Loess Record of Millennial-Scale Climate Events During the Last Glacial Period in the Linfen Basin: Postprint

Authors: Tian Qingchun

Date: 2022-09-26T16:43:27+00:00

Abstract

Optically stimulated luminescence dating was conducted on the Dingcun section in the Linfen Basin, and a grain-size age model was employed to reconstruct the regional chronostratigraphic sequence. Comparative analyses of climate proxy indicators including grain size, frequency-dependent magnetic susceptibility, and chromaticity were performed to characterize the manifestations and regional features of millennial-scale abrupt climate events in the Linfen Basin, revealing linkages between climate instability in the East Asian monsoon region since the Last Glacial Period and the North Atlantic region. The results indicate: (1) The median grain size and frequency-dependent magnetic susceptibility curves of the Dingcun section clearly record 5 Heinrich events and 19 Dansgaard-Oeschger (D-O) cycles between 80-20 ka BP. Among these, the H2 and H6 events exhibit the largest variation amplitudes and most pronounced signal changes, followed by the H5 event, with the H3 and H4 events showing the smallest variations, reflecting that the local climate is controlled not only by large-scale climate changes but also by regional climate dynamics. (2) The climate events recorded in the Dingcun section demonstrate good correspondence with the Greenland ice core $ $18O record, the Lijiayuan section in the western Loess Plateau, and the Zeketai and Tajikistan sections in the westerly zone. In conjunction with existing research, this indicates that the amplitude of rapid climate fluctuations in the monsoon region of China is jointly influenced by the westerlies and the East Asian summer monsoon.

Full Text

Preamble

ChinaXiv Cooperative Journal

Millennial-Scale Climate Events of the Last Glacial Period Recorded in Loess Deposits of the Linfen Basin

TIAN Qingchun[1,2], SHI Xiaojing[1], HAO Xiaolong[1]

[1]College of Geographical Sciences, Shanxi Normal University, Taiyuan 030000, Shanxi, China
[2]Academy of Chinese Early Civilization, Shanxi Normal University, Taiyuan 030000, Shanxi, China

Abstract: Global change represents a major focus of contemporary geographical research, with millennial-scale climate events during the last glacial stage constituting a key area of investigation. Optical stimulated luminescence (OSL) dating was conducted on the Dingcun section in the Linfen Basin, and a grain-size age model was employed to reconstruct the regional chronology. Comparative analysis of climate proxy indicators—including grain size, frequency-dependent magnetic susceptibility, and chromaticity—was performed to characterize the manifestation and regional features of abrupt millennial-scale climate events in the Linfen Basin, revealing linkages between climate instability in the East Asian monsoon region and the North Atlantic region since the last glacial period. Results demonstrate that: (1) The median grain-size and frequency-dependent magnetic susceptibility curves of the Dingcun section clearly record five Heinrich events and 19 Dansgaard-Oeschger cycles between 80–20 ka BP, with the most pronounced amplitude and signal changes observed for the H2 event, followed by H5, while H3 and H4 show the weakest signals. This pattern reflects that local climate was controlled not only by large-scale climate changes but also by regional climatic influences. (2) Climate events recorded in the Dingcun section exhibit excellent correspondence with the Greenland ice core δ^{18}O record, the Lijiayuan section in the western Loess Plateau, and the Zeketai and Tajikistan sections in the westerly-controlled region. (3) The amplitude of rapid climate fluctuations in China's monsoon region was jointly influenced by the westerlies and the East Asian summer monsoon.

Keywords: last glacial period; Heinrich events; Dansgaard-Oeschger cycles; Dingcun section; Linfen Basin

1. Study Area Overview

The Linfen Basin is situated in central-southern Shanxi Province and represents a Cenozoic faulted basin in the southern segment of the Shanxi Graben system. The basin divides the uplifted plateau into two parts, with the Lüliang Mountains to the west and the Zhongtiao and Taiyue mountains to the east, where most areas exceed 1000 m in elevation. The interior of the Linfen Basin is dominated by alluvial plains that primarily formed during the Quaternary period. The northern part of the basin consists of mountainous terrain, while the southern part comprises plains, with loess deposits from various geological periods distributed throughout the central region. These basin sediments contain rich paleoclimatic and environmental change information, providing reliable evidence for studying environmental evolution during geological history.

