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Iron oxide characteristics of mid-Miocene Red Clay deposits on the western Chinese Loess Plateau and their paleoclimatic implications

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ABSTRACT

The middle Miocene climate optimum (MMCO, 14.3–16.3 Ma) was a warm climatic interval that may provide an analog for future climates in the context of ongoing global warming. In continental regions, however, reconstruction of the MMCO remains controversial due to the lack of robust proxies from continuous sedimentary sequences. In this study, we investigated the composition and relative abundance of pedogenic iron oxides in the Zhuanglang Red Clay deposits from the western Chinese Loess Plateau, using rock magnetic, color reflectance, and geochemical analyses. Our aim was to assess the climatic sensitivity of iron oxides in order to produce robust proxies for reconstructing regional temperature and moisture relationships during the MMCO. Our results indicate that the MMCO in the study region was characterized by high effective precipitation, relatively high temperature and strong pedogenesis, suggesting a strong East Asian summer monsoon (EASM). The strengthening of the EASM intensity during the MMCO is consistent with records of enhanced terrigenous chemical weathering in the South China Sea, and the occurrence of a relatively warm and humid climate on a global scale, implying the strong coupling between Asian monsoon evolution and global climate change during the middle Miocene. In addition, the magnetic susceptibility record of the Zhuanglang Red Clay demonstrates that eccentricity played the dominant role in controlling the EASM during the MMCO.

1. Introduction

Earth's climate has experienced numerous significant warming and cooling events during the Cenozoic (Zachos, 2001). Approximately 14.3–16.3 Ma ago, an intriguing warming event, the so-called Middle Miocene Climate Optimum (MMCO), occurred during the overall stepwise cooling trend of Neogene climate (Zachos et al. 2008). Since it is a global warming event unrelated to human activity (e.g., Flower and Kennett, 1994; Zachos, 2001; Holbourn et al., 2007; You et al., 2009; Sun and Zhang, 2008), study of the MMCO may potentially increase our understanding of natural climatic variability and thereby aid predictions of future climate change in the context of ongoing global warming. Flower and Kennett (1994) estimated that the sea surface temperature at high latitudes was about 6 °C warmer than present during the MMCO, and that it was probably the warmest interval during the past 35 Ma. In addition, climate simulations suggest that the global annual mean surface temperature was 18.4 °C at 15 Ma, about 3 °C higher than today (You et al., 2009). Moreover, it has been suggested that during the MMCO tropical vegetation extended polewards (Cosgrove et al. 2002) and the East-Antarctic ice-sheet was smaller than today (Pekar and DeConto 2006).

The coupled monsoonal-arid environment in East Asia is an important subsystem that is dynamically linked to the global climate system (An, 2014), which interacts with global climatic conditions. Although the Miocene climate has been widely studied on a global scale (e.g., Miller et al., 1987; Lear et al., 2000; Zachos, 2001, Zachos et al., 2008), our knowledge of the relationship of the MMCO to the East Asian monsoon system is generally limited to records of pollen and mammal fossils (e.g. Ma et al., 1998; Deng, 2004; Jiang and Ding, 2008; Sun and Zhang, 2008). More importantly, the evolutionary history of the mid-Miocene climate in monsoonal-arid Asia remains controversial. For example, the East Asian summer monsoon (EASM) is interpreted to have weakened during the middle Miocene based on color (a^*/L^*) and soil micromorphology analyses of the Qin'an Red Clay sequences (Guo, 2010), and on the mineralogical composition of the ZL Red Clay core (Sun et al., 2015). However, the dominance of broad-leaved forest within the regional vegetation suggests intensified precipitation within the

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East-Asian monsoon-arid region during the MMCO (Hui et al., 2011). Therefore, in order to better understand the intensity and dynamics of the East Asian monsoon system during the middle Miocene, it is necessary to conduct additional studies of climatically-sensitive proxies retrieved from long and continuous eolian sequences.

The eolian deposits of the Chinese Loess Plateau (CLP), which covers an area of ~440,000 km^2 over the middle latitudes of the Northern Hemisphere (Fig. 1), provide a unique terrestrial record of past climate and environmental changes for the East-Asian monsoon-arid region since the late Oligocene (e.g., Liu, 1985; Liu and Ding, 1998; An, 2000; Guo et al., 2002; Qiang et al., 2010). Recently, an eolian Red Clay drill core of Late Cenozoic age was obtained from Zhuanglang (ZL), in the Western Chinese Loess Plateau. Palaeomagnetic results show that the Red Clay deposits were formed since as early as 25.6 Ma, suggesting that the coupled monsoonal-arid environmental system in East Asia formed by at least the late Oligocene to early Miocene (e.g. Guo et al., 2002, 2008; Qiang et al., 2010). It is widely recognized that the morphology, composition, and iron oxide content of soils is controlled mainly by the degree of pedogenic weathering, which in turn is closely associated with monsoon intensity (e.g. Heller et al., 1993; Maher and Thompson, 1995; Guo et al., 1998; Maher et al., 2002, 2003; Maher and Hu, 2006; Ding et al., 2001; Liu et al., 2012). However, the characteristics of the iron oxides and their related proxies in the Miocene Red Clays have been rarely studied (Hao et al., 2009, 2012).

