

Magnetostratigraphy of a late Miocene-Pliocene loess-soil sequence in the western Loess Plateau in China

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[1] Eolian deposits of Pliocene age have never been reported from the western Loess Plateau in China. Here, a 73.7 m eolian sequence is dated using magnetostratigraphic method and micromammalian fossils. The polarity zonation correlates with the geomagnetic polarity timescale (GPTS), from Chron 3Br.1r to Chron 2An.3n, indicating an age from 7.10 to 3.52 Ma BP. The sequence is characterized by clear expression of eighty-four pairs of loess and soil layers while individual soils are basically indefinable for the eolian deposits of the same age in the eastern Loess Plateau, suggesting that the later has experienced other geological processes. This sequence extends the upper limit of the previously reported Miocene loess-soil sequences at Qinan into the Pliocene, about 3.52 Ma BP. **INDEX TERMS:** 1520 Geomagnetism and Paleomagnetism: Magnetostratigraphy; 3344 Meteorology and Atmospheric Dynamics: Paleoclimatology; 9604 Information Related to Geologic Time: Cenozoic. **Citation:** Hao, Q., and Z. Guo (2004), Magnetostratigraphy of a late Miocene-Pliocene loess-soil sequence in the western Loess Plateau in China, *Geophys. Res. Lett.*, 31, L09209, doi:10.1029/2003GL019392.

1. Introduction

[2] In the Loess Plateau in China (Figure 1), the *Hipparion Red-Earth Formation* (HREF, or *Red-Clay*) from 7–8 to 2.6 Ma BP [Sun *et al.*, 1998a, 1998b; Ding *et al.*, 2001; Qiang *et al.*, 2001] fills a gap of climate records between the loess-soil sequences of the past 2.6 Ma [Heller and Liu, 1982; Liu, 1985; Kukla and An, 1989] and the Miocene loess-soil sequences from 22.0 to 6.2 Ma BP [Guo *et al.*, 2002]. Up to date, HREF has only been reported from an area to the east of the Liupan Mountains, i.e. the eastern Loess Plateau [Sun *et al.*, 1998a, 1998b; Ding *et al.*, 2001; An *et al.*, 2001; Guo *et al.*, 2001], while how eolian deposition occurred in the western Loess Plateau during this time is unknown. Moreover, the origin and post-depositional processes that affected the HREF are still contentious, which would be the basis for climate interpretations. One view is that the formation was derived from weathered mantles transported down gentle slope by creep and rain wash [Mo and Derbyshire, 1991]. An alternative view is that it is of eolian origin [e.g., Sun *et al.*, 1998a]. Some authors also suggested that the HREF might have been partly water-reworked as it contains abundant macromammalian

fossils that appeared to have been rapidly buried [Zhang and Xue, 1996]. More investigations with larger spatial coverage are therefore necessary for a better climate interpretation of the HREF.

[3] In this paper, a newly found eolian sequence from the western Loess Plateau, with a thickness of 73.7 m, is dated by magnetostratigraphic method and micromammalian fossils. It is also comparatively studied with the HREF in the eastern Loess Plateau.

2. General settings and Methods

[4] The studied section (34°58'N, 105°47'E) locates near the Dongwan village (Figure 1), 30 km east of the previously reported Miocene loess-soil sequences (QA-I and QA-II) [Guo *et al.*, 2002]. The 73.7-m-thick section is exposed along an elongated hilly flank with a top elevation of 1880 m. It is characterized by clear alternations of eighty-four visually-definable soil and loess layers. Only two horizons at 52.0–54.0 m and 62.6–63.3 m depths contain stratifications (Figure 2), representing two water-reworked levels.

[5] 319 oriented samples were collected at 20, 25 cm intervals, and 738 bulk samples were taken at 10 cm intervals. Micromammalian fossil tooth (Table 1) were taken to determine the approximate age of the sequence. Oriented samples were cut into 2 cm cubes. They were demagnetized in a MMTD600 thermal demagnetizer and measured with a 2G three-axis cryogenic magnetometer, housed in a magnetically shielded room, at the Paleomagnetism Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences.

