Northwestward decline of magnetic susceptibility for the red clay deposit in the Chinese Loess Plateau

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[1] The loess-paleosol-red clay sequence in the Chinese Loess Plateau has attracted attention for its potential in recording late Cenozoic climatic changes over northern China, although the details of the climatic implications of the proxies (for example, magnetic susceptibility) and the reconstructed summer monsoon changes remain unclear. Here we report on a new section from Baishui, in Gansu province and compare it with the Lingtai and Jingchuan sections. By correlating the magnetic susceptibility from these sections, we show that there is a clear systematic decrease of the magnetic susceptibility in the red clay deposits from the southeast (Lingtai section) to the northwest (Baishui section). This result suggests that the climatic parameters (probably precipitation) had a decreasing northwestward gradient during the red clay deposition. This climatic pattern is similar to the present condition, implying that the influence of the East Asian summer monsoon on the Chinese Loess Plateau has persisted from at least 6 Ma. *INDEX TERMS:* 1512 Geomagnetism and Paleomagnetism: Environmental magnetism; 9320 Information Related to Geographic Region: Asia; 9604 Information Related to Geologic Time: Cenozoic; *KEYWORDS:* Red clay, Magnetic susceptibility, Gradient, East Asian monsoon. **Citation:** Xiong, S. F., W. Y. Jiang, S. L. Yang, Z. L. Ding, and T. S. Liu, Northwestward decline of magnetic susceptibility for the red clay deposit in the Chinese Loess Plateau, *Geophys. Res. Lett.*, *29*(24), 2162, doi:10.1029/2002GL015808, 2002.

1. Introduction

[2] The origin and evolution of monsoon climate is an important topic in paleoclimatic study. Indian monsoon evidence from the Arabian Sea [*Kroon et al.*, 1991] shows an increase in monsoon-related upwelling, while stable oxygen isotope studies of pedogenic carbonate suggest a major change in the meteoric cycle in southern Asia [*Quade et al.*, 1989], at about 6–8 Ma. Little was known about the East Asian monsoon during this period until recent years when the Tertiary eolian red clay sequences were extensively studied [*Ding et al.*, 1998, 1999; *Sun et al.*, 1998a, 1998b; *An et al.*, 2001; *Guo et al.*, 2001; *Xiong et al.*, 2001]. The eolian red clay is mainly developed in the Loess Plateau, underlying the well-known loess-paleosol deposits [*Liu et al.*, 1985]. The base of the eolian red clay can be as old as 7–8 Ma [*Ding et al.*, 1998, 1999; *Sun et al.*, 1998a; *Song et al.*, 2000; *Yang et al.*, 2000], and pedological features suggest loess-like deposits with paleosol alternations [*Ding et al.*, 1998; *Sun et al.*, 1998b; *Ding et al.*, 1999]. By using several climatic proxies and pedological features, several studies have discussed the climatic implications of the red clay deposition and the origin of the East Asian monsoon [e.g., *Ding et al.*, 1999; *An*, 2000]. These studies are mainly based on single sections, however, and correlation between different sections is unsatisfactory due to the relatively poor preservation of most red clay sections [e.g., *An et al.*, 2000]. A critical question is whether the red clay deposit exhibits a similar proxy spatial pattern as that of the loess-paleosol climatic proxies. This is important to improving our understanding of the climatic regimes during the early history of the East Asian monsoon development.

[3] Here we present magnetic susceptibility data from a new section at Baishui, in Gansu province and compare it with previously published data from the Lingtai [*Ding et al.*, 1999] and Jingchuan [*Yang et al.*, 2000] sections. These three sections comprise a southeast-northwest transect, and the magnetic susceptibility of the red clay deposits exhibits a decreasing gradient from Lingtai to Baishui. This result suggests that the climatic parameters that induced the magnetic susceptibility variations have a spatial pattern similar to the present condition, and that the East Asian summer monsoon may have influenced the Loess Plateau when the red clay was deposited.

