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Mineralogical evidence of reduced East Asian summer monsoon rainfall on the Chinese loess plateau during the early Pleistocene interglacials

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ABSTRACT

The East Asian summer monsoon (EASM) is an important component of the global climate system. A better understanding of EASM rainfall variability in the past can help constrain climate models and better predict the response of EASM to ongoing global warming. The warm early Pleistocene, a potential analog of future climate, is an important period to study EASM dynamics. However, existing monsoon proxies for reconstruction of EASM rainfall during the early Pleistocene fail to disentangle monsoon rainfall changes from temperature variations, complicating the comparison of these monsoon records with climate models. Here, we present three 2.6 million-year-long EASM rainfall records from the Chinese Loess Plateau (CLP) based on carbonate dissolution, a novel proxy for rainfall intensity. These records show that the interglacial rainfall on the CLP was lower during the early Pleistocene and then gradually increased with global cooling during the middle and late Pleistocene. These results are contrary to previous suggestions that a warmer climate leads to higher monsoon rainfall on tectonic timescales. We propose that the lower interglacial EASM rainfall during the early Pleistocene was caused by reduced sea surface temperature gradients across the equatorial Pacific, providing a testable hypothesis for climate models.

1. Introduction

The East Asian summer monsoon (EASM) system transports heat and moisture from warm tropical oceans to the continental interior of East Asia, influencing the lives of more than 1.5 billion people (Wang et al., 2000). It is thus critical to understand how EASM rainfall might change with future global warming. However, current predictions of EASM rainfall with global warming remain controversial. According to historical EASM rainfall data (Ding et al., 2008) and climate model simulations with historical forcings (Chang et al., 2000; Yang and Lau, 2004), the arid North China (e.g., Chinese Loess Plateau (CLP)) has become drier and the moist South Central China has become wetter on decadal timescales. However, if global warming leads to northward movement of the Earth's thermal equator (Broecker and Putnam, 2013), then North China is expected to receive more precipitation, and droughts are expected to become more frequent in the south (Yang et al., 2015). In addition, the EASM has shown substantial intensification on decadal timescales due to Hadley and Walker circulation intensification, primarily due to a mega-El Niño/Southern Oscillation (ENSO) and the Atlantic Multidecadal Oscillation (Wang et al., 2013). As instrumental records are too short to constrain climate models, it is useful to examine EASM rainfall variability during the past warm periods, which might provide a geologically analogous mechanism for future EASM rainfall under global warming.

The early Pleistocene Epoch (1.65–2.6 Ma) was characterized by glacial–interglacial cycles that were partially similar to those in the middle and late Pleistocene, but with generally higher temperatures (Herbert et al., 2010; Martínez-Garcia et al., 2010; Snyder, 2016; Wara et al., 2005). Thus, interglacials during this period may serve as a potential geologically analog to assess future variations in EASM rainfall under global warming conditions. However, it remains controversial how the EASM intensity has varied with global temperature from the warm early Pleistocene to the subsequent cold mid–late Pleistocene. Studies have shown that the interglacial boreal monsoon intensity, such as the intensity

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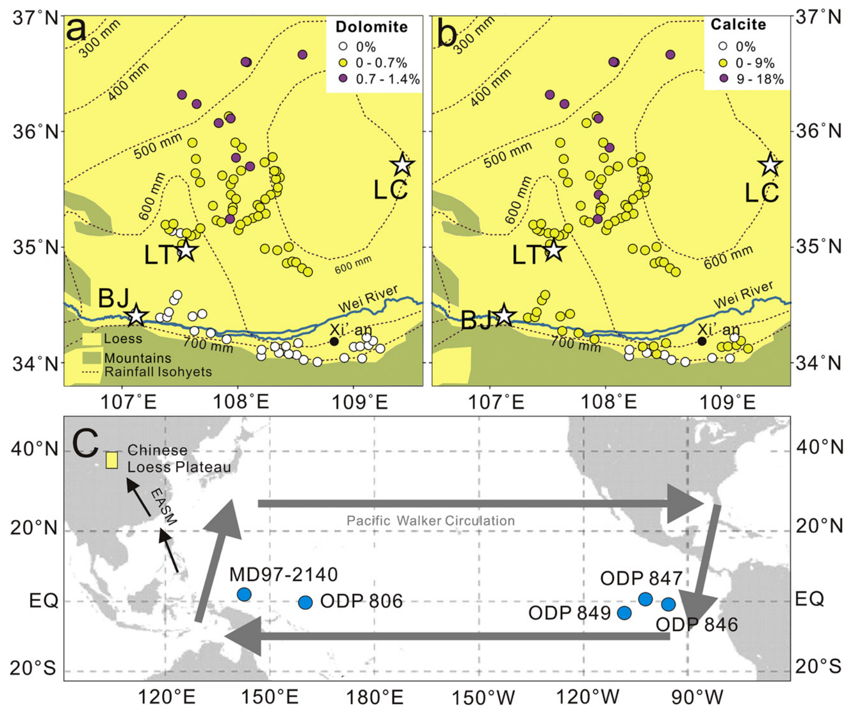

