Initial intensification of East Asian winter monsoon at about 2.75 Ma as seen in the Chinese eolian loess-red clay deposit

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[1] The loess-paleosol-red clay sequence in the Chinese Loess Plateau provides a record of the evolution of atmospheric circulation and monsoon climate over East Asia during the last 7–8 Ma. Detailed analyses of the Baishui and Jingchuan sections show that the grain size of eolian loess increased abruptly at about 2.75 Ma, which is accompanied with a reversal of depositional pattern from the red clay to loess-paleosol deposits, suggesting that the dust transporting circulation was reorganized. This is the earliest clear expression of the East Asian winter monsoon intensification at the Pliocene-Pleistocene climate transition, coincident with the initiation of major Northern Hemisphere glaciation over the Eurasian Arctic and Northeast Asia, implying that at the early stage of the Pliocene-Pleistocene global cooling the East Asian winter monsoon circulation had been closely linked with the build up of ice sheet and climate changes over the high latitudes of Northern Hemisphere. The intensified winter monsoon winds would have in turn acted as an important positive feedback in strengthening global cooling by increasing albedo and dust loading. *INDEX TERMS:* 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9320 Information Related to Geographic Region: Asia; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* Loess-paleosol-red clay, Grain size, East Asian winter monsoon, Northern Hemisphere Glaciation. **Citation:** Xiong, S. F., Z. L. Ding, W. Y. Jiang, S. L. Yang, and T. S. Liu, Initial intensification of East Asian winter monsoon at about 2.75 Ma as seen in the Chinese eolian loess-red clay deposit, *Geophys. Res. Lett.*, *30*(10), 1524, doi:10.1029/2003GL017059, 2003.

1. Introduction

[2] Late Cenozoic global cooling and the major Northern Hemisphere glaciation at the Pliocene-Pleistocene climate transition were documented in benthic foraminfera $\delta^{18}O$ records [e.g., *Shackleton et al.*, 1984], the ice-rafted debris records [e.g., *Jansen and Sjoholm*, 1991; *Maslin et al.*, 1995], and was associated with an increased suppression of the North Atlantic Deep Water [e.g., *Raymo et al.*, 1992]. Several explanations, for example, the closure of the Panama Isthmus [e.g., *Keigwin*, 1978; *Haug and Tiedemann*, 1998], the progressive uplift of the Tibetan-Himalayan region [*Ruddiman and Kutzbach*, 1989] and subsequent lowering CO_2 driven by enhanced chemical weathering [*Raymo and Ruddiman*, 1992], the increase in obliquity amplitude [*Maslin et al.*, 1995; *Haug and Tiedemann*, 1998], and explosive volcanic eruptions have been put forward to explain the initiation of Northern Hemisphere glaciation. However, the mechanism of the major Northern Hemisphere glaciation remains uncertain. More investigations for different climatic records in the world, especially terrestrial records, could contribute to improving our understanding of the interaction between climate systems and the processes and causes of the major Northern Hemisphere glaciation.

[3] The eolian loess-paleosol-red clay deposit in the Chinese Loess Plateau provides a continuous record of atmosphere circulation variations over East Asia and interconnections between climate variability over East Asia and global changes [e.g., *Liu et al.*, 1985; *Ding et al.*, 1999]. By analyzing eolian deposits, the history of aridity over inland Asia can be traced back to 20 Ma [*Guo et al.*, 2002] or even older [*Rea*, 1994]. However, continuous, well-correlated eolian loess-paleosol-red clay deposits are found only within the last 7–8 Ma [*Ding et al.*, 1999; *Xiong et al.*, 2002]. The transition from fine-sized red clay to coarser loess-paleosol deposits represents a major reorganization of the East Asian environment [e.g., *Ding et al.*, 2000], accompanied by significant changes in atmospheric circulation and in climate regimes.

