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Magnetic Susceptibility Evidence of Monsoon Variation on the Loess Plateau of Central China during the Last 130,000 Years

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The magnetic susceptibility of loess and paleosols in central China represents a proxy climate index closely related to past changes of precipitation and vegetation, and thus to summer monsoon intensity. Time series of magnetic susceptibility constructed for three loess–paleosol sequences in the southern part of the Chinese Loess Plateau document the history of summer monsoon variation during the last 130,000 yr. They correlate closely with the oxygen isotope record of stages 1 to 5 in deep-sea sediments. Soils were forming during intervals of strong summer monsoon, whereas loess units were deposited at times of reduced monsoon intensity. The Chinese loess–paleosol sequence can thus be viewed as a proxy record of Asian monsoon variability extending over the last 2.5 myr. © 1991 University of Washington.

INTRODUCTION

The Loess Plateau of central China is built up of a thick succession of loess with interstratified paleosols that register changing environmental conditions during the last 2.5 myr (Liu *et al.*, 1985; Heller and Liu, 1986; Sasajima and Wang, 1984; Kukla and An, 1989; Kukla *et al.*, in press). The uppermost soil commonly has been modified by human activity. Where preserved in its natural state, it is a zonal soil complex formed under a monsoon climate during the early to middle Holocene (Editorial Board of China's Physical Geography (Chinese Academy of Sciences), 1985). Mature paleosols of Pleistocene age in the plateau are the so-called "loessial cinnamon paleosols" (Nanjing Soil Institute of Chinese Academy of Sciences, 1980). They are polygenetic pedocomplexes with characteristic micromorphological features of well-developed, chemically altered soils. They have distinct argillic horizons with frequent argillans and calcans, and show pronounced carbonate illuviation. Argillation, *in situ* translocation and illuviation of clay and iron compounds, and leaching and migration of carbonate, all affected these soils to various degrees. Cinnamon soils correspond approximately to the grey podzolic soils, parabraunerdes, or lessives of western paleosol nomenclatures. Pollen grains in the soils include *Quercus, Ulmus, Betula, Juglans, Alnus, Artemesia,* Gramineae, and Chenopodiaceae, pointing to development under savanas and open woodlands marked by a distinct contrast

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between warm–humid and cold–dry seasons.

These mature soils are separated by much thicker units of relatively unweathered massive, light-colored loess; occasional interlayers show initial stages of pedogenesis, such as frequent insect and worm burrows. Fossil snails of *Cathaica* sp. and *Pupilla aeoli* buried in the carbonate-rich loess indicate a climate drier and colder than the present (Chen *et al.*, 1982). The youngest loess (Malan Loess, designated L1) becomes finer-grained and thinner from northwest to southeast (Liu *et al.*, 1985). This indicates that the dust was transported by northwesterly winds from the central Asian deserts and possibly also from playa-type basins and intermittently flooded river plains. Modern dust storms in northern China occur in winter and spring when the weather is cold and dry (Liu *et al.*, 1985) and dominated by strong northwesterly winds, a condition locally referred to as the dry winter monsoon. In general, the biologic and geologic evidence from the loess units, together with the dynamics of modern dust storms, implies that loess deposition took place under a climate dominated by the dry winter monsoon.

The alternation of paleosols and loess units in the Loess Plateau records a succession of important environmental changes, with intervals of high dust influx alternating with intervals marked by lower dust influx and enhanced pedogenesis. This unique stratigraphic sequence can therefore be interpreted as a continuous record of alternating rise and decline in the intensity of the Asian summer monsoon during the last 2.5 myr.

We stress that dust deposition at most studied sites in the plateau was continuous and that the sections show no signs of erosional hiatuses. This is understandable, for the plateau surface is subhorizontal, and practically all the detritus has been deposited subaerially. Because the loess is highly porous, most precipitation does not accumulate at the surface; instead it seeps through the topsoil into underground aquifers, thereby limiting surface erosion to the margins of gullies. Dust deposition takes place at all times, albeit at varying rates, including times during which soils are formed. The soils, therefore, are accretionary soils which develop as the parent material is accumulating.