2. Material and Method

[4] The Baishui section (35°24′10″N, 106°56′43″E) is located in the northwest part of the central Loess Plateau, 30 km southeast of Pingliang City, Gansu province (Figure 1). This section contains a 214 m loess-paleosol sequence and a 79.2 m red clay deposit. For this study, the section was sampled at 10-cm intervals. The Jingchuan (35°17′30″N, 107°22′05″E) and Lingtai (35°00′33″N, 107°30′33″E) sections (Figure 1), located to the southeast of the Baishui section, have been previously studied [*Ding et al.*, 1998, 1999; *Yang et al.*, 2000; *Xiong et al.*, 2001]. The Jingchuan section comprises a 200 m thick loess-paleosol and 126 m thick red clay, while the Lingtai section has a 175 m thick loess-paleosol and a 130 m thick red clay. In the loess-paleosol sequence, there are more than thirty couplets of loess and soil, with the most-developed soils being S1, S3, S4, S5 and S32. For the red clay deposits, six or seven paleosol-groups, which are labeled R1 to R6 in this study (Figure 2), were observed in field and in magnetic susceptibility measurements.

[5] The Loess Plateau is presently dominated by the East Asian monsoon circulation, and there is a decreasing trend of annual precipitation (most of it occurring in the summer season) towards the northwest. From Lingtai to Baishui, annual precipitation decreases from about 600 mm to about 500 mm.

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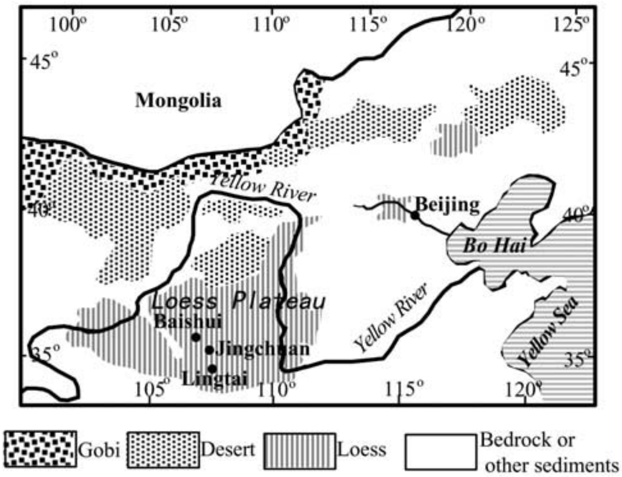

Figure 1. Location map showing the Baishui, Jingchuan and Lingtai sections in the Loess Plateau, China.

[6] The magnetic susceptibility of the Baishui section was measured with a Bartington MS2 susceptibility meter for air-dried samples. The magnetic susceptibility of the Lingtai and Jingchuan sections was analyzed with the same technique as used for the Baishui section, and is provided by previous studies [*Ding et al.*, 1999; *Yang et al.*, 2000].

3. Results

[7] The magnetic susceptibility of the Baishui section is well correlated with the Lingtai and Jingchuan records (Figure 2). Previous studies have concluded that the base of the red clay in Lingtai was deposited at about 7 Ma [*Ding et al.*, 1998] and at about 8 Ma in the Jingchuan section [*Yang et al.*, 2000]. Correlation of the Lingtai and Jingchuan sections indicates that the base of the red clay in the Baishui section is about 6 Ma (Figure 2).

[8] The magnetic susceptibility records of the three sections are compared using peak-to-peak matching (Figure 2 to Figure 4). A general decrease of magnetic susceptibility is observed from the Lingtai through the Baishui sections. The magnetic susceptibility of the Baishui section is clearly lower than the corresponding loess-paleosol units of the Lingtai and Jingchuan sections (Figure 2 and Figure 3). The magnetic susceptibility values of most loess-paleosol units of the Jingchuan section are lower than the Lingtai section values. An exception appears at S5, in which the Jingchuan section has a slightly higher magnetic susceptibility value than the Lingtai section (Figure 3). This trend in the magnetic susceptibility variation, similar to the susceptibility pattern of the surface soil in the Loess Plateau [*Maher and Thompson*, 1995], reflects climatic and pedogenic gradients from the southeast to the northwest induced mainly by East Asian summer monsoon activity.

