

## MIS3 Climate Change Recorded by Loess Deposits in the Linfen Basin (Postprint)

**Authors:** Tian Qingchun

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### Abstract

Climate issues concerning Marine Isotope Stage 3 (MIS3) remain incompletely resolved, necessitating analysis of sedimentary records from additional regions. Loess is widely recognized as an excellent archive for Quaternary climate research. By selecting the Linfen Basin on the southeastern margin of the Loess Plateau as the study area and systematically investigating magnetic susceptibility, total iron, total organic carbon, and grain size of loess deposits in this region, combined with optically stimulated luminescence chronology data, this study preliminarily discusses the characteristics of climate change in the Linfen Basin during the MIS3 stage. Climate change in the Linfen Basin during the MIS3 stage can be divided into three phases: 56-45 ka BP was characterized by weakly warm and humid conditions, corresponding to MIS3c; 45-41 ka BP exhibited a brief cold and dry period, corresponding to MIS3b; and 41-25 ka BP displayed relatively strong warm and humid conditions, corresponding to MIS3a. Although global climate during the MIS3 stage exhibited relatively warm and humid conditions, climate fluctuations in the Linfen Basin during MIS3 show certain differences from other geological records. The cause of this discrepancy may be that under the combined influence of Northern Hemisphere ice sheets and solar radiation received at the Earth's surface, the distribution of heat and moisture varied across different regions, resulting in significant environmental differences between regions. The specific coupling mechanisms require further research.

### Full Text

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TIAN Qingchun<sup>1,2</sup>, YIN Jianan<sup>1</sup>, HAO Xiaolong<sup>1</sup>

<sup>1</sup>College of Geographical Sciences, Shanxi Normal University, Taiyuan 030000, Shanxi, China

<sup>2</sup>Academy of Chinese Early Civilization, Shanxi Normal University, Taiyuan 030000, Shanxi, China

## Abstract

The climate characteristics of Marine Isotope Stage 3 (MIS3) remain incompletely resolved, necessitating analysis of additional regional sedimentary records. Loess is widely recognized as an excellent archive for Quaternary climate research. This study selected the Linfen Basin on the southeastern margin of the Loess Plateau as the research area and systematically investigated magnetic susceptibility, total iron, total organic carbon, and grain size in loess deposits, combined with optically stimulated luminescence (OSL) chronology data, to reconstruct MIS3 climate change characteristics in the basin. The results indicate that MIS3 climate change in the Linfen Basin can be divided into three stages: (1) 56–45 ka BP, corresponding to MIS3c, characterized by weakly warm-humid conditions; (2) 45–41 ka BP, corresponding to MIS3b, showing a brief cold-dry interval; and (3) 41–25 ka BP, corresponding to MIS3a, exhibiting relatively strong warm-humid conditions. While global climate during MIS3 displayed relatively warm-humid features, the Linfen Basin record shows some differences from other geological archives. These discrepancies likely arise from differential heat and moisture distribution across regions under the combined influence of Northern Hemisphere ice sheets and solar radiation receipt at the Earth's surface, leading to substantial environmental heterogeneity between regions. The specific coupling mechanisms require further investigation.

**Keywords:** Linfen Basin; loess deposition; MIS3 characteristics; climate change

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## 1. Study Area Overview

The Linfen Basin is located in southern Shanxi Province, bounded by the Houma Ridge to the north, Emei Platform to the south, Huoshan Mountain to the east, and Luoyun Mountain to the west. The region experiences a temperate continental monsoon climate with annual precipitation of 420–550 mm and mean annual temperatures of 9.0–12.9 °C. The sampling profile is situated near Dingcun in the southern part of the basin (Fig. 1). In 1954, archaeologists from the Institute of Vertebrate Paleontology and Paleoanthropology, Chinese Academy of Sciences, discovered a juvenile parietal bone at this site, designated as “Dingcun Man,” representing early *Homo sapiens* intermediate between Peking Man and modern humans, similar to Ordos Man. The discovery of Dingcun Man fossils attracted considerable academic attention and stimulated research on tectonic movements and environmental evolution in the Linfen Basin and adjacent areas.

The Linfen Basin also represents a sensitive transitional zone from semi-humid to semi-arid regions in China, making its special geographical location highly responsive to climate change.