[6] Stepwise thermal demagnetization up to 580 °C was performed on 76 pilot samples with a step of 25–50 °C. Typical diagrams are shown in Figure 3. Secondary viscous remanent magnetization conforming to the present-day field was removed below 250 °C, occasionally reaching 300 °C.

Table 1. Micromammalian Fossils From the Dongwan Section

Depth (m)	Fossils
5.3, 5.8, 6.5, 6.8, 7.8	<i>Mesosiphneus praetingi</i>
8.50	<i>Ochotona</i> sp. 1
10.10, 22.90	<i>Chardina</i> cf. <i>truncatus</i>
12.00	? <i>Pliosiphneus lyratus</i>
12.55	<i>Ochotona</i> sp.
25.00	<i>Ochotona</i> sp. 2
34.00	<i>Pliosiphneus lyratus</i>
35.75	? <i>Pliosiphneus eriksoni</i> , <i>Ochotona</i> sp.
36.50	<i>Ochotona</i> sp. 3
41.00	? <i>Pliosiphneus eriksoni</i>
49.25	<i>Pliosiphneus eriksoni</i>
49.75	<i>Ochotona</i> sp.
67.30, 74.25	<i>Pseudomeriones abbreviatus</i>
69.00	<i>Pliosiphneus licenti</i>
74.25	<i>Kowalskia</i> sp., <i>Lophocricetus grabau</i>

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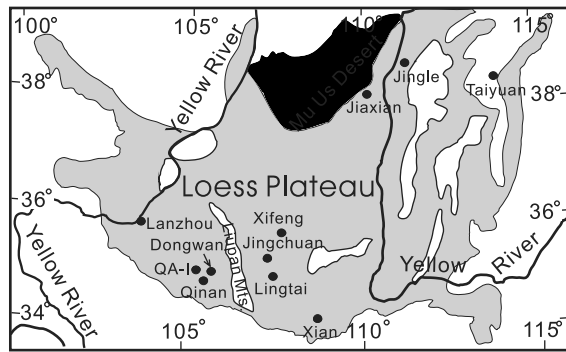


Figure 1. Map showing the Loess Plateau in northern China and the locations of the mentioned sites.

The characteristic remanent magnetization (ChRM) was typically isolated at higher temperature and was unblocked in the temperature range from 500 to 580 °C, suggesting that magnetite is the main remanence carrier. Because most of the pilot samples yield a stable ChRM above 300 °C, thermal demagnetization on the other samples was only carried out at 350 and 400 °C.

[7] Magnetic susceptibility was measured using a Bartington susceptibility meter. Grain-size analyses were performed on a Master Sizer 2000 laser unit. Major elements were analyzed by X-Ray fluorescence using a Philips PW-1400 unit with analytical uncertainties of $\pm 2\%$ for all the major elements except for P_2O_5 and MnO (up to $\pm 10\%$). The samples for trace and rare earth elements (REE) analysis were dissolved with a HF + HNO₃ mixture and analyses were measured on a Finnigan MAT ICP-MS unit with a precision of $\sim 10\%$.

3. Results and Discussions

[8] Micromammalian fossils (Table 1) are characteristic of late Miocene-Pliocene time [Zheng, 1994; Qiu and Qiu, 1995; Flynn et al., 1997]. *Prosiphneus licenti* from the

