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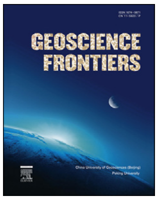

Research paper

Heinrich events recorded in a loess–paleosol sequence from Hexigten, Inner Mongolia

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A B S T R A C T

We describe the last glaciation climatic history Marine Isotope Stage (MIS, 2 to 4) from 66.7 to 14.5 ka in Hexigten, northeast Inner Mongolia, North China. The climate of the region experienced frequent and significant fluctuations between dry-cold and less dry-cold during the late MIS4. The climate was generally warm and humid during early MIS3 (MIS3c) and late MIS3 (MIS3a), whereas it was cold and dry in middle MIS3 (MIS3b) and during MIS2. In this study, the cold and dry conditions were correlated with a stronger East Asian winter monsoon and strong dune activity; whereas, warm and humid conditions were related to a stronger East Asian summer monsoon (EASM) and weak dune activity. This study establishes six distinct dry and cold intervals during the last glacial period (66.7–14.5 ka) based on optically stimulated luminescence data, multi-proxies record (magnetic susceptibility, grain size analysis, Rb/Sr, SiO_2/TiO_2) and chemical index of alteration (CIA). The last glacial period may be correlated with Heinrich events 1 to 6 which were further confirmed by comparison with the Hulu cave stalagmites and Greenland ice core records. It is concluded that the study area was substantially affected by the EASM, as compared with the loess–desert transition zone of the Chinese Loess Plateau, especially in MIS3c and suggested that the East Asian monsoon played a pivotal role in the last glacial period climate and dune activity.

1. Introduction

Instability of the East Asian monsoon (EAM) has been recorded during the last glacial period (An et al., 1994), and some millennial-scale events, such as Heinrich events, have been documented (Heinrich, 1988; Bond et al., 1992). Heinrich events are of great interest because they provide clear evidence of abrupt climate change during the last glacial period (Heinrich, 1988; Broecker, 1994; Hemming, 2004). These remarkable climatic changes offer great opportunities for understanding and modeling the response of the climate system to large boundary changes in ice-sheet dynamics and reorganizations of the ocean-atmosphere system (Sun et al., 2016). The abrupt climatic events are well preserved in the North Atlantic and Greenland ice-core records. Much effort has gone into characterizing the Heinrich events in the monsoon regions. For example, Heinrich events 1 and 2 have been found in the Loess Plateau and South China Sea (Lü et al., 1996). Hulu Cave record shows six intervals characterized by high $\delta^{18}O$ values, which have been correlated with Heinrich events H1 to H6 (Wang et al., 2001). Recently, laminated sedimentary sequence of Lake Xiaolongwan indicated two cold periods at 17.3–17.7 ka and 16.5–16.1 BP (Before Present) that could be associated with the Heinrich event-1a and the Heinrich event-1b (Sun et al., 2016). The changes in the monsoon system may be closely related to global ice volume variations (Liu and Ding, 1998), and the ice volume variation more directly influenced the monsoon climate during the last glacial period than did the orbital solar insolation (Lu and Zhou, 1996). To understand the influence of future climate change, the study on EAM fluctuations during the last glacial period is very important.

Many inland deserts occur in the north of China, such as Badain Jaran Desert, Tengger Desert, Mu Us Desert, Otindag Sandy Land, and Horqin Sandy Land. There are loess–desert transition zones between some deserts like the Chinese Loess

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plateau (CLP) and Hexigten, northeast Inner Mongolia (study area) in North China. Chinese loess and deserts are a coupled system (Liu, 1985; Ding et al., 1999a); loess has its origin in Chinese deserts (Nakano et al., 2004; Yokoo et al., 2004). Therefore, the climate is sensitive in the loess–desert transition zone. There is a close relation between the EAM changes and expansion–contraction of deserts (Ding et al., 1999b, 2005; Xu et al., 2007): desert expansion and contraction may be forced by the EAM (Sun and Ding, 1998).

The study area is located in a special geographical division, between the Northeast China and North China, and belongs to climate sensitive zone near the boundary of semi-humid and arid to semi-arid climate. Compared with the loess–desert transition zones of the CLP, the study area is much closer to the ocean, and the East Asian summer monsoon (EASM) probably had a much greater influence on this area. Most of the previous studies have focused on the Holocene (Lu et al., 2005, 2011, 2012; Zhou et al., 2008; Yang et al., 2010; Gong et al., 2013; Mu et al., 2014) than the last glaciation (Xie and Ding, 2007; Yi et al., 2012). In this study, we describe a last glaciation climate record, with chronological framework by optically stimulated luminescence (OSL), investigated by magnetic susceptibility (MS), grain size analysis and Rb/Sr ratio from loess sediments in Inner Mongolia, North China. We use SiO_2/TiO_2 ratios and the chemical index of alteration (CIA) (Liu et al., 1995, 2013; Qiang et al., 2010) data to decipher the history of EAM variations since the last glaciation in the study area.