MAGNETIC SUSCEPTIBILITY MEASUREMENTS

Recently, we have made continuous field measurements of magnetic susceptibility (SUS) of some well-known loess sections in China using a Bartington MS2 portable susceptibility meter (Kukla and An, 1989; Kukla *et al.*, 1988). The results, expressed in $n \cdot m^3\ kg^{-1}$ units, indicate that SUS is not only a useful aid for discriminating paleosols from loess units and for assessing the degree of pedogenesis, but that it also can serve as an index of monsoon variability throughout the late Pliocene and the Quaternary. SUS is the measure of induced magnetization of objects in an artificial weak magnetic field. The principal carrier of the magnetization in the loess and paleosols is fine-grained (<1 μm) magnetite and maghemite (Kukla *et al.*, 1988; Kukla and An, 1989; Maher and Thompson, 1991). Although the paramagnetic and single domain magnetite grains are present in soils as well as in the loesses, and although the proportion of such magnetite is higher in the soils, it seems that the main contribution to the measured SUS values comes from ultrafine superparamagnetic grains. The magnetite may have been transported from desert areas, may represent volcanic detritus falling from the stratosphere, or may consist of micrometeorite particles of extraterrestrial origin. Alternatively, it may originate *in situ* by pedogenic processes.

Two hypotheses have been advanced to explain the observed SUS variation in the loess–paleosol sequences. According to the first hypothesis, the principal carrier of the susceptibility signal is of depositional origin (Kukla *et al.*, 1988). At any particular site the average accumulation rate of ultrafine magnetic minerals on the time scale of millennia is considered approximately constant over the last million years. The variation in SUS, and the relative abundance of the magnetic minerals in the sequence, is inversely related to the accumulation rate of the coarser dust which has very low susceptibility and is diluting the SUS signal. Low SUS values, characteristic of loess units, indicate accelerated dust accumulation and retarded pedogenesis, while the reverse is true for the soils. This hypothesis is supported by the close correlation of the terrestrial loess/paleosol sequence with astronomically tuned deep-sea chronologies (Hovan *et al.*, 1989), by the close positive correlation of ^{10}Be with susceptibility (Shen *et al.*, 1985; J. Beer, personal communication, 1990), and by the relatively constant accumulated susceptibility values within correlative units (Kukla *et al.*, 1990). The fluctuations of susceptibility values reflect varying surface stability and, indirectly, the degree of pedogenesis.

The second hypothesis postulates that the main carriers of the SUS signal are magnetic grains formed as an inorganic or biogenic product of *in situ* pedogenesis (Maher and Taylor, 1988; Zhou *et al.*, 1990; Maher and Thompson, 1991). If true, the SUS values directly reflect the intensity of pedogenesis and indirectly the amount of precipitation and intensity of the paleomonsoon.

Because the rates of dust accumulation and of pedogenesis are interconnected in both hypotheses, SUS can serve as a proxy index of climate variability closely related to past changes of precipitation. During intervals dominated by strong summer monsoons, precipitation was high, resulting in a dense plant cover, both in the dust source area and in the zone of deposition. Accordingly, the dust accumulation rate decreased and pedogenesis intensified, resulting in a high proportion of ultrafine magnetic grains in the profile; therefore, high SUS values are characteristic of the paleosol units. Conversely, as the summer monsoon weakened, the climate became drier and colder, vegetation density decreased, deflation and dust accumulation accelerated, and pedogenesis declined. A decrease in the concentration of magnetic grains resulted, leading to low SUS values in the loess. The SUS value is therefore a proxy index of summer monsoon intensity.

Since the ultrafine magnetite is bound, in part, on clay minerals, and since the polygenetic soil horizons show the redeposition of clay in cutans, a partial downward relocation of magnetite can be expected. However, we have found no evidence indicating that a significant portion of the ultrafine magnetite and maghemite has moved downward in paleosol profiles. On the contrary, the illuviated ferriargillans of the argillic horizons frequently have lower SUS values than the overlying horizons and the surrounding soil medium. The downward decrease of susceptibility values is gradual and apparently unaffected by illuviation. Consequently, the SUS values at each individual level in both loess and soil units can be regarded as having been locked-in approximately at the time of deposition.

