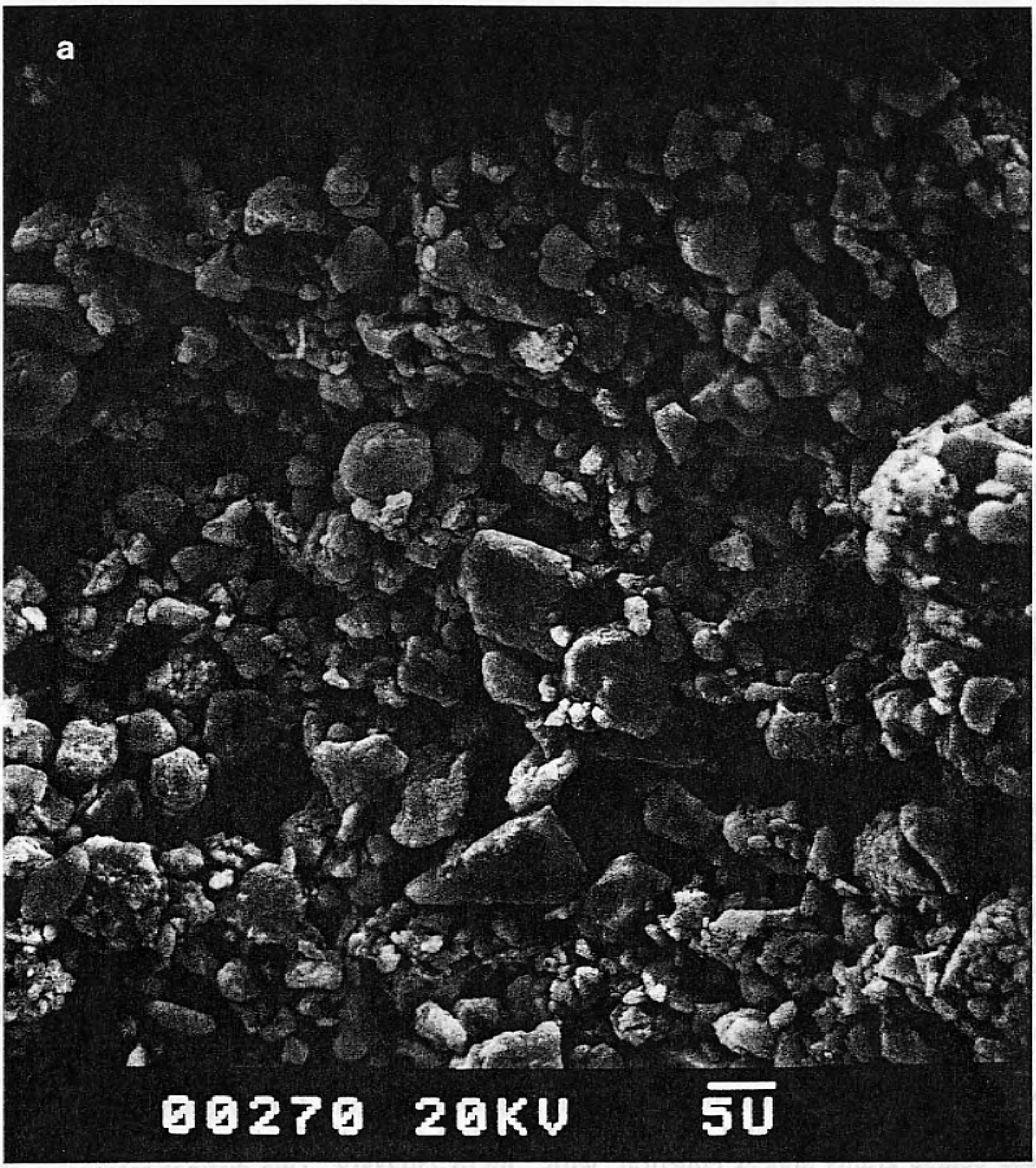

FIG. 2. Scanning electron micrographs of coarse magnetite fraction from L2SS1. (a) Overview of coarse magnetite fraction. (b) Undamaged, euhedral, lithogenic magnetite crystal. (c) Damaged lithogenic magnetite crystal. (d) Magnetite spherule.

by Maher and Taylor (1988), or (b) the bacterially induced reduction of ferric iron under anaerobic conditions (Lovley *et al.*, 1987). The second category of magnetite grains (Type B), which occurs much more rarely than the Type A grains, is represented by the chain of cubic crystals shown in Figure 4d. Type B grains strongly resemble the magnetites formed intracellularly by magnetotactic bacteria (Blakemore, 1982). Such bacteria have been found in a wide range of sedimentary environments, including a colluvial soil in Germany (Fassbinder *et al.*, 1990). Both Type A and Type B mag-