2. Study area

The study area (Fig. 1) is located in Jingpeng Town, Hexigten, Inner Mongolia, North China. The topography is higher in the west and lower in the east. Sandy land and grassland cover the central and northern parts of the area respectively. The region is located at the junction of the Otindag and Horqin Sandy Lands. The western grassland and the lava plateau in the south intermingle with northern hilly mountains at Hexigten. The average elevation is 1100 m, with a temperate continental monsoon climate. The mean annual temperature is 1–4 °C, and the annual rainfall is 250–500 mm (Wei and Han, 2009). The mean and minimum temperatures in January, the coldest month, are −16.8 and −36.7 °C, respectively, and the average and maximum temperatures in July, the hottest month, are 20.1 and 37.8 °C, respectively (Wei and Han, 2009). The area divides the geological landforms and climate between Northeast and North China and has records the edge of the ancient monsoon. Therefore, the area is highly sensitive to environmental changes.

3. Materials and methods

In July 2012, a 24.7 m long loess–soil sequence sediment, the Jingpeng section, was discovered in Hexigten, southeast Inner Mongolia, North China. The section is located at 43°17′42.14″N, 117°31′48.59″E, at an elevation of 1076 m (Fig. 1). The upper part of the section shows a layer of weaker paleosol and two layers of weak paleosol in lower part (Fig. 2). Because of disturbance in the top layer of the soil, the sampling started only from a depth of 1.2 m. Four hundred and thirty-three samples were collected at different depths of the Jingpeng section. The samples were subjected to OSL dating, grain size analysis, MS analysis, and geochemical analysis.

OSL dating of eight samples were performed at the Luminescence Laboratory of the Institute of Crustal Dynamics, China Earthquake Administration. The samples were measured using automatic Risø DA-20-TL/OSL instruments. After removing the 20 cm thick surface soil, the eight OSL samples were collected by hammering stainless steel tubes into aeolian sediments and sealed immediately after extraction. While comparing Simplified Multiple Aliquot Regenerative (SMAR) and Simplified Aliquot Regenerative (SAR) methods of dating, it is observed that the SAR method may give underestimated age value (Wang et al., 2005). Thus, we chose the SMAR method to obtain the age. To determine the environmental dose rate various factors and corrections were followed (Aitken, 1998). In this study, the U, Th, and K contents were determined using a plasma mass spectrometer. The sample depths, OSL ages, ED values, and the dose rates data are presented in Table 1.

Most of the samples collected from the last-glacial loess (L_1) at 5 cm and 10 cm intervals were used for grain-size and MS analyses. The grain size distributions of 433 samples were determined using a laser grain-size analyzer Malvern Mastersizer 2000. Prior to grain-size measurement, all the bulk samples were pretreated with 10% H_2O_2 to remove organic matter, subsequently, with 10% HCl to remove carbonates (Lu and An, 1998). The solution was heated to remove the excess HCl and deionized water was added after cooling. The pH was then measured approximately 24 h after the addition of deionized water. The step was repeated until the pH became neutral. Before the test, ultrasonic pretreatment (with addition of 0.05 mol $(NaPO_3)_6$ solution) was performed to ensure full dispersion of the samples. The measurement range of the Malvern Mastersizer 2000 is 0.02–2000 μm diameter. Low-frequency (0.47 kHz) MS was measured with a Bartington MS2 meter.

Geochemical analyses (Rb, Sr, SiO_2, Al_2O_3, Na_2O, K_2O, and Ti) of two hundred and thirteen samples were carried using an X-ray fluorescence (XRF) spectrometer at Institute of Geophysical and Geochemical Exploration, Chinese Academy of Geological Sciences.

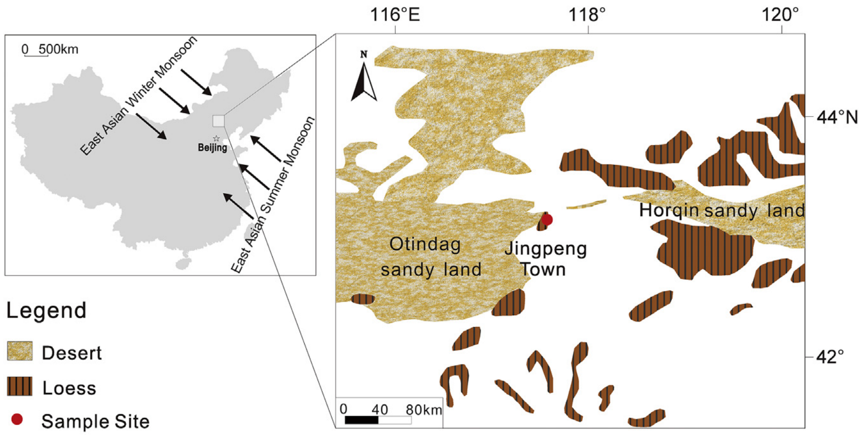

Figure 1. Location map of the Jingpeng section in North China.

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