Dingcun is located in the southern part of the Linfen Basin (Fig. [Figure 1: see original paper]), at the foothills of the Ta'er Mountains. The area experiences a temperate monsoon climate characterized by hot, rainy summers and cold, dry winters. The mean annual temperature ranges from 9.0–12.9 °C, and the mean annual precipitation is approximately 420.1–550.6 mm. Precipitation is concentrated between June and September, with high interannual variability. Summer precipitation accounts for 70–80% of the annual total, while spring precipitation comprises only 10–15% of the yearly amount, creating a climate pattern of summer moisture and winter-spring aridity.

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2. Sample Collection and Processing

2.1 Sample Collection

The Dingcun section (35°49 45 N, 111°25 11 E) has a total thickness of 6.3 m. Samples were collected at 40 cm intervals, yielding 16 samples in total. Additionally, OSL samples were collected at irregular intervals using stainless steel tubes with a diameter of 4.5 cm. The lithology of the section is described as follows: 0–60 cm, loess layer, light yellow, porous, loose texture, relatively coarse grain size; 60–190 cm, weak paleosol layer, light brownish-yellow, compact texture, with white carbonate spots; 190–420 cm, loess layer, light yellow, loose texture, easily broken; 420–570 cm, paleosol layer, light reddish-brown, high clay content, well-cemented and compact, difficult to break, with white carbonate nodules; 570–630 cm, loess layer, light yellow, uniform texture, high silt content.

2.2 Laboratory Processing

Grain-size analysis was performed using a Mastersizer 2000 laser diffraction particle size analyzer with a measurement range of 0.02–2000 m and experimental error less than 1%. Samples of 0.2–0.3 g were treated with hydrogen peroxide to remove organic matter and heated until the solution cleared and no fine bubbles remained. Hydrochloric acid was then added to remove carbonates. After the solution boiled, distilled water was added to fill the container, which was left to stand for 24 hours. Before measurement, the supernatant was removed, sodium hexametaphosphate solution was added, and the sample was ultrasonicated for 5 minutes before instrumental analysis.

Magnetic susceptibility measurements were conducted using a MS2 magnetic susceptibility meter. Samples were pretreated and packed into standard magnetic susceptibility boxes. Both high-frequency (4.7 kHz) and low-frequency (0.47 kHz) magnetic susceptibility were measured in an undisturbed state, with each sample measured three times at each frequency and the average values calculated to determine frequency-dependent magnetic susceptibility.

Chromaticity analysis was performed using a CM-700d colorimeter with a color temperature of 6500 K and error less than 0.04, ensuring stable light source conditions. Detailed procedures followed those described in the literature.

OSL dating was conducted at the OSL Laboratory of Qinghai Normal University, with experimental procedures following established protocols. OSL dating determines the time elapsed since sediment was last exposed to sunlight. After burial, mineral grains accumulate radiation energy from surrounding radioactive elements (U, Th, K). This accumulated energy is reset to zero upon light exposure and subsequently rebuilds after burial. The OSL age represents the ratio of equivalent dose to environmental dose rate. Equivalent dose, representing the total radiation received since burial, is determined by comparing natural luminescence signals with those induced by known laboratory radiation doses. Environmental dose rate, or annual dose, represents the rate of radiation received under burial conditions and is calculated based on U, Th, and K content, water content, and cosmic ray contributions. Element concentrations were measured using neutron activation analysis. Water content was evaluated based on measured values and local precipitation variations. Cosmic ray contributions were calculated according to sampling location, altitude, and depth using formulas and parameters provided by Aitken (1998).

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3. Results and Analysis

3.1 Chronological Sequence Establishment

The chronological sequence for the Dingcun section was established using OSL dating data, with key age control points identified through comparison with standard loess-paleosol stratigraphy and marine oxygen isotope curves. The following control points were selected: the MIS2/3 boundary at 28 ka BP, the MIS3/4 boundary at 59.72 ka BP, the MIS4/5 boundary at 74.36 ka BP, and the MIS5/6 boundary at 129.3 ka BP. Median grain-size content was selected as the variable and incorporated into the grain-size age model to obtain the complete chronological sequence for the section (Fig. [Figure 3: see original paper]).