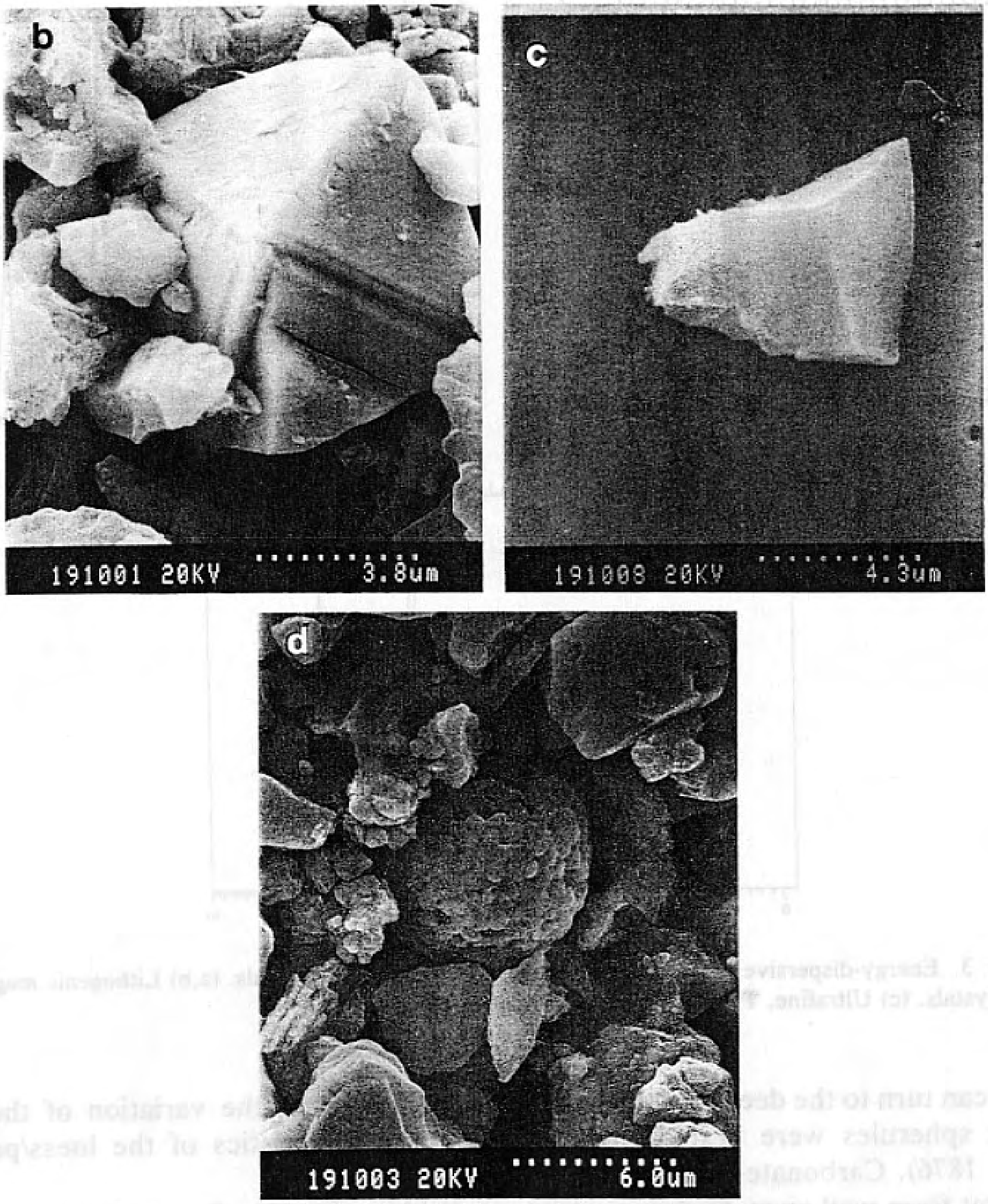

FIG. 2—*Continued*

netites are pure, as determined by energy-dispersive X-ray analysis (Fig. 3c).

In summary, microscopic examination of magnetic minerals extracted from the loess and paleosols identifies a number of distinct size and shape characteristics that can be used to identify their general source. The large >1 μm) geometric grains, with occasional substitution by titanium, are clearly lithogenic in origin, and thus have been transported to the Loess Plateau from a primary source rock. The very fresh condition of some of these crystals suggests that they were transported only a short distance, from a proximal source area. Conversely, the fractured crystals may have been carried and abraded over a longer time and distance. There is little evidence of post-depositional weathering of these crystals, which were extracted from loess unit L2.SS1. The spherical particles are most probably of extraterrestrial origin. To assess the potential contribution of cosmic spherules to the magnetic properties of

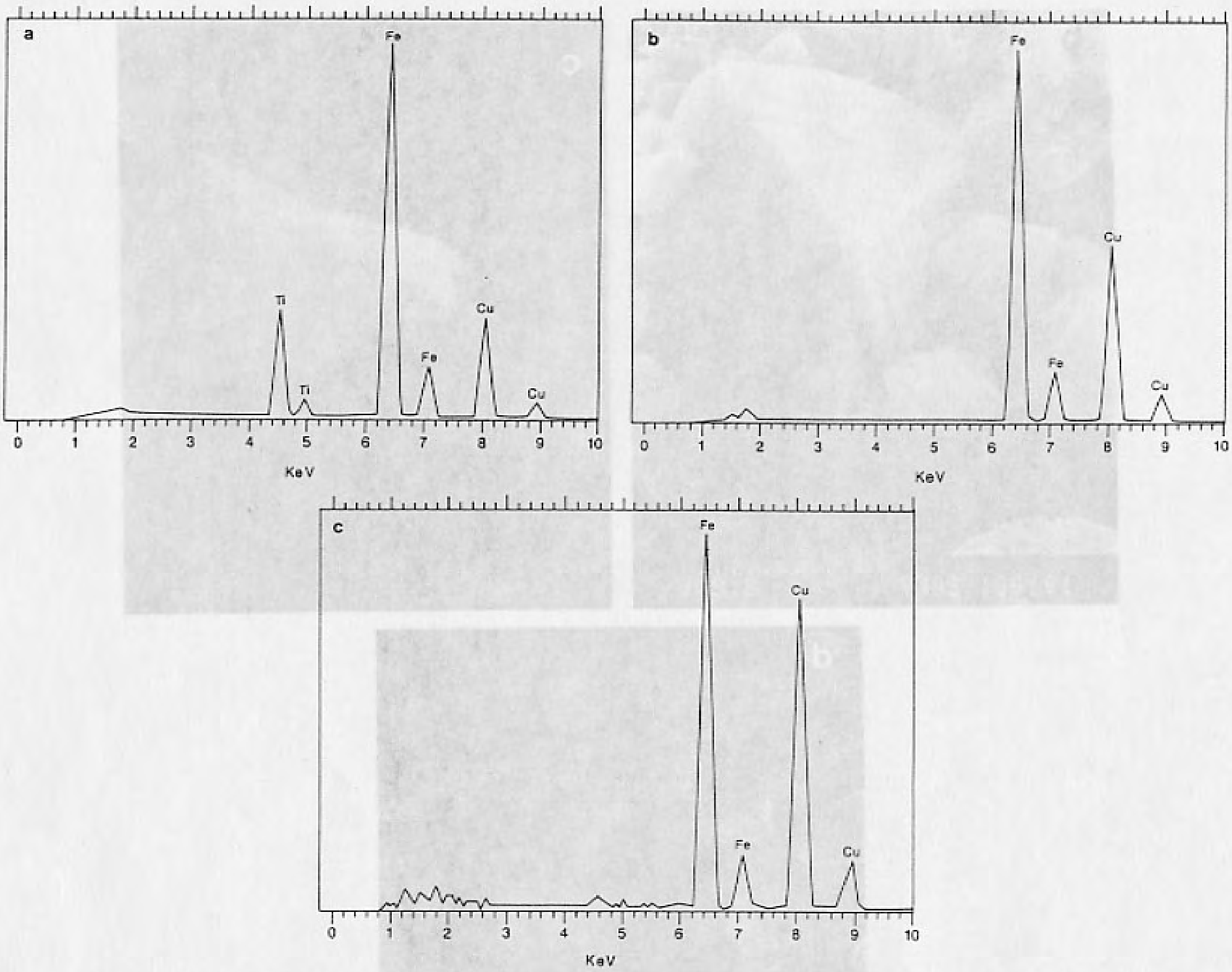

FIG. 3. Energy-dispersive X-ray spectra for extracted magnetite crystals. (a,b) Lithogenic magnetite crystals. (c) Ultrafine, Type A and Type B magnetite crystals.

