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A symmetrical CO_2 peak and asymmetrical climate change during the middle Miocene

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A B S T R A C T

Understanding the future trajectory of Earth's climate requires knowledge of shifts in atmospheric CO_2 concentrations during past warm episodes. The Miocene Climatic Optimum (MCO, ∼17–14 Ma) was likely the warmest episode of the past 25 Myr, and thus atmospheric CO_2 concentrations during this interval are of particular interest. However, CO_2 records across the middle Miocene are rather scattered and data are notably sparse for the latter part of the MCO. Here we present a paleosol-based CO_2 record from the Tianshui Basin, northern China, spanning 17–7 Ma. Our results show elevated mean CO_2 during the second half of the MCO corresponding with some of the lowest benthic $\delta^{18}O$ values and highest benthic $\delta^{13}C$ values, as part of the "Monterey excursion", published for the Neogene. This result supports the idea that the broader Monterey excursion was primarily associated with a CO_2 maximum, not carbon burial and CO_2 minima as previously interpreted. The new CO_2 record, along with previous CO_2 records based on paleosols, stomata and foraminiferal boron isotope compositions, also suggests that mean CO_2 across the MCO was elevated compared with the immediately following (post-MCO, 14–11 Ma, >80% probability) and immediately preceding (pre-MCO, 20–17 Ma, 70% probability) time periods. The most probable magnitude of the MCO CO_2 peak is 20% higher than post-MCO and 12.5% higher than pre-MCO levels. Larger factors, of perhaps 50% higher CO_2, likely apply in narrower (<1 Myr) time slices. CO_2 records from each proxy individually support the conclusion of modestly elevated MCO CO_2, although large temporal gaps exist in records from any one proxy. Using all proxies together, we estimate average MCO CO_2 of 375+150/−100 (84th and 16th percentile) ppm. Although mean MCO CO_2 was elevated, the MCO was also characterized by highly variable CO_2. In addition, determinations from all three proxies suggest that at times during the MCO, CO_2 levels were as low as they were following the ice sheet expansion of the Miocene Climate Transition. Furthermore, pre-MCO CO_2 levels are indistinguishable from post-MCO CO_2 levels (60% probability of pre-MCO CO_2 > post-MCO CO_2), despite significantly lower benthic $\delta^{18}O$ values during the former. We conclude that 1) the MCO was a period of slightly elevated and highly variable CO_2 compared with the immediately preceding and following intervals, and 2) neither CO_2 decrease, orbitally-controlled seasonality over Antarctica nor the confluence of these factors was sufficient to cause Miocene Climate Transition ice sheet expansion. Rather strengthening of the Antarctic Circumpolar Current and Southern Ocean cooling related to closure of the eastern Tethys was a necessary first step.

1. Introduction

Atmospheric CO_2 levels have increased from ∼280 ppm during the late Holocene preindustrial period to above 400 ppm (Dlugokencky and Tans, 2016) and are projected to go higher (Meinshausen et al., 2011). The current atmospheric CO_2 level exceeds the maximum Pleistocene CO_2 levels measured in ice cores (Bereiter et al., 2015) and is roughly similar to those (Kürschner et al., 2008; Greenop et al., 2014) during the Miocene Climatic Optimum (MCO, 17.4–14 Ma, Mudelsee et al., 2014). The MCO is therefore a compelling interval to test our understanding of cli-

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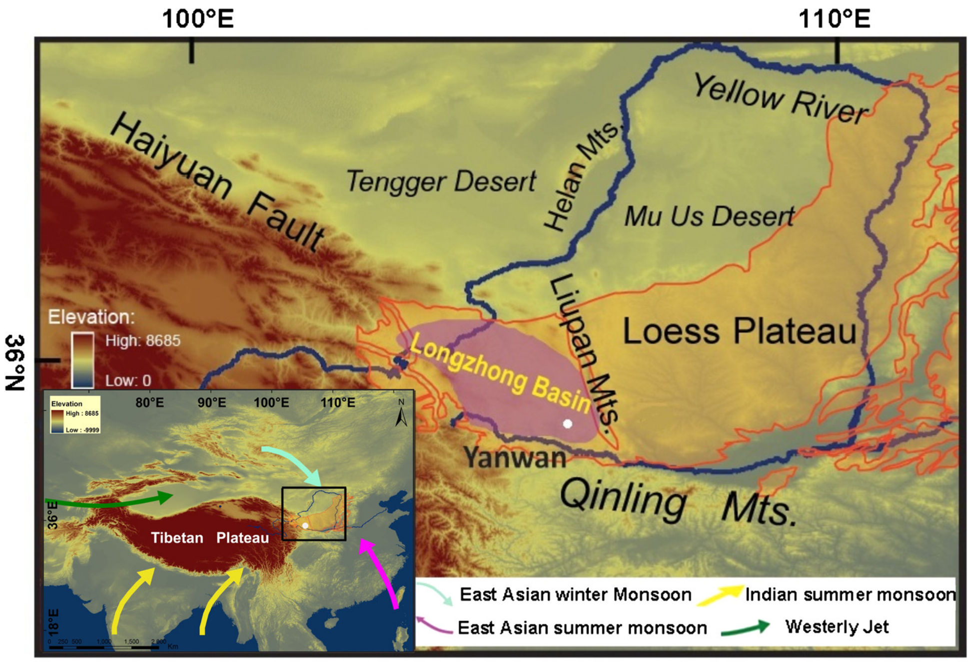

Fig. 1. Map showing the study site in the Tianshui Basin (the Yanwan section, marked by the white dot) on the Chinese Loess Plateau (orange area). (For interpretation of the colors in the figure(s), the reader is referred to the web version of this article.)

mate change and has been targeted for atmospheric pCO_2 research (e.g., Kürschner et al., 2008; Foster et al., 2012; Badger et al., 2013; Greenop et al., 2014).