[9] The red clay deposits also display a magnetic susceptibility gradient, which decreases towards the northwest from Lingtai to Baishui (Figure 4). Comparison of the magnetic susceptibility peak values for each corresponding paleosol-group reveals that this southeast–northwest gradient is clearly exhibited in all paleosol-groups (Figure 5). For example, the peak magnetic susceptibility value of the R5 paleosol-group in the Lingtai section is about 82×10^{-8} m^3 kg^{-1}, while in the Jingchuan and Baishui sections it decreases to about 53×10^{-8} m^3 kg^{-1} and 33×10^{-8} m^3 kg^{-1}, respectively. The R1 paleosol-group peak MS value decreases by about 120×10^{-8} m^3 kg^{-1} from the Lingtai (230×10^{-8} m^3 kg^{-1}) to Baishui (110×10^{-8} m^3 kg^{-1}) sections, which is the steepest gradient observed in the red clay. The magnetic susceptibility gradients of the paleosol-groups in the red clay are steeper than the loess-paleosol gradients (Figure 5).

4. Discussion and Conclusions

[10] Although the pedogenic features and the climatic proxies of the red clay are used to monitor the early history of the East Asian summer monsoon [*Sun et al.*, 1998b; *Ding et al.*, 1999; *An*, 2000], the details of the East Asian summer monsoon evolution are not yet clearly understood. By analyzing a single section, the climatic implications of the proxies from the red clay deposit are hard to evaluate. Thus, the spatial patterns of the climatic proxies recorded in the red clay are an important aspect for the understanding of its implications and for the reconstruction of the East Asian monsoon history.

[11] Our study presents data which show spatial gradients of magnetic susceptibility similar to the present condition existed during the period of the red clay deposition, suggest-

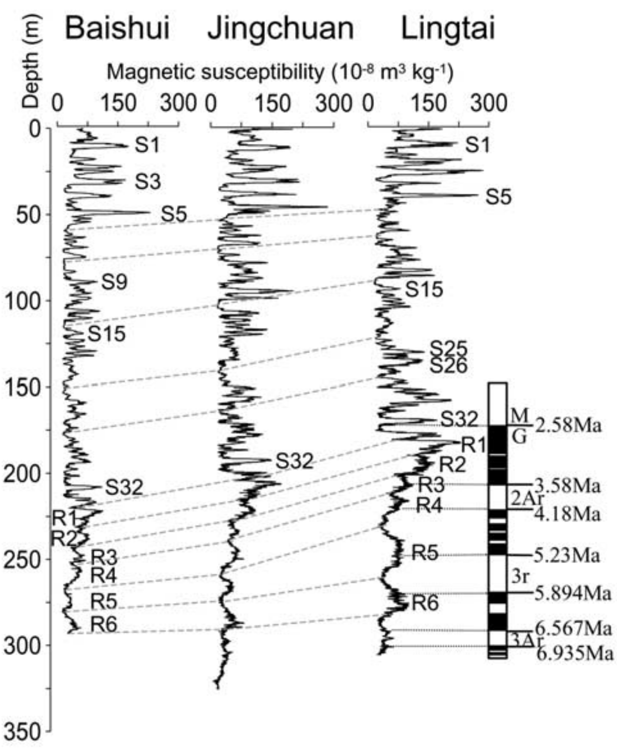

Figure 2. Magnetic susceptibility (MS) correlation between the Baishui, Jingchuan and Lingtai sections (Jingchuan and Lingtai data are from *Yang et al.*, 2000 and *Ding et al.*, 1999, respectively). The prominently developed paleosols in the loess deposits and the paleosol-groups in the red clay deposits are indicated. The magnetostratigraphy of the red clay sequence from the Lingtai section [*Ding et al.*, 1998] is also shown.