SUSCEPTIBILITY RECORDS

Three loess sections were measured to illustrate the variability of the SUS signal in the southern part of the Loess Plateau.

Beiyuan Section in Beiyuan Village, Linxia County, Gansu Province (35°37′N, 103°12′E; Fig. 1)

The section (Figs. 2 and 3) is composed of two parts, the so-called Elevator Station Section (depth below surface of 6.5–35.2 m) and an exposure 500 m to the north (depth = 0–6.5 m). From the surface down, the sequence consists of a modern cultivated layer, the Holocene soil (Black Loam, or S0), the Malan Loess (L1), and paleosol S1. The L1 loess is coarser here than at Luochuan (Liu *et al.*, 1985; Kukla and An, 1989), and a pedocomplex composed of three weakly developed grayish-black pa-

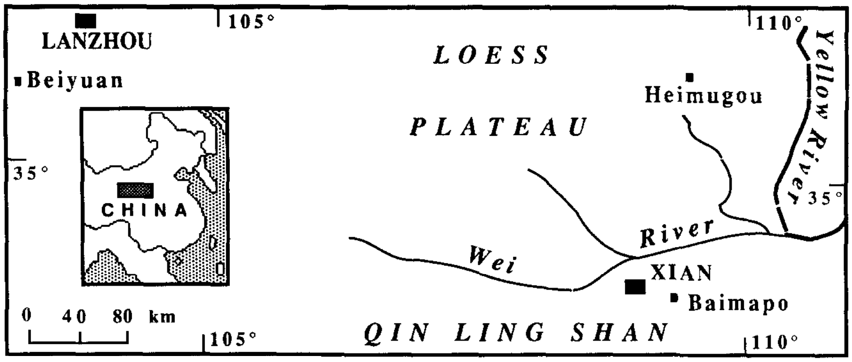

FIG. 1. Map of the southern part of the Loess Plateau in central China showing location of stratigraphic sections discussed in the text.

leosols of the rendzina type can be visually differentiated within it (L1SS1). The S1 paleosol is complex, and consists of three grayish-black humose horizons separated by thin layers of light-colored sediment. Three of the peaks have SUS values of >50 SI units and were individually labeled. Another unlabeled peak lies in the lower part of the S0 soil, and several less-distinct fluctuations occur in the L1SS1 pedocomplex. Thermoluminescence (TL) dating shows that the average accumulation rate of this 35-m-thick section is about 27 cm/10^3 yr over the last 130,000 yr. Such a high accumulation rate is typical of the western part of the Loess Plateau.

Heimugou Section near Luochuan, Shaanxi Province (35°45′N, 109°25′E; Fig. 1)

At the top of this 11.5-m-thick section is a thick cultivated layer above the Holocene soil (the so-called Black Loam, or S0 soil). It is difficult with the naked eye to distinguish the incipient paleosol in the middle part of the L1 loess; only the values of 60–100 SUS units and the frequent insect and worm burrows suggest the effects of weak pedogenesis. The S1 soil is a typical polygenetic leached argillic paleosol ("cinnamon soil" of the Nanjing Soil Institute of Chinese Academy of Sciences, 1980) with its lower part showing higher concentrations of argillans, mangans, and other cutans. At least four SUS peaks of more than 150 SI units occur in the section, three in the S1 soil and one in the S0 soil. The three in the S1 soil have been informally labeled S1SS1, S1SS2, and S1SS3.

Baimapo Section at Baimapo Village, Lantian County, Shaanxi Province (34°10′N, 109°19′E; Fig. 1)

Beneath the thick modern cultivated layer of this 7.5-m-thick section exposed in the wall of the Lantian brickyard is a leached humose black soil (S0) of the so-called "meadow cinnamon" type according to the Nanjing Institute terminology. It resembles a pseudotshernosem of Kubiena's terminology. Neolithic shards and human skeletal remains were discovered in this layer. A grayish-brown meadow cinnamon paleosol complex (L1SS1) is developed in the middle part of the L1 loess. Its lower part is darker. The light-colored loess interlayers in both the upper (L1LL1) and the lower (L1LL2) parts of the L1 loess are rather thin. The underlying S1 paleosol consists of an upper grayish-black to reddish-brown humose meadow cinnamon soil and a lower reddish-brown leached cinnamon soil (parabraunerde or lessive) with well-developed prismatic structure. Three SUS peaks of >150 SI units occur in the S1 soil (S1SS1, S1SS2, and S1SS3), one occurs in the S0 soil, and one occurs in the L1SS1 soil.

