GEOPHYSICAL RESEARCH LETTERS, VOL. 26, NO. 16, PAGES 2485-2488, AUGUST 15, 1999

Millennial-scale climatic change during the last interglacial period: Superparamagnetic sediment proxy from paleosol S1, western Chinese Loess Plateau

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Abstract. Detailed magnetic analyses of samples from the Jiuzhoutai well section on the western Chinese Loess Plateau reveal high-resolution signals of summer monsoon change. The last interglacial period is represented here by the 8-meter thick S1 paleosol complex. We have used low-temperature remanence studies to analyze variations in the concentration of superparamagnetic (SP) grains, which previous studies have shown to be largely of pedogenic origin. The SP concentration, interpreted as a proxy for the extent of pedogenesis, shows millennial scale variations within S1. We conclude that the last interglacial period in Asia was characterized by rapid climate fluctuations, with at least one brief return to near-glacial conditions in the middle of oxygen-isotope substage 5e.

Introduction

Climatic instability during the last interglacial period has become a subject of great debate since contradictory results were obtained from two ice cores in Greenland [Dansgaard et al., 1993; Grootes et al., 1993]. This debate has attracted considerable international attention because climate records for the last interglacial period have fundamental importance for our understanding of current climate trends. Up to now, the debate has been based mostly on climatic records from the North Atlantic and peripheral areas [Thouveny et al., 1994; Maslin and Tzedakis, 1996; Fronval and Jansen, 1996; Kukla et al., 1997]. A few records from the Chinese Loess Plateau, based on magnetic susceptibility, carbonate and grain size, show that the last interglacial Asian monsoon may also have undergone large variations [Fang et al., 1995; An and Porter, 1997].

Bulk magnetic susceptibility has proven to be a relatively precise proxy of summer monsoon strength in the central Loess Plateau [Liu, 1985], but has yielded more problematic results in other loess areas [e.g., Oches and Banerjee, 1996; Grimley et al., 1998]. Magnetic susceptibility in loess and paleosols is largely a function of the type, concentration and grain size of ferrimagnetic minerals. The susceptibility contributions of paramagnetic and diamagnetic minerals are relatively minor in most of these sediments, but they become important when ferrimagnetic concentrations are low. The response of susceptibility to climate variations is the sum of the separate responses of these diverse mineralogies, and it may therefore be rather complex.

A more selective proxy is the abundance of ultrafine superparamagnetic (SP; < 0.03 μm for magnetite [Dunlop, 1973]) grains. Recent rock magnetic investigations have demonstrated that SP grains are mostly pedogenic in origin and are largely responsible for the enhancement of magnetic susceptibility in soil [Maher and Taylor, 1988; Banerjee et al., 1993; Evans and Heller, 1994]. The content of SP grains changes tremendously with the degree of soil development, which in turn is controlled by summer monsoon precipitation and temperature [Banerjee et al., 1993; Liu et al., 1995], as well as time.

We have carried out a detailed study of the variation in concentration of SP grains for the last-interglacial S1 paleosol complex in the Jiuzhoutai well loess section in Lanzhou (36°N and 103°50'E), on the western Chinese Loess Plateau. As we will show, the results allow us to resolve a millennial-scale summer monsoon history for the last interglacial period.

Geology and Sampling

Lanzhou is located at the northwestern front of summer monsoon circulation. This front encompasses a strong gradient between warm, humid air masses over the Pacific and Indian Oceans, and cold, dry air masses centered on Siberia and West Mongolia. Thus, modern precipitation, vegetation and soil biological activity in Lanzhou are very sensitive to any summer monsoonal circulation changes. Furthermore, the Jiuzhoutai section is the highest-resolution loess record in the world, containing the greatest total accu-

Paper number 1999GL008335.
0094-8276/99/1999GL008335$05.00

mulation (318 m), which formed in a relatively short time (1.3 Ma) [Burbank and Li, 1985], yielding a mean sedimentation rate of about 245 mm/ka. The embedded S1 paleosol complex formed mainly between about 150 and 75 ka, and it reaches a thickness of 8 m near Lanzhou, three to four times thicker than the corresponding paleosols in the central Loess Plateau [Liu, 1985].

To obtain fresh samples, a 40-meter deep well was dug at the top of the Jiuzhoutai section. The well section consists of a distinctive dark paleosol complex (S0) at the top, the Malan loesses (L1-1 to L1-5) and their embedded weak paleosols of the Sm complex (Sm-1 to Sm-4) in the middle, and the Lishi loesses (L2-1 to L2-3) with their embedded yellowish-brown paleosols of the S1 complex (S1-a to S1-c) at the bottom.

