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Mega-pulses and megacycles in East Asian monsoon variations recorded in Chinese loess-red clay magnetic susceptibility

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[1] Three mega-pulses (first order variations) and four megacycles (second order variations) in loess-red clay magnetic susceptibility are identified in a loess section in the central Chinese Loess Plateau, implying pulsed fluctuations in East Asian monsoon intensity on tectonic timescales. Comparisons of the loess record with the mineral flux from ODP Site 758 and the diatom record in Lake Baikal core BDP-98 suggests that the loess-red clay magnetic susceptibility may represent a continental-scale signal of climate change. It is apparent that the stepwise-diachronous rise of the Tibetan Plateau and its resulting climatic influence may be the main cause of the observed monsoon pulses. **Citation:** Xiong, S., W. Jiang, and T. Liu (2006), Mega-pulses and megacycles in East Asian monsoon variations recorded in Chinese loess-red clay magnetic susceptibility, *Geophys. Res. Lett.*, *33*, L18702, doi:10.1029/2006GL027842.

1. Introduction

[2] Ten years ago, *Kukla and Cílek* [1996] published a paper on climate megacycles recorded in deep-sea sediments and loess deposits, and distinguished ten megacycles in the Chinese loess sequences with an average duration of 255 ka. Prior to this work, *Zhu and Ding* [1994] proposed seven main climatic-tectonic cycles, each with a period of about 0.4 Ma, based mainly on the Chinese loess pedostratigraphy. The following decade witnessed a rapid expansion of studies on the millennial and orbital time-scale climate changes recorded in the Chinese loess, whereas relatively less attention has been paid to tectonic timescale signals in the climatic proxies preserved in the Chinese loess deposits. The Chinese loess, as well as the underlying red clay, with its continuous record and excellent correlation among sections, is an important potential resource for understanding tectonic timescale East Asian monsoon variations since the late Miocene. With recent advances in the Chinese loess-red clay pedo-stratigraphy [e.g., *Ding et al.*, 1999], it is appropriate to re-examine the tectonic timescale features of these climate records.

[3] Here we re-examine the magnetic susceptibility data from the Baishui section [*Xiong et al.*, 2002, 2003] in the central Loess Plateau and compare it with deep sea records from the Indian Ocean and a climate proxy from Lake Baikal. The main purpose of this manuscript is to address the following questions: Are there any significant megacycles in the Chinese loess records? If so, what are the causes of these megacycles? The results show that the loess-red clay magnetic susceptibility exhibits first order variations comprised of three mega-pulses that can be correlated with a climate record from the Indian Ocean and second order variations (megacycles) in some intervals that are correlated with eccentricity modulations. This implies pulsed fluctuations in East Asian monsoon intensity over tectonic time scales which overprint or modify the orbital-scale variations. The proposed stepwise-diachronous rise of the Tibetan plateau may be the main cause of these climate pulses.

2. Materials and Correlation

[4] The Baishui (35°24′10″N, 106°56′43″E) section [*Xiong et al.*, 2002] is located in the northwest part of the central Loess Plateau (Figure 1). Previous study has revealed that the magnetic susceptibility record is well correlated among the Baishui, Lingtai and Jingchuan sections [*Xiong et al.*, 2002]. The age control of the Baishui section was obtained by correlating the magnetic susceptibility record with the Jingchuan record, in which the age control points were based on the magnetic reversal stratigraphy [*Ding et al.*, 2001]. The base of the red clay in the Baishui section is about 6.2 Ma old [*Xiong et al.*, 2003]. The magnetic susceptibility of the Baishui section was measured with a Bartington MS2 susceptibility meter using air-dried samples [*Xiong et al.*, 2002], and the frequency-dependent magnetic susceptibility (X_{fd}) was expressed as a ratio of low field magnetic susceptibility (X_{Lf}, 470 Hz) and high field magnetic susceptibility (X_{Hf}, 4700 Hz) (i.e., $X_{fd} = 100*(X_{Lf} - X_{Hf})/X_{Lf}$).

[5] The variation patterns of the Baishui loess magnetic susceptibility was compared with the climate proxy (diatom abundance) in the BDP-98 core from Lake Baikal [*Antipin et al.*, 2001] and the mineral flux record from ODP Site 758 [*Hovan and Rea*, 1992] (Figure 1). The diatom abundance from Lake Baikal varied from 0% to 90% grains, with a transition in variation pattern occurring at about 2.8 Ma [*Antipin et al.*, 2001]. The variations in the terrigenous mineral accumulation rates in sediments from ODP site 758 exhibit four maximum pulses since about 9.5 Ma [*Hovan and Rea*, 1992]. Over the last 7.0 Ma, pulses are observed between 7.0 to 5.6 Ma, 3.9 to 2.0 Ma and from 0.5 Ma [*Nath et al.*, 2005].