loess we can turn to the deep-sea sediments in which spherules were first discovered (Murray, 1876). Carbonate-rich ocean sediments that form well away from terrestrial dust sources are diamagnetic (i.e., their initial susceptibility is negative). This means their ferro-/ferrimagnetic content must be less than one part per million. Assuming that the flux of cosmic spherules falling on the loess plateau and the deep-sea sites is similar, and noting that (i) the ocean sediment accumulation rates are lower than on the loess plateau, and (ii) metallic iron is not even the dominant magnetic phase in the ocean sediments, we calculate that cosmic iron spherules contribute less than one part in ten thousand to the loess magnetic properties. Hence, for all practical purposes, cosmic spherules can be discounted from explanations of the variation of the magnetic characteristics of the loess/paleosol sequences.

Within the ultrafine-grained magnetite fraction, two types of magnetite particle can be identified: Type A, which are pure magnetites with a rather variable grain size distribution; and Type B, also with no substitution by foreign cations, but with an extremely narrow grain-size spread and distinctive association of crystals in chains. The Type A magnetites, which comprise by far the larger proportion of the ultrafine fraction, most likely result from inorganic precipitation of magnetite during soil formation. In contrast, the Type B magnetites probably indicate formation of bacterial magnetosomes during periods of enhanced soil wetness. These direct observations of the size and shape characteristics of the loess magnetic carriers show that they span the entire spectrum of magnetic domain states. The lithogenic magnetites are large enough to exhibit multidomain behavior, while the submicron grains dominantly fall within the single domain (ca. 0.05–0.02 μm), and the superparamagnetic (<ca. 0.02 μm) size ranges.

QUANTITATIVE MODELING OF THE LOESS MAGNETIC ASSEMBLAGES

In addition to qualitative interpretations of the magnetic contrasts between the loess and soil units (Maher and Thompson, 1991; Zhou *et al.*, 1990), quantitative estimates can be made of the contribution of each magnetic component to the loess magnetic record. Here, we adopt the magnetic modeling approach of Thompson (1986) and apply it to the magnetic hysteresis data of Maher and Thompson (1991). At low or modest concentrations of a few percent, the mineral magnetic properties of magnetic mixtures add linearly (Stacey, 1963). This important characteristic of additivity allows magnetic measurements to be modeled quantitatively by minimization or regression methods. In this case, the magnetic measurements on the loess and paleosol samples were fitted by multiple regression against magnetic data from synthetic analogues of known grain size and composition to give quantified estimates of the constituent magnetic components. Error bounds associated with the least-squares fit were also produced for all the modeled components.

Table 1 shows the results of the constrained, multiple regression calculations. The magnetic properties of 11 samples of loess and 10 samples of paleosol were modeled. For each sample, the magnetic parameters used in these calculations were seven measurements of acquisition of isothermal remanence at fields between 20 and 1000 mT, six measurements of the anhysteretic remanence following partial af demagnetization in fields up to 80 mT, and two measurements of initial magnetic susceptibility at frequencies of 1 and 10 kHz. The model was constrained to fit the data against the following magnetic components: hematite, single domain ("hard") magnetite, superparamagnetic (SP)/viscous magnetite, and paramagnetic minerals. Multidomain ("soft") magnetite was not included in the modeling approach. Although easily identified by scanning electron microscopy, multidomain grains can be seen to contribute little to the susceptibility of the loess and paleosols (Fig. 5). This figure shows the low-temperature behavior of the magnetic susceptibility for a loess sample and a paleosol. The paleosol displays a significant loss in susceptibility with decreasing temperature, due to the large contribution to susceptibility of magnetite grains of SP/viscous size (Maher, 1988). The loess shows a slight increase in susceptibility with decreasing temperature that can be accounted for by a combination of ferrimagnetic and paramagnetic components. Neither sample exhibits the low-temperature transitions in susceptibility behavior associated with multidomain magnetic components (Radhakrishnamurty and Deutsch, 1974).

The modeling quantifies the major difference in magnetic mineralogy between the loess and the paleosols. Compared to the loess units, the ratio of magnetite to hematite for the soils is higher by a factor of 3. Increases in the concentration of the SP/viscous magnetite component are the major cause of the higher ratios in the soil units (Table 1). The model also identifies slightly reduced concentrations of hematite in the soils.

We can use Table 1 to assess the relative contribution of the magnetic components to the contrasts in susceptibility between the soil and loess units. By subjecting the data in Table 1 to an analysis of variance, it can be shown that over 90% of the susceptibility contrasts between the loess and paleosols is accounted for by the SP/viscous magnetite component.