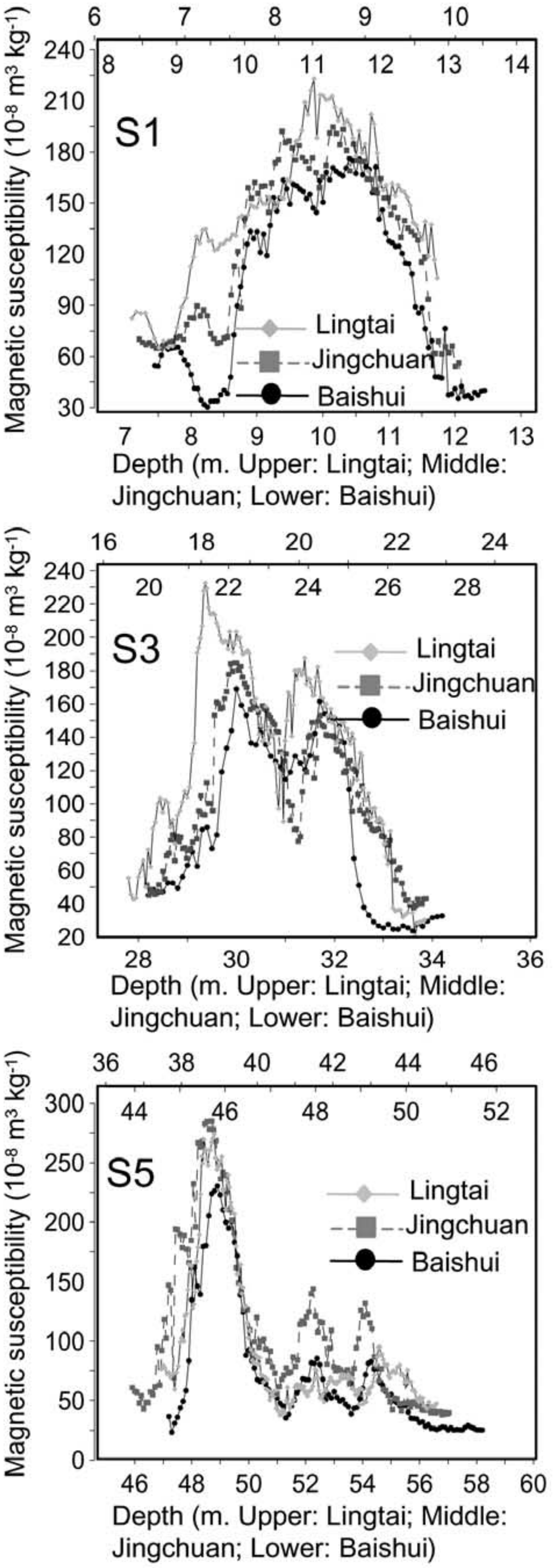

Figure 3. Peak-to-peak matching and comparison of the magnetic susceptibility (MS) for paleosols S1, S3 and S5 between the Baishui, Jingchuan and Lingtai sections.

ing the presence of a climatic-pedogenic gradient over the central Loess Plateau. This interpretation agrees with other field observations. *Ding et al.* [1992] noticed distinct pedological strength differences from the southeast to the northwest in the Loess Plateau in the red clay deposit. Our observations also show that carbonate leaching within the red clay deposit from the Baishui section is apparently weaker than in the Jingchuan and Lingtai sections. In the Lingtai and Jingchuan sections, carbonate nodules (or nodule horizons) are developed in the red clay sequence, whereas in the Baishui section carbonate nodules are very few. From Lingtai to Baishui, soil color of the corresponding paleosol-groups changes from reddish towards more brown or yellowish, and the typical developed paleosols in the red clay deposit change from fine, medium to coarse sub-angular blocky structures to very coarse angular blocky or massive structures.

[12] The spatial pattern of the magnetic susceptibility for the red clay seems to have no apparent relationship with the grain size of the particles. A previous study has shown that in the Loess Plateau, the red clay particles do not show considerable spatial variation in size [*Ding et al.*, 1998]. The grain size of the Baishui red clay (not shown) also exhibits no apparent coarsening trend compared with the Lingtai and Jingchuan sections. This may imply that the spatial pattern of the magnetic susceptibility reflects mainly a climatic-pedogenic impact rather than a dust source influence.