[6] There is a general similarity between the loess-red clay magnetic susceptibility and the diatom record from Lake Baikal since about 5 Ma (Figure 2). We did not compare these two records before 5 Ma because of direct riverine influence on the sedimentation near the BDP-98 drill site in Lake Baikal during this period [*Antipin et al.*, 2001]. From about 4.5 Ma to 2.8 Ma, both loess-red clay

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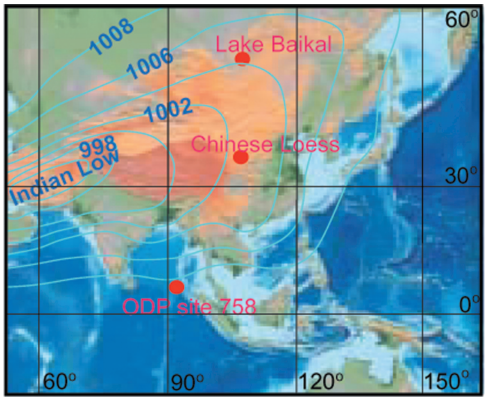

Figure 1. Map showing the locations of the Baishui section in the Chinese Loess Plateau, Lake Baikal and ODP site 758. Also shown are Asian surface barometric pressures (millibars) for July [from *Christopherson*, 1997].

and Lake Baikal records trend towards higher values punctuated by some tectonic to orbital timescale variations. From 2.8 Ma onward, high frequency orbital timescale fluctuations dominate both records.

[7] Although the loess-red clay magnetic susceptibility record is dominated by orbital timescale fluctuations, three longer-period variations can be identified in the Baishui record (Figure 2). These three first order variations can be correlated with the pulses of mineral flux recorded in ODP Site 758 sediments (Figure 2). As with megacycles, we refer these three clusters of maximum susceptibility values in the loess-red clay magnetic susceptibility as mega-pulses (mega-pulse I to mega-pulse III). The loess magnetic susceptibility mega-pulses are generally synchronous with the mineral flux pulses observed in the record from ODP site 758, except that no analogue is found in the loess magnetic susceptibility mega-pulses that corresponds to the maximum in the mineral flux pulse 3 of ODP site 758 (Figure 2). Probably a minor mega-pulse in the loess magnetic susceptibility can be assigned during 1.7–0.9 Ma, but no corresponding maximum is observed in the mineral flux record of ODP site 758 (Figure 2).

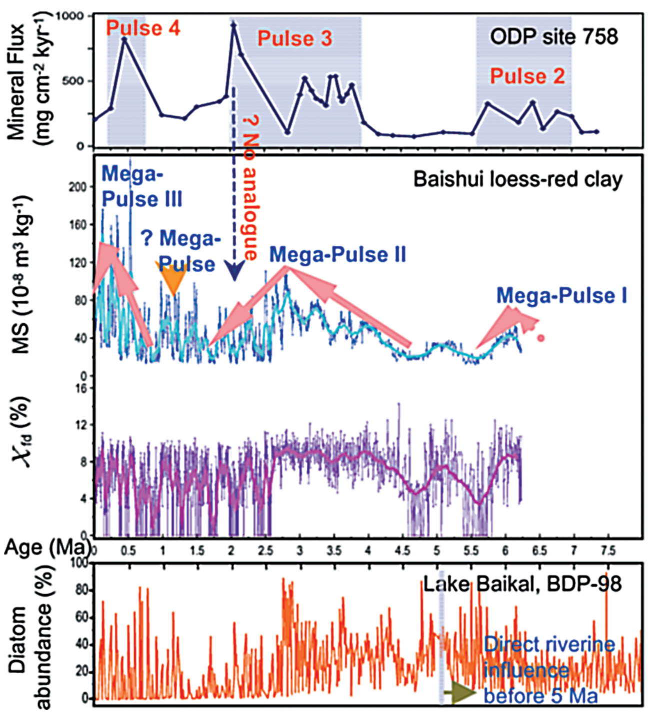

Figure 2. Correlation of magnetic susceptibility (MS) and frequency-dependent magnetic susceptibility (X_{fd}) (and the 51-point moving averages, indicated by heavy lines) of the Baishui loess section with the mineral flux record of ODP site 758 [*Hovan and Rea*, 1992] and the diatom abundance of Lake Baikal [*Antipin et al.*, 2001]. Pulses (pulse 1 is not shown) in mineral flux record [*Hovan and Rea*, 1992] and mega-pulses in loess record are indicated.