## 2.1 Sample Collection

This study focuses on loess deposits in the Linfen Basin to preliminarily explore MIS3 climate change. Through field investigation, we selected a profile near the Dingcun paleoanthropological site. The loess-paleosol profile has a total thickness of approximately 630 cm and is located on the third terrace of the Fen River, consistent with the stratigraphic layers of the “Dingcun Group” (Fig. 2). The profile is described as follows: 0–60 cm, modern cultivated layer; 60–190 cm, weakly developed paleosol layer with light brownish-yellow color, dense texture, and local distribution of small white carbonate spots; 190–420 cm, loess layer with light yellow color, high silt content, uniform and loose texture with abundant pores; 420–570 cm, paleosol layer with light reddish-brown clay, good cementation, distribution of white carbonate mycelia and white/black spots, and relatively dense texture; 570–630 cm, loess layer with light yellow color, high silt content, uniform texture, and obvious compaction in the lower part.

Samples were collected at 10–20 cm intervals from the profile top, yielding 40 samples. Simultaneously, OSL dating samples were collected using 4.5 cm diameter stainless steel tubes at 0.6–1 m intervals, with five samples obtained.

## 2.2 Analytical Methods

Naturally air-dried samples were analyzed for magnetic susceptibility, grain size, total organic carbon, and total iron content at the Laboratory of Geographical Sciences, Shanxi Normal University. Magnetic susceptibility was measured using a Barington magnetic susceptibility meter. To ensure reliability, both high-frequency and low-frequency magnetic susceptibility were measured three times per sample, with average values reported. Grain size analysis employed established pretreatment methods and was performed using a Mastersizer 2000 laser particle size analyzer with a measurement range of 0.02–2000  $\mu\text{m}$  and repeat measurement error <3%. Total organic carbon content was determined using the potassium dichromate-sulfuric acid oxidation titration method. Total iron content was measured using a novAA400 atomic absorption spectrometer.

OSL dating was conducted at the Key Laboratory of Optically Stimulated Luminescence, Qinghai Institute of Geography. The experimental procedure followed reference [17]. OSL dating primarily targets quartz and feldspar minerals, which are abundant and easily extracted. Key considerations include: (1) mineral purity affects dating results; (2) saturation dose affects the dating range—feldspar has a larger saturation dose than quartz, providing a wider dating range; (3) signal intensity affects dating precision, with feldspar showing stronger signals than quartz for young samples; (4) thermal transfer phenomena severely affect young sample testing, with quartz showing stronger thermal transfer than

feldspar, which is detrimental to young sample measurement. In this study, the upper limit of post-IR IRSL (pIRIR) feldspar dating could meet the requirements for accurately obtaining ages since the last interglacial period. Therefore, feldspar ages were selected as more precise (Table 1). These age data effectively constrain the depositional timeframe of the Dingcun profile, though they cannot determine the specific age of each depositional layer. Since OSL dating has inherent uncertainties and simple linear interpolation yields large errors, we used the grain-size age model proposed by Porter and An [18] to calculate the age sequence of the Dingcun profile (Fig. 3). During model calculation, we introduced standard loess-paleosol stratigraphic age node data from previous studies. While curve correlation can provide some age control points, too many control points may be forced. Therefore, we only selected four standard stratigraphic ages: MIS2/3 boundary at 25.37 ka BP, MIS3/4 boundary at 59.69 ka BP, MIS4/5 boundary at 74.22 ka BP, and MIS5/6 boundary at 128.80 ka BP. Due to missing MIS1 and Holocene strata at the profile top, the uppermost part corresponds to approximately 20 ka BP.

### 2.3.1 Grain Size

As a fundamental physical property of soils, grain size is a basic indicator in sediment research and holds important significance in paleoclimate studies. Chinese loess accumulation is considered a product of the East Asian monsoon system, with grain size coarseness related to wind strength. Previous research on loess-paleosol sequences has identified grain size as the most sensitive proxy for East Asian winter monsoon variations, with coarse particle fractions positively correlated with winter monsoon intensity. As different regions respond differently to monsoons, the environmental significance of grain size fractions varies by region. Therefore, different parameters are selected for climate analysis in different areas. In this study, we chose the median grain size and  $>63 \mu\text{m}$  coarse particle fraction as winter monsoon proxies.