CHRONOSTRATIGRAPHIC SUBDIVISION

Figure 3 shows the SUS curves plotted

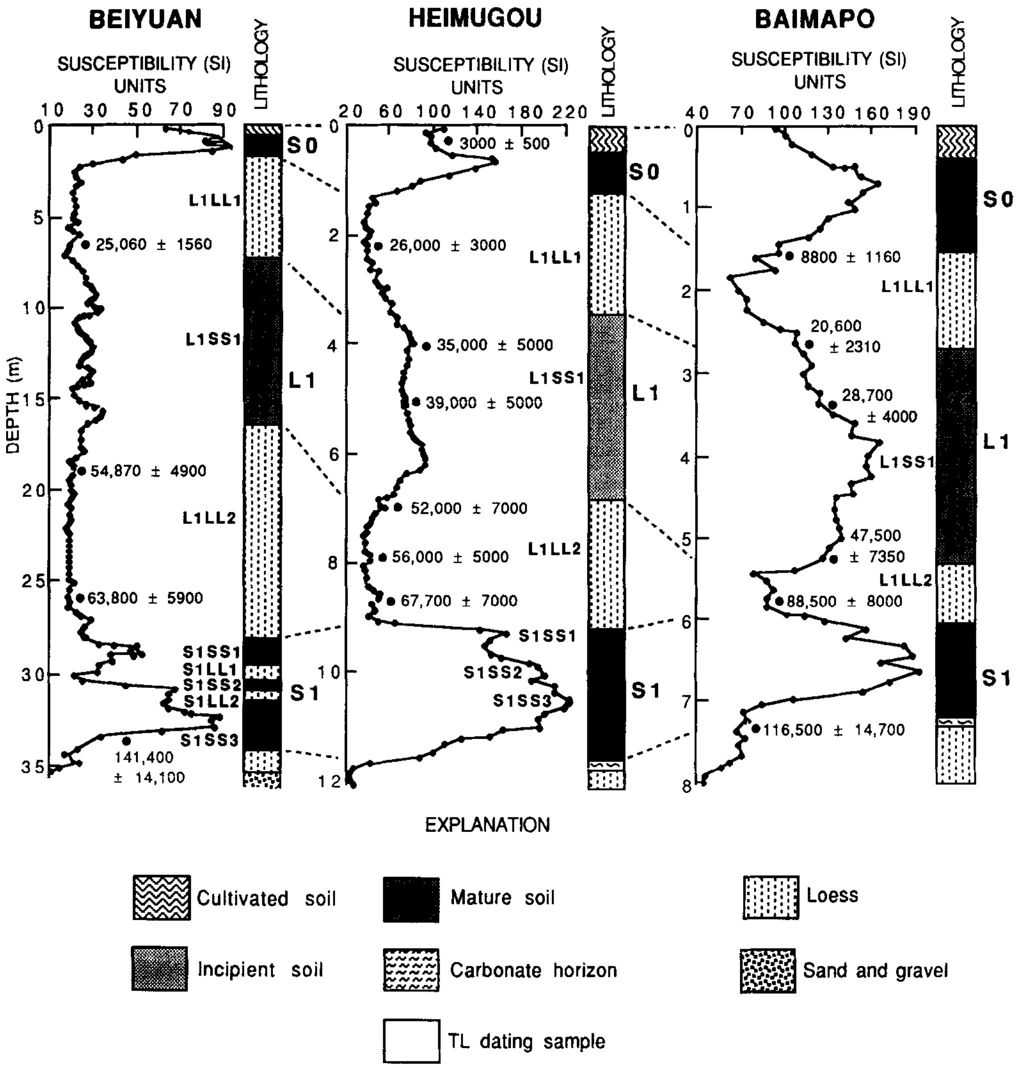

FIG. 2. Lithology and low-field magnetic susceptibility (in arbitrary Bartington SI units, n · m^3 kg^{-1}) of three loess sections covering the last 130,000 yr. TL dates by Lu and Forman (see text). Designation of lithologic units (e.g., S0, S1, L1SS1) after Kukla and An (1989).