[8] Detailed examination of the loess-red clay record further reveals second-order variations that comprise several maxima of magnetic susceptibility on orbital timescales (Figures 2 and 3). These second-order variations (mega-

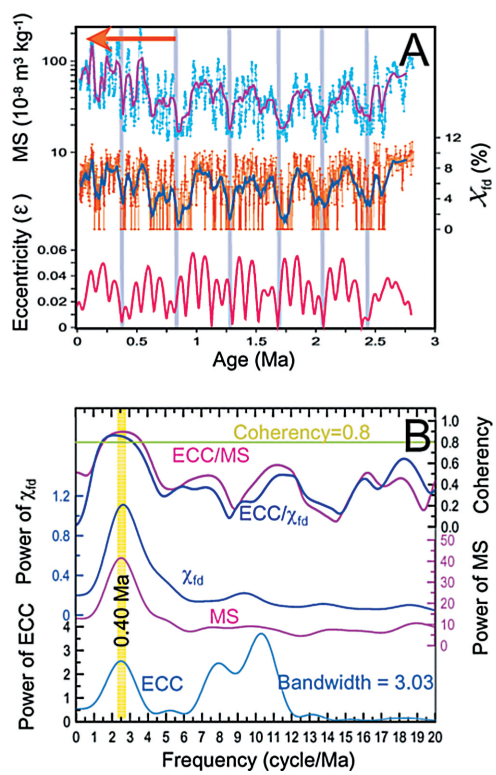

Figure 3. (a) Correlation of magnetic susceptibility (MS, in logarithmic scale) and frequency-dependent magnetic susceptibility (X_{fd}) of the Baishui loess section with the eccentricity variations [*Berger and Loutre*, 1991] from 2.4 Ma to 0.8 Ma. The 51-point moving averages are indicated by heavy lines. After 0.8 Ma (indicated by an arrow), the correlation is poor, probably due to the MS cycles at about 400,000 years being forced by the ice sheet cycles at about 100,000 years. (b) Power spectrum of the 51-point moving averages of magnetic susceptibility (MS) and frequency-dependent magnetic susceptibility (X_{fd}) of the Baishui Section from 2.4 Ma to 0.8 Ma and the coherency between the ECC (eccentricity) and MS, X_{fd} variations. The horizontal solid line denotes the 80% coherency level. The analyses were performed using the Paillard software [*Paillard et al.*, 1996].

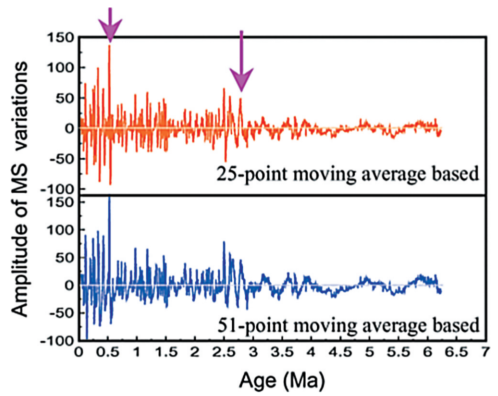

Figure 4. Amplitude of loess magnetic susceptibility variations expressed as deviations between magnetic susceptibility value and its 25-point and 51-point moving averages. The amplitude increased at about 2.8 Ma and 0.6 Ma (indicated by arrows).

cycles) are especially apparent in the record after 2.5 Ma, and from 2.5 Ma to 0.8 Ma, four megacycles, each about 0.4 Ma long, are observed in the magnetic susceptibility and in X_{fd} records (Figure 3). We also observed a change in the amplitude of magnetic susceptibility variations over this interval, with large amplitude increases at 2.8 Ma and 0.6 Ma (Figure 4). This pattern is associated with an increasing trend in background values in loess magnetic susceptibility and particle grain size from about 0.6 Ma (Figure 5).

3. Discussion

[9] The underlying mechanism of the magnetic susceptibility enhancement in paleosols developed on loess deposits remains debatable [e.g., *Heller and Liu*, 1986; *Zhou et al.*, 1990; *Maher and Thompson*, 1992; *Evans and Heller*, 2003]. However, studies of near-surface soil samples [e.g., *Liu et al.*, 1995; *Maher and Thompson*, 1995; *Porter et al.*, 2001] and paleosols [e.g., *Maher and Thompson*, 1995; *Derbyshire et al.*, 1995; *Liu et al.*, 1995; *Evans and Rokosh*, 2000] from the Chinese Loess Plateau all show a southeastward increasing trend of magnetic susceptibility, implying a climatic, most probably precipitation-dominated signal [*Maher and Thompson*, 1995; *Liu et al.*, 1995]. Our previously published data have shown that for the underlying red clay, the magnetic susceptibility also exhibits a southeastward increasing trend [*Xiong et al.*, 2002], probably reflecting a paleoprecipitation signal [e.g., *Liu et al.*, 2003]. The high values of the frequency-dependent magnetic susceptibility (X_{fd}) measurements corresponding to the layers with high magnetic susceptibility (Figure 2) indicate enrichment of super-paramagnetic particles [e.g., *Maher and Thompson*, 1999], partly reinforcing a climate-pedogenic interpretation for the magnetic susceptibility enhancement.