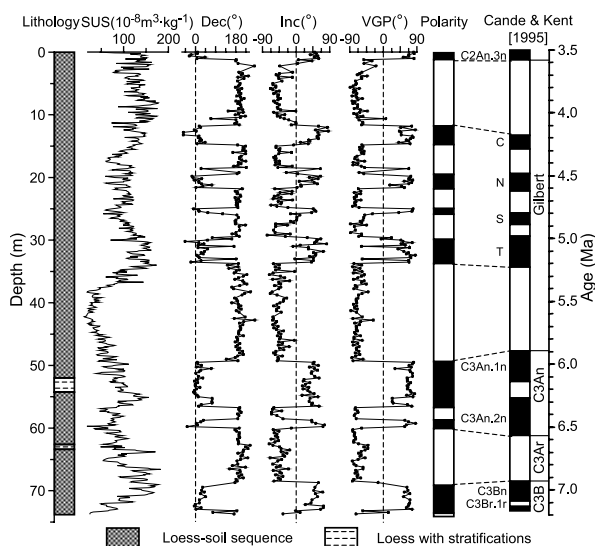


Figure 2. Lithology and magnetostratigraphy of the Dongwan loess-soil sequence. Black bars indicate normal polarity and white, reversed.

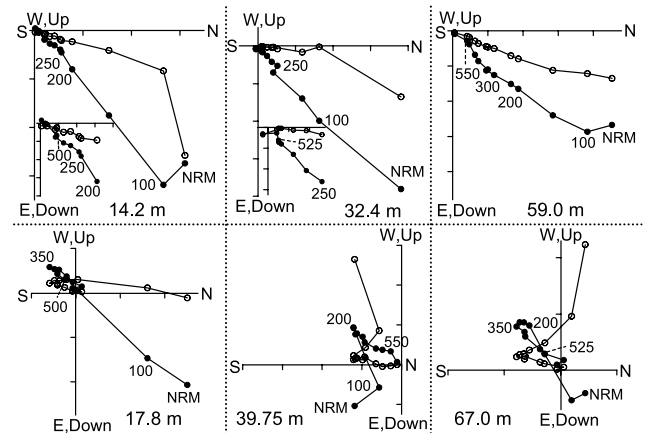


Figure 3. Orthogonal projections of representative progressive thermal demagnetization. The open (solid) circles refer to the horizontal (vertical) plane.

bottom is correlative to MN12 (8.2–7.1 Ma BP) [Zheng, 1994] in European Neogene Mammal Chronology (ENMC) [Mein, 1990]. *Mesosiphneus praetingi* and *Chardina cf. truncates* in the top 22.9 m are correlative to MN15 (4.2–3.4 Ma BP) [Zheng and Zhang, 2001] in ENMC. *Prosiphneus eriksoni* between 35.75 and 49.75 m was correlated in earlier studies to MN13 or 14 [Qiu and Qiu, 1995; Flynn et al., 1997].

[9] The obtained magnetostratigraphy is shown in Figure 2. The interval from 1.1 to 49.3 m is fairly correlative with the Gilbert reversal in the geomagnetic polarity timescale [Cande and Kent, 1995] with the four normal polarity zones corresponding to Cochiti, Nunivak, Sidufjall and Thvera subchrons, respectively. Consequently, the normal polarity zone at the top is correlative with the Subchron C2An.3n of the Gauss Epoch. We correlate the portion below 49.3 m with the chrons from C3An.1n to C3Br.1r. The proportionally shorter 3An.2n (58.6–59.9 m) may be attributable to water-reworking or lower accumulation rate. Extrapolations by sedimentation rates based on adjacent polarity zones yield a basal age of 7.10 Ma BP and a top age of 3.52 Ma BP. The geomagnetic results are highly consistent with the fossil chronology. The top boundary of the water-reworked portion at 52.0 m is dated for 6.01 Ma BP, and the lower one at 63.3 m for 6.70 Ma BP.