Fig. 1. Geographic context and carbonate contents in modern surficial soils. The three sections analyzed in this study are shown in (**a**) and (**b**) with black outlined stars. (**a**) illustrates the distribution of dolomite and (**b**) calcite in modern surface soils of the CLP. The white circles indicate a 0% concentration level for either dolomite or calcite in the soil; in other words, the mineral has been completely dissolved. The purple dashed lines are modern mean annual rainfall isohyets. The bottom panel (**c**) shows the locations of the Ocean Drilling Program cores (blue circles), where have main orbital-timescales resolution of SST in the Tropical Pacific. The gray cell represents the Pacific Walker circulation. The yellow rectangle in panel (**c**) indicates the location of the CLP shown in panels (**a**) and (**b**). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of the North African and Asian monsoon (Clemens et al., 1996; DeMenocal, 1995; Ding et al., 2005; Wu et al., 2007), has gradually weakened with global cooling since 2.6 Ma (Herbert et al., 2010; Martínez-Garcia et al., 2010; Snyder, 2016; Wara et al., 2005). It has also been reported that the interglacial EASM experienced stepwise weakening since 2.6 Ma based on evidences of desert expansion (Ding et al., 2005) and paleovegetation pollen records (Wu et al., 2007) on the CLP as well as hematite/goethite ratios in the southern South China Sea (Zhang et al., 2009). In contrast, studies based on pedogenic, mineralogical and/or chemical weathering characteristics in paleosol samples from the CLP (An et al., 1990; Balsam et al., 2004; Chen et al., 2007; Ji et al., 2001; Sun et al., 2010; Zhang et al., 2016) and elemental and mineralogical ratios in marine sediments from the South China Sea (Clemens et al., 2008; Clift et al., 2008; Tian et al., 2011) indicated that interglacial EASM intensity may have been weaker during the warm early Pleistocene than the cold mid–late Pleistocene. One major reason for these conflicting results is that the monsoon proxies fail to disentangle the monsoon rainfall signal from the temperature signal (An et al., 1990; Chen et al., 2000; Ding et al., 2005; Ji et al., 2001; Wu et al., 2007; Yu et al., 2016).

Loess-paleosol deposits on the CLP alternate between strongly weathered paleosol layers (interglacials) and weakly weathered loess layers (glacials). These deposits are unique terrestrial archives for studying past EASM changes on orbital and tectonic timescales (An et al., 1990, 2001; Balsam et al., 2004; Chen et al., 2000; Ji et al., 2001). Being terrestrial deposits, loess-paleosol sequences directly record information about terrestrial monsoon rainfall. Recently, a new rainfall proxy independent of temperature was established based on the dissolution phases of carbonate minerals (i.e., dolomite and calcite) on the CLP (Meng et al., 2015). In this study, we apply this novel rainfall proxy to qualitatively reconstruct the EASM rainfall changes since 2.6 Ma and explore the link among interglacial EASM rainfall on the CLP, global temperature changes and the tropical Pacific sea surface temperature (SST) gradients during the Pleistocene.

2. Materials and methods

2.1. Sampling and dating methods

Approximately 3000 samples were analyzed from three loess-paleosol sequences and modern surface soils on the CLP. All the surface soils samples were taken from the uppermost soil (∼20 cm) of loess tablelands on the CLP. The samples of loess-paleosol sequences were collected from three sections positioned on a north–south transect on the CLP: a section at Baoji (BJ; 34.20°N, 107.00°E, modern mean annual precipitation (MAP) = 680 mm), one at Lingtai (LT; 35.0°N, 107.5°E, modern MAP = 650 mm) and one at Luochuan (LC; 35.76°N, 109.42°E, modern MAP = 620 mm) (Fig. 1). The sampling intervals of the loess sequences were 20 cm in the LT section and 9–15 cm in the LC and BJ sections. The age models for the LC and BJ sections were established by magnetic susceptibility (MS) chronostratigraphy with respect to the LT section, which was determined using integrated paleo-magnetic polarity and astronomical tuning (Sun et al., 2006).

2.2. Dolomite and calcite measurements

Dolomite and calcite contents were measured by Thermo Nicolet 6700 Fourier transform infrared spectroscopy (FTIR) with a diffuse reflectance attachment at the Ministry of Education, Key Laboratory of Surficial Geochemistry, Nanjing University (Ji et al., 2009; Meng et al., 2015). First, 1 g of sample was prepared for measurement of total carbonate content. Then, to determine the dolomite content, calcite was removed from each sample following the procedures described in Meng et al. (2015). Briefly, for each sample, 0.5 g of sample was placed into a 50-ml centrifuge tube with