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Vegetation response during the lead-up to the middle Miocene warming event in the Northern Rocky Mountains, USA

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ABSTRACT

The mid-Miocene climatic optimum (MMCO; initial warming beginning ca. 18 Ma and with peak warming ca. 17–14.75 Ma) constitutes the Earth's most recent greenhouse episode, characterized by a transient shift to higher global atmospheric CO_2 levels and warmer, possibly wetter, climatic conditions. Combined with the spread of grass-dominated habitats, it has been suggested that the MMCO lead to significant turnover and modernization of fauna and flora. However, records documenting local vegetation change during the MMCO are rare, hence this hypothesis remains largely untested. Herein, we combine phytolith assemblages and $\delta^{13}C$ records from paleosol organic matter from the Railroad Canyon section (RCS), eastern Idaho, to provide the first direct, detailed, and continuous, long-term record of vegetation composition and structure in a single basin during the lead-up to the MMCO (22.9–15.2 Ma; late Arikareean–early Barstovian). Phytolith assemblage analysis indicates that grasses, primarily C_3 pooids, dominated early–middle Miocene vegetation. Potential C_4 PACMAD grasses were present by ca. 21.6–20.7 Ma (late Arikareean) and vary in abundance (0.4–17.2% of diagnostic phytoliths) through the section. Although relatively rare overall, PACMAD grasses decrease significantly through time, in parallel with declining diatom abundances and an increase in pooid grasses. In contrast, paleosol $\delta^{13}C_{org}$ indicates 0–29.1% C_4 vegetation but no consistent temporal change. Where both phytolith- and isotope-based estimates are made from the same paleosol, they are within error most (82%) of the time; thus, the apparent discrepancy in temporal trends could either be due to differences in the resolution of the two records, or could be explained if many PACMADs were not C_4 grasses, but instead water-loving C_3 species. Overall, these data suggest that open-habitat mosaic vegetation with grass-dominated grasslands and open woodlands occurred in the North Rocky Mountains, USA, by at least the early Miocene, more comparable to the timing for the spread of grass-dominated habitats in the Great Plains than previously thought. Additionally, phytolith data suggest that overall vegetation structure remained relatively stable throughout the RCS, inconsistent with published paleosol morphology data. This points to regionally unique floral patterns decoupled from global climate change leading into the MMCO.

1. Introduction

The early to middle Miocene was an important transitional period in Earth's geologic history when climate change coincided with reorganization and modernization of paleoecological communities world-wide (e.g., Beerling and Royer, 2011; Kürschner et al., 2008; Leopold and Denton, 1987; Tedford et al., 2004). The interval was marked by an increase in global mean annual temperatures during the mid-Miocene climatic optimum (MMCO; peak warming ca. 17–14.75 Ma; Zachos et al., 2001, 2008) as well as a potential transient shift to higher atmospheric CO_2 concentrations (Beerling and Royer, 2011). Floristic evidence from European pollen, macrofossils, and fossil wood remains suggest increasingly warm and humid climates associated with widespread broadleaved evergreen forests during the early–middle Miocene (e.g., Ivanov et al., 2011; Jiménez-Moreno et al., 2008). Similarly, phytolith data suggest a transition from palm shrubland to increasingly wet sclerophyllous forest habitats in South America ca. 20–15 Ma (Dunn et al., 2015). However, in other regions of the globe, a trend towards more forested environments is less evident. Pollen, phytolith, and paleosol data from the Central Great Plains and western North America suggest that more open vegetation (C_3 grasslands and woodlands) spread and replaced forested habitats during the early–middle Miocene

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(Leopold and Denton, 1987; Retallack, 2007; Strömberg, 2005). Although this vegetation transformation has often been linked to climate change (Strömberg, 2005; Webb and Opdyke, 1995; Wing, 1998), there have been no explicit tests for a correlation between mid-Miocene climatic warming and regional- to local-scale vegetation responses. In large part, this is because the long-term, detailed paleobotanical records necessary for testing such hypotheses have been lacking. Here, we present a record that fits these criteria, from the Railroad Canyon section (RCS) of central eastern Idaho.

The RCS preserves evidence of climate, animals, and plants (Barnosky et al., 2007; Retallack, 2009, 2007; Strömberg, 2005) that lived in the U.S. Northern Rocky Mountains (NRM) before and during peak MMCO warming (22.9–15.2 Ma; Harris et al., 2017), making it an ideal place to study the biotic effects of the MMCO at the ecosystem level. Previous studies in the RCS focusing on understanding characteristics of the local climate and atmosphere, vegetation change, and faunal turnover have led to environmental reconstructions that are in part incongruous. Both analyses of paleopedological features (Retallack, 2007) and of a handful of fossil phytolith assemblages (Strömberg, 2005) indicate that grass communities expanded in the NRM during the late early Miocene. However, whereas Retallack (2007) used morphology and major elemental geochemistry of RCS paleosols to conclude that Idaho and Montana were characterized by a warm, wet, subhumid climate during the MMCO, Strömberg (2005) proposed instead that the spread of open-habitat grasslands in the RCS may have been stimulated by increased seasonal aridity. Barnosky et al. (2007) similarly suggested a shift to increasingly arid climates during deposition of the RCS based on changes in local lithology. However, to date no work has successfully teased apart these contradictory climatic interpretations, in part because high-resolution reconstructions of vegetation have been lacking.

To address these issues, we use phytoliths and other biosilica as well as organic matter preserved in paleosols throughout the RCS to: 1) establish independent estimates of local water availability during the early to middle Miocene; 2) develop a temporally high-resolution vegetation record that better constrains the timing of the spread of open-habitats in the U.S. Northern Rocky Mountains (NRM) and establishes a temporal sequence of grass-community composition during the MMCO. We hypothesize that if there was a change in moisture regime during the early–middle Miocene in the NRM then we should expect to see a change in the abundance of moisture limited plants through the RCS. Additionally, we hypothesize that higher global temperatures during the MMCO (coupled with changes in local water availability) could have resulted in an increase in biomass of warm-adapted, C_4 grasses in the RCS.

