Mineral magnetic variation of the Jingbian loess/paleosol sequence in the northern Loess Plateau of China: Implications for Quaternary development of Asian aridification and cooling

Chenglong Deng a,b,*, John Shaw b, Qingsong Liu a,c, Yongxin Pan a, Rixiang Zhu a

a Paleomagnetism and Geochronology Laboratory (SKL-LE), Institute of Geology and Geophysics, Chinese Academy of Sciences, Beijing 100029, China
b Geomagnetism Laboratory, Department of Earth and Ocean Sciences, University of Liverpool, Liverpool L69 7ZE, UK
c Earth Sciences Department, University of California, Santa Cruz, CA 95064, USA

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Abstract

A high-resolution mineral magnetic investigation has been carried out on the Jingbian loess/paleosol sequence at the northern extremity of the Chinese Loess Plateau. Results show that the magnetic assemblage is dominated by large pseudo-single domain and multidomain-like magnetite with associated maghemite and hematite. Variations in the ratios of SIRM_{100mT}/SIRM, SIRM_{100mT}/SIRM_{30mT} and SIRM_{100mT}/SIRM_{60mT} (SIRM is the saturation isothermal remanent magnetization; SIRM_{n mT} represents the residual SIRM after an n mT alternating field demagnetization) have been used to document regional paleoclimate change in the Asian interior by correlating the mineral magnetic record with the composite δ^{18}O record in deep-sea sediments. The long-term up-section decreasing trend in those ratios in both loess and paleosol units has been attributed to a long-term decrease in the relative contributions of eolian hematite during glacial extrema and of pedogenic hematite during interglacial extrema, respectively, which reveals a long-term decreasing trend in chemical weathering intensity in both glacial-stage source region (the Gobi and deserts in northwestern China) and interglacial-stage depositional area (the Loess Plateau region). We further relate this long-timescale variation to long-term increasing aridification and cooling, during both glacial extrema in the dust source region and interglacial extrema in the depositional area, over the Quaternary period. Changes in those ratios are most likely due to Quaternary aridification and cooling driven by ongoing global cooling, expansion of the Arctic ice-sheet, and progressive uplift of the Himalayan–Tibetan complex during this period.

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1. Introduction

The wind-blown deposits derived from the arid Gobi and associated deserts of northwestern China cover much of the arid and semi-arid regions in northern China, and in particular the Chinese Loess Plateau [1]
where loess/paleosol sequences contain essentially continuous both geomagnetic and paleoclimate records from Late Pliocene throughout the entire Quaternary (see reviews by Heller and Evans [2], Liu and Ding [3], Evans and Heller [4] and Porter [5]). Over the past two decades, studies on these sequences have provided a wealth of information on both global and regional paleoclimate change, as revealed by a number of proxy indicators (see Ding et al. [6] and references therein). These proxies consistently demonstrate that the rhythm of Chinese loess/paleosol alternations was directly influenced by alternating strengthening and weakening of the Eastern Asian paleomonsoon, with loess deposited during glacial periods and soils developed during interglacial periods. In particular, mineral magnetic proxies have been successfully used to retrieve the paleoclimatic signals recorded in Chinese loess/paleosol sequences [7–11]. Since the pioneering work of Heller and Liu [12–14] on Chinese loess in the early 1980s, environmental magnetism has played an indispensable role in reconstructing the variability of the Eastern Asian monsoons over the Quaternary period (see reviews by Heller and Evans [2], Verosub and Roberts [15] and Maher [16]).

Heller and Liu [12,13] conducted hallmark work on the magnetoclimatological records in Chinese loess/paleosol sequences. They firstly suggested a possible link between magnetic properties and paleoclimate recorded in the sequences [12], and further proposed that low-field magnetic susceptibility variations can be correlated with marine oxygen isotope records [13,14]. Subsequently, this correlation was further examined by a series of mineral-magnetic and non-magnetic proxies, especially by low-field magnetic susceptibility [17–20] and bulk grain size [6,20]. There is currently a consensus that there are genetic relationships between the Chinese eolian deposits, the volume of land-based ice and global climate [17], making the Chinese loess/paleosol sequence one of the best terrestrial archives of paleoclimate.

