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Controls on Sr isotopic evolution in lacustrine systems: Eocene green river formation, Wyoming

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ABSTRACT

Strontium isotopes from lacustrine carbonates record detailed weathering histories of exposed bedrocks, and thus are potentially useful for understanding interactions between tectonics and climate that may be driven by local or regional factors in basin-scale hydrologic systems. We combine extensive $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ datasets from the Green River Formation in order to identify environmental factors driving the evolution of Sr concentration and isotopic composition in lacustrine systems through the use of Sr mass balance modeling. Two models are developed. The first tests the effect of drainage capture that drove a constant-volume lake from balance-filled to overfilled conditions, and is applied to the Laney Member of the Green River Formation. The second model focuses on lacustrine evolution in response to changing the concentration, composition, and mass of water influx in a variable-size Sr reservoir (lake). This model is applied to the Wilkins Peak Member of the Green River Formation.

$^{87}Sr/^{86}Sr$ ratios are correlated with $\delta^{18}O$ values only during the Laney Member, when both are readily explained by a common forcing mechanism (drainage capture). Modeling of Sr isotope compositions and concentrations indicates a short residence time for Sr (~10^3–10^4 years or less) in both balance-overfilled and underfilled phases of the Green River Formation lacustrine system. This in turn suggests that paleo-lacustrine sediments in most lakes can preserve Sr isotope records with high-resolution (~10^2 years) timescales. Rates of Sr sequestration in carbonate are shown to have a strong influence on lacustrine Sr concentration, and high Sr concentrations of lacustrine carbonate consistent with high salinity are observed in the underfilled Wilkins Peak Member and the balance-filled Tipton and lower Laney Members. In the Laney Member, $^{87}Sr/^{86}Sr$ mass-balance modeling results provide additional support for previous interpretations that the introduction of a large drainage system produced an isotopic shift across the lower LaClede/upper LaClede boundary. Major drainage reorganization is not required to drive high variability in $^{87}Sr/^{86}Sr$ ratios, however. Modeling shows that variability in $^{87}Sr/^{86}Sr$ ratios of ~0.004 observed in the Wilkins Peak Member can be explained by change in the characteristics of intrabasinal water sources during highstand vs. lowstand conditions.

1. Introduction

Sediments from lacustrine basins can archive sedimentological, geochemical, and climatic variability over periods of hundreds to millions of years, in some cases with up to annual resolution (e.g., Glenn and Kelts, 1991; Andrews et al., 2010; Giguet-Covex et al., 2010). Consequently, they provide unique archives of the integrated effects of uplift and erosion (e.g., Martel and Gibling, 1991; Paz and Rossetti, 2005; Newell et al., 2010; Lease et al., 2012), climate variability and paleoecology (e.g., McGlue et al., 2012).

The $^{87}Sr/^{86}Sr$ ratios of authigenic carbonate sediments in a lacustrine setting may record the provenance of water entering the basin (Benson and Peterman, 1995; Talbot and Williams, 2000; Rhodes et al., 2002; Holmes et al., 2007; Kober et al., 2007; Gierlowski-Kordesch et al., 2008; Fan et al., 2010), combining the isotopic compositions of incoming river water and groundwater as a concentration-weighted average. Residence times of Sr reported in modern freshwater lacustrine systems range from years to centuries (e.g., Grove et al., 2003; Ojiambo et al., 2003; Nakano et al., 2005). Rates and magnitudes of $^{87}Sr/^{86}Sr$ variation in lakes, however, are not well characterized and likely differ widely in different hydrologic settings. The strontium evolution of lakes vary according to the relative differences in $^{87}Sr/^{86}Sr$ of influx, as well as the relative sizes and Sr concentrations of Sr influxes (e.g. rivers), outfluxes (e.g. rivers, sequestration in sediment), and the reservoir itself

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(the lake). For example, because carbonate rocks typically have high Sr concentrations and are easily weathered relative to igneous or metamorphic basement rocks, they are likely to exert a strong control on $^{87}Sr/^{86}Sr$ ratios of dissolved Sr in rivers and lakes if present in the catchment area (e.g., Jacobson et al., 2002; Oliver et al., 2003; Jin et al., 2010). Mass-balance modeling can help to address questions about the rates and magnitudes of variability expected in lacustrine systems. Furthermore, demonstration that primary lacustrine processes are capable of generating the observed range of variability in a dataset helps provide confidence in the primary nature of the $^{87}Sr/^{86}Sr$ record in this study.