In this study, the composition and relative abundance of pedogenic iron oxides in the ZL Red Clay sequence covering the interval from 12 to 18 Ma were investigated using rock magnetic, optical spectroscopy, and geochemical analyses. Our aim was to assess the possible relationships between iron oxides and climatic parameters, and subsequently

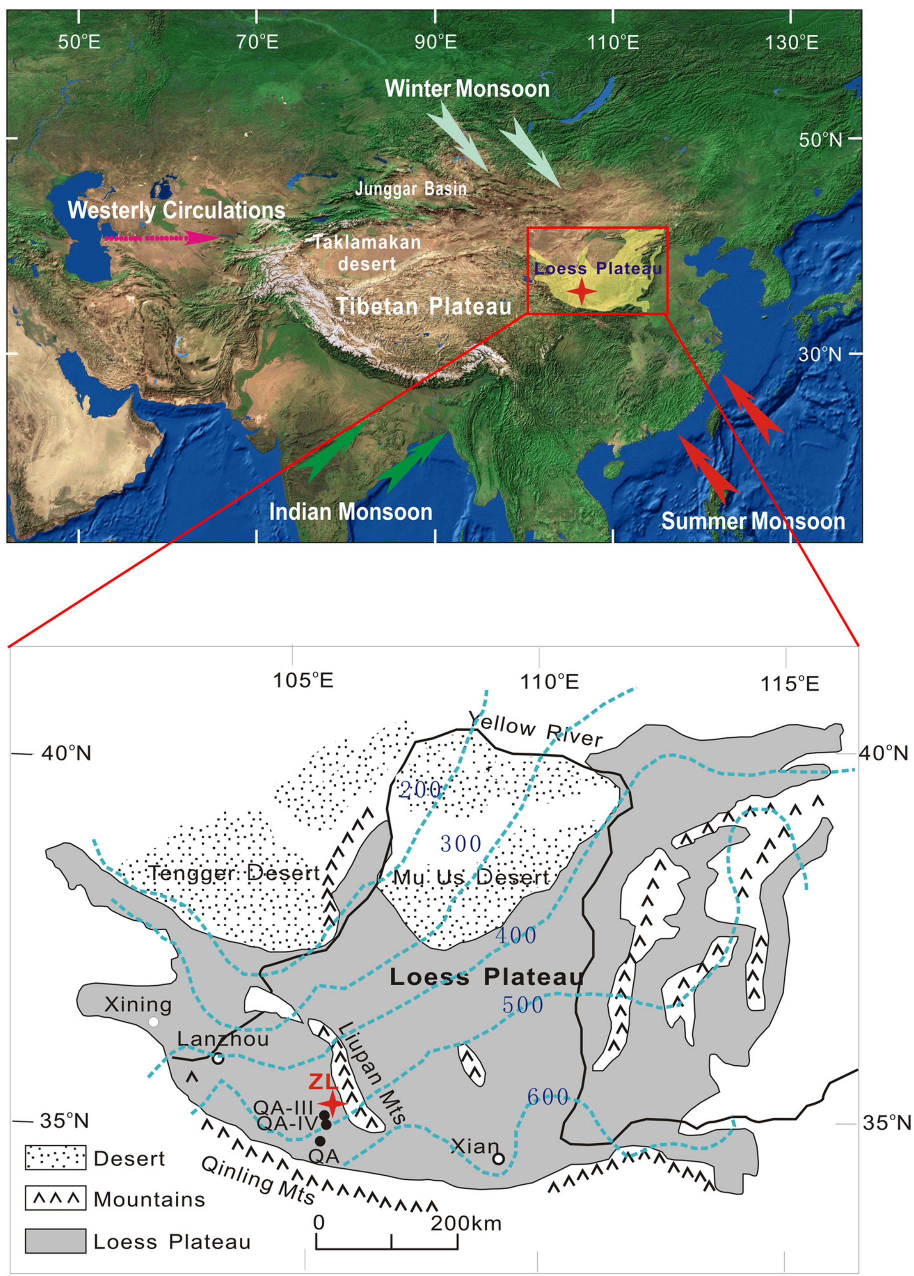

Fig. 1. Location of the ZL drill core (red star) and referenced profiles (solid black dots) on the Chinese Loess Plateau (gray-shaded area), and the atmospheric circulation system over China (after Qiang et al., 2010). Blue dotted lines are the isohyets (units: mm). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)