The Chinese loess/paleosol sequences can also be used to monitor the evolution of Asian deserts and atmospheric circulation [1,21–24]. These sequences originate mainly from the Gobi and desert lands in northwestern China and are therefore expected to be sensitive to the aridification and cooling history of the Asian interior. However, mineral magnetic investigations of the long-term evolution of Quaternary Asian aridification and cooling remain very scarce [10]. Recent developments in magnetic “unmixing” techniques [26,27] now allow us to quantitatively determine the eolian inputs.

This study aims to explore the long-term development of Asian aridification and cooling over the Quaternary period in terms of mineral magnetic data from the Jingbian loess/paleosol sequence at the northern extremity of the Chinese Loess Plateau. This site appears to be an ideal natural recorder of climate change because of its high dust sedimentation rates and because it is in the transition zone between the dust source region and the deposition area, which is sensitive to Quaternary climate change [28].

2. Geological setting, stratigraphy and sampling

The Jingbian loess section (108.8°E, 37.4°N) is located in the transition zone between the Gobi and associated deserts in northwestern China and the northern part of the Chinese Loess Plateau (Fig. 1). The region, dominated by an arid/semi-arid continental climate [29], has a mean annual precipitation of 395.4 mm and a mean annual temperature of 7.8 °C. The mean July temperature is 22.5 °C and the mean January temperature −8.8 °C [30].

The 252-m-thick Jingbian loess/paleosol sequence consists of Holocene soil (S0), the Malan Formation (L1), the Lishi Formation (S1/L2 to S14/L15) and the Wucheng Formation (S15/L16 to S32/L33) [28] (according to the nomenclature of Chinese loess stratigraphy by Liu [1]). The Pliocene Red Clay underlying the loess/paleosol sequence is about 28 m thick [28].
this area, the paleosols are weakly developed and visually indistinct in the field [31]. However, some pedostratigraphic marker layers and magnetostratigraphy give a reliable stratigraphic constraint on this sequence. The prominent paleosol unit S5, two thick and coarse-textured loess layers L9 and L15, and some thick loess units, such as L24, L27 and L32 [1,6], were initially identified and then used as stratigraphic markers in the field. Previous magnetostratigraphic investigations have provided robust age control for the Jingbian sequence [31,32]. The Matuyama–Brunhes boundary was identified in the middle to lower part of loess unit L8 and the upper and lower boundaries of the Jaramillo normal subchron in loess L10 (close to the stratigraphic boundary L10/S9). The Jaramillo normal subchron is found in the lower part of loess layer L12, the upper and lower boundaries of the Olduvai normal subchron in the middle part of loess unit L25 and in the lower part of paleosol S26, and the Gauss–Matuyama boundary in the middle part of loess unit L33. The positions of geomagnetic reversals and subchrons at Jingbian are essentially similar to those of other loess/paleosol sequences over the Loess Plateau (e.g., Heller and Evans [2], Evans and Heller [4] and references therein).

Samples were collected from the Holocene soil (S0) to the bottom of the Pliocene Red Clay at 5–10 cm intervals. A total of 4400 samples were collected in this section. 1584 samples at 10–20 cm intervals were used in this study, 1564 from the Quaternary loess and paleosols (S0/L1 to S32/L33), and 20 from the upper part of the Pliocene Red Clay.

3. Methodology

Saturation isothermal remanent magnetizations (SIRM) of all samples were produced in a steady constant field of 1 T and demagnetized at peak alternating fields (AFs) of 10, 20, 30, 40, 60, 80 and 100 mT. These magnetic measurements were made using a 2G Enterprises Model 760-R cryogenic magnetometer situated in a magnetically shielded room.

High-temperature magnetic susceptibilities ($\chi-T$) of selected loess and paleosol samples were measured using a KLY-3 Kappabridge with a CS-3 high-temperature furnace (Agico Ltd., Brno) in an argon atmosphere. The sample holder and thermocouple contributions to magnetic susceptibility were subtracted.

Hysteresis parameters of selected samples were measured using a MicroMag 2900 Alternating Gradient Magnetometer (AGM) (Princeton Measurements Corp., USA). The magnetic field was cycled between ±1.5 T for each sample. Saturation magnetization ($M_s$), saturation remanence ($M_r$) and coercivity ($B_c$) were determined after correction for the paramagnetic contribution identified from the slope at high fields. Samples were then demagnetized in alternating fields up to 150 mT, and an isothermal remanent magnetization (IRM) was imparted from 0 to 1.5 T also using the MicroMag 2900 AGM. Subsequently, the 1.5 T IRM was demagnetized in a stepwise backfield to obtain the coercivity of remanence ($B_{cM}$).