Climate models do not reproduce the climate of the MCO using available proxy-based CO_2 estimates. To maintain warmth consistent with MCO proxy data, model simulations suggested the required CO_2 concentration is 800 ppm or above (Goldner et al., 2014). These CO_2 levels are higher than most proxy-based CO_2 determinations reported in the literature (e.g., Kürschner et al., 2008; Greenop et al., 2014). This data-model mismatch requires testing of existing proxy-based CO_2 records and consideration of other processes that might contribute to MCO warmth.

The MCO is recognized by a negative excursion in the $\delta^{18}O$ values of benthic foraminifera that temporarily interrupts the longer term trend of increasing benthic $\delta^{18}O$ values extending from Eocene to present (Zachos et al., 2008). The MCO is a distinctly asymmetric excursion beginning with a smaller magnitude (-0.2 to $-0.4‰$) ramp at its onset, centered at 17.4 Ma, and ending with a larger magnitude (0.9‰) ramp known as the Miocene Climate Transition (MCT) centered at 14 Ma (Mudelsee et al., 2014). The MCT is recognized as one of the major cooling steps of the Cenozoic (e.g. Flower and Kennet, 1994). The intervening 3.4 Myr constitutes the MCO, characterized by the lowest benthic $\delta^{18}O$ values of the Neogene (Zachos et al., 2008) and a global mean annual temperature $7.6 \pm 2.3\,°C$ warmer than preindustrial.

A 4 Myr positive excursion in benthic $\delta^{13}C$ values, superimposed with eccentricity-paced $\delta^{13}C$ fluctuations (Holbourn et al., 2007), referred to as the Monterey Carbon Isotope Excursion (Vincent and Burger, 1985), largely coincides with, but clearly ends after, the benthic $\delta^{18}O$ minimum (Zachos et al., 2008) suggesting the occurrence of coupled carbon cycle–climate perturbations during the middle Miocene (Flower and Kennett, 1993). The Monterey Carbon Isotope Excursion was originally interpreted to record organic carbon burial and thus drawdown of CO_2 and associated cooling (Vincent and Burger, 1985). However, evidence for warming during the excursion (e.g. Miller et al., 1987) contradicted this interpretation. In addition, early records showed low and invariant atmospheric CO_2 concentrations across the Miocene (Pagani et al., 1999), further complicating interpretation of the Monterey excursion. More recent CO_2 records show elevated CO_2 during part of the Monterey excursion (Kürschner et al., 2008; Foster et al., 2012), lending support to the idea that carbon emitted to the atmosphere as a result of the contemporaneous Columbia River volcanism/magmatism supported MCO warmth (e.g. McKay et al., 2014).

Cooling and polar ice sheet expansion across the MCT has been attributed to a decrease in CO_2 (Vincent and Burger, 1985; Foster et al., 2012; Holbourn et al., 2014), to orbitally-controlled decrease in seasonality over Antarctica (Holbourn et al., 2005, 2007) and to thermal isolation of Antarctica resulting from closure of the eastern Tethys and strengthened circumpolar circulation (Woodruff and Savin, 1989; Flower and Kennett, 1994; Shevenell et al., 2004). In this paper, we report a paleosol-based CO_2 record that augments late MCO CO_2 records and allows us to present a comprehensive, multiproxy perspective on climate-CO_2 relationships preceding, during, and immediately following the warmest global interval since the Eocene.

2. Material and methods

2.1. Setting and samples

Carbonate nodules were sampled from the paleosols preserved in the fluvio-lacustrine depositional sequences of the Yanwan section (34°58′N, 105°34′E) in the north of the Tianshui Basin, Gansu, China (Zhang et al., 2013a) (Fig. 1). The Tianshui Basin is the southeast sub-basin of the Longzhong Basin, which is bounded by the Huajia Ling Mountain to the north, the Liupan Mountains to the east and northeast, and the western Qinlin Mountain to the south.

The Neogene strata in Yanwan section are ~280 m thick. The sedimentary environment of Yanwan's Neogene strata can be divided into three units (Fig. S1), from bottom to top, Unit 1 is from 280 to 148 m; Unit 2 is from 148 to ~20 m; Unit 3 is the uppermost ~20 m (Zhang et al., 2013a). The sedimentary environments of Units 1, 2, and 3 correspond to flood plains/distal fans, lake mudflats with sheet-floods, and flood plains, respectively (Fig. S1). The Yanwan section was dated by magnetostratigraphy to extend from 17.1 to 6.1 Ma (Zhang et al., 2013a). Coupled with