against the magnetic susceptibility time scale of Kukla *et al.* (1988). Three fixed-age reference points were used in this calibration: the base of the S1 soil (128,000 yr B.P.), the top of S1 (71,000 yr B.P.), and the base of soil S0 at 10,000 yr B.P. The ages of the stratigraphic boundaries have been derived from the correlation of SUS with the oxygen isotope chronology of Imbrie *et al.* (1984). The age calculation of other horizons follows the formula given by Kukla *et al.* (1988) which assumes a constant deposition and/or formation rate of magnetite within the bracketed segments. It should be noted that the susceptibility age of the top of the S1 would range from 70 to 77 thousand yr if only two points (base of S0 and of S1) are used in the interpolation.

The resulting SUS ages (Fig. 3) are consistent, within the limits of dating accuracy, with TL ages determined by Lu *et al.* (in press) of the Xian Laboratory of Loess and Quaternary Geology and by Forman (1991; for the Luochuan section). The samples from Beiyuan and Beimapo were collected by the authors and by Zhang Shingshao and Xie Jun, and those from Luochuan by Forman. The results from Beiyuan and Bai-

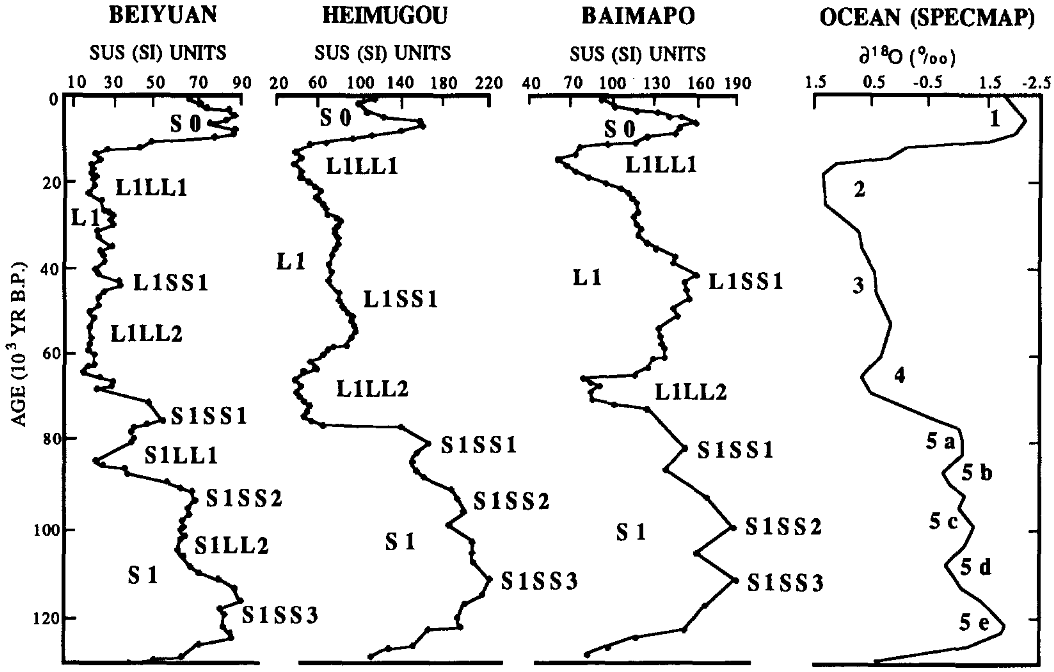

FIG. 3. Susceptibility of the three loess sequences plotted on the susceptibility time scale of Kukla *et al.* (1988), compared with the SPECMAP oxygen isotope record of Imbrie *et al.* (1984) and Prell *et al.* (1986).

mapo were obtained using the fine-grain (4–11 μm) TL technique (Lu *et al.*, in press). The preparation procedure and the TL measurements are similar to those described by Lu *et al.* (1987, 1988). The regeneration and/or residual (in the surface sample) methods have been employed to determine the paleodose (P). The error of weighted mean of the paleodose for the plateau range was less than 10% for each sample. The environmental radiation dose rate was calculated from U, Th, and K contents of each sample using the conversion factor of Aitken (1985). The methodology used for the Luochuan samples is described in detail by Forman (1991).