One loess sample at a depth of 4.0 m was extracted at 1.5 T field. X-ray diffraction (XRD) analysis of the magnetic extracts was carried out using a DMAX2400 X-ray diffractometer with the following parameters: Cu-Kα/40 kV/80 mA, scattering slit of 1°, receiving slit of 0.15 mm, continuous scan mode, scanning speed of 2°/min and a scanning step of 0.02°.

4. Results

4.1. High-temperature magnetic susceptibility ($\chi-T$) and XRD

All selected samples display a clear susceptibility drop near 585 °C (Fig. 2), suggesting the existence of nearly stoichiometric magnetite in both loess and paleo-

![Fig. 2. Temperature-dependence of magnetic susceptibility of selected samples of loess and paleosols.](image-url)
sol samples. A steady (but nearly reversible) increase of susceptibility below ~200 °C is observed for the paleosol samples, which can be ascribed to gradual unblocking of fine-grained (near the superparamagnetic/single-domain (SP/SD) boundary) ferrimagnetic particles [33,34]. The further drop of magnetic susceptibility between ~300 °C and ~450 °C is generally interpreted as the conversion of ferrimagnetic maghemite to weakly magnetic hematite [35–38]. Liu et al. [34] further show that this susceptibility decrease results from the inversion of fine-grained maghemite to hematite. Such a susceptibility drop is more prominent for paleosol than loess samples, suggesting that paleosols contain more fine-grained pedogenic maghemite grains.

Unlike the paleosol samples, however, the heating curves for the loess samples is almost flat up to ~550 °C. The weakness or absence of the 250–300 °C hump in the heating curves is indicative of absence of fine-grained pedogenic maghemite grains [38]. This almost temperature-independent nature of low-field susceptibility below 585 °C, the Curie point of magnetite, indicates that detrital coarse-grained MD-like magnetite is the major contributor to the magnetic susceptibility of the loess samples [10,39].

Paleosol samples show a sharp increase in magnetic susceptibility when cooled below 580 °C. The increase in susceptibility is mainly due to the transformation from iron-containing silicates/clays to magnetite during thermal treatment [33,38]. In the northern and northwestern Loess Plateau, where pedogenesis is much weaker than in the central and southern plateau, the weathering has not depleted the supply of weatherable Fe-minerals in loess and paleosols and has left most of the iron-bearing precursor phases nearly untouched, leading to a sufficiency of iron that can serve as the source for the formation of new magnetite during laboratory heating [33].

The XRD spectrum reveals that a mixture of magnetite and hematite is present in the loess (Fig. 3). Maghemite, another important ferrimagnetic phase responsible for the enhanced magnetic susceptibility and remanences of Chinese loess sediments [34,37,38,40,41], was not clearly indicated by the XRD spectrum, possibly because its grain size is too fine to be extracted.

4.2. Hysteresis properties

Fig. 4 shows the hysteresis loops for representative loess and paleosol units. All the samples display a significant paramagnetic contribution (not shown). Loess samples generally have wider hysteresis loops than paleosols. The loops do not close even at 500 mT, especially for the very weakly weathered loess units L6, L9, L15 and L33, which may arise from high contributions of high-coercivity phases, such as hematite, goe-
thite and partially oxidized eolian magnetite [33,42]. Some hysteresis loops are slightly wasp-waisted [43], such as S5, L15, S18 and S32, which have been interpreted as resulting from the competing contributions of the composition, concentration and grain-size of magnetic minerals [33,44]. In addition, the values of $M_{rs}/M_s$ versus $B_{cr}/B_c$ when plotted on a Day diagram [45] indicate that the magnetic mineralogy is dominated by large PSD or MD-like magnetic grains (Fig. 5).

4.3. SIRM and AF demagnetization of SIRM

SIRM values of the entire Jingbian sequence show variations that correspond to loess/paleosol alternations, with high values in paleosols and low values in loess horizons (Fig. 6a). The highest SIRM is observed in the most prominent paleosol unit S5.

