Palaeogeography, Palaeoclimatology, Palaeoecology 459 (2016) 440–452

Contents lists available at ScienceDirect

Palaeogeography, Palaeoclimatology, Palaeoecology

journal homepage: www.elsevier.com/locate/palaeo

Early Holocene multi-centennial moisture change reconstructed from lithology, grain-size and chemical composition data in the eastern Mu Us desert and potential driving forces

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ARTICLE INFO

Article history:
Received 19 September 2015
Received in revised form 22 July 2016
Accepted 26 July 2016
Available online 28 July 2016

Keywords:
Mu Us desert
Early Holocene
Grain-size analysis
Elemental compositions
Solar forcing
Moisture change

ABSTRACT

The sequence of paleo-aeolian sands and sandy paleosols from the Shenmu section in the eastern Mu Us desert was used to reconstruct the history of moisture change during the early Holocene. Analyses of lithologies, grain-size distributions and elemental compositions revealed that the early Holocene climate in the eastern Mu Us desert experienced at least seven multi-centennial oscillations between humid and arid episodes. Four humid episodes occurred at 10,800 to 10,200 cal. (calendar) yr BP, 9800 to 9400 cal. yr BP, 8900 to 8300 cal. yr BP and 8000 to 7700 cal. yr BP. Three arid episodes occurred at 10,200 to 9800 cal. yr BP, 9400 to 8900 cal. yr BP, and 8300 to 8000 cal. yr BP. These humid-arid oscillations were representative of multi-centennial fluctuations in the history of waxing and waning of the East Asian summer monsoon (EASM) and the East Asian winter monsoon (EAWM) in the eastern margin of the Mu Us desert. Comparisons with other climate records based on pollen-based annual precipitation (PANN) reconstructed from Gonghai Lake and the stalagmite $\delta^{18}O$ records from Dongge cave, southern China, supported certain influences of the Indian summer monsoon on moisture variations in the eastern margin of the Mu Us desert. Our results also revealed a possible climatic connection between the variability of the East Asian winter monsoons and air temperature changes at high latitudes in the northern hemisphere and North Atlantic thermohaline circulation during the early Holocene. The similarity between early Holocene climate evolution in the eastern Mu Us desert and several proxies ($\Delta^{14}C$ residuals, sunspot numbers, spectral analysis of grain-size and elemental compositions) supports the hypothesis that variations in solar insolation are a major external force responsible for East Asian Monsoon variations at the multi-centennial scale during the early Holocene.

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1. Introduction

The early Holocene is defined as the period from 11,650 to 7000 cal. (calendar) yr BP (Walker et al., 2009; Smith et al., 2011). Much past research has been conducted on the early Holocene climate; its major features can be described as follows: rising atmospheric temperatures and sea levels, increasing rainfall in sub-tropical regions, melting of glaciers, shrinkage of desert and tundra regions, and spread of forest ecosystems to cover a much larger area (Hoek and Bos, 2007; Lang et al., 2010; Smith et al., 2011; Törnqvist and Hijma, 2012; Larsen et al., 2014). Moreover, a large number of high-resolution paleoclimatic records have shown that the early Holocene was a climatologically unstable period with several rapid, high-amplitude climate oscillations (Alley et al., 1997; NGRIP members, 2004; Wiersma and Renssen, 2006; Rasmussen et al., 2007; Berner et al., 2010; Lang et al., 2010; Hou et al., 2012; Zelanko et al., 2012). At least two separate early Holocene climate oscillations, the "Preboreal Oscillation" and an 8.2 ka cold event, were clearly recognized from various proxy records (Alley et al., 1997; NGRIP members, 2004; Rasmussen et al., 2007; Lang et al., 2010; Zelanko et al., 2012). In addition to these events, other early Holocene climate events such as short events at approximately 10.7, 10.3, and 9.5 ka BP were recognized from terrestrial and marine records (Bond et al., 1997; von Grafenstein et al., 1999; McDermott et al., 2001; Rasmussen et al., 2007; Hoek and Bos, 2007; Bamberg et al., 2010; Gavin et al., 2011). Similar climate oscillation events during the early Holocene have also been reconstructed from speleothems, peats, and ice cores in China (Wang et al., 2002, 2005; Zhou et al., 2002). However, the causes of early Holocene climate variation are not known with certainty. Two forcing mechanisms have been suggested as possible factors: freshwater forcing (changes in the thermohaline circulation) and solar forcing

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http://dx.doi.org/10.1016/j.palaeo.2016.07.035
0031-0182/© 2016 Published by Elsevier B.V.