[10] This is the first eolian section from the western Loess Plateau that is contemporaneous with part of the HREF [Sun et al., 1998a, 1998b; Ding et al., 2001; Qiang et al., 2001] from the eastern Loess Plateau. Linear accumulation rate of the upper 52.0 m portion is given in Figure 4a and compared with those of the HREF. The average accumulation rate at Dongwan is $\sim 2.09 \text{ cm} \cdot \text{ka}^{-1}$, significantly higher than for most of the HREF sites in the eastern Plateau (except for Lingtai where the average accumulation rate is unusually high [Sun et al., 1998a]). This spatial pattern is similar to that of Quaternary loess deposition, more intense in the western region [Liu, 1985]. Variations of the accumulation rate at Dongwan are broadly consistent with those at Lingtai and Jiaxian, higher from 6.0 to 5.2 Ma BP, lower from 5.2 to 4.5 Ma BP, indicating higher aridity of the source areas [Hovan et al., 1989] from 6.0 to 5.2 Ma BP. The higher accumulation rate from 6.0 to 5.2 Ma BP is, however, not obvious at Xifeng (Figure 4a).

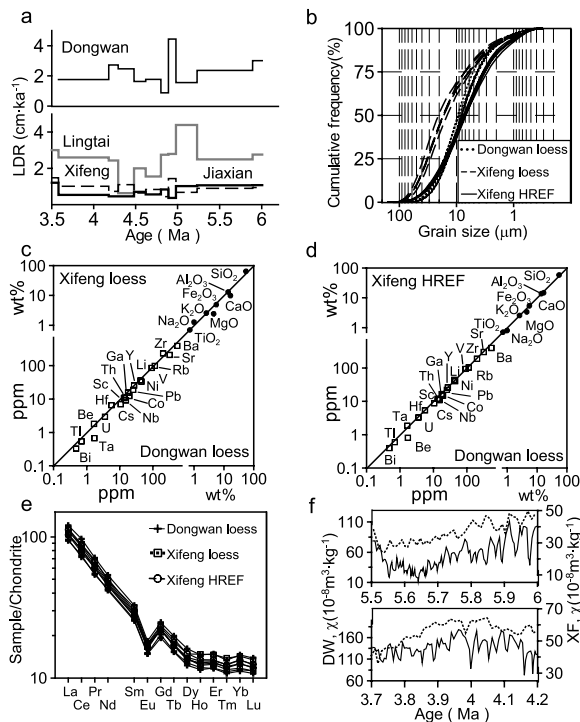


Figure 4. Comparison of the Dongwan loess-soil sequence with the Hipparian Red-Earth formation from the eastern Loess Plateau. (a) Linear accumulation rate of the upper 52.0 m portion from Dongwan and compared with those of the HREF type sections (Data of Lingtai, Xifeng and Jiaxian are from *Sun et al.* [1998a], *Sun et al.* [1998b], and *Qiang et al.* [2001], respectively). (b)–(e) Comparison of grain-size distribution, major and trace element compositions (average of 5, 6, 4 samples for loess of Dongwan, Quaternary loess and HREF of Xifeng, respectively), REE patterns between the Dongwan loess and the Xifeng HREF/Quaternary loess. (f) Zoomed magnetic susceptibility (χ) of the Dongwan (DW) loess-soil sequence (solid line) and of the Xifeng (XF) HREF section (dotted line).

[11] Grain-size distributions of selected samples from Dongwan loess layers are given in Figure 4b and compared with those of the HREF and typical Quaternary loess samples from Xifeng. All of them are characteristic of eolian dust deposits. The median grain-size at Dongwan ranges from 7.99 to 9.91 μm , slightly coarser than the HREF at Xifeng, from 6.85 to 7.56 μm . This is also consistent with the spatial pattern of Quaternary loess, coarser in the western Loess Plateau and finer in the eastern Plateau [*Liu*, 1985]. Because eolian grain-size in northern China depends upon the strength of dust-carrying wind or/and the distance from the sources, the much finer grain-size of Pliocene samples at both Xifeng and Dongwan indicates weaker winds or smaller desert extent than for the Quaternary.