AF demagnetization of SIRM reflects the magnetic hardness of a material [10,27,39,46]. Loess and paleosols display different behavior during AF demagnetization of SIRM (Figs. 6 and 7). Generally, the SIRM of paleosols is more easily AF demagnetized than that of loess. Paleosol SIRM shows a steep decrease in intensity between 0 and 30 mT. Specifically, the spectra of the median destructive field of SIRM ($M_{DS_{SIRM}}$) for some representative loess and paleosol samples are shown in Fig. 7a. The $M_{DS_{SIRM}}$ values of the selected paleosols range from 16.7 mT to 26.2 mT with a mean value of $(19.6 \pm 2.1)$ mT ($N=30$), and of the selected less weathered loess samples, from 19.7 mT to 36.8 mT with a mean value of $(31.0 \pm 4.2)$ mT ($N=31$). $M_{DS_{SIRM}}$ decreases non-linearly with increasing pedogenesis (represented by the increased SIRM, Fig. 7b).

Fig. 6b shows the variations of the residual SIRM after progressive AF demagnetization normalized by the initial SIRM. Similar to SIRM behavior, the normalized residual SIRM of the entire Jingbian sequence exhibits variations that correspond to loess/paleosol alternations, with low values in paleosols and high values in loess units. In this paper, we use SIRM$_{n mT}$ to represent the residual SIRM after an $n$ mT AF demagnetization. In particular, there is a long-term up-section decreasing trend in the SIRM$_{10–100 mT}$/SIRM ratios. This feature becomes more and more pronounced with increasing alternating fields (Fig. 6b). In addition, the ratios of SIRM$_{100 mT}$/SIRM$_{50 mT}$ and SIRM$_{100 mT}$/SIRM$_{60 mT}$ show a long-term up-section decreasing trend, with the former almost paralleling that of the SIRM$_{100 mT}$/SIRM ratio and the latter showing no obvious changes in loess/paleosol rhythms (Fig. 8d,e). Stratigraphic variations of $M_{DS_{SIRM}}$ exhibit distinct loess/paleosol alternations; however, this parameter does not show a clear long-term increasing or decreasing trend (Fig. 8b). The paleoclimatic significance of these long-term variations will be addressed in detail in the Discussion section.

5. Discussion

5.1. Magnetic mineralogy of the Jingbian loess/paleosol sequence

High-temperature magnetic susceptibility measurements (Fig. 2) and XRD spectrum (Fig. 3) reveal the presence of a mixture of magnetite, maghemite and hematite in the Jingbian loess and paleosols. In this section, maghemite makes significant contributions to the magnetic susceptibility of paleosols but only a minor contribution to that of loess units (Fig. 2). Maghemite was not positively detected by the XRD analysis (Fig. 3), supporting the concept that maghemite particles are fine-grained grain and generally not extractable [42,47]. In addition, the magnetite grains in the loess samples display a coarse-grained MD-like behavior, as suggested by the nearly temperature-independent nature of low-field susceptibility below 585 °C (Fig. 2). Hematite, another important carrier of the natural remanence [12,37,47], is not clearly present in the $\chi$–$T$ curves because of its inherently weak magnetism. Its presence, however, is unambiguously indicated by the XRD spectrum (Fig. 3). Furthermore, the open nature of hysteresis loops...
above 300 mT (Fig. 4) strongly indicates the presence of high-coercivity phases in the weakly weathered loess layers.

Loess samples generally exhibit higher coercivities than paleosols, clearly suggested by their higher MDF_{SIRM} values and higher ratios of SIRM_{100mT}/SIRM, SIRM_{100mT}/SIRM_{10mT} and SIRM_{100mT}/SIRM_{60mT} in our study (Fig. 8). Three magnetic components may be responsible for this behavior: partially oxidized coarse-grained eolian magnetite, eolian hematite and goethite, and pedogenic hematite and goethite. Their contributions to the high-coercivity fraction of SIRM are addressed below.