Previous and new systematic dating of the section by radiocarbon, thermoluminescence (TL) and paleomagnetism [Li et al., 1992; Fang et al., 1997] shows that loess L0 and paleosol series S0 are Holocene in age, whereas loess series L1 and paleosols Sm were deposited during the last glaciation, and L2 and S1 during the last Pleistocene interglacial period. These assignments are broadly in accord with those for the sequence from the central part of the Loess Plateau [Liu, 1985], and they correlate well with standard marine oxygen-isotope stages (MIS) [Martinson et al., 1987]: S0, Sm and S1 correspond with warm periods, MIS-1, 3 and 5, respectively.

This study focuses on the stratigraphic interval of depth 35.3-38.55 m, which encompasses the peak interglacial paleosol (S1-c) of MIS-5e. Bulk sediment samples for rock magnetic analysis were taken at 2.5-cm intervals, providing a nominal resolution of ca. 180 years. Since TL ages have large errors, we follow the conventional method [An and Porter, 1997] of refining the chronology: first we correlate the boundaries of L1-5/S1-a, L2-2/S1-c and S1-c/L2-3 to those of MIS 4/5 (74 ka), MIS 5d/5e (114 ka) and MIS 5/6 (130 ka), respectively [Martinson et al., 1987]; then we apply an age-depth model based on grain size data [Fang et al., 1995] to calculate ages for levels between the boundary ages. This method is better than linear interpolation between dated horizons, because the winter monsoon and loess deposition rates have changed sharply in the past [Liu, 1985].

Magnetic Measurements

The purpose of our detailed magnetic studies was to isolate the contributions of different magnetic minerals and different size fractions to the room-temperature low-field susceptibility signal in the Jiuzhoutai section. In particular, we aimed to quantify the ultrafine SP fraction of magnetite and maghemite grains, which have been linked by previous studies to pedogenic processes.

Low-temperature magnetic measurements are the most definitive means of quantifying the concentration of magnetic grains that are SP at room temperature [Hunt et al., 1995]. A low-temperature saturation isothermal remanent magnetization (SIRM) will be partially thermally demagnetized warming in zero field. The unblocking temperature spectrum is closely related to the distribution of particle sizes in the SP fraction, and the total remanence loss by thermal unblocking is a direct measure of the total mass of SP material present [Banerjee et al., 1993; Hunt et al., 1995].

In addition to the continuous loss of remanence due to thermal unblocking, there are several other mechanisms that may contribute to remanence loss during zero-field warming, and these must be recognized and accounted for separately. Magnetite-bearing sediments generally exhibit a sharp loss of remanence over a narrow temperature interval associated with both the Verwey transition (110-120 K) and the magnetocrystalline K1 isotropic point (~130 K) [Verwey, 1939; Dunlop and Özdemir, 1997]. Low-temperature remanence carried by other minerals may also drop sharply over characteristic temperature ranges corresponding to Néel points or other transitions. Analysis of the thermal decay of low-temperature SIRM thus provides an effective means of identifying magnetic minerals and of quantifying SP grain concentration [Hunt et al., 1995].

The samples of this study were analyzed using a Quantum Designs MPMS (magnetic property measurement system). A 2.5 Tesla (T) field was used to saturate the samples at 20 Kelvin (K). The resultant SIRM (carried by MD, SD and SP grains with blocking temperatures above 20 K) was then measured during warming to 300 K in zero field. Between about 100 and 120 K, a sharp drop in magnetization is observed for all samples (Fig. 1). This drop, associated with the Verwey transition, confirms that magnetite is a significant remanence carrier in all samples. No other magnetic minerals are indicated by discontinuous or sharp variations in remanence at other temperatures. Previous studies have shown that the magnetic minerals in Chinese loess and paleosols are chiefly magnetite, maghemite and hematite [Heller and Liu, 1984; Heller and Evans, 1995; Hunt et al., 1995]. Our data are consistent with this conclusion, although they directly confirm only the magnetite contribution.

Because the sharp loss of remanence around 110 K is due to the structural phase transition, and not to thermal unblocking, it must be tallied separately in the estimation of total SP content. A simple graphical method [Banerjee et al., 1993; Hunt et al., 1995] was used to partition the low-temperature SIRM into three fractions: the stable remanence remaining

