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Lacustrine $^{87}Sr/^{86}Sr$ as a tracer to reconstruct Milankovitch forcing of the Eocene hydrologic cycle

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ABSTRACT

The Green River Formation (GRF) provides one of the premier paleoclimate archives of the Early Eocene Climatic Optimum (~50 Ma), representing the apex of the early Cenozoic greenhouse climate. Rhythmic lake-level variability expressed in the GRF has inspired numerous hypotheses for the behavior of the Eocene hydrologic cycle, including its linkage to astronomical forcing, solar variability, and the El Niño Southern Oscillation (ENSO). However, the lack of sufficient proxy data to document atmospheric water-mass transport and the geographic pattern of evaporation/precipitation/runoff has made it difficult to discriminate between different models for astronomical forcing. Variable $^{87}Sr/^{86}Sr$ ratios of bedrock that encompass the GRF provide an opportunity to reconstruct the spatial expression of the Eocene hydrologic cycle and its linkage to lake level. Here Sr isotope data from the Wilkins Peak Member, a rhythmic succession that has been demonstrated to record Milankovitch forcing of lake levels, indicate that high lake levels reflect an increased proportion of runoff from less radiogenic rocks west of the basin, eliminating a number of the existing astronomical-forcing hypotheses. The $^{87}Sr/^{86}Sr$ variability is consistent with a change in mean ENSO state, which is predicted by climate models to be linked to orbital-insolation. Thus, the $^{87}Sr/^{86}Sr$ data reveal a coupling of high frequency (ENSO) and low frequency (astronomical) climate variability, and also predict the existence of sizable astronomically-forced alpine snowpack during the last greenhouse climate. More broadly, this study demonstrates the utility of $^{87}Sr/^{86}Sr$ as a powerful tool for reconstructing the deep-time hydrologic cycle.

1. Introduction

The Eocene GRF contains rhythmic deposits that have been the focus of cyclostratigraphic inquiry for almost a century (Bradley, 1929), and it represents one of the most well-constrained (radioisotopically) and rigorously-tested records of astronomical-forcing from the last greenhouse (Fischer and Roberts, 1991; Roehler, 1993; Machlus et al., 2008; Meyers, 2008; Smith et al., 2010, 2014; Aswasereelert et al., 2013; Machlus et al., 2015). A number of hypotheses have been offered to explain its astronomically-forced depositional cycles, including global changes in temperature and humidity (Bradley, 1929; Roehler, 1993), changes in local incident shortwave radiation (and thus evaporation) on the lake's surface (Morrill et al., 2001), and changes in catchment or lake characteristics (Morrill et al., 2001). Modeling studies support a strong link between GRF deposition and high frequency (ENSO) to astronomical scale-climate variability (Sloan and Morrill, 1998; Huber and Caballero, 2003). Providing another perspective, Lawrence et al. (2003) suggest that lacustrine depositional processes could have been extremely sensitive to small regional climate changes, rather than representing large magnitude climate change. Thus, while the GRF provides a remarkable window into Eocene paleoclimate – at a time when high quality paleoclimate records from the marine realm are scarce (Zachos et al., 2001; Pälike and Hilgen, 2008) – its relation to larger-scale global climate change during the last greenhouse remains uncertain.

Establishing the link between the GRF record and global scale climate requires an understanding of the geographic expression of climate variables such as evaporation and precipitation. Unfortunately, proxy-based studies have not yet been able to constrain the geographic footprint of the hydrologic cycle and the role of regional moisture sources in controlling GRF lake levels. Oxygen isotope compositions offer one potential means for investigating such changes, based on differences in $\delta^{18}O$ of atmospheric moisture derived from different marine sources (Chamberlain et al., 2012). This approach, however, is also subject to substantial uncertainties