Firstly, the coarse-grained (large PSD or MD) magnetites of eolian origin have usually been altered by low-temperature oxidation, which, at the initial stage of pedogenesis, can significantly increase the coercivity by increasing the internal stress caused by the coupling between the maghemite rim and the magnetite core of the particles [42,48,49]. However, with further pedogenic enhancement, pedogenesis can further oxidize the coarse-grained lithogenic magnetites, thus decreasing

![Fig. 6. (a) Intensity of SIRM after AF demagnetization at peak fields of 0, 10, 20, 30, 40, 60, 80 and 100 mT for the Jingbian loess/paleosol sequence. (b) Stratigraphic variations of the residual SIRM after AF demagnetization normalized by the initial SIRM.](image)
the coercivity of these magnetites by decreasing the oxidation gradient between the magnetite core and the maghemite rim [50]. A 30 mT AF demagnetization can significantly attenuate the pedogenic ferrimagnetic particles contributions to SIRM (Figs. 6 and 7a). In addition, Liu et al. [11] show that the partially oxidized eolian coarse-grained magnetite makes significant contributions to SIRM$_{60mT}$. However, the much elevated peak field of AFs to 100 mT can efficiently remove the contributions of these particles and simultaneously enhance the relative contributions of the magnetically harder phases, e.g., hematite or goethite.

The presence of goethite in Chinese loess/paleosols has been suggested by heavy mineral analysis [1], color indices [51] and diffuse reflectance spectrophotometry [52]. However, the goethite in terrestrial environments is usually Al-substituted. Al-substitution may sufficiently suppress its Néel temperature ($T_N$) below room temperature (300 K). Around $T_N$, Al-substituted goethite has maximum magnetic susceptibility but loses its ability to carry a remanence [53]. In addition, low-temperature magnetic susceptibility measurements indicate that in Chinese loess/paleosols the dominant antiferromagnetic phase is hematite rather than goethite [54]. Liu et al. [47] has further examined the thermal behavior of the high-coercivity fraction of SIRM. Their findings show a dominant unblocking temperature of ~670 °C, unambiguously suggesting that hematite rather than goethite dominates the SIRM. Thus, the contribution of goethite to the laboratory SIRM of the Jingbian loess/paleosols is possibly negligible. We therefore believe that SIRM$_{100mT}$ is carried dominantly by hematite.

In less weathered loess units, it has been suggested that eolian hematite grains dominate high-coercivity fraction [46]. In paleosols, however, much pedogenic hematite was formed due to strong weathering during interglacial periods [33,47,52]. Considering all the evidence together, it is reasonable to hypothesize that in Chinese loess/paleosols the high-coercivity fraction SIRM$_{100mT}$ is dominated by hematite. Thus, SIRM$_{100mT}$ can serve as a measure of hematite contributions in the Chinese loess/paleosol sequences, and the SIRM$_{100mT}$/SIRM ratio can be used as a proxy for variations in the relative contributions of hematite in the sequences, which mainly originates from the dust source region in less weathered loess layers and is mainly produced due to in situ pedogenesis in weathered paleosol units.

The most striking feature in the mineral magnetic records of the Jingbian loess/paleosol sequence is the up-section gradual decrease of the SIRM$_{100mT}$/SIRM ratio for both loess and paleosol units over the entire sequence (Fig. 8c). This behavior is more pronounced for the glacial loess than for the interglacial paleosols. To remove the effects of pedogenic ferrimagnetic components, and then better isolate the magnetic responses of the long-term paleoclimate evolution separately in glacial and interglacial stages, we further employ SIRM$_{30mT}$ and SIRM$_{60mT}$ as normalizing parameters. The SIRM$_{30mT}$ is dominated by hematite and low-temperature oxidized coarse-grained lithogenic magnetite, and at least partly by pedogenic magnetite/maghemite while the SIRM$_{60mT}$ is dominated by hematite and low-temperature oxidized coarse-grained lithogenic magnetite.

5.2. Interpretation of the long-term mineral magnetic variations

The dust source region in the Gobi and sand deserts of northwestern China is dominated by an arid conti-
nental climate [29] where there are moderately high temperatures and short periods of limited rainfall in summer. It is expected that the formation of hematite due to in situ chemical weathering in the source region is favored under such a climate regime [52]. In glacial periods, the formation of hematite in the source region may be reduced due to increased aridification and cooling. However, the hematite in interglacial paleosols is
dominantly formed by in situ chemical weathering in the depositional area. In the Jingbian section, where loess layers are very weakly weathered and paleosols moderately to well developed [28], hematite in loess layers is dominantly of eolian origin and in paleosol units is mainly of pedogenic origin. Therefore, the content of hematite in loess and paleosols mainly reveals the degree of chemical weathering intensity relatively in the glacial-stage source region (the Gobi and deserts in northwestern China) and in the interglacial-stage depositional area (the Loess Plateau region), further reflecting the degree of aridification and cooling respectively in glacial-stage source region and in interglacial-stage depositional area.