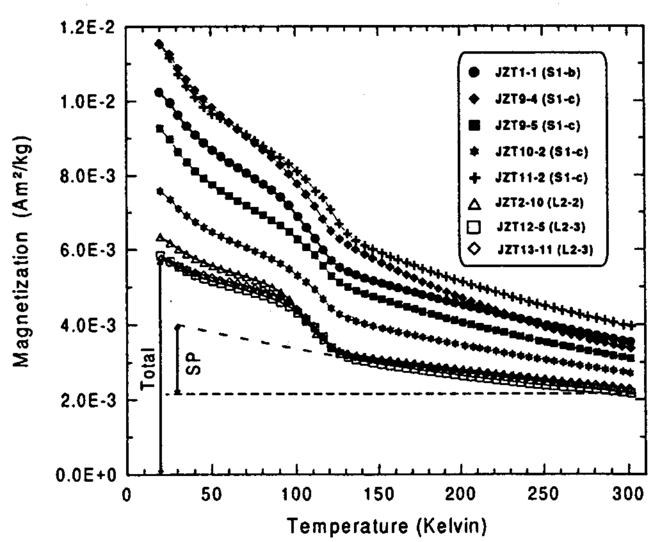

Figure 1. Thermal demagnetization of low-temperature SIRM acquired at 20 K, for a few representative loess and paleosol samples. Superparamagnetic (SP) content can be determined by an extrapolation of a fitted remanence decay curve (see text for details). Note the two groups of curves separate clearly the paleosols (solid symbols) and loesses (open symbols) except for soil sample JZT10-2, which marks a significant fluctuation during the mid-last interglacial maximum. Locations of the samples are in Figure 3.

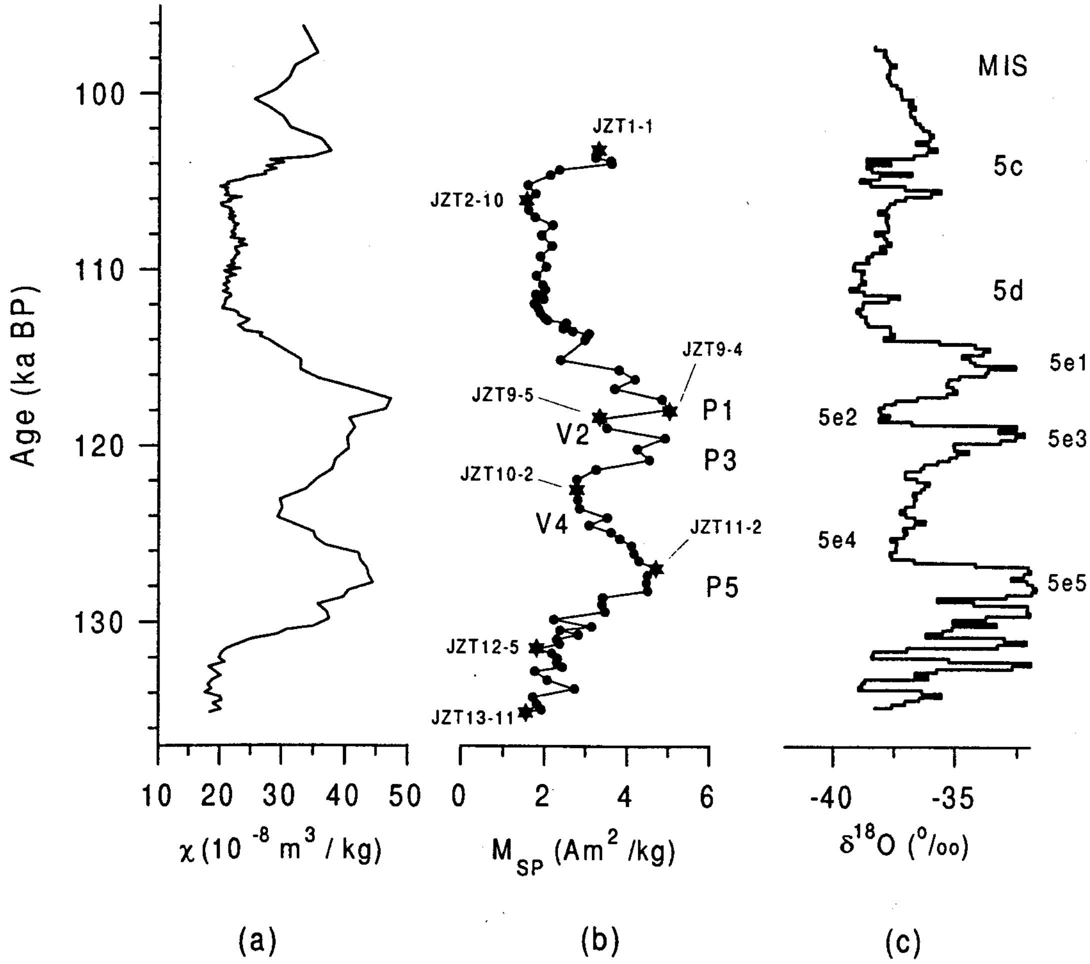

Figure 2. Comparison of stratigraphic variations in mass-specific magnetic susceptibility (a) and remanence carried by SP grains (b) to the oxygen-isotope climatic record from the Greenland GRIP ice core (c). Asterisks show the locations of samples whose thermal remanence decay curves are shown in Figure 1.

after warming to 300 K; the remanence unpinned near 110 K by the magnetocrystalline and structural transitions of magnetite; and the continuous, quasi-exponential decay associated with thermal unblocking of the particles that are SP at room temperature (Fig. 1).