[12] The chemical compositions of the Dongwan loess are also compared with those of the HREF and Quaternary loess at Xifeng (Figures 4c and 4d). They are basically similar in major and trace elemental compositions. The REE geochemistry of these samples (Figure 4e) also shows an extreme homogeneity. These suggest that the materials might have been derived from approximately similar sources,

and that all were derived from well-mixed sedimentary protoliths, which underwent numerous upper crustal recycling processes [*Taylor et al.*, 1983].

[13] The lithostratigraphic divisions of the HREF in the eastern Loess Plateau vary by authors [*Sun et al.*, 1998a, 1998b; *Ding et al.*, 2001; *Qiang et al.*, 2001] and only broad units were defined. The main reason is the ambiguous distinction between soil and loess units. At Xifeng, the sequence older than 3.6 Ma BP shows a relatively homogeneous reddish color. This is also expressed by small amplitudes of magnetic susceptibility fluctuations (Figure 4f). The occurrence of calcareous horizons has no regular relationship with the color changes at Xifeng [*Guo et al.*, 2001]. On the contrary, the Dongwan sequence is characterized by much clearer alternation of soil and loess layers. Eighty-four soils can be explicitly recognized with the thickness of each varying from 20 to 100 cm. They have reddish brown (5YR 4/6, or 4/8) to bright brown (7.5YR 5/6, or 5/8) color, silty-clay or clay texture, and moderate to strong angular blocky structure. Most of the soils are underlain by a carbonate nodule horizon, similar to those in Quaternary loess. Loess layers (from 10 cm to 90 cm thick) are yellow-brown or brown with mostly a massive structure. The clear distinction between soil and loess layers at Dongwan is also expressed by magnetic susceptibility, much higher in soils than in the surrounding loess (Figures 2 and 4f), as is basically similar to the Quaternary loess-soil sequences [*Liu*, 1985; *Kukla and An*, 1989] and the Miocene loess-soil sequences in China [*Guo et al.*, 2002]. Fine-grained ferromagnetic minerals of pedogenic origin were invoked to explain the higher susceptibility in soils [*Zhou et al.*, 1990].

[14] The Dongwan sequence has much higher susceptibility values than the HREF in the eastern Loess Plateau (Figure 4f). Susceptibility in the upper 52.0 m portion varies from 11.5 to $178.0 \times 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$ and averaged to $97.7 \times 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$, compared with an average of $64.4 \times 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$ at Lingtai [*Sun et al.*, 1998a], $43.1 \times 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$ at Xifeng [*Sun et al.*, 1998b] and $43.8 \times 10^{-8} \text{ m}^3 \cdot \text{kg}^{-1}$ at Jingchuan [*Ding et al.*, 2001].

[15] Typical loess-soil sequences can only be formed at the sites without surface and groundwater affections, such as river terraces and highlands. The above differences between the Dongwan loess-soil sequence and the HREF are apparently attributable to different geomorphic conditions in the western and eastern parts of the Loess Plateau. Earlier studies on the Xifeng HREF type section revealed that the lower part (>6.2 Ma BP) was water-reworked while the middle part (~ 6.2 to ~ 3.6 Ma BP) was derived from in situ eolian deposits, but was affected by the oscillations of groundwater table during its formation. This has significantly disturbed the normal sedimentary and soil-forming processes, and consequently weakened the difference between the loess and soil layers [*Guo et al.*, 2001]. Only the sequence < 3.6 Ma BP is of typical loess-soil sequence. The much lower susceptibility values at Xifeng may be attributable to the groundwater affection as humid conditions are favorable to the degradation of magnetic minerals.

[16] The Dongwan sequence is synchronous with the middle part of HREF at Xifeng, but the clear alternation of loess and soil layers and the lack of water-reworked features in the upper 52.0 m indicate a typical loess-soil sequence without surface or groundwater affection since 6.01 Ma BP.