Therefore, the long-term up-section decreasing trend in the ratios of SIRM100mT/SIRM, SIRM100mT/SIRM30mT and SIRM100mT/SIRM60mT suggests a long-term decreasing trend in the relative contributions of both eolian hematite in the glacial loess units and pedogenic hematite in the interglacial paleosols. This long-timescale variation possibly further signals a long-term increasing aridification and cooling during both glacial extrema in the source region and interglacial extrema in the depositional area over the entire Quaternary period. In addition, we note that the long-term variation in the glacial loess layers is clearly shown by all the three ratios. However, in the interglacial paleosol units, this feature is weakly revealed by the SIRM100mT/SIRM ratio and much more distinctly defined by the other two ratios because SIRM is more affected by fine-grained pedogenic ferrimagnetic grains.

Following the long-term ongoing deterioration of Cenozoic climate [55], our observed trend coincides well with the long-term increase in δ18O values seen in the marine oxygen isotopic record [56–59] (Fig. 8f), which reflects a long-term global cooling trend and expansion of the Arctic ice-sheet. Each of the glacial–interglacial climatic oscillations show a close match between the ratios of SIRM100mT/SIRM and SIRM100mT/SIRM30mT and the composite marine oxygen record, with a discrepancy present only in the upper sandy loess unit L9, which will be separately addressed in the last paragraph of this section. However, all the three ratios mentioned above and the composite marine oxygen records show a good correlation over the whole 2.6 Ma time period (Fig. 8).

The onset of desertification in the Asian interior has been believed to be at least 22 Myr ago in terms of magnetostratigraphic results of the Miocene loess/paleosol sequences in the western Loess Plateau [24]. The ultimate cause for the onset and development of aridification and cooling in the Asian interior remains unsettled although several factors have been invoked as driving forces for this scenario such as ongoing global cooling, uplift of the Himalayan–Tibetan Plateau and changes in land–sea distribution [21,22,24,60,61], with the former two being the main forces responsible for the Quaternary development of Asian aridification and cooling, and the last one playing a background role in the long-term Cenozoic climate deterioration.

Firstly, ongoing global cooling and expansion of the Arctic ice-sheet during the Quaternary contributed significantly to the development of Asian aridification and cooling. A cooler high-latitude ocean provides less moisture to the continental interior, thus promoting aridification in the Asian mainland [24,60]. Secondly, climate simulations suggest that the Himalayan–Tibetan uplift could serve as a key contributor to the development of Asian aridification [22,60]. Plateau uplift enhances summer monsoon and brings wetter climates to India and Southeast Asia, but this moisture cannot reach the Asian interior because the uplifted Himalayan–Tibetan topography blocks airflow from the south [24]. Meanwhile, the plateau uplift strengthens the winter monsoon, causing additional mid-latitude to high-latitude Asian interior cooling by greatly increasing the atmospheric dust loading [21,22,24]. As a result, the interior of Asia becomes increasingly dry and cold as a climatic response to the progressive uplift, leading to an effective increase in aridification and cooling during the Quaternary and ultimately resulting in a long-term decreasing trend in chemical weathering intensity in both the dust source region and the dust depositional area over that period. This is reflected in our observed long-term trend in the relative content of hematite in both glacial loess and interglacial paleosols of the Jingbian section (Fig. 8).