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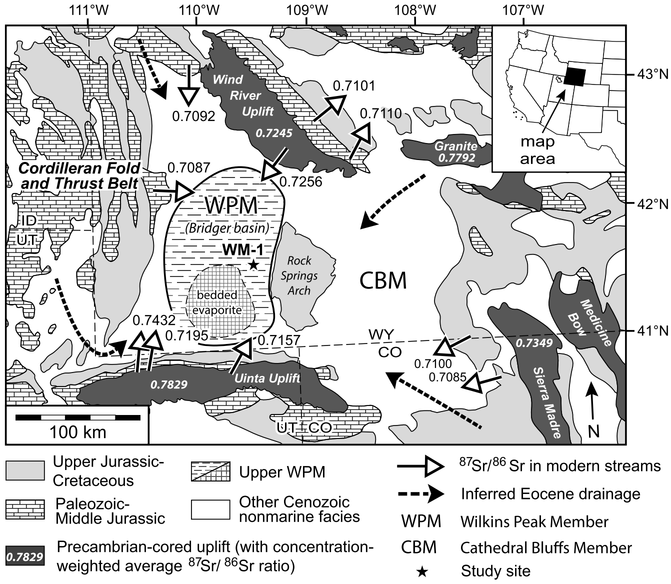

Fig. 1. Simplified geological map of the Green River Basin region and location of the White Mountain Core #1 (WM-1) in Wyoming, including ^{87}Sr/^{86}Sr ratios of modern rivers and concentration-weighted averages for Precambrian ^{87}Sr/^{86}Sr reported by Doebbert et al. (2014). Inferred Eocene rivers modified from Smith et al. (2014). Note that lower ^{87}Sr/^{86}Sr ratios generally correspond to streams that drain marine carbonate strata, and ratios greater than ~0.710 are exclusively associated with Precambrian rocks. The Cathedral Bluffs Member (CBM) of the Wasatch Formation consists primarily of Precambrian detritus, which should therefore be characterized by higher ^{87}Sr/^{86}Sr values, and was deposited by rivers that drained toward the WPM. Relatively low ^{87}Sr/^{86}Sr ratios near the Sierra Madre likely reflect local influence of Cretaceous marine carbonate units within the Mancos Group. The Bridger Basin lies between the Cordilleran Fold and Thrust Belt and the Rock Springs Arch.

related to fractionation of meteoric δ^{18}O along atmospheric transport pathways and during lake-surface evaporation, transpiration by plants, precipitation of authigenic mineral phases, and diagenesis (Talbot, 1990). In contrast, the ^{87}Sr/^{86}Sr ratio imparted on source waters by bedrock geology does not experience significant meteorologic or biologic fractionation (Capo et al., 1998), and consequently, strontium isotope ratios can be used to directly trace the geographic source of runoff into a lake, based on the known compositions of rocks and sediment within a lake's watershed (Placzek et al., 2011; Joordens et al., 2011). Changes in lake water ^{87}Sr/^{86}Sr ratios may therefore be used to infer changes in runoff patterns, which in turn imply changes in the regional distribution of precipitation/runoff. Here we present 51 carbonate ^{87}Sr/^{86}Sr measurements through 28 meters of rhythmic lake deposits of the Wilkins Peak Member (WPM), to help discriminate between competing climatic explanations for precessional-scale lake level fluctuations, and provide new constraints on the Eocene hydrologic cycle.

