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Rapid Middle Eocene temperature change in western North America

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ABSTRACT

Eocene hyperthermals are among the most enigmatic phenomena of Cenozoic climate dynamics. These hyperthermals represent temperature extremes superimposed on an already warm Eocene climate and dramatically affected the marine and terrestrial biosphere, yet our knowledge of temperature and rainfall in continental interiors is still rather limited. We present stable isotope ($\delta^{18}O$) and clumped isotope temperature (Δ_{47}) records from a middle Eocene (41 to 40 Ma) high-elevation mammal fossil locality in the North American continental interior (Montana, USA). Δ_{47} paleotemperatures of soil carbonates delineate a rapid $+9/-11\,^{\circ}C$ temperature excursion in the paleosol record. Δ_{47} temperatures progressively increase from $23\,^{\circ}C \pm 3\,^{\circ}C$ to peak temperatures of $32\,^{\circ}C \pm 3\,^{\circ}C$ and subsequently drop by $11\,^{\circ}C$. This hyperthermal event in the middle Eocene is accompanied by low $\delta^{18}O$ values and reduced pedogenic carbonate concentrations in paleosols. Based on laser ablation U/Pb geochronology of paleosol carbonates in combination with magnetostratigraphy, biostratigraphy, stable isotope, and Δ_{47} evidence, we suggest that this pronounced warming event reflects the Middle Eocene Climatic Optimum (MECO) in western North America. The terrestrial expression of northern hemisphere MECO in western North America appears to be characterized by warmer and wetter (sub-humid) conditions, compared to the post-MECO phase. Large and rapid shifts in $\delta^{18}O$ values of precipitation and pedogenic $CaCO_3$ contents parallel temperature changes, indicating the profound impact of the MECO on atmospheric circulation and rainfall patterns in the western North American continental interior during this transient warming event.

1. Introduction

Short-term hyperthermals such as the Paleocene–Eocene Thermal Maximum (PETM) or the Eocene Thermal Maximum 2 (ETM2) reflect rapid global warming events and are a recurrent phenomenon of early and middle Eocene climate dynamics (e.g., Zachos et al., 2008). Both events punctuated an already warm Paleogene climate, interrupted the long-term mid-to-late Eocene cooling trend and coincided with perturbations in the global carbon cycle (e.g., Bowen et al., 2015; Sluijs et al., 2013; Zachos et al., 2008). In contrast to the short-lived (<100 ka) Early Eocene hyperthermals, the Middle Eocene Climatic Optimum (MECO) about 40 Ma ago is unique in terms of its long duration (500–750 ka) and gradual temperature increase (Bohaty and Zachos, 2003; Bohaty et al., 2009; Edgar et al., 2010). A suite of globally distributed deep-sea sediment cores revealed that this warming event was characterized by a transient temperature increase of 3 °C to 6 °C of both surface and intermediate deep-waters, a brief global shoaling of the calcite compensation depth due to acidification of the oceans, and shifts in species distribution and abundance patterns (Bijl et al., 2010; Bohaty and Zachos, 2003; Bohaty et al., 2009; Boscolo Galazzo et al., 2013; Edgar et al., 2010; Witkowski et al., 2012). An increase in atmospheric CO_2 concentrations by a factor of 2–3 compared to pre- and post-MECO pCO_2 levels further characterizes the MECO (Bijl et al., 2010). The postulated global rise in pCO_2 and temperature, accounting for deep and shallow ocean warming, should exhibit substantial influence on continental environments as increasing mean global temperature will affect atmospheric and ocean circulation dynamics and thus alter continental rainfall patterns (e.g., Allen and Ingram, 2002; Chou et al., 2013; Held and Soden, 2006; Marvel and Bonfils, 2013). However, the implications of continental temperature change during the MECO on continental hydrology are still largely elusive: Palynological and