Several lines of geological evidence from the loess/paleosol sequences at the studied Jingbian section, in the central and southern Loess Plateau support this argument. For example, the >63 and >25 μm% records, which mainly reflect proximal signals of the sand-sized particle content, at Jingbian show four stepped increases. These four increases indicate that the Mu Us Desert migrated southward at 2.6, 1.2, 0.7 and 0.2 Ma, further suggesting a stepwise weakening of the East Asian summer monsoon during the past 3.5 Ma [28]. A general up-section increase in the ratios of Na/Al and Fe2+/Fe3+ from the Lingtai (35.1°N, 107.7°E) sequence indicates a long-term increase in the rate of mechanical weathering and erosion in the source regions over the last 2.6 Myr [62]. A general coarsening trend in bulk median grain size from the Luochuan (35.75°N, 109.42°E) sequence suggests a long-term
intensification of the winter monsoon over the last 2.6 Myr [63]; multiple mineral magnetic parameters retrieved from the Jiaodao (35.8°N, 109.4°E) sequence suggest a long-term decrease in summer monsoon intensity and a long-term increase in winter monsoon intensity over the last 2.6 Myr [10]. A general decreasing trend in the \( ^{87}\text{Sr}/^{86}\text{Sr} \) ratio of the Luochuan sequence indicates a long-term decrease in source area weathering intensity in the Asian interior over the last 2.6 Myr [64]. Sporopollen records obtained from the Chaona (107°12′E, 35°7′N) sequence indicate shifts of vegetations from forest-steppe (1.5–0.95 Ma) to open forest and steppe (0.95–0.5 Ma) and then to steppe (0.5 Ma to present), implying a stepwise drying in the southern central plateau over the last 1.5 Myr [65]. High-temperature magnetic susceptibility measurements of the Jiaodao section also indicate a general decrease in weathering intensity over the last 1.2 Myr [33]. And an up-section increasing trend in illite content in the Baoji sequence may indicate an increase in aridity over the last 1.2 Myr [66].

Specifically, there is an exception in the upper sandy loess layer L9 of the Jingbian section, which was given an age of 0.865–0.943 Ma by the new astronomical timescale for the Chinese loess/paleosol sequences developed by Ding et al. [6]. This loess layer has prominent low coercivities, namely, low values of MDF$_{SIRM_{}}$, SIRM$_{100mT}$/SIRM$_{60mT}$, SIRM$_{100mT}$/SIRM$_{30mT}$ and SIRM$_{100mT}$/SIRM$_{60mT}$ (Fig. 8). This behavior is inconsistent with the general changes of these parameters. This abnormal behavior may be related to an episode of accelerated uplift of the Tibetan Plateau (at least the northern and northeastern Tibetan Plateau) about 0.9 Myr ago [10,63]. The accelerated tectonic uplift enhanced rock weathering and mountain erosion in the Tibetan Plateau and its adjacent mountainous regions, leading to the dominant input of weakly weathered materials rich in coarse-grained magnetite grains into the source sedimentary basins near the plateau in northwestern China [10]. Subsequently, these coarse-grained magnetite grains with low coercivities were transported through the East Asian monsoonal circulation and deposited in the Loess Plateau region.

### 6. Conclusions

We have analyzed in detail a high-resolution mineral magnetic record from the Jingbian loess/paleosol sequence at the northern extremity of the Chinese Loess Plateau. Results show that the ratios of SIRM$_{100mT}$/SIRM$_{60mT}$, SIRM$_{100mT}$/SIRM$_{30mT}$ and SIRM$_{100mT}$/SIRM$_{60mT}$ all display a long-term up-section oscillatory decreasing trend in both glacial and interglacial periods over the Quaternary period. This long-term trend is attributed to a long-term decrease in the relative contributions of eolian hematite during glacial extrema and of pedogenic hematite during interglacial extrema. We then interpret this long-term variation pattern to reveal a long-term decreasing trend in chemical weathering intensity in both glacial-stage source region (the Gobi and other deserts in northwestern China) and interglacial-stage depositional area (the Loess Plateau region) over the Quaternary period. This long-timescale variation also indicates a long-term increasing aridification and cooling during both glacial extrema in the source region and interglacial extrema in the depositional area over this period. In addition, the three ratios and the composite marine oxygen records show good correlation between glacial–interglacial climatic oscillations and/or long-term trends. In summary, the up-section gradual decrease of these ratios over the entire Jingbian loess/paleosol sequence possibly reflects an increasing aridification and cooling of the climate system in the Asia interior over the last 2.6 Myr, which is most likely controlled by ongoing global cooling, expansion of the Arctic ice-sheet and progressive uplift of the Himalayan–Tibetan Plateau complex within this interval.

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