### 2.3.2 Magnetic Susceptibility

Magnetic susceptibility is commonly used as an indicator of pedogenic intensity and rainfall in Quaternary paleoclimate research. The primary mechanism for magnetic susceptibility enhancement is the formation of superparamagnetic particles during pedogenesis, which increases the content of ferrimagnetic minerals and can thus indicate East Asian summer monsoon intensity. However, magnetic susceptibility reflects comprehensive magnetic information from different minerals and is influenced by source, particle size, type, and content, presenting certain limitations in reflecting climate environments. Under high temperature and precipitation conditions, magnetic susceptibility reversal can occur. The glacial-interglacial cycle is an important feature of Quaternary climate, with magnetic susceptibility showing different trends during glacial-interglacial transitions. The transition from interglacial to glacial periods is slow and staged, with decreasing magnetic susceptibility, while the transition from glacial to inter-

glacial periods is relatively rapid, with increasing magnetic susceptibility. The Linfen Basin is located in the southeastern Loess Plateau, where even during interglacial periods, mean annual temperature and precipitation do not exceed the critical threshold beyond which magnetic susceptibility decreases with increasing temperature and precipitation. Therefore, magnetic susceptibility can serve as a proxy indicator for paleoclimate change in the Linfen Basin. Since pedogenesis is controlled by multi-year precipitation and temperature, magnetic susceptibility values are somewhat smoothed, so climate analysis should combine multiple indicators.

Throughout the profile, magnetic susceptibility and frequency-dependent magnetic susceptibility show synchronous variation trends, with the latter showing more pronounced fluctuations. Magnetic susceptibility values range from  $45.67 \times 10^{-8}$  to  $203.53 \times 10^{-8}$  m<sup>3</sup>/kg, averaging  $152.89 \times 10^{-8}$  m<sup>3</sup>/kg. Frequency-dependent magnetic susceptibility ranges from 0 to  $11.59 \times 10^{-8}$  m<sup>3</sup>/kg, averaging  $4.80 \times 10^{-8}$  m<sup>3</sup>/kg. Both show valley-peak-valley changes, with higher peaks in the later stage.

### 2.3.3 Total Iron (TFe)

Total iron (TFe) includes both free iron and silicate iron. Total iron content is related to the weathering degree of iron-bearing silicates, with content levels reflecting pedogenic intensity and thus summer monsoon strength. Research indicates that loess TFe content is closely linked to climate on the Loess Plateau and has potential for quantitative conversion. In the Dingcun profile, TFe and magnetic susceptibility values show synchronous variation with slight internal differences, though TFe shows larger fluctuation amplitude. Throughout the profile, TFe content ranges from 1.63% to 3.43%, averaging 2.36%, showing valley-peak-valley changes consistent with magnetic susceptibility, with higher peaks in the later stage.

### 2.3.4 Total Organic Carbon (TOC)

Total organic carbon (TOC) content in loess can reflect regional biomass and vegetation cover under certain climate conditions, thereby revealing paleoclimate status. In arid and semi-arid regions, vegetation is primarily controlled by moisture, so TOC is commonly used to indicate humidity changes and indirectly reflect summer monsoon intensity. As buried organic carbon continuously decomposes over time, its content tends to decrease, making TOC suitable for high-resolution short-term rather than long-term climate change studies. In the Dingcun profile, TOC ranges from 0.58% to 3.20%, averaging 1.84%, showing valley-peak-valley changes consistent with other indicators. Considering that the Linfen Basin is in a semi-arid region where vegetation growth is mainly controlled by moisture, TOC can serve as a proxy indicator for humidity changes.

### 3.1 MIS3 Climate Characteristics Recorded in the Dingcun Profile

Based on OSL dating results, the Dingcun loess deposition recorded MIS3 from approximately 56 to 25 ka BP. Fluctuations in magnetic susceptibility, frequency-dependent magnetic susceptibility, total iron, total organic carbon, and grain size throughout MIS3 show a “two peaks sandwiching a valley” pattern—two weak paleosol layers enclosing a loess layer. The analysis follows stratigraphic order:

**56–45 ka BP (MIS3c):** Magnetic susceptibility shows fluctuations but generally increases, with several small peaks. Frequency-dependent magnetic susceptibility, total iron, and total organic carbon also show mainly fluctuating increases, with larger fluctuation amplitudes than magnetic susceptibility, indicating an enhanced summer monsoon trend with unstable climate. Median grain size shows fluctuating decreases followed by increases, while  $>63$   $\mu\text{m}$  grain size content shows the same trend, indicating weak winter monsoon. Overall, this stage shows slowly weakening winter monsoon and strengthening summer monsoon, representing a weak warm-humid period.

**45–41 ka BP (MIS3b):** Magnetic susceptibility, frequency-dependent magnetic susceptibility, total iron, and total organic carbon all show peak-valley-peak patterns, with the later peak being higher. Median grain size is coarser than the previous stage with small internal fluctuations, and  $>63$   $\mu\text{m}$  grain size content shows two small peaks, indicating brief winter monsoon strengthening. However, total iron and total organic carbon are relatively low with small fluctuations, while frequency-dependent magnetic susceptibility shows an obvious valley, indicating weakened summer monsoon and pedogenesis. Magnetic susceptibility shows only slight decreases, demonstrating its limitations in reflecting climate environment. Overall, this stage represents a brief cold-dry interval.