Oxidation of magnetite (maghemitization) suppresses the Verwey transition [Özdemir et al., 1993]. The loss of remanence near 110 K is thus attributable mainly to near-stoichiometric magnetite. Maghemite may contribute both to the SP fraction that unblocks on warming to 300 K and to the stable fraction that survives at room temperature [Sun et al., 1995]. For our purposes, it is not important how the SP fraction is partitioned into magnetite and maghemite contributions; we assume that SP particles of both species result from pedogenesis [Verosub, 1994], and therefore the total SP fraction represents the signal of soil formation. We also assume that enough of the fine SP fraction survives to preserve this signal.

Summer monsoon changes suggested by SP grains

Figure 2 shows the stratigraphic variation in SP grain abundance, in terms of the contribution made to the low-temperature SIRM by particles that are SP at room temperature. Note that this is a measure of absolute concentration of SP particles, rather than the proportion of ferrimagnetic material in the SP state. The SP content differs strongly in loesses and paleosols, with respective means of 2.0 x 10^{-3} Am^2/kg and 3.9 x 10^{-3} Am^2/kg. The most impressive feature in the SP concentration curve is the large drop (V4) in the center of S1-c, where it falls nearly to the levels characteristic of the loesses (Fig. 2b). The low-SP interval spans approximately 3.5 ka, with a central age of ca. 123 ka. This feature is also clearly visible in both volume- and mass-specific magnetic susceptibilities (Fig. 2a).

A smaller decrease of shorter duration (V2) can be observed in the SP concentration in the upper part of S1-c (Fig. 2). This drop, though less dramatic than V4, represents a significant change in the pedogenic signal. It is not seen in the susceptibility, which exhibits a continuous broad maximum over the same interval. The source of the enhanced susceptibility here is not yet understood; all three of the low-temperature remanence components are somewhat diminished in V2 samples. The sharp minimum in SP concentration argues against the conventional picture of pedogenic susceptibility enhancement in this interval.

The two drops V2 and V4 divide the S1-c record into three peaks (P1, P3 and P5), two of which are characterized by a rapid initial increase at the base and a more gradual upward decline (Fig. 2c). Peak 5 is the most striking of these. The three peaks have durations of about 1-3 ka, with central ages estimated at ca. 115, 120 and 127 ka, respectively.

These variations in SP content suggest that the summer monsoon during 5e underwent several large changes: an enhancement at the transition from the penultimate glaciation (MIS 6) to the last interglacial stage (MIS 5), with its warmest climate at about 127 ka; a gradual weakening of the summer monsoon and/or a temperature drop to a nearly glacial level at about 120 ka; and at least one more similar cycle of increase and subsequent decrease of monsoon leading into substage 5d (Fig. 2). This indicates that the Asian summer monsoon has an unstable nature, even on a millennial scale. The inferred pattern bears a strong resemblance to the record of Eemian climatic instability (5e1-5e5) in the Greenland GRIP ice core [GRIP, 1993] (Fig. 2c), while the sharp drop of summer monsoon in the middle of S1 seems to correlate with so-called mid-5e (drop) event documented in the North Atlantic deep sea records [Maslin and Tzedakis, 1996; Fronval and Jansen, 1996]. Our results suggest fast climatic change during the last interglacial interval, and may indicate a teleconnection between the summer monsoon and the North Atlantic climate.

Acknowledgment: We gratefully acknowledge help in initial well digging and sampling by Wang Jintai, Edward Derbyshire, Dai Xuerong and others, and constructive reviews by Joseph Rosenbaum, Nicolas Thouveny and an anonymous reviewer . This work was co-supported by Ministry of Education of China (grant for Trans-Century Excellent Researchers and the Key Program), Visiting Fellowship Fund of IRM, the National Key Project for Basic Research on Tibetan Plateau, the NSFC (No. 49871010), and the INQUA 1997 Project. The IRM is funded by the Instruments and Facilities Program, Earth Sciences Division, National Science Foundation, and by the W. M. Keck Foundation. This is IRM contribution number 9904.

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(Received March 9, 1999; revised May 24, 1999; accepted June 15, 1999)