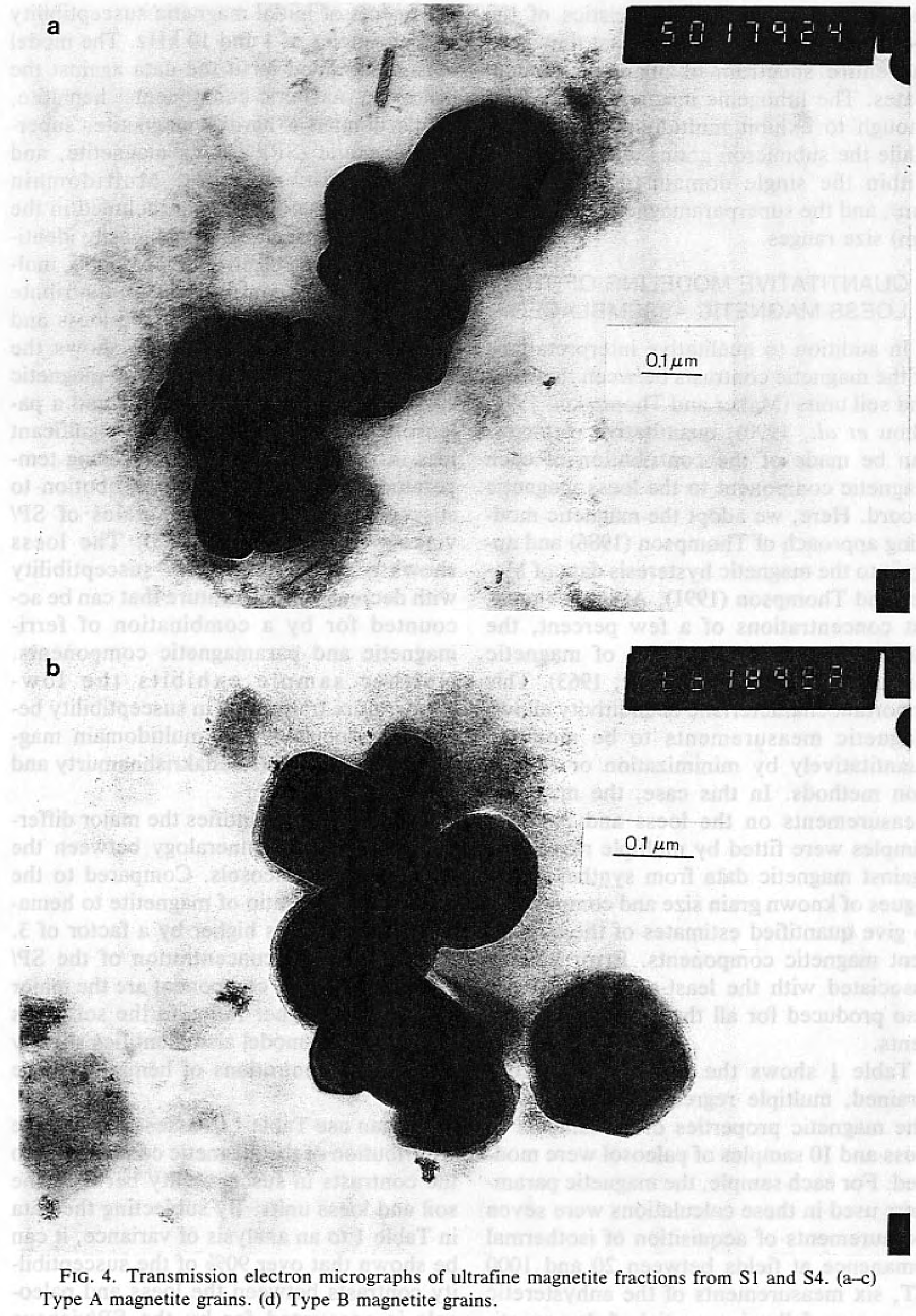

FIG. 4. Transmission electron micrographs of ultrafine magnetite fractions from S1 and S4. (a–c) Type A magnetite grains. (d) Type B magnetite grains.

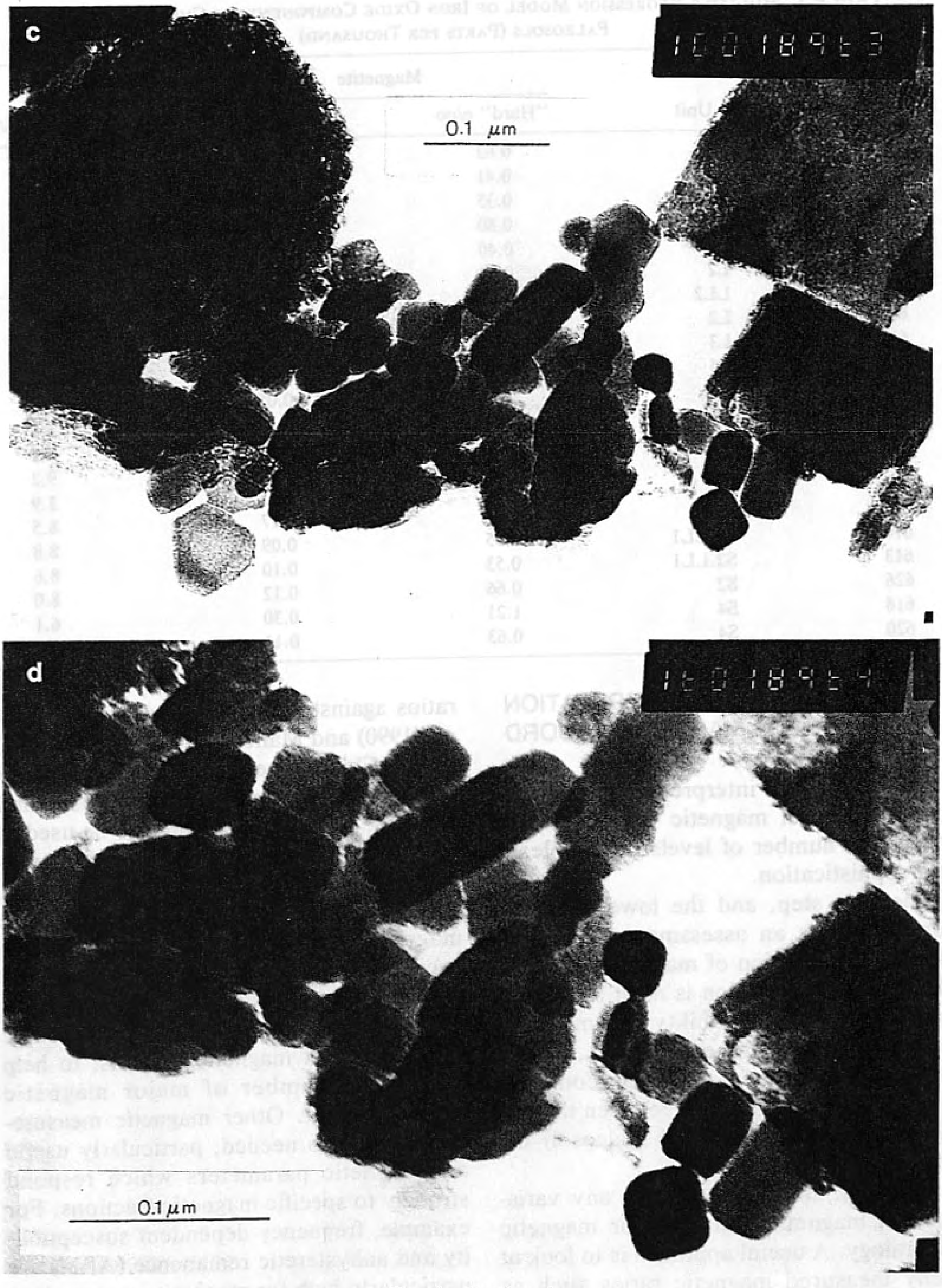

FIG. 4—*Continued*

Table 2 shows the mean concentrations of the modeled iron-oxide components for the 10 paleosol and 11 loess samples. Compared to the loess samples, the mean magnetic mineralogy of the paleosols is richer in magnetite, particularly of SP/viscous grain size, and has a threefold higher magnetite/hematite ratio.