(Barber et al., 1999; Van et al., 2001; Ineson et al., 2011). Therefore, more well-dated proxy records are required to determine the relative importance of these mechanisms and improve our understanding of the mechanisms behind the climate evolution during the early Holocene.

The desert-loess boundary is a transitional region between desert and loess regions of northern China that provides one source of such proxy records (Jin et al., 2001; Zhou et al., 2002; Peng et al., 2005; Chen et al., 2015; Liu et al., 2015). This region is also a representative agro-pastoral transitional zone and has a fragile ecological environment. Therefore, it exhibits significant spatial and temporal instability in its response to climatic changes and is an ideal region in which to study paleoclimate (Lu et al., 2005; B.S. Li et al., 2007; S.H. Li et al., 2007; Li et al., 2014; Mason et al., 2009; Zhou et al., 2009; Jia et al., 2015). In this region, the widespread aeolian deposits and intercalated sediments (including lacustrine facies, peats, and paleosols) have recorded a long history of changing environmental conditions under the influence of the Asian monsoons (An, 2000; Jin et al., 2001; Porter, 2001; B.S. Li et al., 2007; S.H. Li et al., 2007; Wen et al., 2009; Chen et al., 2015; Liu et al., 2015). Dozens of studies of natural geological sections have shown widespread multilayers of sandy paleosols interbedded with aeolian dune sands during the Holocene. For example, there are three or four layers of paleosol units in the sandy lands of northeastern China, four or five layers in the Mu Us Sandy Land and the Hunshandake (Otindag) Sandy Land, and more than four layers in the Qinghai Lake region and the Gonghe Basin of Qinghai Province (Jin et al., 2001; Lu et al., 2005; Porter and Zhou, 2006; Mason et al., 2009; Li et al., 2014; Jia et al., 2015). These sequences of sandy paleosols and aeolian dune sands provide direct evidence of the desert's expansions and contractions and related moisture changes over geological time periods (Jin et al., 2001; Porter and Zhou, 2006; B.S. Li et al., 2007; S.H. Li et al., 2007; Wen et al., 2009; Liu et al., 2014).

In this paper, we report the results of a study of the Shenmu section, which appears to have the largest number of layers of paleosols from the early Holocene in the deserts of China. We will mainly synthesize the data on lithology, chronology, grain-size distributions, and elemental compositions to reconstruct the multi-centennial-scale moisture changes and then discuss the possible driving forces by linking our data with other climatic records in the northern hemisphere during the early Holocene.

2. Study area

The Mu Us desert (Fig. 1) (37°27′–39°22′ N, 107°20′–113°30′ E) lies on the northwestern margin of the modern Asian summer monsoon and covers an area of ca. 42,200 km^2 (Liu et al., 2014). The ground surface is dominated by semi-fixed, fixed, and mobile dunes, of which the semi-fixed and fixed dunes consist of the honeycomb dunes and several vegetated dunes, and the mobile dunes are composed of crescent dunes and chains of sand dunes (Liu et al., 2014).

Our study area is located in the eastern margin of the Mu Us desert and the northwestern fringe of the Loess Plateau, which belongs to the Shenmu county of Shaanxi Province based on the administrative division. Geomorphologically, it is also located in the transition zone from desert to loess hill and gully with an elevation range of 800 to 1800 m a.s.l. (Liu et al., 2013). A few scattered outcrops of Mesozoic and Paleogene-Neogene strata appear throughout the region. These consist of thick layers of sandstone, mudstone, and sandy mudstone (Liu et al., 2013). The soil types include light chestnut soils, brown calcic soils under the dry steppes, and sandy black loams under the desert steppes (Jin et al., 2001).