The section contains totally 84 visually definable soils and loess layers within a time coverage of 3.58 Ma, suggesting an average frequency of 42.6 ka for each soil-loess pair. This rhythm is consistent with the oscillations at 41 ka frequency of the late Miocene-Pliocene marine $\delta^{18}\text{O}$ record [Shackleton *et al.*, 1995], attributable to the variations of Earth's obliquity [Berger and Loutre, 1991]. Detailed analyses on the climate cycles will be reported elsewhere.

[17] Up to date, geomagnetic measurements on the HREF type sections to the east of the Liupan Mountains dated the lower boundaries for 7 to 8 Ma BP and the oldest for 8.35 Ma BP [Qiang *et al.*, 2001]. On the contrary, eolian deposits were well preserved since the early Miocene in the area west to the Liupan Mountains [Guo *et al.*, 2002]. This indicates that the dust sedimentary basins in the western Loess Plateau were formed by the early Miocene while those in the eastern region were formed around ~ 8 Ma BP. This must imply different tectonic backgrounds of the two regions delimited by the Liupan Mountains. A tectonic event would have occurred in the late Miocene time, leading to the formation of dust sedimentary basins in the eastern Loess Plateau.

4. Conclusions

[18] This study provides a first Pliocene eolian record of paleoclimate in the western Loess Plateau consisting of clearly expressed soil and loess layers. Geomagnetic measurements and micromammalian fossils date the sequence for the interval from 7.1 to 3.5 Ma BP with two thin portions older than 6.0 Ma BP having been water-reworked. It is contemporaneous with the HREF in the eastern Loess Plateau. However, the studied sequence greatly differs from the HREF, by the much clearer expression of loess and soil units, higher magnetic susceptibility and much greater contrasts of susceptibility between the loess and soil layers. It is therefore a typical loess-soil sequence similar to those of the Quaternary [Liu, 1985; Kukla and An, 1989] and to the recently reported Miocene loess-soil sequences [Guo *et al.*, 2002]. This supports our previous interpretations that some HREF sequences older than 3.6 Ma BP in the eastern Loess Plateau were affected by groundwater oscillations [Guo *et al.*, 2001]. These are attributable to the geomorphic backgrounds in the eastern and western Loess Plateau delimited by the Liupan Mountains. As the studied section is only 30 km from the QA-I site where loess-soil sequences from 22 to 6.2 Ma BP were reported [Guo *et al.*, 2002], combination of the two sections provides a near continuous terrestrial record of paleoclimate from 22 to 3.5 Ma BP.

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References

An, Z. S., J. E. Kutzbach, W. L. Prell, and S. C. Porter (2001), Evolution of Asian monsoons and phased uplift of the Himalaya-Tibetan Plateau since late Miocene time, *Nature*, *411*, 62–66.