[4] Although studies on the loess-paleosol-red clay deposit have focused on the climatic implications, the connection between the East Asian climate recorded in this eolian deposit and global climate changes during late-Miocene and Pleistocene remains largely unclear. Here we report on a new section at Baishui, in Gansu province and a section from Jingchuan. The grain size records show that the eolian loess coarsened at about 2.75 Ma, coeval with the initiation of Northern Hemisphere glaciation. We associate the loess coarsening at 2.75 Ma with the onset and significantly enhancement of the East Asian winter monsoon winds that closely linked with the initiation and intensification of Northern Hemisphere glaciation.

2. Material and Method

[5] The Baishui section (35°24′10″N, 106°56′43″E) is located in the northwest part of the central Loess Plateau [see Figure 1 in *Xiong et al.*, 2002]. This section consists of a 214-m loess-paleosol and a 79.2-m red clay deposit. The Jingchuan (35°17′30″N, 107°22′05″E) section [*Yang et al.*, 2000] contains a 200-m-thick loess-paleosol and a 126-m-thick red clay. Previous study has concluded that the base of the red clay in the Jingchuan was deposited at about 8 Ma [*Yang et al.*, 2000]. Correlation with the Jingchuan section indicates that the base of the red clay of the Baishui section is about 6.2 Ma (Figure 1).

[6] Together with the Lingtai (35°00′33″N, 107°30′33″E) section [*Ding et al.*, 1999], the Baishui and Jingchuan

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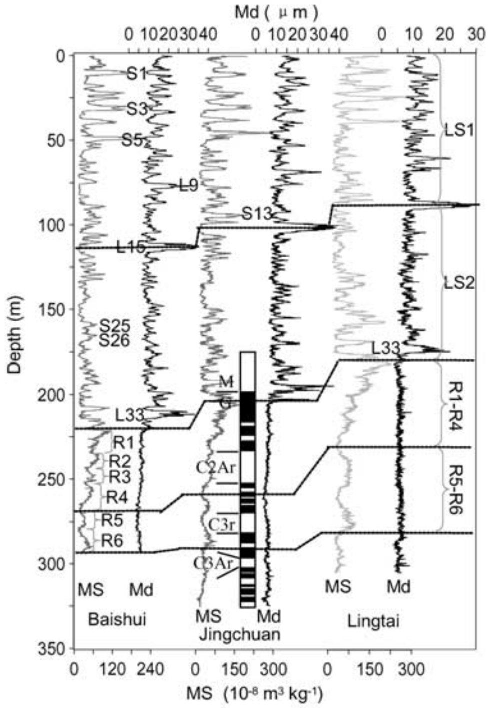

Figure 1. Correlation of the magnetic susceptibility (MS) and grain size variations between the Baishui, Jingchuan and Lingtai sections [Data of the Jingchuan and Lingtai sections are from *Yang et al.*, 2000 and *Ding et al.*, 1999, respectively]. The prominently developed paleosols and thick loess horizons and the loess-paleosol (LS*i*) and red clay (R*i*) groups are indicated. The magnetostratigraphy of the red clay sequence from the Jingchuan section [*Yang et al.*, 2000] is also shown.

sections comprise a southeast-northwest transect in the central Loess Plateau [*Xiong et al.*, 2002]. Each section consists of two parts of deposits, loess-paleosol and red clay. In this study, we divide the loess-paleosol sequence into two parts, LS1 (from S0 to the middle part of L15) and LS2 (from the middle part of L15 to the upper limit of R1). The red clay deposit is grouped into six or seven paleosol units, which are labeled R1 to R6 [*Xiong et al.*, 2002] (Figure 1).

[7] The Baishui section was sampled at an interval of 10cm and nearly 3000 samples were subjected to magnetic susceptibility and grain size measurements. The magnetic susceptibility was measured with a Bartington MS2 susceptibility meter for the air-dried samples and the data were published in a previous study [*Xiong et al.*, 2002]. The grain size measurements were conducted with a Sald-3001 diffraction particle analyzer after the carbonate-free samples had been ultrasonically treated in a 20% $(NaPO_3)_6$ solution, respectively. The magnetic susceptibility and grain size data of the Jingchuan (with intervals of 5 cm) and Lingtai sections were published in previous studies [*Yang et al.*, 2000; *Ding et al.*, 1999].