TABLE 1. MULTIPLE REGRESSION MODEL OF IRON OXIDE COMPONENTS IN CHINESE LOESS AND PALEOSOLS (PARTS PER THOUSAND)

		Magnetite		
Sample no.	Unit	"Hard" o/oo	SP/Visc o/oo	Hematite o/oo
609	L1	0.63	0.09	8.2
629	L1	0.41	0.04	8.4
627	L1	0.35	0.03	9.3
624	L1.SS1	0.80	0.15	6.9
625	L2	0.40	0.04	10.5
616	L2	0.34	0.04	11.4
623	LL2	0.47	0.07	10.8
630	L2	0.26	0.02	10.1
611	L3	0.73	0.15	7.2
619	L5	0.22	0.01	9.4
621	L5	0.43	0.05	8.6
604	S0	0.85	0.13	5.8
608	S1	1.36	0.25	7.2
614	S1	1.32	0.26	9.2
605	S1	0.98	0.21	3.9
622	S2	1.03	0.17	8.5
617	S2.LL1	0.55	0.09	8.8
613	S2.LL1	0.53	0.10	8.6
626	S2	0.66	0.12	8.0
618	S4	1.21	0.30	6.1
620	S4	0.63	0.11	5.7

ENVIRONMENTAL INTERPRETATION OF THE LOESS MAGNETIC RECORD

Environmental interpretations of stratigraphic mineral magnetic records can be made at a number of levels of complexity and sophistication.

The first step, and the lowest level of complexity, is an assessment of changes in the concentration of magnetic minerals. Magnetic concentration is most simply estimated from susceptibility (X) measurements. For the Chinese loesses, Kukla (1987) demonstrated the clear contrasts in magnetic concentration between the glacial (loess) and interglacial (paleosol) deposits.

A second step is to identify any variations in magnetic grain size or magnetic mineralogy. A useful approach is to look at easily measured magnetic ratios such as saturation remanence to susceptibility (SIRM/X), or isothermal remanences produced in moderate and high fields (e.g., $S = \mathrm{IRM}_{0.1T}/\mathrm{IRM}_{1T}$). This type of data is conveniently displayed as plots of magnetic ratios against depth, as shown by Zhou *et al.* (1990) and Maher and Thompson (1991) for the Chinese loess sequences. Biplots of magnetic parameters (e.g., Thompson and Oldfield, 1986, chap. 4) can also be used to distinguish monomineralic from two-component assemblages.

However, the Chinese loess is even more magnetically complex. More steps are needed to make fuller use of the magnetic variations in this multicomponent material. An important additional step is microscopic examination of magnetic extracts, to help assess the number of major magnetic phases present. Other magnetic measurements are also needed; particularly useful are magnetic parameters which respond strongly to specific magnetic fractions. For example, frequency-dependent susceptibility and anhysteretic remanence (ARM) are particularly high for magnetite grains close to the SP/viscous boundary (Ozdemir and Banerjee, 1982; Maher, 1988). For multicomponent magnetic systems, modeling techniques, such as the multiple regression approach employed here, are of particular

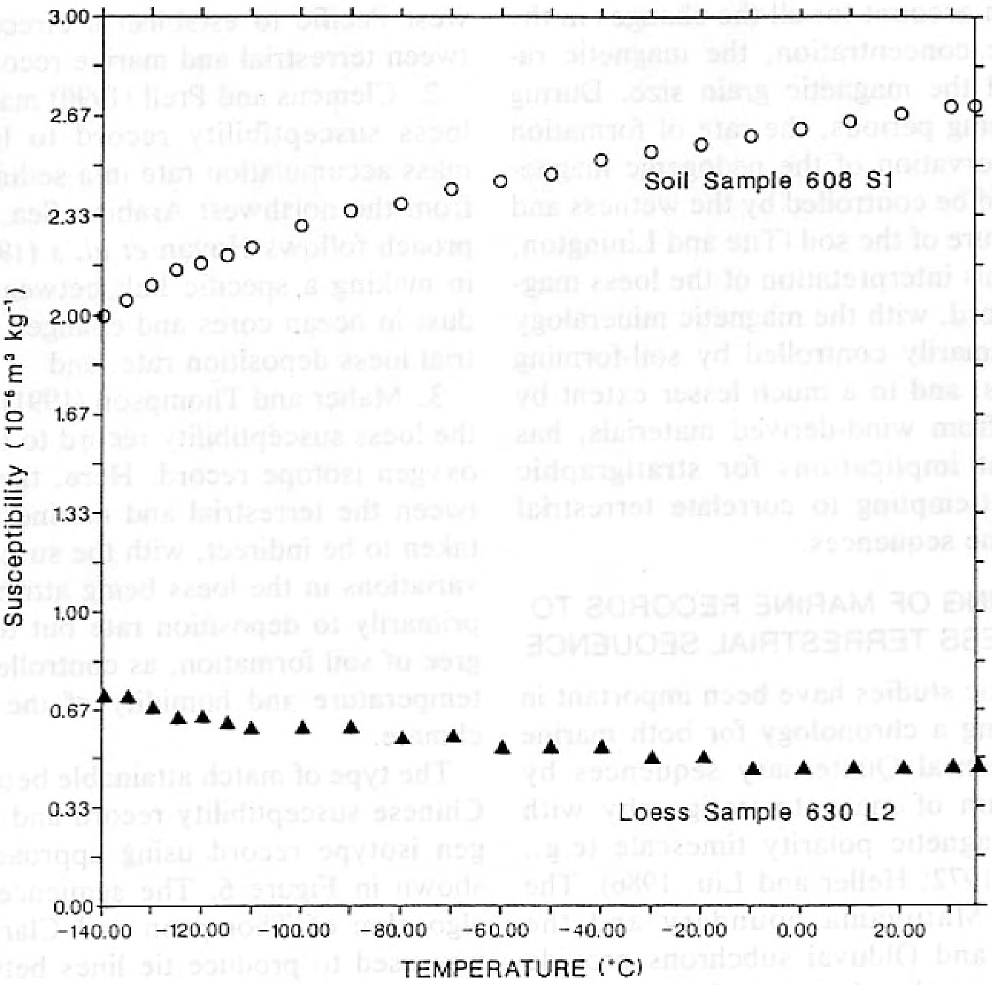

FIG. 5. Low-temperature behavior of magnetic susceptibility for a paleosol sample from S1 and a loess sample from L2.

value as they allow quantitative estimation of the major magnetic phases.