**41–25 ka BP (MIS3a):** Magnetic susceptibility shows a high peak followed by decreasing trends, with peak magnitude second only to the last interglacial period. Frequency-dependent magnetic susceptibility shows corresponding peaks, slightly higher than MIS3c with small internal fluctuations. Total iron and total organic carbon also fluctuate upward then downward, showing large peaks exceeding those of MIS3c, indicating enhanced summer monsoon, stronger pedogenesis, and higher vegetation cover, representing relatively warm-humid conditions. Median grain size shows low values, and  $>63$   $\mu\text{m}$  component content shows low valley values, indicating weak winter monsoon. This stage represents the warmest and most humid interval recorded in the Dingcun profile during the last glacial period, consistent with climate research results from the Dali area. However, the peaks are lower than those of the last interglacial period, indicating the warm-humid degree was less than that of the last interglacial.

### 3.2 Preliminary Discussion of MIS3 Climate Characteristics

The above analysis shows that MIS3 climate in the Linfen Basin exhibited obvious warm-humid (or weakly warm-humid) features, consistent with weakly

warm-humid characteristics revealed by other geological records globally. This demonstrates that Quaternary climate in this region was consistent with global climate changes at the ten-thousand-year scale, controlled by Earth's orbital parameters. However, significant differences exist between regions. Current conclusions mainly include: (1) some regions were warmer and more humid than the Linfen Basin, such as the central Loess Plateau (Luochuan, Xifeng) and northwestern margin; (2) some regions showed similar warm-humid degrees, such as Baoji and Duangiapo; and (3) some regions on the southeastern margin (Dali, Baimapo) showed even higher warm-humid degrees than the Linfen Basin. These phenomena indicate that the Loess Plateau has a large environmental gradient in the latitudinal direction.

The Linfen Basin is located in the southeastern Loess Plateau, and its climate change is controlled by the East Asian monsoon system. During MIS3a, enhanced summer monsoon control led to relatively unstable climate. The East Asian monsoon system is generally considered to be influenced by Northern Hemisphere ice volume and solar radiation receipt. An et al. [57] suggested that solar radiation controls East Asian summer monsoon intensity, while Prell and Kutzbach [58] demonstrated that monsoon circulation intensity in monsoon regions increases with solar radiation. Shackleton et al. [59] proposed that East Asian monsoon evolution is controlled by global ice volume, which affects monsoon variation by regulating the position and intensity of the Siberian-Mongolian High. Sun et al. [60] found that magnetic susceptibility of Chinese loess seems more closely related to global ice volume changes. Research on the Weinan loess sequence in the central Loess Plateau suggests that monsoon climate changes are consistent with global ice volume changes indicated by marine oxygen isotopes, though monsoon variation amplitude and evolution trends differ significantly from global ice volume, possibly resulting from Northern Hemisphere solar radiation changes. Ding et al. [61] found that paleosol stages since the last interglacial correlate with precession cycles, possibly representing a climate system response to solar radiation changes caused by precession. The Dingcun profile environmental indicators generally show features consistent with marine oxygen isotope records representing global ice volume, demonstrating global climate consistency controlled by Earth's orbital parameters, while also showing features similar to the Guliya ice core, such as higher temperatures in the later stage of MIS3. Shi et al. [62] attributed this characteristic in the Guliya ice core to strong influence from precession-cycle solar radiation changes—a special phenomenon involving global mid-low latitude ranges caused by Earth's orbital changes—suggesting that climate changes in this region may also respond to solar radiation caused by precession cycles.

Numerical simulations show that Pleistocene East Asian summer monsoon changes were driven by solar radiation and should exhibit precession-cycle signals, but the existence of Northern Hemisphere ice sheets made high-latitude regions show glacial-interglacial cycles as the main feature. During MIS3, precession-caused solar radiation increase in mid-low latitudes was about  $20 \text{ W} \cdot \text{m}^{-2}$  [63]. This increased solar radiation, combined with the semi-preserved

state of Northern Hemisphere ice sheets, caused the Siberian-Mongolian High to weaken, reducing East Asian winter monsoon intensity and increasing summer monsoon intensity, thus developing paleosols on the Loess Plateau. The loess record from the Linfen Basin also reflects this climate change. Since solar radiation increase was mainly in mid-low latitudes with little increase at high latitudes [64], large temperature differences emerged between regions. Meanwhile, the southward shift of the westerlies affected by this situation would increase precipitation in western Tibet, and the intensity of southward cold air flow would also be greater than present [65]. The cold high pressure generated by ice sheets would also create large environmental gradients, which may be why the Loess Plateau did not exhibit the “high temperature and large precipitation event” and showed obvious environmental gradients. During this period, Northeast China not only failed to show warm-humid conditions but instead exhibited colder environmental features with periglacial phenomena and cold-adapted flora and fauna [66], possibly also related to large environmental gradients caused by surface solar radiation receipt and Northern Hemisphere ice sheet presence.