3.2 Climate Events Recorded in the Dingcun Section

Previous studies have discussed the climate evolution framework of the last interglacial period in this region. This paper focuses on analyzing unstable fluctuations in millennial-scale climate during the last glacial period. As shown in Fig. [Figure 4: see original paper], climate proxy indicators from the Dingcun section clearly record millennial-scale climate events. Heinrich cold events are characterized by coarser median grain size and decreased frequency-dependent magnetic susceptibility, while Dansgaard-Oeschger cycles correspond to finer grain size and increased magnetic susceptibility values. Comparative analysis reveals that median grain size and frequency-dependent magnetic susceptibility show particularly clear responses to millennial-scale climate events, while chromaticity indicators, though less pronounced than the former, still clearly reflect climate events with high variation frequency, sensitively capturing more subtle climate fluctuations.

The results also show that the Dingcun section records five Heinrich cold events between 80–20 ka BP. The H2 event exhibits the greatest amplitude and most obvious signal change, followed by H5, while H3 and H4 show the smallest signals. This suggests that regional climate was influenced not only by large-scale climate changes but also by local climatic conditions. The relatively high temperatures during MIS3 may have weakened the signals of these cold events. Additionally, the geographical location, topographic features, and regional climate of the Dingcun section may contribute to this pattern. Situated in a basin open to the north and south but closed to the east and west, the site experiences strong winter monsoon influence with minimal obstruction during glacial or cold periods, amplifying cold event signals. During interglacial or warm periods, increased summer monsoon influence raises temperatures and precipitation, partially weakening cold event signals.

The study also reveals that Dansgaard-Oeschger cycles show varying correspondence across different indicators at certain stratigraphic levels. For example, in some intervals, median grain-size changes appear earlier than magnetic susceptibility changes, and warm events show similar patterns, indicating asynchronous responses among environmental proxies to climate events. Research suggests that grain size is primarily controlled by wind transport, responding relatively directly to environmental changes with minimal influence from deposition time and conditions. In contrast, magnetic susceptibility is more strongly influenced by pedogenic processes that accumulate over time, resulting in a delayed environmental response compared to grain-size indicators.

Current research on the causes of millennial-scale climate events during the last glacial period remains a key focus. The thermohaline circulation (THC) hypothesis suggests that cold freshwater from melting ice in the northern North Atlantic and North Sea reduced surface water salinity, weakening North Atlantic Deep Water formation and decreasing northward heat transport via oceanic conveyor circulation, thereby cooling northern regions until temperature-driven density increases restored deep water formation. During relatively warm interstadial or interglacial periods, strong surface circulation transported warm water to the North Atlantic, enhancing deep water formation. During Heinrich events, massive IRD (ice-rafted debris) input further weakened or shut down deep water formation. Solar activity-driven hypotheses propose that centennial-scale solar variations may drive millennial-scale climate events, with studies showing good correspondence between North Atlantic ice-rafted debris content and primary solar activity cycles. Regardless of whether high-latitude ice volume, tropical convergence zone migration, or thermohaline circulation mechanisms are considered, the fundamental forcing ultimately derives from solar radiation. Therefore, we hypothesize that millennial-scale climate changes in the Linfen Basin during the last glacial period were primarily influenced by solar radiation, though more precise conclusions require further investigation of additional high-resolution regional geological records.

Comparison of climate indicator curves between the Linfen Basin and Greenland ice core δ^{18}O records reveals significant differences. Both records can be divided into three stages corresponding to marine oxygen isotope stages, indicating that millennial-scale climate instability in the Dingcun section was influenced by global ice volume changes. However, the fluctuation patterns differ substantially. Greenland ice core records show high-frequency variations, rapid transitions, and equal-amplitude oscillations during the last glacial period, whereas Linfen Basin proxy indicators exhibit neither high-frequency changes nor rapid transitions, with relatively small fluctuation amplitudes. This discrepancy likely relates to the basin's distance from winter monsoon source areas, low sedimentation rates, and the effects of strong post-depositional pedogenesis and leaching processes on paleoenvironmental records.

3.3 Regional Climate Event Comparison

Millennial-scale climate events recorded in grain-size and magnetic susceptibility indicators from the Dingcun section since the last glacial period show good correspondence with Greenland ice core isotope records. Coarsening events appear at approximately 23.9, 31.3, 37.5, 47.6, and 61.4 ka BP, consistent with the timing of Heinrich events in Greenland ice core δ^{18}O records. This similarity aligns with previous research interpreting these correlations through teleconnection mechanisms, suggesting that under the influence of westerly circulation and Siberian-Mongolian cold high pressure, strengthened East Asian winter monsoons correspond to the coldest periods recorded in Greenland ice cores. During these times, enhanced westerly circulation and winter monsoon forces coarsened grain sizes, demonstrating that North Atlantic ice-rafting events are clearly reflected not only in westerly-controlled regions but also in loess sequences of the East Asian monsoon-dominated Linfen Basin.