Application of these techniques to the Chinese loess sequences has identified and quantified the importance of ultrafine, SP/viscous magnetite in the magnetic assemblages of the paleosols. This has led us to interpret the loess magnetic record in terms of processes other than those invoked by earlier workers. For instance, Kukla's (1987) model of constant windborne magnetic flux can account for the observed fluctuations in magnetic concentration by inferring glacial/interglacial dilution contrasts, but the model is unable to explain the threefold variation in the magnetite to hematite ratios. Similarly, Heller and Liu's (1986) model of enrichment of detrital magnetite during soil formation accounts for the changes in neither magnetic ratios nor magnetic grain size. However, *in situ* formation of ultrafine magnetite during soil develop-

TABLE 2. AVERAGE MAGNETIC CHARACTERISTICS OF 11 LOESS AND 10 PALEOSOLS

Oxide		Loess	Paleosol
Hard	Magnetite	0.46 + 0.06	0.92 + 0.10
SP/Viscous	Magnetite	0.07 + 0.01	0.18 + 0.02
Total	Magnetite	0.53 + 0.07	1.1 + 0.1
Total	Hematite	9.2 + 0.4	7.2 + 0.6
Magnetite to Hematite ratio		0.06 + 0.01	0.161 + 0.02

Note. Means + standard error of mean, o/oo.

ment can account for all the changes in the magnetic concentration, the magnetic ratios, and the magnetic grain size. During soil-forming periods, the rate of formation and preservation of the pedogenic magnetite would be controlled by the wetness and temperature of the soil (Tite and Linington, 1975). This interpretation of the loess magnetic record, with the magnetic mineralogy being primarily controlled by soil-forming processes, and to a much lesser extent by dilution from wind-derived materials, has important implications for stratigraphic studies attempting to correlate terrestrial and marine sequences.

MATCHING OF MARINE RECORDS TO THE LOESS TERRESTRIAL SEQUENCE

Magnetic studies have been important in establishing a chronology for both marine and terrestrial Quaternary sequences by comparison of magnetostratigraphy with the geomagnetic polarity timescale (e.g., Opdyke, 1972; Heller and Liu, 1986). The Brunhes–Matuyama boundary and the Jaramillo and Olduvai subchrons provide important marker horizons for erecting a global chronology spanning the last two million years. Higher-resolution geomagnetic dating, using high-amplitude secular variation or excursions, is hazardous and unreliable (e.g., Opdyke, 1972; Thompson and Berglund, 1976). However, the mineral magnetic stratigraphy of loess and deep-sea sediments may provide another basis for high-resolution intercorrelation.

Three approaches to using the mineral magnetic stratigraphy of the Chinese loess in this way have been proposed:

1. Kukla *et al.* (1988) proposed a susceptibility-based chronology for the loess sequences, assuming a constant rate of aeolian influx of magnetite through time. This chronology, using susceptibility to interpolate between polarity reversals, has also been used by Hovan *et al.* (1989). These authors matched troughs in the magnetic susceptibility record to peaks in aeolian "flux" in a sediment core from the northwest Pacific to establish a direct link between terrestrial and marine records;
2. Clemens and Prell (1990) matched the loess susceptibility record to lithogenic mass accumulation rate in a sediment core from the northwest Arabian Sea. This approach follows Hovan *et al.'s* (1989) work in making a specific link between aeolian dust in ocean cores and changes in terrestrial loess deposition rate; and
3. Maher and Thompson (1991) matched the loess susceptibility record to the global oxygen isotope record. Here, the link between the terrestrial and marine record is taken to be indirect, with the susceptibility variations in the loess being attributed not primarily to deposition rate but to the degree of soil formation, as controlled by the temperature and humidity of the regional climate.

The type of match attainable between the Chinese susceptibility record and the oxygen isotope record using approach (3) is shown in Figure 6. The sequence-slotting algorithm of Thompson and Clark (1989) was used to produce tie lines between all the data points of the two records.

The same sequence-slotting algorithm has been used to match Clemens and Prell's (1990) ^{18}O data in Ocean Core 722 to the ^{18}O reference curve of Imbrie *et al.* (1984) (Fig. 7). The resulting age/depth relationship for Core 722 has been differentiated to obtain sediment accumulation rates. These sediment accumulation rates have been combined with Clemens and Prell's measurements of the lithogenic component of Core 722, to produce new estimates of lithogenic mass accumulation (Fig. 7d). Figure 7a shows the loess susceptibility data using the Maher and Thompson (1991) timescale. The data thus compiled in Figure 7 can then be used to compare the terrestrial loess susceptibility record with oceanic records. In contrast to Hovan *et al.* (1989) and Clemens and Prell (1990), we find only a general correspondence between the loess magnetic susceptibility and the rate of lithogenic mass accumulation. Instead, we find a very