A combination of Sr and O isotope data is also informative in lacustrine settings, because these isotopic systems provide independent constraints on driving mechanisms behind depositional change in lacustrine systems (e.g., Chamberlain et al., 2013). $^{87}Sr/^{86}Sr$ ratios are not fractionated by temperature or evaporation, and hence are not directly influenced by climate, although climate-induced changes in weathering may affect Sr isotope compositions. In contrast, O isotopes are commonly applied as a paleoclimate indicator in lacustrine settings, and respond to complex interactions between numerous forcing mechanisms including temperature, aridity, elevation, and drainage and atmospheric patterns (e.g., Chamberlain et al., 1999; Chamberlain and Poage, 2000; Fricke, 2003; Carroll et al., 2008; Doebbert et al., 2010).

In this study, we investigate the controls on the evolution of Sr in lacustrine basins using an extensive $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ dataset from the Green River Formation of Wyoming. Several factors, including a long history of study that provides constraints on the evolution of lacustrine conditions over time, make the Green River Formation an ideal setting for a comprehensive study of lacustrine Sr. Arguably the most studied pre-Quaternary lake system in the world, its carbonate-rich deposits are the subject of more than 1000 publications, and it has detailed age control that is unavailable in other basins.

2. Geologic setting

The Greater Green River basin within the Sevier foreland is bounded by Precambrian-cored Laramide uplifts to the north, south, and east, and the Sevier fold and thrust belt to the west (Fig. 1). Laramide deformation in southern Wyoming was in its late stages by the early Eocene (e.g., Dickinson et al., 1988; DeCelles, 2004; Carroll et al., 2006), which suggests that during the Eocene the major basin-bounding features were likely to have been similar to this current configuration. Precambrian cores of basin-bounding uplifts were exposed by the Eocene (Crews and Ethridge, 1993; Carroll et al., 2006; Fan et al., 2011). Magmatism in both the Absaroka and Challis volcanic fields was active during Green River Formation deposition (e.g., McIntyre et al., 1982; Fisher et al., 1992; Harlan et al., 1996; Hiza, 1999; Feeley et al., 2002; Smith et al., 2008b), and ash falls from one or both of these sources were intermittently incorporated into lacustrine sediments. Present-day $^{87}Sr/^{86}Sr$ ratios of basement rocks and overlying sedimentary cover units in these basin-proximal mountain ranges vary widely, between a minimum of 0.7058 (concentrated weighted-mean $^{87}Sr/^{86}Sr$ average of the Absarokas; Peterman et al., 1970; Meen and Eggler, 1987, 1989; Hiza, 1999; Feeley et al., 2002) and a maximum of 0.7829 (concentration weighted-mean $^{87}Sr/^{86}Sr$ average of the Uintas; Crittendon and Peterman, 1975), indicating that drainages from different source uplifts had the potential to drive significant variability within the lake. In this paper, we frame our discussion relative to these modern (measured) $^{87}Sr/^{86}Sr$ ratios. Correcting measured $^{87}Sr/^{86}Sr$ ratios in basement rocks from the region to the 50 Ma age of Green River Formation deposition changes locally-averaged ratios of basin-bounding uplifts by 0.003 or less, a relatively small change compared to the larger regional range (Fig. 1). Both surface and shallow groundwaters are expected to have $^{87}Sr/^{86}Sr$ ratios that reflect this variety of regional lithologies.