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sedimentological data in Central Asia indicate a major aridification step associated with monsoonal intensification possibly as a consequence of post-MECO cooling (Bosboom et al., 2014). Oxygen (δ^{18}O) and carbon (δ^{13}C) isotope analyses of lacustrine carbonates (Elko Basin, NV, USA) reveal large shifts in lake water δ^{18}O, most likely due to rapid lake water freshening at the climax of the MECO and indicate that temperature seasonality was sufficiently strong to (re-)establish regular lake overturn (Mulch et al., 2015). These two terrestrial MECO records indicate changes in the hydrological cycle of northern hemisphere mid-latitudes in concert with either surface uplift processes of the Tibetan Plateau for Central Asia and a southward encroachment of an Eocene plateau (SWEEP) in western North America (Mix et al., 2011) and/or retreats of epicontinental seas (proto-Paratethys and Mississippi Embayment, respectively). Redistribution of rainfall patterns, and thus δ^{18}O values of precipitation, results from changes in atmospheric circulation and hydrological cycling that are both sensitive to global warming (e.g., Marvel and Bonfils, 2013). Despite being a key element in global climate dynamics, continental rainfall patterns in a warmer world are far from being understood and predictions range from wet-get-wetter and dry-get-drier patterns (e.g., Allen and Ingram, 2002; Chou et al., 2013; Held and Soden, 2006) to an overall (mid-latitude) drying in a warmer future (Sherwood and Fu, 2014).

In order to evaluate the impacts of global warm periods on terrestrial temperature and rainfall records we sampled a suite of middle Eocene (~40 Ma) paleosols in the hinterland of the North American Cordillera. Stable isotope (δ^{18}O) and clumped isotope paleo-temperature (Δ_{47}) data, together with laser ablation inductive coupled plasma-mass spectrometry (LA-ICP-MS) U–Pb dating of carbonates permits to develop a middle Eocene terrestrial temperature record and investigate changes in the hydrological cycle and consequently in atmospheric circulation patterns over western North America during an important Cenozoic warm period.

2. Geological setting

Beginning in the early Eocene, the North American continental interior underwent extension at various levels of the crust with accompanying magmatism, formation of metamorphic core complexes, and basin formation within the North American Cordillera (e.g., Constenius, 1996; Dickinson, 2002; Fields et al., 1985; Sonder and Jones, 1999). Most basins in western Montana (and east–central Idaho) resulted from Paleogene extensional deformation in the hinterland of the Sevier fold-and-thrust belt (e.g., Constenius, 1996; Fields et al., 1985; Rasmussen, 2003) and basins evolved as intermontane half-grabens in a north–south trending rift system (Janecke, 1994; Sears and Ryan, 2003).

In an overall extensional context, the Sage Creek Basin (MT) has been described as an extensional intermontane basin (Constenius, 1996), a flexural basin (Janecke et al., 1999), as part of the "Renova braidplain" on the uplifted eastern rift shoulder (Sears and Ryan, 2003) or as part of a continuous depositional system of the Dillon-Renova Basin, flanked by volcanic highlands (Fritz et al., 2007). Independent of the mode of basin formation sedimentation in the Sage Creek Basin started in the early to middle Eocene and lasted until the mid-Miocene, thus making the Sage Creek Basin one of the temporally most extensive basins in western Montana that also yielded a vast amount of vertebrate fossils spanning the Bridgerian (~51 Ma) to Barstovian (~12 Ma) NALMAs (North American Land Mammal Ages) (Fields et al., 1985; Tabrum et al., 1996). Age constraints of the Sage Creek Basin deposits are based on biostratigraphic, paleomagnetic and radiometric dating (Fields et al., 1985; Kent-Corson et al., 2006; M'Gonigle and Dalrymple, 1996; Tabrum et al., 1996). Based on vertebrate fossil assemblages, Paleogene sediments exposed in the Sage Creek Basin can be divided into the Bridgerian Sage Creek Formation (~51.0–46.3 Ma), the Uintan Dell Beds (46.3–40.0 Ma), and the Chadronian–Orellan Cook Ranch member (37–32 Ma) (see compilations of Fields et al. (1985) and Tabrum et al. (1996); ages in parenthesis indicate age limits of NALMA in Woodburne (2004), modified for the Bridgerian after Smith et al. (2008)). Even though southwestern Montana local faunas reflect high levels of provincialism/endemism, which make correlations with other North American mammal assemblages challenging (Tabrum et al., 1996), these age zones were confirmed by paleomagnetic (Tabrum et al., 1996) and geochronologic analyses (Fritz et al., 2007; Kent-Corson et al., 2006; M'Gonigle and Dalrymple, 1996; Rothfuss et al., 2012).