Thus, both Northern Hemisphere ice volume and solar radiation changes affect climate, but their relative contributions and specific mechanisms remain unclear and difficult to separate. They likely represent combined effects. Chen et al. [67] also suggested that while solar radiation changes and Northern Hemisphere ice volume both show certain correlations with Loess Plateau paleoclimate, their correspondence is not ideal, likely representing simultaneous combined effects. The climate changes in the Dingcun profile during MIS3 were probably also influenced by these two factors, showing certain local characteristics. The “high temperature and large precipitation event” in the Tibetan Plateau and north-western inland areas may have been mainly caused by changes in water vapor transport paths and increased intensity of the southwest monsoon and westerlies, also related to combined effects of solar radiation and Northern Hemisphere ice volume [62,65,69-70]. Therefore, a comprehensive understanding of MIS3 climate evolution mechanisms requires more regional records and comparisons.

#### 4. Conclusions

Based on the above analysis, the following conclusions can be drawn:

1. The climate of the Linfen Basin during MIS3 can be divided into three stages: 56–45 ka BP (MIS3c) was a weakly warm-humid period; 45–41 ka BP (MIS3b) was a brief cold-dry interval; and 41–25 ka BP (MIS3a) was a relatively strong warm-humid period.
2. The overall warm-humid climate of the Linfen Basin during MIS3 is consistent with other geological records showing weakly warm-humid characteristics, demonstrating that regional Quaternary climate changes at the ten-thousand-year scale are consistent with global climate changes controlled by Earth’s orbital parameters.

3. The significant differences in climate characteristics between regions during MIS3 may not necessarily result from different driving forces but likely arise from differential heat and moisture distribution across regions under the combined effects of Northern Hemisphere ice sheets and solar radiation, leading to large environmental differences between regions.
4. When analyzing MIS3 climate change, we should not focus solely on whether the “high temperature and large precipitation event” is reasonable but should fully understand and study the climate change characteristics and history of each region. Only in this way can we better explain regional differences and abrupt events during MIS3.

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## References

- [1] Imbrie J, Hays J D, Martinson D G, et al. The orbital theory of Pleistocene climate: Support from a revised chronology of the marine  $\delta^{18}\text{O}$  record[J]. *Milankovitch and Climate*, 1984, 126(1): 269-305.
- [2] Yao Tandong, Thompson L G, Shi Yafeng, et al. Climate variation since the last interglaciation recorded in the Guliya ice core[J]. *Science in China (Series D)*, 1997, 40(6): 662-668.
- [3] Zheng Mianping, Liu Junying, Qi Wen. Palaeoclimatic evolution of the Qinghai-Xizang Plateau since 40 ka BP evidences from saline lake deposits[C]//Zheng Mianping. *Saline Lake Resources and Environments with Its Relative Global Change*. Beijing: Geological Publishing House, 1996: 6-20.
- [4] Shi Yafeng, Liu Xiaodong, Li Bingyuan, et al. A very strong summer monsoon event during 30-40 ka BP in the Qinghai-Xizang (Tibet) Plateau and its relation to precessional cycle[J]. *Chinese Science Bulletin*, 1999, 44(20): 1851-1858.
- [5] Zhang X L, Ha B B, Wang S J, et al. The earliest human occupation of the high altitude Tibetan Plateau 40 thousand to 30 thousand years ago[J]. *Science*, 2018, 362(6418): 1049-1051.
- [6] Li Chunhai, Tang Lingyu, Feng Zhaodong, et al. A high resolution Late Pleistocene record of pollen vegetation and climate change from Jingning, NW China[J]. *Science in China (Series D)*, 2006, 36(5): 453-460.
- [7] Zhai Xinwei, Wu Song, Li Fuqiang. Geochemistry characteristics of elements in Loess in the Huining profile in MIS3 and climate change[J]. *Arid Zone Research*, 2013, 30(1): 156-161.
- [8] Liu Dongsheng, Wang Kelu. Some problems of quaternary stratigraphy in North China[C]//Institute of Geology, Chinese Academy of Sciences. *Problems of Quaternary Geology*. Beijing: Science Press, 1964: 65-76.
- [9] Jia Lanpo. Excavation report of human fossils and paleolithic artifacts in Dingcun, Xiangfen County, Shanxi Province[J]. *Chinese Science Bulletin*, 1955,

6(1): 46-51.