[8] The age model was based on the magnetic reversal stratigraphy of the Jingchuan section [*Yang et al.*, 2000] using the *Cande and Kent* [1995] timescale with linear interpolation between the age control points. The age control of the Baishui section was assigned by correlating the magnetic susceptibility record with the Jingchuan section (Figure 1, Table 1). Previous studies have shown that the magnetic susceptibility of red clay deposits can be well correlated between different sections to estimate age [*Yang et al.*, 2000; *Xiong et al.*, 2002], as with the loess-paleosol sequences. The similarity of the magnetic susceptibility variations of the red clay between the Baishui and Jingchuan sections made the correlation satisfactory.

3. Results

[9] It is apparent that the grain size record of the loess-paleosol-red clay has two different patterns (Figure 1). The red clay typically consists of eolian particles less than 6–7 μm, with a relatively smooth sequence of variation. The loess-paleosol deposit is characterized by significant variations in grain size between loess and paleosol units, with alternations of coarse loess unit (consists of particles often larger than 15–25 μm) and fine paleosol unit (with particles within 7.5–12 μm).

[10] The most pronounced feature of the grain size record is an abrupt transition occurring at about 2.75 to 2.6 Ma (Figure 1, Figure 2). In the Baishui section, the median grain size increases from less than 7.5 μm to 11–14 μm between 2.75 and 2.7 Ma, and to 20–29 μm between 2.6 and 2.55 Ma. The sand grain content (>63 μm) increases from less than 1.5 wt % to 3–4 wt % between 2.75 and 2.7 Ma. From 2.6 to 2.55 Ma, the sand grain content reaches a peak value of 15–21 wt %. The grain size record of the Jingchuan section has a similar variation pattern (Figure 2). From 2.75 to 2.68 Ma, the median grain size of the Jingchuan section increases from less than 7.5 μm to 10–25 μm, and reaches a peak value of 25–32 μm between 2.6 and 2.54 Ma. The magnetic susceptibility of the Baishui and Jingchuan sections decreases from 2.78–2.77 Ma, with the lowest value occurring at about 2.72–2.74 Ma. After 2.6 Ma, magnetic susceptibility decreases again to a low value which correlates with the highest peak of grain size at 2.6–2.55 Ma.

[11] To further investigate the nature of the loess-paleosol and red clay transition, we compared the variations in the thickness and the inferred accumulation rate of the loess-paleosol and the red clay for the Baishui, Jingchuan and Lingtai sections (Figure 1, Figure 3). It is clear that from the red clay (R1–R6) to the loess-paleosol deposits (LS1, LS2) the accumulation rate has abruptly increased and the spatial pattern (gradient) of thickness and the accumulation rate has

Table 1. Depth and Corresponding Ages of the Jingchuan and Baishui Sections

Jingchuan section		Baishui section	
Depth (m)	Age (Ma)	Depth (m)	Age (Ma)
158.2	2.15	168.0	2.15
199.0	2.581	213.8	2.581
216.0	3.04	232.0	3.04
218.0	3.11	234.0	3.11
232.8	3.58	247.0	3.58
251.25	4.18	262.3	4.18
268.0	5.23	277.0	5.23
282.0	5.894	285.0	5.894
318.0	7.65		

The ages of the Jingchuan section are based on the magnetostratigraphical measurement [*Yang et al.*, 2000], and the age control points of the Baishui section are estimated by correlating with the Jingchuan section using magnetic susceptibility records.

