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Mid-latitude terrestrial climate of East Asia linked to global climate in the Late Cretaceous

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We thank Li (2015) for his constructive Comment on our recent paper (Gao et al., 2015) reporting stable isotope measurements from paleosol nodules in the Sifangtai and Mingshui Formations of the Songliao Basin (northeast China) SK-1 core. The paleosols in the Sifangtai and Mingshui Formations of the SK-1 core are characterized by fossil root traces, paleosol horizons (e.g., Bk horizons), and paleosol structures (e.g., carbonate nodules/mottling). Although we did not provide detailed sedimentary descriptions, Huang et al. (2013) studied the petrography of the carbonate nodules, and Cheng et al. (2009) described the paleosols developed in the floodplain environment (their plates 7-8, 18-19). They observed circumgranular cracks cemented by microsparite in the carbonate nodules, a typical feature of pedogenic carbonates. Microsparite crystals organized in multiple layers along septaric voids are commonly formed over drying-wetting cycles in soils (Khormali et al., 2006). In addition, the carbonates could not be of palustrine origin as suggested by Li (2015). Palustrine carbonates typically form on previous lacustrine mud, and have characteristic facies and features such as nodular and brecciated limestones, mottled limestones, limestones with vertical root cavities, pseudo-microkarst, peloidal and/or intraclastic limestones (Alonso-Zarza, 2003). None of these features were observed in the carbonates of the SK-1 core.

Pedogenesis occurs in aerially exposed depositional environments. In the Sifangtai and Mingshui Formations, fluvial to flood-plain environments occurred in the depth ranges of 1020–940 m, 905–765 m, 632–555 m, and 468–292 m, which accounts for >60% of the total depth (Cheng et al., 2009; Wang et al., 2015).

The 131 carbonate samples reported in our paper were collected from 90 layers. Following Li (2015), each "paleosol cycle" averages 8.24 m thick, or ~115 k.y., within the ~95 to 125 k.y. eccentricity periodicity. However, multiple factors control paleosol development (e.g., climate, topography, biology, parent material, time), which do not necessarily follow Milankovitch cycles. If we take 50 cm as the average Bk layer depth, the average soil development duration is ~7 k.y. Today, the common paleosol types found in SK-1 core (aridisol, alfisol, and histosol) develop in 1–10 k,y., and the Bk horizon develops in 1–100 k.y. (Retallack, 2001).

Additionally, although no estimates of mean annual precipitation (MAP) have been made for the Cretaceous Songliao Basin, pedogenic carbonates are usually thought to form in semi-arid to arid environments with MAP <800 cm/yr (Retallack, 2001). Previous work suggests that the paleosols in the Sifangtai and Mingshui Formations were formed in a strongly seasonal climate. In modern environments with MAP >800 cm/yr, pedogenic carbonates can form (Retallack, 2005), especially in climates with strong seasonality (Breecker et al., 2009), suggesting that calcic features are a more reliable indicator of seasonal precipitation. Cumulatively, the sedimentary evidence suggests that the depositional setting and climate led to pedogenic carbonate development during deposition of the Sifangtai and Mingshui Formations.

We interpret the negative covariation in $\delta^{13}C$-$\delta^{18}O$ as recording climate variations. Lake water geochemistry or diagenesis is unlikely to cause this negative covariance, as suggested by Li (2015). In closed lakes, positive, not negative, covariance, of $\delta^{18}O$ and $\delta^{13}C$ reflects the effects of long residence times on isotopic evolution of closed water bodies (e.g., Talbot and Kelts, 1990). During warming events, $\delta^{18}O$ increases due to temperature increases and/or poleward-shifted westerlies, while $\delta^{13}C$ increases due to increased soil respiration. During cool periods, the isotopic changes are driven by the opposite mechanism.

Finally, the $\delta^{13}C$ data do not appear to reflect changes in pCO_2: (1) $\delta^{13}C$ decreases in the latest Cretaceous, despite estimated increases in pCO_2 due to Deccan Trap volcanism, which should increase $\delta^{13}C$, and (2) except in arid environments, respiration is the dominant driver of soil CO_2 and, thus, $\delta^{13}C$ (Caves et al., 2014). The pCO_2-paleobarometer uses a single assumed respiration rate, which is unrealistic given the documented climatic changes in the Late Cretaceous Songliao Basin. Because our $\delta^{13}C$ data appear to record a quantity other than pCO_2, we attribute changes in $\delta^{13}C$ to changes in soil respiration. Thus, warmer periods are associated with greater respiration (and likely plant productivity), providing an explanation for the negative covariation of $\delta^{18}O$ and $\delta^{13}C$ observed in the stable isotope record.

In conclusion, the stable isotope data from the pedogenic carbonates in the Sifangtai and Mingshui Formations of the SK-1 core record a high-fidelity record of paleoclimatic changes in the Late Cretaceous.

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