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Dramatic local environmental change during the Early Eocene Climatic Optimum detected using high resolution chemical analyses of Green River Formation stromatolites

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A B S T R A C T

The Eocene Green River Formation represents a system of lakes that covered parts of what is now Wyoming, Colorado, and Utah, and captures the Early Eocene Climatic Optimum (EECO, 52–50 million years ago or Ma), the warmest period of the Cenozoic Era, and a period associated with very high levels of atmospheric CO_2. Lakes, especially closed basin lakes, can respond dramatically to environmental change because of their sensitivity to precipitation and evaporation. In this study, stromatolites from the Rife Bed of the Green River Formation are used as fine-scale records of terrestrial paleoenvironmental change during a global hothouse climate, and to investigate how the environmental dynamics within the lake system affected the growth of stromatolites. The stromatolites are composed of branching microdigitate columns laminated on the 10–100 μm scale. Laminae are grouped in cm-scale layers that alternate between calcite fan, micritic, and mixed microstructures. The fan layers are depleted in ^{18}O, Na, and Mg/Ca. The micrite layers, in contrast, are comparatively enriched in ^{18}O, Na, and Mg/Ca. The $\delta^{13}C$ and $\delta^{18}O$ are strongly positively correlated, suggesting the stromatolites formed in a closed basin lake, consistent with the regional stratigraphy. Additionally, clumped isotope analyses provide the first quantitative values for water temperatures in lake water from the Green River Formation (~35 °C for micrite layers and ~28 °C for fan layers). Changes in $\delta^{18}O$ and sodium ion concentration are likely related to periods of evaporation and recharge, and thus can be used to estimate lake volume change during stromatolite growth. Two models, one using sodium ion concentrations in a conserved system, the other using Rayleigh fractionation and mixing equations to explain changes in oxygen isotopes, converge upon similar results for lake volume changes, revealing multiple episodes of meter-scale lake level rise and fall during the accretion of the ~30 cm thick stromatolite. Because of the broad, flat bathymetry of the lake, such lake volume and depth changes would have been accompanied by shoreline shifts on the order of tens of kilometers while the stromatolites were actively growing, challenging the view of a single stromatolite paleoenvironment in the lake. Therefore, the fan microfabric, interpreted here as abiogenic in nature, formed in cooler waters when the lake was deeper, possibly below a thermocline. In contrast, the micrite microfabric, for which there is evidence of biogenicity, formed when the lake was shallow and warm. The alternation between biogenic and abiogenic microfabrics present in the Rife Bed stromatolites is hypothesized to result from dramatic changes in lake level influencing the microbiology and chemistry of the waters in which the stromatolites formed, indicating that stromatolite growth can occur under disparate conditions and therefore does not necessarily represent a single facies.

1. Introduction

1.1. The Green River Formation

The Eocene Green River Formation, one of the most extensive and best-characterized paleolake systems in the world, represents the remains of a large system of sporadically interconnected intermountain lakes that covered much of southwestern Wyoming, northwestern Colorado, and northeastern Utah (Fig. 1). The formation contains a record of lacustrine deposition in several different sub-basins over 10 million years during the first half of the Eocene (e.g., Bradley, 1929, 1964; Picard and High, 1968; Trudell et al., 1970; Eugster and Surdam, 1973; Eugster and Hardie, 1975; Surdam and Stanley, 1979; Smoot, 1983; Fischer and Roberts, 1991; Roehler, 1991, 1992, 1993; Clyde et al., 2001; Rhodes et al., 2002; Carroll et al., 2003; Keighley et al., 2003;

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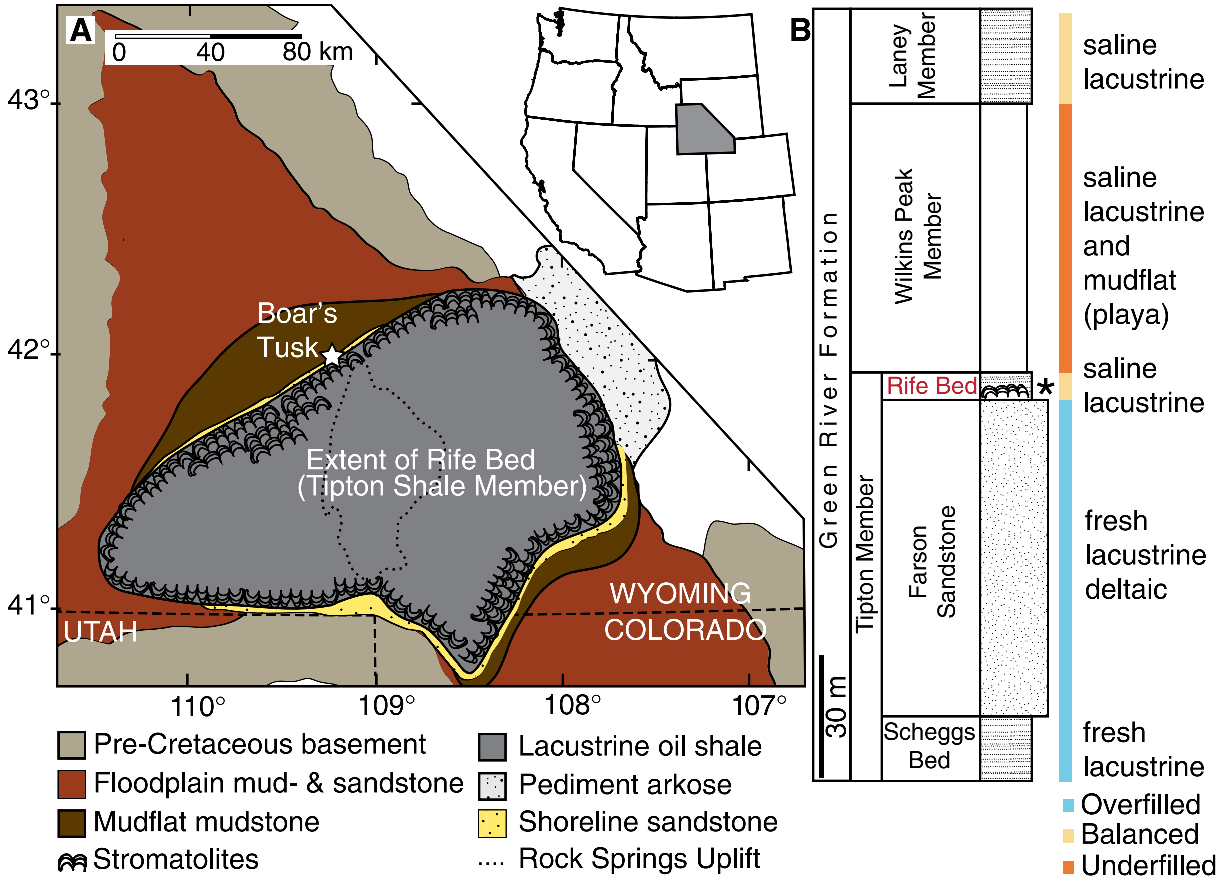