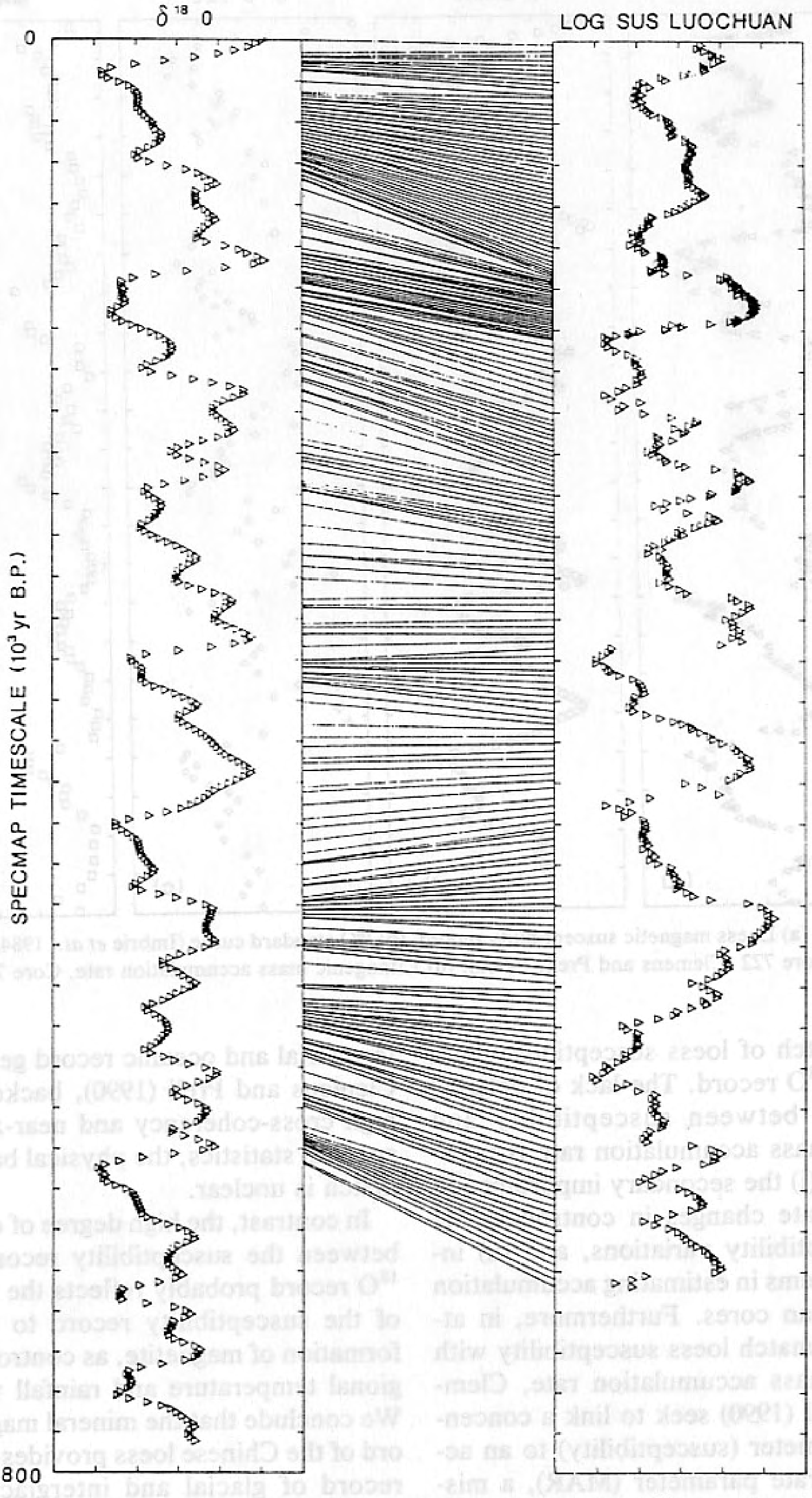

FIG. 6. Magnetic susceptibility record from Luochuan against the global ^{18}O record (Imbrie *et al.*, 1984).

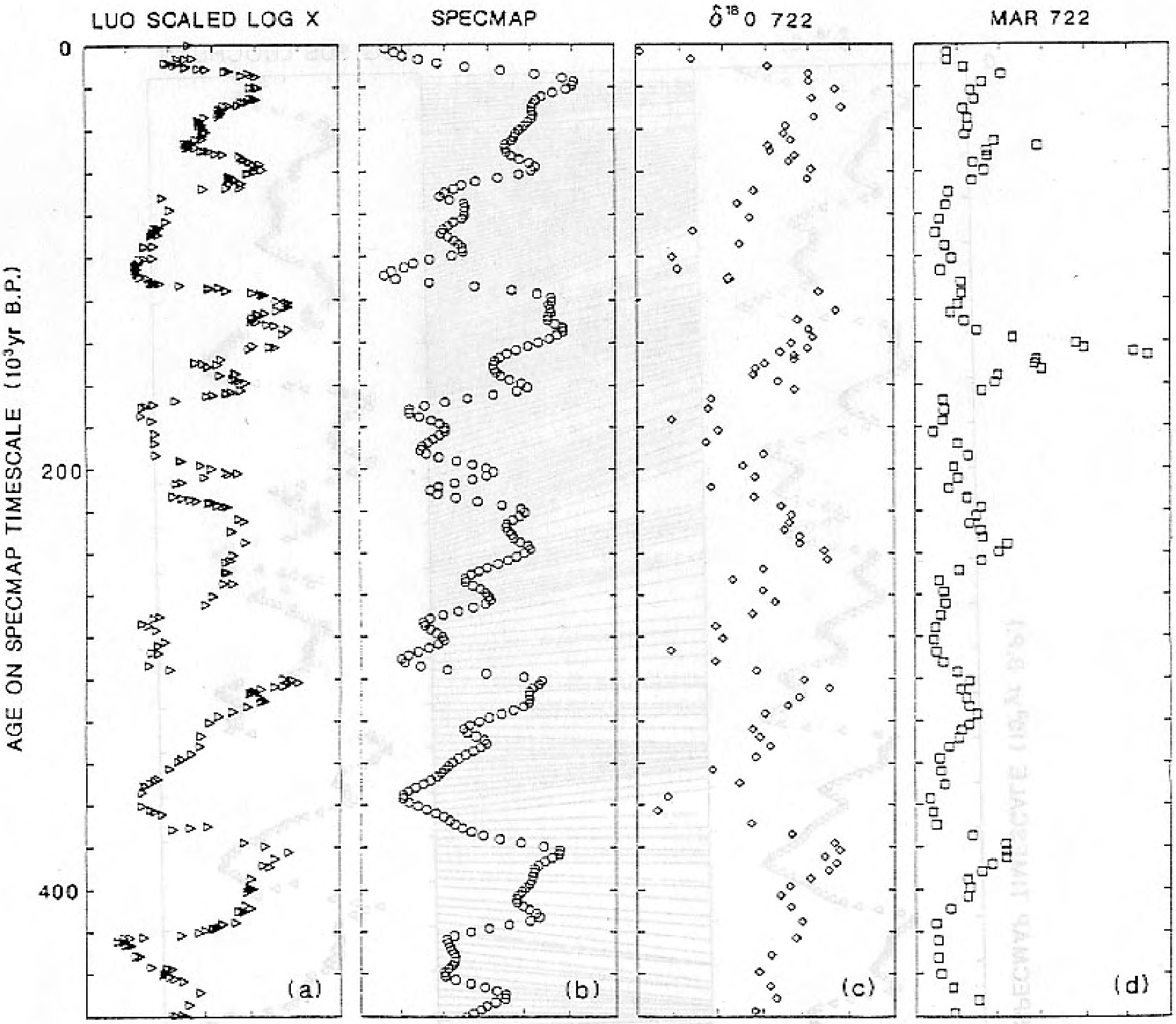

FIG. 7. (a) Loess magnetic susceptibility record. (b) ^{18}O standard curve (Imbrie *et al.*, 1984). (c) ^{18}O record, Core 722 (Clemens and Prell, 1990a). (d) Lithogenic mass accumulation rate, Core 722.

detailed match of loess susceptibility with the global ^{18}O record. The lack of detailed correlation between susceptibility and lithogenic mass accumulation rate is probably due to (i) the secondary importance of deposition-rate changes in controlling the loess susceptibility variations, and (ii) inherent problems in estimating accumulation rates in ocean cores. Furthermore, in attempting to match loess susceptibility with lithogenic mass accumulation rate, Clemens and Prell (1990) seek to link a concentration parameter (susceptibility) to an accumulation rate parameter (MAR), a mismatch of parameter types which is physically inappropriate. Thus, despite the apparently good visual match between a terrestrial and oceanic record generated by Clemens and Prell (1990), backed up with high cross-coherency and near-zero phase spectral statistics, the physical basis for the match is unclear.