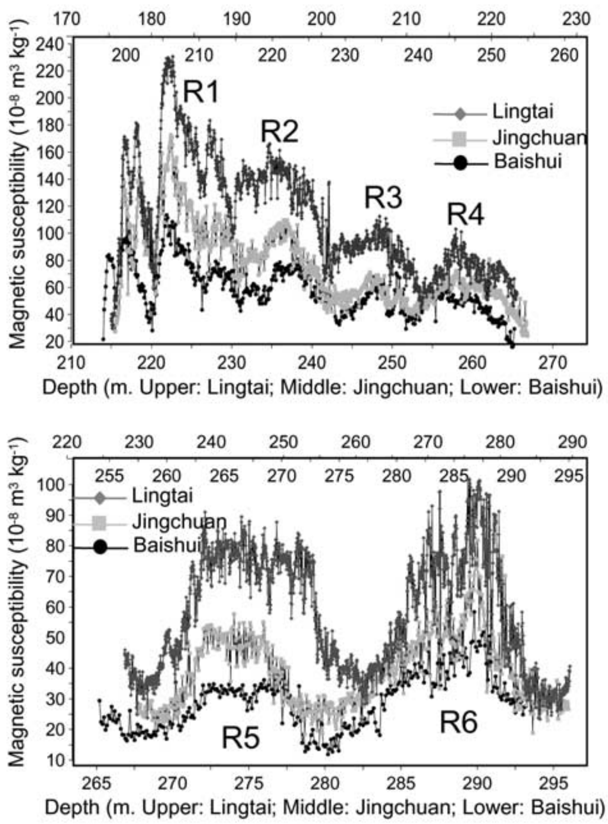

Figure 4. Peak-to-peak matching and comparison of the magnetic susceptibility (MS) for the paleosol-groups R1 to R6 in the red clay between the Baishui, Jingchuan and Lingtai sections.

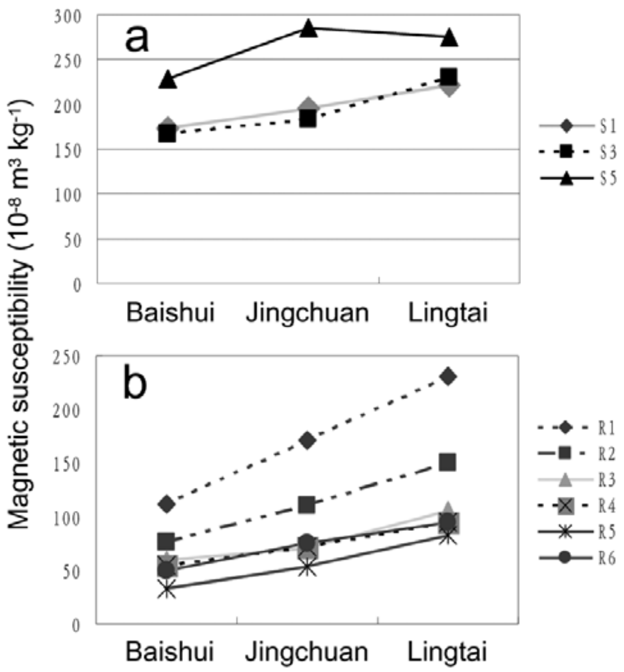

Figure 5. Comparison of the peak-value of magnetic susceptibility of the paleosols (a) and paleosol-groups in the red clay sequences (b).

[13] Although the mineralogical causes of the magnetic susceptibility enhancement in paleosols remain uncertain [e.g., *Heller and Evans*, 1995], the northwestward decreasing trend of magnetic susceptibility for the near-surface soil samples [e.g., *Maher and Thompson*, 1995] and for the paleosols over the Loess Plateau [e.g., *Maher and Thompson*, 1995] does suggest a climatic origin. The East Asian summer monsoon creates a southeast-northwest gradient of decreasing precipitation over the Loess Plateau [*Chen et al.*, 1991]. This climatic regime may have influenced the pedogenic processes and resulted in the northwestward decrease of magnetic susceptibility for the loess-paleosols. The data presented here show that there is a decreasing trend of the magnetic susceptibility towards the northwest in the red clay deposit, providing new evidence that suggests the East Asian summer monsoon has, similar to present conditions, prevailed during the red clay deposition. As the Baishui red clay was deposited beginning about 6 Ma, the magnetic susceptibility gradient between Baishui and Lingtai implies that the influence of East Asian summer monsoon on the Chinese Loess Plateau has persisted at least from 6 Ma. The results also show that the northwest–southeast gradient of the magnetic susceptibility for the red clay is steeper than that for the Pleistocene paleosols (e.g., S1, S3, S5), implying an enhanced northwest–southeast climatic gradient for the red clay.

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References

An, Z. S., The history and variability of the East Asian paleomonsoon climate, *Quaternary Science*, *19*, 171–187, 2000.