[10] The correlation of the loess-red clay magnetic susceptibility with the diatom abundance of BDP-98 core from Lake Baikal suggests a plausible underlying causal link. Diatom abundance in the lake is influenced by silicate availability [*Round et al.*, 1990], and iron enrichment can also cause diatom blooms in some instances [e.g., *Wells*, 2003]. The silicate and iron inputs are largely determined by weathering intensity and riverine runoff surrounding the lake, which reflects the influence of precipitation. Thus the variations in diatom abundance in Lake Baikal sediment may reflect long-term climate (precipitation) changes in this region. The underlying causal link between the variations of the loess-red clay magnetic susceptibility and the diatom abundance of Lake Baikal sediment is likely climate-related.

[11] The main pulses in terrigenous mineral flux at ODP site 758 signals major Himalayan uplift and its associated erosional discharge [*Hovan and Rea*, 1992], the later being indicative of monsoon intensity. The correlation of the susceptibility mega-pulses in the loess record with the marine mineral flux pulses suggests that, over tectonic timescales, both records are related to the pulsed Himalayan and Tibetan uplift and the associated monsoon intensification.

[12] The present summertime Indian Low covers almost all of the Asian continent (Figure 1), and intensification of this low pressure would draw in more moisture from the surrounding oceans, resulting in strengthened summer precipitation (intensified monsoon) over the continent. Previous model results have suggested that the enhanced uplift of the Tibetan Plateau would strengthen the monsoon low and monsoon precipitation [*Ruddiman and Kutzbach*, 1989; *An et al.*, 2001]. Thus the pulsed variations in terrigenous mineral flux at ODP Site 758, the mega-pulses of the loess-red clay magnetic susceptibility, and the diatom abundance of core BDP-98 may all indicate pulsed strengthened Asian monsoon precipitation in response to the stepwise-diachronous uplift of the Tibetan Plateau (in height and in extension) since the late Miocene [e.g., *Tapponnier et al.*, 2001]. However, we can't exclude the probably important roles of other mechanisms, for example, the reorganization of the ocean-atmosphere system over the tropical Pacific Ocean during the late Miocene-Pliocene [e.g., *Ravelo et al.*, 2006], in inducing the pulsed intensification of Asian monsoon. Nevertheless, the correlation of the loess-red clay magnetic susceptibility between sections demonstrates that it is a regional signal rather than a local signal, and the correlations of the loess record with the ODP Site 758 and the BDP-98 records indicate that the loess-red clay magnetic susceptibility represents continent-scale records of climate change over tectonic timescales.

[13] The second-order variations in the loess-red clay magnetic susceptibility, the megacycles, may be a clipped monsoon response to eccentricity-amplified precession

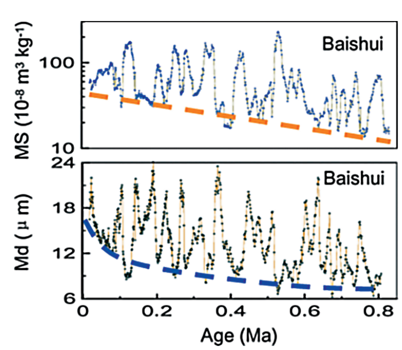

Figure 5. From 0.6 Ma onward, loess magnetic susceptibility (MS, in logarithmic scale) and median grain size (Md) both show an increasing trend in background value.

cycles at a period near 400,000 years (Figure 3). The occurrence of the 400,000 years megacycle from 2.5 Ma to 0.8 Ma may reflect the combined effect of the tectonic uplift and ice sheets on monsoon intensity. We speculate that the major phase of tectonic uplift of the Tibetan Plateau during the Pliocene-early Pleistocene which corresponds to ODP site 758 pulse 3 and mega-pulse II in loess record may have significantly amplified the monsoon response sensitivity to orbital-scale variations in insolation [*Prell and Kutzbach*, 1997; *Ruddiman*, 1997], inducing an apparent monsoon clipped response at 400,000 years periods as well as the higher amplitude variations in magnetic susceptibility (Figure 4). From 0.8 Ma$\sim$0.6 Ma, further tectonic uplift and ice sheet development in the northern Hemisphere could have resulted in greatly amplified fluctuations in monsoon intensity (Figure 4) and higher proportions of coarse-grained and un-weathered detrital magnetite which could produce the observed increasing background trend in loess magnetic susceptibility (Figure 5), because the earlier monsoon response at 400,000 year periodicity was overwhelmed by the ice sheet forcing at100,000 year periodicity (Figure 3).

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