[10] Jia Lanpo, Wei Qi. Application of palaeoanthropology and archaeology to setting up Quaternary standard sections in China[J]. *Acta Geologica Sinica*, 1982, 56(3): 255-263.

[11] Yang Jingchun, Liu Guangxun. Some problems on Dingcun Group[J]. *Journal of Stratigraphy*, 1979, 3(3): 194-199, 235.

[12] Wang Jian, Tao Fuhai, Wang Yiren. Unearth briefing for investigation of Dingcun Paleolithic sites[J]. *Journal of Chinese Antiquity*, 1994, 5(3): 1-75.

[13] Lu Huayu, An Zhisheng. Pretreatment methods influences on grain size measurement of loess[J]. *Chinese Science Bulletin*, 1997, 42(23): 2535-2538.

[14] Chongyi E, Lai Zhongping, Sun Yongjuan, et al. A luminescence dating study of loess deposits from the Yili River basin in western China[J]. *Quaternary Geochronology*, 2012, 10(3): 50-55.

[15] Huntley D J, Lamothe M. Ubiquity of anomalous fading in K-feldspars and the measurement and correction for it in optical dating[J]. *Canadian Journal of Earth Sciences*, 2001, 38(7): 1093-1106.

[16] Li B, Jacobs Z, Roberts R G, et al. Review and assessment of the potential of post-IR IRSL dating methods to circumvent the problem of anomalous fading in feldspar luminescence[J]. *Geochronometria*, 2014, 41(3): 178-201.

[17] Porter S C, An Z S. Correlation between climate events in the North Atlantic and China during the last glaciation[J]. *Nature*, 1995, 375(6529): 305-308.

[18] Forster T, Heller F. Magnetic enhancement paths in loess sediments from Tajikistan, China and Hungary[J]. *Geophysical Research Letters*, 1997, 24(1): 17-20.

[19] Wang Xisheng, Yang Zhenyu, Reidar Løvlie, et al. Environmental magnetic results and paleoclimatic significance of loess-paleosol sequence in the south-eastern margin of the Loess Plateau[J]. *Chinese Science Bulletin*, 2006, 51(13): 1575-1582.

[20] Deng Chenglong, Liu Qingsong, Pan Yongxin, et al. Environmental magnetism of Chinese loess-paleosol sequences[J]. *Quaternary Sciences*, 2007, 27(2): 193-209.

[21] Deng C L, Zhu R X, Verosub K L, et al. Mineral magnetic properties of loess/paleosol couplets of the central Loess Plateau of China over the last 1.2 Myr[J]. *Journal of Geophysical Research*, 2004, 109(1): B01103, doi: 10.1029/2003JB002532.

[22] Deng C L, Vidic N J, Verosub K L, et al. Mineral magnetic variation of the Jiaodao Chinese loess/paleosol sequence and its bearing on long-term climate variability[J]. *Journal of Geophysical Research*, 2005, 110(B3): B03103, doi: 10.1029/2004JB003451.