Deposition of the Green River Formation corresponded with the warm climate of the Early to Middle Eocene (Smith et al., 2008a, 2010), a time period that is also associated with high atmospheric CO_2 levels (e.g., Sloan, 1994; Sewall and Sloan, 2001; Zachos et al., 2001, 2005). Under these conditions, high chemical weathering rates are expected, and high rates of both chemical and physical weathering are estimated from clastic and evaporite sediment volumes in the Wilkins Peak Member (Smith et al., 2008a).

In the Greater Green River Basin (Fig. 1), the Green River Formation is divided into the Luman, Tipton, Wilkins Peak, and Laney Members

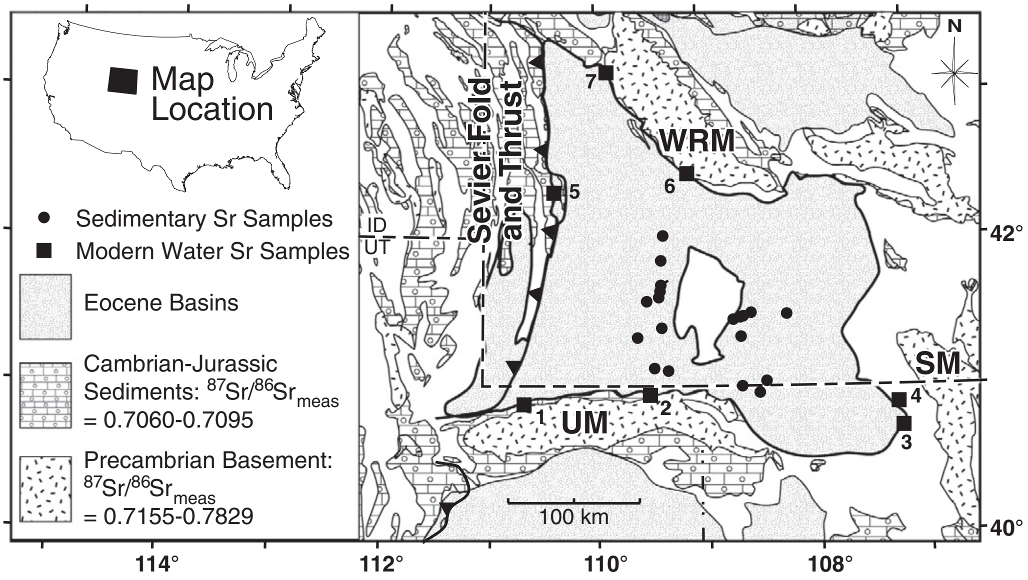

Fig. 1. Geologic map of study area modified from Rhodes et al. (2002). Geologic units are patterned to highlight differences in the expected strontium isotope composition of drainage interacting with regional rock types. The range in $^{87}Sr/^{86}Sr$ associated with Precambrian basement is the range of concentration-weighted average values of published data from the Uinta Mountains (UM), Wind River Mountains (WRM), Sierra Madre (SM), Beartooth Mountains, Owl Creek Mountains, and Granite Mountains. Data from: Crittendon and Peterman (1975), DePaolo and Wasserburg (1979), Divis (1977), Frost et al. (1998), Hedge et al. (1986), Mueller et al. (1985), (1982), Patel et al. (1999), Peterman and Hildreth (1978), Simmons and Lambert (1982), Wooden et al. (1982) and Zielinski et al. (1981). Modern water sample locations are numbered by location: 1) Blacks Fork River, Uinta Mountains, 2) Carter Creek, Uinta Mountains, 3) Elkhead Creek, Sierra Madre, 4) Little Snake River, Sierra Madre, 5) LaBarge Creek, Sevier Thrust, 6) Big Sandy River, Wind River Mountains, 7) Green River, Wind River Mountains. Sweetwater Creek and the Shoshone River (Absaroka Range) are north of the field of view.