In contrast, the high degree of correlation between the susceptibility record and the ^{18}O record probably reflects the sensitivity of the susceptibility record to pedogenic formation of magnetite, as controlled by regional temperature and rainfall variations. We conclude that the mineral magnetic record of the Chinese loess provides not only a record of glacial and interglacial stages (Kukla, 1988), but also within-stage climatic fluctuations. The loess and paleosol sequences thus record a high-resolution magnetic stratigraphy, directly related to changes in paleoclimate during the last 2.5 myr.

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REFERENCES

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

Blakemore, R. P. (1982). Magnetotactic bacteria. *Annual Review of Microbiology* 36, 217–238.

Bloemendal, J., and de Menocal, P. (1989). Evidence for a shift in the climatic variability of the African and Asian monsoons at 2.5 Ma: An application of whole-core magnetic susceptibility measurements to palaeoclimatology. *Nature* **342**, 897–900.

Clemens, S. C., and Prell, W. L. (1990). Late Pleistocene variability of Arabian Sea summer monsoon winds and continental aridity: Eolian records from the lithogenic component of deep-sea sediments. *Palaeoceanography* 5, 109–145.

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

Freeman, R. (1986). Magnetic mineralogy of pelagic limestones. *Geophysical Journal of the Royal Astronomical Society* **85**, 433–452.

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

Heller, F., and Liu, T. S. (1984). Magnetism of Chinese loess deposits. *Journal of Geophysical Research* 77, 125–141.

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

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

Hovan, S. A., Rea, D. K., Pisias, N. G., and Shackleton, N. J. (1989). A direct link between the China loess and marine 180 records: Aeolian flux to the north Pacific. *Nature* **340**, 296–298.

Imbrie, J., Hayes, J. D., Martinson, D. G., McIntyre, A., Mix, A. C., Morley, J. H., Pisias, N. G., Prell, W. L., and Shackleton, N. J. (1984). The orbital theory of Pleistocene climate: Support from a revised chronology of the marine delta ^{18}O record. *In* "Milankovitch and Climate Part I: Boston" (A. L. Berger *et al.*, Eds.), pp. 169–395. Reidel, Dordrecht.

Kent, D. V. (1982). Apparent correlations of palaeomagnetic intensity and climatic records in deep-sea sediments. *Nature* 299, 538–539.

Kukla, G. (1987). Loess stratigraphy in Central China. *Quaternary Science Reviews* 6, 191–219.

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

Lovley, D. R., Stolz, J. F., Nord, G. L., and Phillips, E. J. P. (1987). Anaerobic production of magnetite by a dissimilatory iron-reducing microorganism. *Nature* **330**, 252–254.

Maher, B. A. (1988). Magnetic properties of some synthetic sub-micron magnetites. *Geophysical Journal of the Royal Astronomical Society* **94**, 83–96.

Maher, B. A., and Taylor, R. M. (1988). Formation of ultrafine-grained magnetite in soils. *Nature* **336**, 368–370.

Maher, B. A., and Thompson, R. (1991). Mineral magnetic record of the Chinese loess and paleosols. *Geology* 19(1), 3–6.

Murray, J. M. (1876). On the distribution of volcanic debris over the floor of the oceans—Its character, source and some products of its disintegration and decomposition. *Proceedings of the Royal Society of Edinburgh* 9, 247–261.

Opdyke, N. D. (1972). Palaeomagnetism of deep-sea cores. *Review of Geophysics and Space Physics* **10**, 213–249.

Ozdemir, O., and Banerjee, S. K. (1982). A preliminary magnetic study of soil samples from west-central Minnesota. *Earth and Planetary Science Letters* **59**, 383–403.

Petersen, N., von Dobeneck, T., and Vali, H. (1986). Fossil bacterial magnetite in deep-sea sediments from the S. Atlantic Ocean. *Nature* **320**, 611–615.

Prell, W. L., Niitsuma, N., *et al.* (1991). "One Million Year Record of Summer Monsoon Winds and Continental Aridity from the Owen Ridge (Site 722), Northwest Arabian Sea." Proceedings of ODP Scientific Results 117. College Station, TX (Ocean Drilling Program), pp. 365–388.

Radhakrishnamurty, C., and Deutsch, E. R. (1974). Magnetic techniques for ascertaining the nature of iron oxide grains in basalts. *Journal of Geophysics* **40**, 453–465.

Robinson, S. G. (1986). The late Pleistocene palaeoclimatic record of N. Atlantic deep-sea sediments revealed by mineral magnetic measurements. *Physics of the Earth and Planetary Interiors* **42**, 22–48.

Stacey, F. D. (1963). The Physical Theory of Rock Magnetism. *Advances in Physics* 12, 45–133.

Taylor, R. M., Maher, B. A., and Self, P. G. (1988). Magnetite in soils. I. The synthesis of superparamagnetic and single domain magnetite. *Clay Minerals 1987* 22, 411–422.

Thompson, R. (1986). Modelling magnetization data using SIMPLEX. *Physics of the Earth and Planetary Interiors* 42, 113–127.

Thompson, R., and Berglund, B. (1976). Late Weichselian geomagnetic "reversal" as a possible example of the reinforcement syndrome. *Nature* 263, 490–491.

Thompson, R., and Oldfield, F. (1986). "Environmental Magnetism." Allen and Unwin, London.

Thompson, R., and Clark, R. M. (1989). Sequence slotting for stratigraphic correlation between cores: Theory and practice. *Journal of Paleolimnology* 2, 173–184.

Tite, M. S., and Linington, R. C. (1975). Effect of climate on the magnetic susceptibility of soils. *Nature* 256, 565–566.

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