- [23] Liu Q S, Deng C L, Torrent J, et al. Reviews of recent developments in mineral magnetism of the Chinese loess[J]. *Quaternary Science Reviews*, 2007, 26(3-4): 368-385.
- [24] Liu Qingsong, Deng Chenglong. Magnetic susceptibility and its environmental significances[J]. *Chinese Journal of Geophysics*, 2009, 52(4): 1041-1048.
- [25] Xiong Shangfa, Liu Dongsheng, Ding Zhongli. Paleoclimatic records of the Loess in the vicinity of Beijing Region during the last two glacial-interglacial cycles and its implications[J]. *Scientia Geographica Sinica*, 2002, 22(1): 18-23.
- [26] Lu Yue, Zha Xiaochun, Huang Chunchang, et al. Pedogenesis characteristics and pedogenic environmental change of loess-paleosol sequences at Yun County in the upper reaches of the Hanjiang River[J]. *Journal of Desert Research*, 2014, 34(4): 992-997.
- [27] Lyu Houyuan, Han Jiamao, Wu Naiqin, et al. The magnetic susceptibility characteristic and the paleoclimatic implication of modern soil in China[J]. *Science in China (Series B)*, 1994, 24(12): 1290-1297.
- [28] Wen Qizhong. *Loess Geochemistry in China*[M]. Beijing: Science Press, 1989: 95-114.
- [29] Liu Tungsheng, Ding Zhongli. Chinese loess and the paleomonsoon[J]. *Annual Review of Earth and Planetary Sciences*, 1998, 26(1): 111-145.
- [30] Huang C C, Pang J L, Huang P, et al. High resolution studies of summer monsoon at the Loess Plateau during the last 150 ka[J]. *Science in China (Series D)*, 2002, 32(2): 130-138.
- [31] Gasse F, Arnold M, Fontes J C, et al. A 13000-year climate record from western Tibet[J]. *Nature*, 1991, 353(6346): 742-745.
- [32] Zhou W J, Donahue D J, Porter S C, et al. Variability of monsoon climate in east Asia at the end of the last glaciation[J]. *Quaternary Research*, 1996, 46(3): 219-229.
- [33] Wen Qizhong, Diao Guiyi, Jia Rongfen, et al. Geochemical records of paleoclimate change in loess sections[J]. *Quaternary Sciences*, 1995, 15(3): 223-231.
- [34] Zhang Zonghu, Wei Mingjian. Quantitative relationships between total Fe content in loess and climate parameters[J]. *Chinese Science Bulletin*, 1995, 40(13): 1219-1221.
- [35] Sun Jianzhong, Zhao Jingbo. *Quaternary in Loess Plateau*[M]. Beijing: Science Press, 1991: 1-355.
- [36] Sun Donghuai, An Zhisheng, Wu Xihao, et al. Evolution of the oldest cultivated soils in the southern Loess Plateau of China[J]. *Catena*, 2002, 47(1): 29-42.
- [37] Xiong Shangfa, Liu Dongsheng, Ding Zhongli. Phase difference between summer and winter paleomonsoon variations over East Asia and the tropical

Pacific forcing of monsoon evolution[J]. *Quaternary Sciences*, 1996, 16(3): 202-210.

[38] Li Yumei, Liu Dongsheng, Wu Wenxiang, et al. Paleoenvironment in Chinese Loess Plateau during MIS3: Evidence from Malan Loess[J]. *Quaternary Sciences*, 2003, 23(1): 69-76.

[39] Liu Xiuming, An Zhisheng, Qiang Xiaoke, et al. Magnetic research of the Neogene red clay and its palaeoclimatic significance from Gansu, NW China[J]. *Science in China (Series D)*, 2001, 31(3): 192-205.

[40] An Zhisheng, Kukla G, Porter S, et al. Magnetic susceptibility evidence of monsoon variation on the loess plateau of central China during the last 130000 years[J]. *Quaternary Research*, 1991, 36(1): 29-36.

[41] Sun Youbin, An Zhisheng. Variation of the East Asian winter monsoon recorded by Chinese Loess during the last four glacial-interglacial cycles[J]. *Earth Science*, 2002, 27(1): 19-24.

[42] Lu Huayu, An Zhisheng. Paleoclimatic significance of grain size of loess-paleosol deposition Chinese Loess Plateau[J]. *Science in China (Series D)*, 1998, 28(3): 278-283.

[43] Chang Hong, Zuo Hejun, Wang Haibing, et al. Multifractal features and their significances of surface sediments along both banks of the Yellow River reach in the Ulanbuh Desert[J]. *Arid Zone Research*, 2019, 36(6): 1559-1567.

[44] Cai Yingying, Li Jiyan, Qu Xin, et al. Grain size characteristics of earth forest sediments in the Datong Basin[J]. *Arid Zone Research*, 2021, 38(3): 892-900.

[45] Liu F, Tan W F, He J Z. Changes of clay mineral association after gradient magnetic separation[J]. *Pedosphere*, 1998, 8(1): 79-85.

[46] Ding Zhongli, Sun Jimin, Yu Zhiwei, et al. Paleoclimatic events in Chinese Loess Plateau during the last 130 ka BP[J]. *Chinese Science Bulletin*, 1998, 43(6): 567-574.

[47] An Zhisheng, Wu Xihao, Wang Pinxian, et al. China monsoon and global change[J]. *Science in China (Series B)*, 1991, 34(10): 1076-1081.

[48] Sun Y B, Wang X L, Liu Q S, et al. Impacts of post-depositional processes on rapid monsoon signals recorded by the last glacial loess deposits of northern China[J]. *Earth and Planetary Science Letters*, 2009, 289(1): 171-179.

[49] Jouzel J, Lorius C, Petit J R, et al. Vostok ice core: A continuous isotope temperature record over the last climatic cycle (160,000 years)[J]. *Nature*, 1987, 329(6138): 403-408.

[50] Dansgaard W, Johnsen S J, Clausen H B, et al. Evidence for general instability of past climate from a 250-kyr ice core record[J]. *Nature*, 1993, 364(6434): 218-220.

