Grain Size Component Separation of Zeketai Loess and Its Imprint of Last Glacial Climate Fluctuations

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Date: 2018-11-13T00:00:00+00:00

Abstract

Climate fluctuations during the Last Glacial Period in the North Atlantic region have been widely documented globally. The Ili region, as a marginal zone transitioning from the westerlies to the monsoon region, is sensitive to climate change, yet how millennial-scale climate fluctuations affected this area remains to be further addressed. Loess, as an important geological archive for paleoclimate reconstruction, is conducive to investigating the aforementioned issues. This study conducted grain-size end-member analysis on loess deposits from the Zeketai section in the Ili region, and the results indicate that the grain size of the Zeketai loess can be divided into four end-members: EM1 (0.8 m), EM2 (8 m), EM3 (25.1 m), and EM4 (51.6 m). EM1 represents the pedogenic component; EM2 represents the upper-level westerly component; EM3 and EM4 represent dust storm components, but the EM4 component better reflects the expansion of the Siberian High in the Ili region during the Last Glacial Period. Both EM2 and EM4 can record millennial-scale climate fluctuations, but their response magnitudes differ: during 51.3–20 ka, millennial-scale climate events are more distinctly recorded in the variation curve of EM4 content; however, after 20 ka, such events become more prominent in the variation curve of EM2 content. This suggests that both the westerlies and the Siberian High serve as important diffusion mechanisms for millennial-scale climate signals, and the cause of the aforementioned differences is likely changes in Northern Hemisphere ice volume driven by solar radiation.

Full Text

Preamble

DOI: 10.12118/j.issn.1000-6060.2018.06.13
Journal: ARID LAND GEOGRAPHY (ChinaXiv Partner Journal)

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1. Introduction

Millennial-scale climate changes such as Dansgaard-Oeschger (DO) cycles [?] and Heinrich (H) events [?] are well-documented in the North Atlantic region. These events are characterized by temperature fluctuations of approximately 16°C [?] and have been recorded in various archives including marine sediments, ice cores, loess-paleosol sequences, and speleothems [?]. Previous studies have demonstrated that these abrupt climate changes significantly influenced the climate of the Ili region in Central Asia [?], with the Siberian High pressure system playing a crucial role in dust storm activity [?]. However, the specific mechanisms by which these millennial-scale fluctuations affected the region require further investigation.

The Zeketai loess section, located in the Ili Basin of Xinjiang, China (43°32 13 N, 83°18 51 E, 894 m elevation), provides an excellent archive for studying these climate dynamics. The section has a total thickness of 20.35 m and was sampled at 5 cm intervals, yielding 407 samples. The upper 12 m of the profile, which encompasses the last glacial period, was selected for detailed grain-size analysis. The modern climate of the region is characterized by a mean annual temperature of 8.1°C and annual precipitation of 480 mm, with prevailing westerly winds.

End-member modeling of the grain-size distribution reveals four distinct components with modal sizes of 0.8 m (EM1), 8 m (EM2), 25.1 m (EM3), and 51.6 m (EM4). EM1 represents a pedogenic component, EM2 reflects upper-level westerly wind activity, while EM3 and EM4 correspond to dust storm events. Notably, EM4 is particularly sensitive to the expansion of the Siberian High pressure system over the Ili region during glacial periods.

5.2 Zeketai End-Members and Paleoclimatic Interpretation

The four end-members exhibit distinct climatic signatures. EM1 (0.8 m) represents fine-grained pedogenic material, EM2 (8 m) tracks upper-level westerly wind strength, and EM3 (25.1 m) and EM4 (51.6 m) reflect dust storm intensity. EM4 shows a particularly strong correlation with the expansion of the Siberian High pressure system.

Both EM2 and EM4 record millennial-scale climate fluctuations, but their responses differ significantly. During Heinrich events, EM4 content increases while EM2 content decreases. This pattern reflects the mechanism whereby increased ice volume in the Northern Hemisphere during cold events strengthened the Siberian High, which then expanded into the Ili region, generating large-scale dust storms. Under westerly wind transport, this dust accumulated on the north bank of the Gongnaisi River. The blocking effect of the Qinghai-Tibet Plateau divides the westerly belt into two branches during winter, with the main axis lying south of the Himalayas, thereby weakening the direct influence of westerlies on the region.

During the period 51.3–20 ka, millennial-scale events are more clearly expressed in the EM4 record. After 20 ka, the Younger Dryas (YD) and H1 events are more prominent in the EM2 record. This temporal divergence suggests that both the Siberian High and westerly winds served as important mechanisms for transmitting millennial-scale climate changes, with their relative influence varying over time. The shift likely reflects changes in global ice volume driven by orbital-scale solar insolation variations, though regional factors also influenced grain-size variations at Zeketai.

[Figure 6: see original paper] shows comparisons between Zeketai end-members and previous research, including correlations with DO cycles (DO 4, 5, 7, 8, 11) and Heinrich events (H2 at 24 ka, H3 at 28 ka, H4 at 40 ka, H5 at 49 ka). The EM4 record exhibits a bimodal grain-size distribution similar to that described by Sun et al. [?], with modes at 9 m and 51.6 m. The coarser mode (51.6 m) is particularly effective at recording dust storm events associated with Siberian High expansion.

[Figure 7: see original paper] compares EM2 and EM4 content variations with other climate records, including (a) 65°N summer insolation [?], (b) NGRIP ^{1} O [?], and (c–d) Zeketai grain-size records. The data demonstrate that EM2 and EM4 provide complementary records of millennial-scale climate variability, with EM4 being more sensitive to earlier glacial events and EM2 capturing later deglacial events more clearly.

6. Conclusions

This study yields three main conclusions:

(1) The Zeketai loess section contains four end-members with modal sizes of 0.8 m (EM1), 8 m (EM2), 25.1 m (EM3), and 51.6 m (EM4). EM1 represents pedogenic processes, EM2 reflects upper-level westerly winds, and EM3–EM4 represent dust storm events. EM4 is particularly effective at recording Siberian High expansion during the last glacial period.

(2) EM2 and EM4 both record millennial-scale climate fluctuations, but with different temporal responses. During 51.3–20 ka, climate events are more clearly expressed in EM4; after 20 ka, the YD and H1 events are more prominent in EM2. This indicates that both Siberian High expansion and westerly wind changes were important mechanisms for transmitting millennial-scale climate signals.

(3) The differential response of EM2 and EM4 likely reflects orbitally-driven changes in global ice volume and solar insolation, modulated by regional

factors such as the Qinghai-Tibet Plateau’ s influence on atmospheric circulation patterns.

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