- Berger, A., and M. F. Loutre (1991), Insolation values for the climate of the last 10 million years, *Quat. Sci. Rev.*, *10*, 297–317.
- Cande, S. C., and D. V. Kent (1995), Revised calibration of the geomagnetic polarity time scale for the Late Cretaceous and Cenozoic, *J. Geophys. Res.*, *100*, 6093–6095.
- Ding, Z. L., S. L. Yang, S. S. Hou, X. Wang, Z. Chen, and T. S. Liu (2001), Magnetostratigraphy and sedimentology of the Jingchuan red clay section and correlation of the Tertiary eolian red clay sediments of the Chinese Loess Plateau, *J. Geophys. Res.*, *106*, 6399–6407.
- Flynn, L. J., W. Wu, and W. R. Downs III (1997), Dating vertebrate microfaunas in the late Neogene record of northern China, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *133*, 227–242.
- Guo, Z. T., S. Z. Peng, Q. Z. Hao, P. E. Biscaye, and T. S. Liu (2001), Origin of the Miocene-Pliocene red-earth formation at Xifeng in northern China and implications for paleoenvironments, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *170*, 11–26.
- Guo, Z. T., W. F. Ruddiman, Q. Z. Hao, H. B. Wu, Y. S. Qiao, R. X. Zhu, S. Z. Peng, J. J. Wei, B. Y. Yuan, and T. S. Liu (2002), Onset of Asian desertification by 22 Myr ago inferred from loess deposits in China, *Nature*, *416*, 159–163.
- Heller, F., and T. S. Liu (1982), Magnetostratigraphical dating of loess deposits in China, *Nature*, *300*, 431–433.
- Hovan, S. A., D. K. Rea, N. G. Pisias, and N. J. Shackleton (1989), A direct link between the China loess and marine $\delta^{18}\text{O}$ records: Aeolian flux to the North Pacific, *Nature*, *340*, 296–298.
- Kukla, G. J., and Z. S. An (1989), Loess stratigraphy in central China, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *72*, 203–225.
- Liu, T. S. (1985), *Loess and the Environment*, 251 pp., China Ocean Press, Beijing.
- Mein, P. (1990), Updating of MN zones, in *European Neogene Mammal Chronology, NATO ASI Ser., Ser. A*, vol. 180, edited by E. H. Lindsay, V. Fahlbusch, and P. Mein, pp. 73–90, Plenum, New York.
- Mo, D. W., and E. Derbyshire (1991), The deposition environment of the late Pliocene red clay, Jing-Le Basin, Shanxi Province, China, *Sediment. Geol.*, *70*, 33–40.
- Qiang, X. K., Z. X. Li, C. Powell, and H. B. Zheng (2001), Magnetostratigraphic record of the late Miocene onset of the East Asian monsoon, and Pliocene uplift of northern Tibet, *Earth Planet. Sci. Lett.*, *187*, 83–93.
- Qiu, Z. X., and Z. D. Qiu (1995), Chronological sequence and subdivision of Chinese Neogene mammalian faunas, *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, *116*, 41–70.
- Shackleton, N. J., M. A. Hall, and D. Pate (1995), Pliocene stable isotope stratigraphy of Site 846, *Proc. Ocean Drill. Program Sci. Results*, *138*, 337–355.
- Sun, D. H., J. Shaw, Z. S. An, M. Y. Chen, and L. P. Yue (1998a), Magnetostratigraphy and paleoclimatic interpretation of a continuous 7.2 Ma late Cenozoic eolian sediments from the Chinese Loess Plateau, *Geophys. Res. Lett.*, *25*, 85–88.
- Sun, D. H., Z. S. An, J. Shaw, J. Bloemendal, and Y. B. Sun (1998b), Magnetostratigraphy and paleoclimatic significance of late Tertiary aeolian sequence in the Chinese Loess Plateau, *Geophys. J. Int.*, *134*, 207–212.
- Taylor, S. R., S. M. McLennan, and M. T. McCulloch (1983), Geochemistry of loess, continental crustal composition and crustal model ages, *Geochim. Cosmochim. Acta*, *47*, 1897–1905.
- Zhang, Y. X., and X. X. Xue (1996), Taphonomic characteristics of Longjiagou Hipparion fauna and genus of 'Hipparion red clay' in Wudu county, Gansu Province, *Chin. Sci. Bull.*, *41*, 238–241.
- Zheng, S. H. (1994), Classification and evolution of the Siphneidae, *Natl. Sci. Mus. Monogr.*, *8*, 57–76.
- Zheng, S. H., and Z. Q. Zhang (2001), Late Miocene-early Pleistocene biostratigraphy of the Leijiahe area, Lingtai, Gansu (in Chinese with English abstract), *Vertebr. PalAsia*, *39*(3), 215–228.
- Zhou, L. P., F. Oldfield, A. G. Wintle, S. G. Robinson, and J. T. Wang (1990), Partly pedogenic origin of magnetic variations in Chinese loess, *Nature*, *346*, 737–739.

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