- [51] Yang Bao, Shi Yafeng, Braeuning A, et al. Evidence for a warm mid-Holocene climate in arid northwestern China during 40-30 ka BP[J]. *Quaternary Science Reviews*, 2004, 23(23-24): 2537-2548.
- [52] Feng Z D. Gobi dynamics in the Northern Mongolian Plateau during the past 20000 yr: Preliminary results[J]. *Quaternary International*, 2001, 76(8): 77-83.
- [53] Andreev Andrei A, Siebert Christine, Klimanov Vladimir A, et al. Late pleistocene and holocene vegetation and climate on the Taymyr lowland, Northern Siberia[J]. *Quaternary Research*, 2002, 57(1): 138-150.
- [54] Chen Xiaoyun, Wu Naiqin. Relatively warm humid climate recorded by mollusk species in the Chinese Loess Plateau during MIS3 and its possible forcing mechanism[J]. *Quaternary Sciences*, 2008, 28(1): 154-161.
- [55] Shi Yafeng, Jia Yulian, Yu Ge, et al. Features, impacts and causes of the high temperature and large precipitation event in the Tibetan Plateau and its adjacent area during 40-30 ka BP[J]. *Journal of Lake Sciences*, 2002, 14(1): 1-11.
- [56] Jia Yulian, Shi Yafeng, Ma Chunmei, et al. Comparison of palaeoclimatic evolution in Asian and African Monsoon areas since 40 ka BP and Pan lake period of Tibetan Plateau[J]. *Acta Geographica Sinica*, 2004, 59(6): 829-840.
- [57] Prell W L, Kutzbach J E. Monsoon variability over the past 150000 years[J]. *Journal of Geophysical Research*, 1987, 92(D7): 8411-8425.
- [58] Ding Z L, Liu T S, Rutter N W, et al. Ice volume forcing of East Asian winter monsoon variations in the past 80000 years[J]. *Quaternary Research*, 1995, 44(2): 149-159.
- [59] Shackleton N J, An Z, Dodonov A E, et al. Accumulation rate of loess in Tadjikistan and China: Relationship with global ice volume cycles[J]. *Quaternary Proceeding*, 1995, 4: 1-6.
- [60] Liu T S, Guo Z T, Liu J Q, et al. Variation of Eastern Asian monsoon over the last 140000 years[J]. *Bulletin de la Societe Geologique de France*, 1995, 166(2): 221-229.
- [61] Ao H, Dekkers M J, Xiao G Q, et al. Different orbital rhythms in the Asian summer monsoon records from North and South China during the Pleistocene[J]. *Global and Planetary Change*, 2012, 80(1): 51-60.
- [62] Berger A. Long-term variations of caloric insolation resulting from the Earth's orbital elements[J]. *Quaternary Research*, 1978, 9(2): 139-167.
- [63] Winograd I J. The magnitude and proximate cause of ice sheet growth since 35 000 yr BP[J]. *Quaternary Research*, 2001, 56(3): 301-307.
- [64] Barron E, Pollard D. High Resolution climate simulations of oxygen Isotope Stage 3 in Europe[J]. *Quaternary Research*, 2002, 58(3): 296-309.

- [65] Shi Y F, Yu G, Liu X D, et al. Reconstruction of the 30-40 ka BP enhanced India monsoon climate based on geological records from the Tibetan Plateau[J]. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 2001, 169(2): 69-83.
- [66] Laskar J, Robutel P, Joutel F, et al. A long-term numerical solution for the insolation quantities of the Earth[J]. *Astronomy & Astrophysics*, 2004, 428(1): 261-285.
- [67] Zhou Kunshu, Yan Fuhua, Ye Yongying, et al. Surface pollen assemblages of different vegetation zones in the northern slope of the Changbai Mountains. *Quaternary Pollen Analysis and Environment*[M]. Beijing: Science Press, 1984: 115-122.
- [68] Chen Yimeng, Rao Zhiguo, Zhang Jiawu, et al. Comparative study of MIS3 climatic features recorded in Malan Loess in the western part of the Loess Plateau and global records[J]. *Quaternary Sciences*, 2004, 24(3): 359-365.
- [69] Shi Yafeng, Zhao Jingdong. The special warm humid climate and environment in China during 40-30 ka BP: Discovery and review[J]. *Journal of Glaciology and Geocryology*, 2009, 31(1): 1-10.
- [70] Chen Xiaoyun, Wu Naiqin. Relatively warm humid climate recorded by mollusk species in the Chinese Loess Plateau during MIS3 and its possible forcing mechanism[J]. *Quaternary Sciences*, 2008, 28(1): 154-161.

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