Comparative analysis of the Dingcun section in the southeastern Loess Plateau with the Lijiayuan section in the western Loess Plateau, the Zeketai section in Xinjiang, the Tajikistan section, and Greenland ice core δ^{18}O records reveals that all four loess sections record millennial-scale climate event signals from the last glacial period, suggesting that climate instability during this time may have global significance. However, specific manifestations differ among regions. On one hand, the timing of Dansgaard-Oeschger cycles recorded in each loess section cannot be precisely correlated, likely due to dating precision, control point selection, different age models, and unique regional climatic conditions. On the other hand, a gradual weakening trend in Dansgaard-Oeschger cycle amplitude exists from the North Atlantic to Central Asia and then to East Asia, with Tajikistan loess showing the most pronounced rapid climate fluctuations, followed by the Xinjiang Zeketai section, then the Lijiayuan section, and finally the Dingcun section. This pattern is also observed in other East Asian monsoon region sections. Studies comparing high-resolution loess records from Wangguan and Shagou sections with other Chinese loess sequences found that rapid climate fluctuations during the last glacial period gradually decreased in amplitude from west to east, likely resulting from combined westerly and East Asian summer monsoon influences. This suggests that North Atlantic climate signals were likely transmitted to the Loess Plateau via westerly circulation, but westerly migration, wind strength weakening, and East Asian monsoon system effects reduced the expression of millennial-scale climate signals in the Loess Plateau compared to Central Asia.

The study indicates that the intensity of millennial-scale climate events in the Linfen Basin differs from that in westerly and North Atlantic regions. The distance of Heinrich event transmission from the North Atlantic to East Asia results in varying regional climate fluctuation amplitudes, with event intensity in the East Asian monsoon region being weaker than in westerly and North Atlantic regions. For Dansgaard-Oeschger cycle research, the key is to explore East Asian summer monsoon influences while considering tropical ocean effects. While westerly-controlled regions are primarily influenced by westerly circulation with minimal tropical ocean impact, the Loess Plateau, especially the East Asian monsoon region, was dominated by the East Asian monsoon system during the last glacial period. Although summer monsoon forces were relatively weak, they were not negligible and partially offset westerly and winter monsoon effects, resulting in smaller Dansgaard-Oeschger cycle amplitudes in the Loess Plateau compared to westerly regions and Greenland. In summary, westerly regions are primarily controlled by westerly circulation, while monsoon regions are influenced by both westerlies and the East Asian summer monsoon, leading to stronger millennial-scale climate signals in westerly regions and weaker signals in monsoon regions. These changes are only evident between westerly and monsoon regions, not within the monsoon region itself, differing from some previous studies and requiring further investigation.

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4. Conclusions

Based on comparative analysis of climate proxy indicators from the Dingcun section in the Linfen Basin and millennial-scale climate events across different regions, the following conclusions are drawn:

1) Paleoclimate proxy indicators from the Linfen Basin record five Heinrich events and 19 Dansgaard-Oeschger cycles between 80–20 ka BP. The H2 event shows the greatest amplitude and most obvious signal change, followed by H5, while H3 and H4 exhibit the smallest signals. Elevated temperatures during the MIS3 stage and unique regional climatic characteristics may have weakened the recording of these cold events.

2) Climate events recorded in the Linfen Basin show excellent correspondence with Greenland ice core $\delta^{18}O$ records, indicating that the regional loess contains information about North Atlantic ice-rafting events and correlates with paleoclimate changes recorded in Greenland ice cores.

3) Millennial-scale climate events in the Linfen Basin demonstrate good consistency with records from the Lijiayuan section in the Loess Plateau, the Zeketai section in Xinjiang, the Tajikistan section, and Greenland ice core $\delta^{18}O$ records. In terms of variation intensity, the closer to the summer monsoon activity region, the weaker the event signal and expression, indicating that rapid climate fluctuation amplitudes in the East Asian monsoon region are jointly influenced by westerly circulation and the East Asian summer monsoon.

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