2. Geologic setting and age of the RCS

The Cenozoic was a tectonically active time in the history of western North America. In southern Montana $\delta^{18}O_{carbonate}$ data have been used to suggest the creation of a broad regional plateau during the late Eocene–early Oligocene, the formation of which was temporally variable across Montana, Idaho, and Nevada (Chamberlain et al., 2012). By the middle Miocene (ca. 17.5 Ma), $\delta^{18}O$ and leaf physiognomic data suggest the onset of diachronous collapse of this broad plateau with the initiation of Basin and Range extension, which continued to alter the landscape in the US Northern Rocky Mountains (NRM) through the late Miocene (Chamberlain et al., 2012). During the middle-late Hemingfordian (see North American land mammal ages in Fig. 4) the Yellowstone Hotspot resumed intense volcanic activity in the Snake River Plain and continued to track northward into northwestern Wyoming (Parsons, 1995; Rasmussen, 2003). To the northwest, deposits from the Columbia River Basalt flows indicate volcanism in this region from 17.5 to 6 Ma in eastern Washington, northeastern Oregon, and western Idaho (Swanson et al., 1979). It was during this period of continued crustal extension and volcanism that the early–middle Miocene sediments within the Railroad Canyon were deposited.

The RCS is located in Bannock Pass, approximately 19 km northeast of Leadore, Idaho, and exposes nearly 360 m of sedimentary rock (Fig. 1). A recent study used moderate- and high-precision U-Pb dating of single zircon crystals from four ash horizons (RCS1-RCS4) throughout the RCS to show that these deposits formed during the early–middle Miocene (Harris et al., 2017). Using the resulting zircon dates (RCS1 = 22.65 ± 0.37 Ma; RCS2 = no good age estimate; RCS3 = 21.24 ± 0.27 Ma; RCS4 = 15.76 ± 0.22 Ma) along with a magnetostratigraphic record from the RCS (Barnosky et al., 2007), a radiometrically calibrated age model was created that constrains the age of the section to ca. 22.9–15.2 Ma, approximately 5 Ma older than previous estimates (Harris et al., 2017). The RCS contains rocks from the upper Renova Formation and lower Sixmile Creek Formation, which are thought to be separated by a regional unconformity (Barnosky et al., 2007). The Renova Formation locally consists of grey to white mudstone and siltstone layers with occasional gypsum and halite deposits potentially indicative of an arid, closed basin with intermittent saline lakes (Barnosky et al., 2007; Fields et al., 1985). The Sixmile Creek Formation is locally distinguished by pinkish to tan siltstone and sandstone beds with occasional conglomeratic lenses suggestive of a sediment-choked fluvial system (Barnosky et al., 2007; Fields et al., 1985). Overall, both units have been interpreted as dominantly composed of fluvial deposits, reflecting sediment deposition in an increasingly arid floodplain environment (Barnosky et al., 2007).

3. Paleovegetation reconstruction

Phytoliths are microscopic silica bodies formed in the tissues of many vascular plants that are deposited in the soil after plants die and decay (e.g., Hodson et al., 2005; Piperno, 2006; Strömberg et al., 2017). Because phytoliths vary in how taxonomically sensitive they are, they do not provide detailed floral information (e.g., Strömberg, 2004; Strömberg et al., 2017). Instead, they allow inference of local (to regional) vegetation structure (i.e., closed vs. open habitats) (Bremond et al., 2005; Chen et al., 2015; Fredlund and Tieszen, 1994; Piperno and Becker, 1996; Strömberg et al., 2013; WoldeGabriel et al., 2009). Additionally, unlike grass pollen (but see Mander et al., 2013) and most macrofossils, phytoliths are taxonomically distinct within the Poaceae and so can provide approximate constraints for the relative abundances of different types of closed- and open-habitat grasses (e.g., C_3 bamboos and pooids, and C_4 chloridoids and panicoids), making them particularly useful for studying the Cenozoic evolution of grasslands (e.g., Cotton et al., 2014, 2012; Strömberg and McInerney, 2011; Strömberg, 2011, 2005). Finally, phytoliths provide information about the relative abundances of climatically sensitive taxa that can help constrain local climate reconstructions. Such taxa include moisture- and temperature-limited plants (e.g., palms, spiral gingers and relatives; Chen and Smith, 2013; Miller et al., 2012), and C_4 lineages adapted to hot and/or dry climates (e.g., Chloridoideae; Piperno and Pearsall, 1998; Strömberg, 2004). Because of the way phytolith assemblages form, the spatial resolution of phytoliths is typically higher than for palynomorphs, permitting reconstruction of spatial heterogeneity of vegetation across a landscape (Piperno, 2006, 1988; Strömberg et al., 2017).

Stable carbon isotope compositions ($\delta^{13}C$) of kerogenized rootlets from middle Miocene paleosols are used here to reconstruct local vegetation. Assuming diagenetic temperatures below 150 °C, the composition of bulk soil organic material (SOM) should reflect the original carbon signature of the plants that inhabited an ancient soil, and as a result, soil organic carbon isotopes have been used regularly to reconstruct the abundance of C_3/C_4 vegetation (e.g., Cotton et al., 2014, 2012; Fox and Koch, 2004, 2003; Quade and Cerling, 1995).

By combining these different lines of evidence for plant community composition, a more detailed view of vegetation change can be attained: stable carbon isotopes and phytoliths both record the relative abundance of potential C_4 plants, and phytoliths provide information about

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