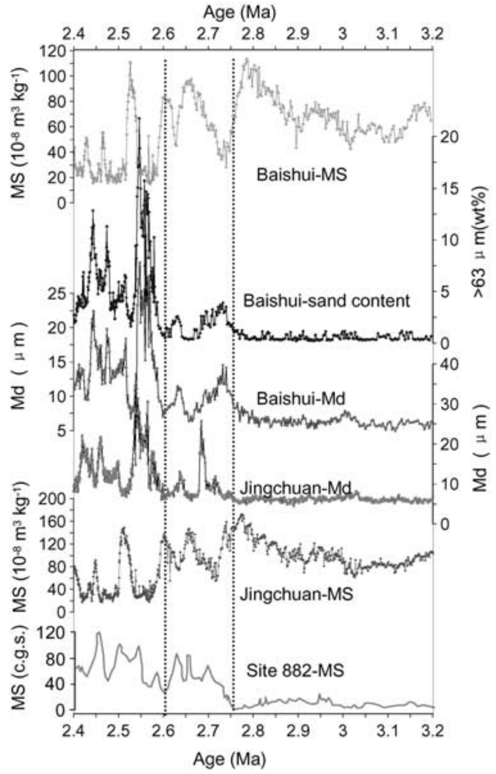

Figure 2. Comparison between the grain size and magnetic susceptibility parameters of the Baishui and Jingchuan sections and the magnetic susceptibility record of site 882 [*Maslin et al.*, 1996] for the time interval 2.4–3.2 Ma. Md: median grain size; MS: magnetic susceptibility. The dotted lines represent the timing of the coarsening of the eolian loess in the Baishui and Jingchuan sections and the large increase in ice-rafted detritus at site 882 (magnetic susceptibility) at 2.75 Ma and 2.6 Ma, respectively.

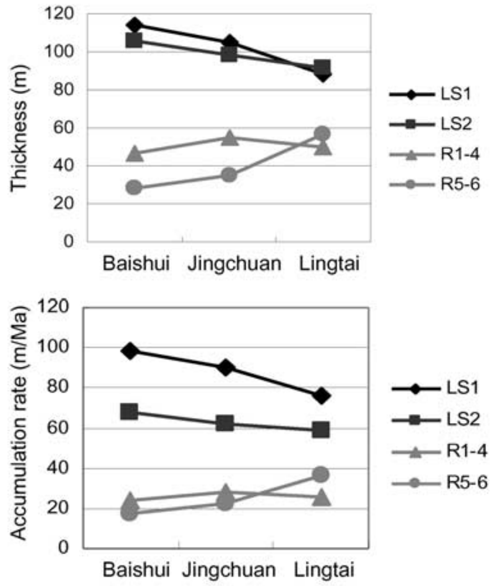

Figure 3. Comparison of the thickness (upper) and inferred accumulation rate (lower) gradient between the loess-and-paleosol and red clay groups from the Baishui to Lingtai sections. The ages of the boundaries between the loess-paleosol and red clay groups are based on the magnetostratigraphical measurement and magnetic susceptibility correlation.

reversed (Figure 1, Figure 3). The thickness and accumulation rate of the loess-paleosol deposits decrease from the northwest (Bsishui) to the southeast (Lingtai), similar to that observed on the Malan loess [*Liu et al.*, 1965], whereas they had a southeastward increasing gradient during the red clay deposition, suggesting that the wind regimes responsible for the dust transport have been changed at the loess/red clay transition. The different pattern is also observed in the relationship between magnetic susceptibility and median grain size, which exhibits a transition from red clay to the loess-paleosol deposits (Figure 4). For the red clay, magnetic susceptibility and median grain size data have a nearly linear relationship, with larger grain size corresponding to higher magnetic susceptibility. For the loess-paleosol deposit, magnetic susceptibility and median grain size have a parabolic relationship, with higher magnetic susceptibility at finer grain sizes. These different relationships may be attributed to the abrupt change in climatic regimes at the red clay-loess-paleosol transition.