An, Z. S., D. H. Sun, M. Y. Chen, Y. B. Sun, L. Li, and B. Q. Chen, Red clay sequences in Chinese Loess Plateau and recorded paleoclimate events of the Late Tertiary, *Quaternary Science*, *20*, 435–446, 2000. (in Chinese with English abstract)

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

Chen, L., J. Zhu, and H. Lou, *Monsoon over East Asia*, 362 pp., Meteorology Press, Beijing, 1991. (in Chinese)

Ding, Z. L., N. Rutter, J. T. Han, and T. S. Liu, A coupled environmental system formed at about 2.5 Ma in East Asia, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *94*, 223–242, 1992.

Ding, Z. L., J. M. Sun, S. Y. Yang, and T. S. Liu, Preliminary magnetostratigraphy of a thick eolian red clay-loess sequence at Lingtai, the Chinese Loess Plateau, *Geophysical Research Letters*, *25*, 1225–1228, 1998.

Ding, Z. L., S. F. Xiong, J. M. Sun, S. L. Yang, Z. Y. Gu, and T. S. Liu, Pedostratigraphy and paleomagnetism of a ~7.0Ma eolian loess-red clay sequence at Lingtai, Loess Plateau, north-central China and the implications for paleomonsoon evolution, *Palaeogeography, Palaeoclimatology, Palaeoecology*, *152*, 49–66, 1999.

Ding, Z. L., N. W. Rutter, J. M. Sun, S. L. Yang, and T. S. Liu, Rearrangement of atmospheric circulation at about 2.6 Ma over northern China: Evidence from grain size records of loess-paleosol and red clay sequences, *Quaternary Science*, *19*, 547–558, 2000.

Heller, F., and M. E. Evans, Loess magnetism, *Review of Geophysics*, *33*, 211–240, 1995.

Kroon, D., T. Steens, and S. R. Troelstra, Onset of monsoonal related upwelling in the western Arabian Sea as revealed by planktonic foraminifers, in *Proceedings of the Ocean Drilling Program, Scientific Results*, **117**, edited by W. L. Prell and N. Niitsuma, et al., pp. 257–263, College Station, TX (Ocean Drilling Program), 1991.

Liu, T. S., et al. (unnamed), *Loess and Environment*, 251pp., China Ocean Press, Beijing, 1985.

Maher, B. A., and R. Thompson, Paleorainfall reconstructions from pedogenic magnetic susceptibility variations in the Chinese loess and paleosols, *Quaternary Research*, *44*, 383–391, 1995.

Quade, J., T. E. Cerling, and J. R. Bowman, Development of Asian Monsoon revealed by marked ecological shift during the latest Miocene in northern Pakistan, *Nature*, *342*, 163–166, 1989.

Song, Y. G., X. M. Fang, J. J. Li, Z. S. An, D. Yang, and L. Q. Lu, Age of red clay at Chaona section near Liupan Mountain and its tectonic significance, *Quaternary Science*, *20*, 457–463, 2000. (in Chinese with English abstract)

Sun, D. H., J. Shaw, Z. S. An, M. Y. Chen, and L. P. Yue, Magnetostratigraphy and paleoclimatic interpretation of a continuous 7.2 Ma Late Cenozoic eolian sediments from the Chinese Loess Plateau, *Geophysical Research Letters*, *25*, 85–88, 1998a.

Sun, D. H., Z. S. An, J. Shaw, J. Bloemendal, and Y. B. Sun, Magnetostratigraphy and paleoclimatic significance of late Tertiary aeolian sequences in the Chinese Loess Plateau, *Geophys. J. Int.*, *134*, 207–212, 1998b.

Xiong, S. F., Z. L. Ding, and S. Y. Yang, Abrupt shifts in the late Cenozoic environment of north-western China recorded in loess-palaeosol-red clay sequences, *Terra Nova*, *13*, 376–381, 2001.

Yang, S. L., S. S. Hou, X. Wang, Z. Chen, S. F. Xiong, and Z. L. Ding, Completeness and continuity of late Tertiary red clay sequence in northern China: Evidence from the correlation of magnetostratigraphy and pedostratigraphy between Jingchuan and Lingtai, *Quaternary Science*, *20*, 423–434, 2000. (in Chinese with English abstract)

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