According to the instrumental records in the county, annual meteorological data (Li et al., 2010; Wu, 2013) show that the county has a warm-temperate continental monsoon climate dominated by the

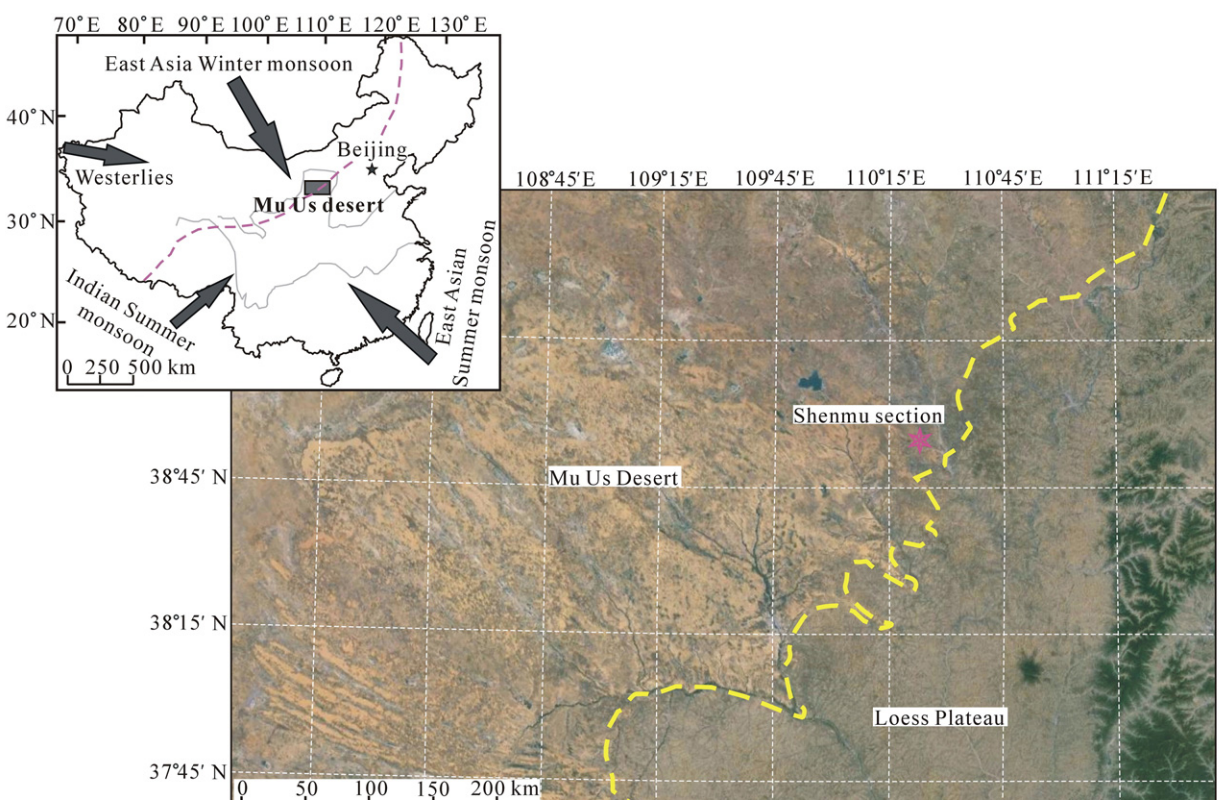

Fig. 1. Map of the Mu Us desert and the sampling site and major atmospheric circulation regimes in China. The modern Asian summer monsoon limit in the upper left corner is shown by the red dashed line (after Gao, 1962). Shaded arrows represent the dominant circulation systems of the East Asian summer monsoon, the East Asian winter monsoon, the Indian Summer monsoon, and Westerlies. The yellow dashed line defines the boundary between the Mu Us desert and the northwestern fringe of the Loess Plateau. The red asterisk denotes the location of the Shenmu section.

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