4. Discussion and Conclusions

[12] Previous studies have revealed that the eolian grain size variability is a proxy indicator of wind intensity changes [*Rea*, 1994]. For the Chinese loess, geological and meteorological observations all demonstrate that the eolian dust that constitutes the loess is mainly transported from inland deserts by winter monsoon winds from Siberia and by the westerlies [*Liu et al.*, 1985]. The westerlies are mainly responsible for the high-level dust transport (fine particles), whereas the winter monsoon winds cause the near-surface dust transport (coarse particles). For the loess-paleosol sequence, grain size generally varies with the alternations of the loess and paleosol deposits, and the coarser loess horizons are linked to stronger winter mon-

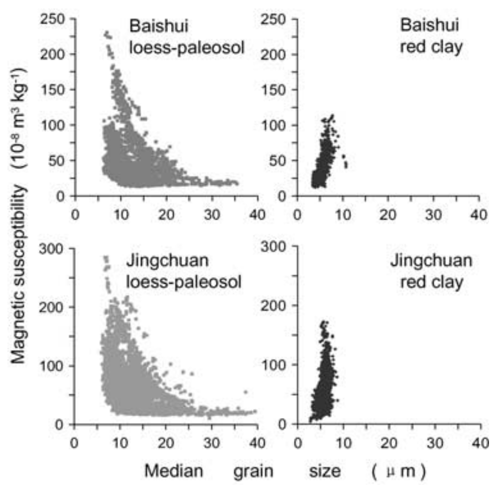

Figure 4. Comparison of magnetic susceptibility and grain size relationships for the red clay and loess-paleosol deposits from the Baishui and Jingchuan sections.

soon winds during glacial times. The loess coarsening from 2.75 Ma, in which the grain size increased from less than 7–8 μm to about 12 to 20 μm, suggests that a significantly strengthened dust transporting agent has replaced a weaker one. The reversed spatial pattern in the thickness and accumulation rate for the red clay compared with the loess-paleosol deposits suggests the source regions and the paleo-wind regimes may have reorganized over the Loess Plateau. The southeastward thickening trend of the red clay implies that the northwesterly East Asian winter monsoon winds have not been the dominate transporting agent until the loess-paleosol was initially deposited, and the westerlies may be responsible for the dust transport of the red clay [e.g., *Ding et al.*, 2000]. The different grain size-magnetic susceptibility relationships, although we don't know the exact cause of it, and the abrupt transition in the accumulation rate did suggest different climate regimes under which the red clay and loess-paleosol were deposited. Therefore, the abrupt coarsening of eolian loess at 2.75 Ma is likely the earliest clear expression of winter monsoon onset and intensification over East Asia during the Pliocene-Pleistocene climate transition.

[13] The abrupt coarsening of eolian loess is synchronous with the dramatic increase in ice rafting in the Northwest Pacific [*Maslin et al.*, 1995, 1996] (Figure 2) and Norwegian Sea [*Jansen and Sjoholm*, 1991], suggesting a climatic linkage between the strengthened dust transporting winds over East Asia and the initiation and intensification of Northern Hemisphere glaciation (especially over the Eurasian Arctic and Northeast Asia). The initiation and intensification of Northern Hemisphere glaciation (caused by long term uplift-weathering induced CO_2 lowering?) would cool further the high latitudes of the North Atlantic ocean with altered wind patterns, produce more extensive Arctic sea ice, reduce the amount of winter moisture and warmth that had previously been reaching south-central Eurasia, therefore/and cause a cooler and strengthened airflow from the Eurasia Arctic and an intensified Siberia High and consequent stronger winter monsoon winds. Thus the significant increase in loess grain size at 2.75 Ma and the depositional pattern change from red clay to the loess-paleosol, and higher eolian dust input to the North Pacific [*Yamazaki and Ioka*, 1997], may be closely related with the initiation and intensification of Northern Hemisphere glaciation. In addition, as indicated by abrupt increase in accumulation rate, the reversed gradient in the thickness and the different grain size-magnetic susceptibility relationships, there is a transition in depositional pattern and climate regime over East Asia when red clay was replaced by loess-paleosol deposit at about 2.75 Ma.

[14] The intensified winter monsoon winds would cause East Asia a more arid, more continental environment, vegetation zones southward displacement, desert expansion. The resultant increased albedo, together with the increased dust loading due to more frequent dust storms and increased dust input with iron addition to the ocean that may increase phytophankton activity and then lower atmospheric carbon dioxide level [e.g., *Martin*, 1990], would have acted as an important positive feedback in strengthening global cooling and the Northern Hemisphere glaciation which should be more positively considered in future climate modeling.

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