Fig. 1. (A) Map showing the location of the Boar's Tusk outcrop in the context of the mapped extent of the Rife Bed (Tipton Shale Member, Green River Formation) and surrounding depositional environments at the time when the stromatolites in this study were forming near the shoreline of Paleolake Gosiute (Modified from Roehler, 1993). (B) Stratigraphic representation of the Boar's Tusk Outcrop showing the location of the stromatolite bed (marked with *) and the transitioning of paleolake Gosiute from overfilled to balance-filled to underfilled and back (after Roehler, 1991; Pietras and Carroll, 2006).

Pietras et al., 2003; Pietras and Carroll, 2006; Smith et al., 2008; Aswasereelert et al., 2012).

The Green River Formation records the Early Eocene Climatic Optimum (EECO) from 52 to 50 Ma, the warmest period of the Cenozoic (Fig. 2). The EECO was associated with high levels of atmospheric CO_2 and has been compared to future climate projections (Zachos et al., 2008), thus providing a benchmark for research on future environmental change. As the most recent hothouse climate period (Tripati et al., 2003), the EECO may be a geological analog for understanding the impact of high greenhouse gas levels on climate and used for testing the predictions of models. Paleolake Gosiute, which formed the deposits of the Greater Green River Basin, was a very broad depositional system with relatively flat bathymetry, not unlike the Great Salt Lake, today (only larger). Bradley (1964) suggests a bathymetric gradient of ~0.2–0.4 m/km, implying a small change in volume might result in a dramatic lateral shift in facies. Thus, despite its large lateral extent, Lake Gosiute would have been very sensitive to changes in climate that would affect precipitation and lake recharge/evaporation during the EECO. Doebbert et al. (2010) provided an isotopic modeling framework to understand broad-scale changes in the hydrologic budget of the Laney Member of the Green River Formation. Here, stromatolites are used to investigate the lake system as a finer scale, complementing the previous studies.

Stromatolites are present in the Green River Formation and are typically considered near-shore deposits (e.g., Buchheim and Surdam, 1977; Roehler, 1993). While the actual duration of stromatolite lamination is not well understood, the formation of stromatolite laminae in other systems are considered diurnal (Golubić and Focke, 1978; Vanyo and Awramik, 1982; Berelson et al., 2011), seasonal (Jones, 1981), annual (e.g., Grotzinger and Knoll, 1999 and references therein), or even multi-annual (Petryshyn et al., 2012). However, Green River Formation stromatolites existed within the lifetime of the shoreline system, and their laminated nature provides a unique opportunity to study environmental change in the basin on a potentially highly resolved temporal scale.

This study focuses on the petrography and geochemistry of a stromatolite from a period when one of the large Green River Formation lakes transitioned from a balance-filled, freshwater lake to an underfilled (closed), saline lake (Pietras et al., 2003). This work permits estimates of environmental change at a critical period in the lake's evolution on a fine temporal scale and gives insight into the dynamics of the climate during the height of the EECO, which may better inform future climate projections. Furthermore, the study elucidates how the changing lake environments affected the growth of the stromatolites, impacting how stromatolites are viewed as environmental indicators in deep time.

1.2. Geological setting

Stromatolites for this study were collected from the Boar's Tusk outcrop (41.97°N, 109.25°W) on the eastern side of White Mountain, approximately 41 km north of Rock Springs, Wyoming (Fig. 1 of this paper, described by Roehler, 1991, as the type locality for the Farson Sandstone). The outcrop is named for a distinctive volcanic tower, the Boar's Tusk, located 6.5 km to the west of the outcrop (Fig. 1A). The site is within the Bridger Basin of the greater Green River Basin.