It can be seen in Figure 3 that the three SUS curves correlated broadly with the deep sea $\delta^{18}O$ curve of Imbrie *et al.* (1984). Up to five substages (three SUS peaks and two minima) can be recognized in the lower part of the records (Fig. 2) apparently corresponding to oxygen isotope substages 5e–a. The threefold subdivision of the Malan loess (L1) was first proposed by An and Lu (1984), based on the presence of the L1SS1 paleosol in the middle of the section. The SUS curves in Figures 2 and 3 suggest that the L1SS1 is more complex and could be further subdivided in Beiyuan and Heimugou sections into at least two incipient paleosols separated by a less-weathered unit in between.

The middle part of the L1 loess in the Baimapo section has exceptionally high SUS values compared to the other loess sections. The present climate is rather warm and humid in this southern part of the Loess Plateau, leading to stronger pedogenesis. In this situation, a higher proportion of magnetite than elsewhere can be formed by *in situ* processes.

CLIMATIC INTERPRETATION

The three measured SUS curves reflect the climatic evolution of the Loess Plateau during the last 130,000 yr and indicate five relatively humid intervals apparently correlating with oxygen isotope substages 5e, 5c, and 5a, with stage 3, and with the early part of stage 1. The severe dry and cold periods, which in the isotope record peaked at 65,000 yr B.P. (stage 4) and 18,000 yr B.P. (stage 2), correlate with carbonate-rich, low-susceptibility loess in the Loess Plateau. Between approximately 60,000 and 25,000 yr B.P. (isotope stage 3) the climate was warmer and, particularly in the southern margin of the plateau, also more humid than during the preceding and subsequent time. The interval from 125,000 to almost 115,000 yr B.P., coinciding with the initial phase of S1 paleosol development, apparently had a warmer and more humid climate than that of the early and middle Holocene.

We infer that the paleosols marked by the peaks in the three SUS curves represent intervals during which the summer monsoon circulation dominated and precipitation increased. It is consistent with additional evidence showing that the interval between 9000 and 5000 yr B.P., when the S0 soil formed on the Loess Plateau, was a time of increased monsoonal precipitation and higher summer temperature (An *et al.*, in press). The inference is also consistent with the results of global climate model simulations of Kutzbach and Guetter (1986). Output of their latest run for the early Holocene (9000 yr B.P.) gives higher July temperature and precipitation/evaporation values than at present. This was also a time of continuing widespread ice sheet shrinkage and rapid sea-level rise, reflected in the marine record by a rapid shift of oxygen isotope ratios. The SUS peaks near 55,000 and 30,000 yr B.P. coincide with intervals of intensified summer monsoon during isotope stage 3. The SUS minima at about 65,000 and 18,000 yr B.P. coincide with the coldest phases of the last glacial age (isotope stages 4 and 2, respectively). At those times, the summer monsoon circulation was weakest and the dry winter winds strengthened, leading to accelerated loess accumulation.

The SUS curves from the Beiyuan and Heimugou sections are similar to the oxygen isotope deep-sea curves and seem to display a cyclic variation with a period of approximately 20,000 yr, which is the period of the Earth's precessional cycle (Fig. 3). The four intervals of strongest summer monsoon are also times of peak summertime radiation to central China and to the Northern Hemisphere in general (Prell and Kutzbach, 1987).

We concur with Kutzbach and Guetter (1986) that the strengthening of summer solar radiation during the early Holocene and during warm intervals of the late Pleistocene gave rise to an increased atmospheric pressure gradient between the continents and the oceans, thereby producing a strong summer monsoon that brought more moisture from the ocean onto the land. This, in our view, is the main reason why the loess record in the middle latitudes is in general agreement with the cyclic variation of solar radiation. However, summer monsoon penetration into the Loess Plateau may also have been affected by the changing distance of the coastline, due to fluctuations of sea level. For example, during the last glacial maximum at about 18,000 yr B.P., the sea level fell approximately 120 m (Fairbanks, 1989) and the coastline of China retreated about 800 to 1000 km eastward (An *et al.*, in press), leaving the plateau farther inland.