Within this depositional context we collected micritic carbonate samples and wherever present pedogenic carbonate nodules from different pedogenic horizons of the well characterized middle Eocene Upper Dell Beds (Sage Creek Basin, SW Montana, USA; Fig. 1; e.g., Kent-Corson et al., 2006, 2010; Retallack, 2007, 2009; Tabrum et al., 1996). The Dell Beds unconformably overlie the early Eocene Sage Creek Formation and represent a sequence of stacked paleosols, which mainly consist of tuffaceous mudstone interbedded with sandstone and minor conglomerates (Tabrum et al., 1996). The sampling locality (corresponding to the "Kay Draw" or "Hough Draw 1" locality of Tabrum et al., 1996; Fig. 1c) reflects the stratigraphically highest part of the Dell Beds and consists of tuffaceous mud- and siltstones with abundant paleosol formation. Pedogenic accumulation of carbonate occurred in B horizons (Hanneman et al., 2003); these range in thickness from 0.1 m to 0.4 m and are typically well indurated. A shallow carbonate formation environment is reported by Retallack (2007, 2009) with carbonate formation depths of the Dell Beds (at Douglass Draw) estimated to range between 27 cm and 120 cm, averaging 54 cm ± 22 cm (Retallack, 2007, 2009, and downloadable Excel files therein). We measured a composite section covering about 50 m (Figs. 1c and 1d, see Appendix for field photographs and detailed sections) and analyzed micritic paleosol carbonate and pedogenic carbonate nodules for δ^{18}O and clumped isotope analyses as well as U–Pb geochronology.

3. Methods

3.1. Stable isotope analyses

Oxygen (δ^{18}O), carbon (δ^{13}C) and clumped (Δ_{47}) isotope analyses of pedogenic carbonates were performed at the Joint Goethe University – BiK-F Stable Isotope Facility at the Institute of Geosciences, Goethe University Frankfurt, Germany. Carbonate powders were drilled at 1 to 5 different spots within the same hand specimen using a low-speed dental drill. After digestion of 0.1 mg to 0.5 mg carbonate powder with H_3PO_4 at 72 °C in a sealed reaction vessel flushed with helium gas, the evolved CO_2 was sampled by a Finnigan Gas Bench and isotope ratios were measured on a Finnigan MAT 253 mass spectrometer. Repeated measurements of an in-house standard (Carrara marble) yielded external precision of $<0.07‰$ for δ^{18}O and $<0.03‰$ for δ^{13}C. All isotopic results are reported in standard delta notation and corrected to VSMOW (δ^{18}O) or VPDB (δ^{13}C). Carbonate contents (in %) were calculated by relating the signal size of the samples and the averaged signal size of the daily standards (Carrara marble, $n = 12$) and assuming 100% $CaCO_3$ for the Carrara marble (Appendix Tabs. A.1 and A.2). The oxygen isotopic composition of soil water ($\delta^{18}O_{water}$) was calculated from Δ_{47} temperature and $\delta^{18}O_{carbonate}$ value pairs using the oxygen isotope fractionation coefficient of Kim and O'Neil (1997) (Appendix Tab. A.9).

3.2. Clumped (Δ_{47}) isotope analyses

Clumped isotope analyses were performed using a Thermo Finnigan MAT 253 mass spectrometer modified to measure a mass