2. Geologic background

2.1. Sedimentary facies of the Wilkins Peak Member

The WPM was deposited in the Green River Basin (GRB) of southwest Wyoming (Fig. 1). It alternates between discrete intervals of lacustrine carbonate- and evaporite-rich lithologies deposited by Eocene Lake Gosiute, versus intervals of alluvial siliciclastic strata (Fig. 2). Wilkins Peak Member lacustrine facies have previously been interpreted to record repetitive deepening and shallowing of a saline to hypersaline lake that at its maximum covered much of the Bridger basin (Eugster and Hardie, 1975; Smoot, 1983; Roehler, 1993; Bohacs et al., 2000; Pietras and Carroll, 2006; Smith et al., 2015). The maximum lake depth is unknown, but shoreline facies preserved within the basin suggest that the lake rarely (if ever) rose above the relatively low-gradient basin floor to directly contact the bedrock of the basin-bounding uplifts. Continuously high salinities are supported by the presence of Na-evaporite minerals and the complete absence of fish or other megafossils, and there is no evidence that the lake spilled into downstream basins. Individual lacustrine expansion–contraction cycles typically begin with interbedded carbonate-rich mudstone, calcareous sandstone, and intraclast conglomerate interpreted to represent littoral facies deposited during transgression. Minor scours, desiccation cracks, wave ripples, and wavy bedding are all consistent with shallow water and intermittent subaerial exposure. These deposits grade upward into kerogen-rich, dark gray to brown, finely laminated, calcitic to dolomitic mudstone (oil shale), interpreted to represent sublittoral deposition (e.g., Carroll and Bohacs, 2001). Primary trona and halite are closely associated with the profundal facies near the basin depocenter, and diagenetic shortite crystals sometimes disrupt primary lamination. Finally, the kerogen-rich facies grade upward into gray-green carbonate-rich mudstone and siltstone facies that record gradual regression of the lake. Wavy lamination, mudcracks, brecciation, and displacive shortite crystals are common and reflect deposition in littoral to palustrine environments.

2.2. Bedrock ^{87}Sr/^{86}Sr and lake water provenance

During deposition of the WPM the drainage catchment of Lake Gosiute was largely restricted to mountain ranges lying within 100–200 km of the GRB, based on paleocurrent and sedimentary provenance evidence (Smith et al., 2014). Previous studies have established large geographic differences in bedrock ^{87}Sr/^{86}Sr (Beard and Johnson, 2000; Bataille and Bowen, 2012), which are reflected in the isotopic composition of modern rivers (Doebbert et al., 2014; Fig. 1). These differences are strongly bimodal. To the west of the GRB, the Cordilleran Fold and Thrust Belt (CFTB) contains several imbricated, Sr-rich marine carbonate intervals totaling several hundred meters. Modern rivers draining this area have ^{87}Sr/^{86}Sr ratios of 0.70869 to 0.70917 (Doebbert et al., 2014). In contrast, ranges to the north, south, and east of the GRB are cored by highly-radiogenic Precambrian rocks. Marine carbonate strata thin or disappear going eastward and were generally eroded from the range crests prior to deposition of the WPM (Carroll et al., 2006), unroofing crystalline cores that shed broad aprons of alluvial, arkosic detritus. Modern rivers that drain these cores typically have ^{87}Sr/^{86}Sr ratios of 0.7157 to 0.7432 (Doebbert et al., 2014). The overall structure and lithology of ranges bounding the GRB have changed little since the Eocene; the strong east–west bimodality evident in modern river water ^{87}Sr/^{86}Sr is also reflected in the isotopic composition of older lacustrine carbonates. For example, ^{87}Sr/^{86}Sr ratios in lacustrine carbonate in Utah associated with drainage from the CFTB average 0.7100 (Gierlowski-Kordesch et al., 2008), whereas capture of an eastern drainage by Eocene Lake Gosiute following WPM deposition increased carbonate ^{87}Sr/^{86}Sr ratios to 0.7146 in the Laney Member (Doebbert et al., 2014). Based on these observations, we infer that the present-day ^{87}Sr/^{86}Sr bimodality provides an approximate analogue during WPM deposition.

3. Materials and methods

This study is based on a 28 m interval of the uppermost WPM recovered in the White Mountain #1 drill core (Fig. 1). The study interval is bounded below by a composite alluvial bedset (the arkosic "I" bed; Culbertson, 1961), and above by the Laney Member of the GRF (Fig. 2). Carbonate Sr isotope ratios, Rb and Sr concentrations, and percent carbonate (Supplementary Table S1) were measured on 100 mg aliquots of powder material obtained from splits of the White Mountain #1 drill core. The analyzed powders