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REFERENCES

Aitken, M. J. (1985). "Thermoluminescence Dating." Academic Press, London.

An, Z. S., and Lu, Y. C. (1984). A climatostratigraphic subdivision of late Pleistocene strata named Malan formation in north China. *Kexue Tongbao (Scientific Communique)* **29,** 1239–1242.

An, Z. S., Wu, X. H., Lu, Y. C., Zhang, D. E., Sun, X. J., and Cong, G. R. (In press). Paleoenvironmental changes in China during the last 20,000 years. *In* "Loess, Quaternary Geology, and Global Change" (T. S. Liu, Ed.). Science Press, Beijing.

Chen, D. N., Lu, Y. C., and An, Z. S. (1982). Snail assemblages in loess strata and their environmental implication. *In* "Proceedings of the 3rd Chinese National Quaternary Conference," pp. 7–15. Science Press, Beijing.

Editorial Board of China's Physical Geography (Chinese Academy of Sciences) (1985). "Physical Geography of China: General," pp. 3–20, 104–132. Science Press, Beijing.

Fairbanks, R. G. (1989). A 17,000-year glacio-eustatic sea level record: Influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. *Nature* **342,** 637–642.

Forman, S. L. (1991). Late Pleistocene chronology of loess deposition near Luochuan, China. *Quaternary Research* **36,** 19–28.

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

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

Imbrie, J., Hays, J. D., Martinson, D. C., McIntyre, A., Mix, A. C., Morley, J. J., Pisias, N. G., Prell, W. L., and Shackleton, N. J. (1984). The orbital theory of Pleistocene climate: Support from the revised chronology of the marine delta ^{18}O record. *In* "Milankovich and climate, Part I" (A. L. Berger *et al.,* Eds), pp. 169–305. Reidel, Boston.

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

Kukla, G., An, Z. S., Melice, J. L., Gavin, J., Xiao, J. L. (1990). Magnetic susceptibility record of Chinese Loess. *Transactions of the Royal Society of Edinburgh: Earth Sciences* **81,** 263–288.

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

Kutzbach, J. E., and Guetter, P. J. (1986). The influence of changing orbital parameters and surface boundary conditions on climate simulations for the past 18,000 years. *Journal of the Atmospheric Sciences* **43,** 1726–1759.

Liu, T. S., *et al.,* (Eds). (1985). "Loess and the environment." China Ocean Press, Beijing.

Lu, Y. C., Prescott, J. R., Robertson, G. B., and Hutton, J. T. (1987). Thermoluminescence dating of the Zhaitang section of the Malan loess, China. *Geology* **15,** 603–605.

Lu, Y. C., Zhang, J. Z., and Xie, J. (1988). Thermoluminescence dating of loess and paleosols from the Lantian section, Shaanxi Province, China. *Quaternary Science Reviews* **7,** 251–255.

Lu, Y. C., Zhang, J. Z., Xie, J., and Zhao, H. (in press). A report of TL dating results. *In* "Loess, Quaternary Geology, Global Change" (T. S. Liu, Ed.). Science Press, Beijing.

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

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

Nanjing Soil Institute of Chinese Academy of Sciences. (1980). "Soil in China," pp. 446–464, 578–582. Science Press, Beijing.

Prell, W. E., and Kutzbach, J. E. (1987). Monsoon variability over the past 150,000 years. *Journal of Geophysical Research* **92,** 8411–8425.

Sasajima, S. and Wang, Y. Y., (Eds.). (1984). "The recent research of loess in China." Kyoto University and Northwest University, Kyoto, Japan.

Shen, C. D., Liu, T. S., Beer, J., Oeschger, H., Bonani, G., Suter, M., and Wolfli, W. (1985). ^{10}Be in Chinese loess. *In* "Aspects of Loess Research" (T. S. Liu, Ed.), pp. 277–282. China Ocean Press, Beijing.

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.