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Stromatolites in Walker Lake (Nevada, Great Basin, USA) record climate and lake level changes ~35,000 years ago

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A B S T R A C T

Walker Lake is a closed-basin remnant of the large Pleistocene glacial Lake Lahontan system that has experienced multiple high amplitude (100–200 m) changes in water level over the past ~40,000 years in response to changes in climate. A laminated carbonate stromatolite composed of varying proportions of calcite fans and micrite was collected from a paleoshoreline located at approximately 58 m above present lake level. Radiocarbon dating revealed that the stromatolite spans approximately 2000 years of growth, from 35,227 to 33,727 calibrated years before present (YBP), a time period during which paleolake level is not well constrained. Distinct laminae were drilled along the growth axis, and the resulting powders were collected for clumped isotope analyses to generate formation temperatures (lake water temperatures) during stromatolite formation, from which $\delta^{18}O_{water}$ was calculated.

Results indicate that the stromatolite experienced an initial increase in temperature and water $\delta^{18}O$ values followed by a decrease in both during the course of accretion. The resulting temperature and isotopic data were input into a Rayleigh distillation model for lakewater evaporation in order to estimate the magnitude of lake level and volume fluctuations over the course of accretion. Modeling results reveal a lake level decrease between 8.1 and 15.6 m, followed by an increase of between 4.3 and 8.8 m during the course of stromatolite growth. The results of this study indicate that Walker Lake experienced significant lake volume change over the course of 2000 years, perhaps as a response to precipitation changes driven by fluctuations in the polar jet stream and accompanying changes in regional climate, and/or evaporation-induced changes in lake level. These results add to a growing body of research indicating that stromatolites and other lacustrine tufas represent a detailed and extensive terrestrial archive that can potentially be used to reconstruct the timing and magnitude of climate change.

1. Introduction

Accurate terrestrial reconstructions of paleotemperature and paleohydrology are critical for understanding surface environments throughout Earth history. Terrestrial paleoclimate data can aid in building reliable climate models and can help us understand the links between continental and oceanic climate data (e.g., Rowley and Garzione, 2007; Hren and Sheldon, 2012). Such data are also relevant to constraining the sensitivity of the Earth system to climate forcing (MARGO, 2009).

Various archives have been used to reconstruct climate parameters in terrestrial settings, (e.g., leaf margin analysis, palynology, glacial deposit distributions, and stable isotopes of lacustrine deposits). In many cases, terrestrial signals yield qualitative but not high-resolution quantitative results because of the non-continuous nature of such archives. While overall trends (wetter/drier, cooler/warmer) may be discernable, absolute values cannot be determined with a high degree of confidence. Speleothems can provide insights into terrestrial climate, although in some cases the proxy data derived from speleothems are subject to multiple influences (e.g., Affek et al., 2008; Daëron et al., 2011) and therefore can be challenging to interpret (Johnson and Ingram, 2004; Dayem et al., 2010). Lake sediment cores represent another useful terrestrial archive of climate (Rosenthal and Broccoli, 2004); however, not all hydrologic proxies are easy to interpret (Yuan et al., 2006a), and sediment cores are limited to the geologically recent.

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This study dates stromatolites from Walker Lake, Nevada, and applies carbonate "clumped" isotope thermometry to reconstruct paleolake temperatures, shifts in lake level and terrestrial paleoclimate that occurred ~30,000 years ago (30 ka), during which the Lahontan lake level record is spotty and unresolved. Clumped isotope thermometry, despite being a relatively young proxy, has an extensive record of use in lacustrine systems (e.g., Huntington et al., 2010; Quade et al., 2011; Hren and Sheldon, 2012; Lechler et al., 2013; Frantz et al., 2014; Petryshyn et al., 2015), discussed below.

1.1. Traditional paleothermometry vs. clumped isotope paleothermometry

Changes in $\delta^{18}O$ ratios in lacustrine carbonates can be a useful tool for the study of temperature, vapor sources, and changes in evaporation/precipitation as they pertain to lake level fluctuations (e.g., Benson et al., 1996; Solari et al., 2010). The traditional, most widely used method of determining the temperature of formation of a carbonate mineral, the oxygen isotope paleothermometer, requires knowledge of both the oxygen isotope ratio of the fluid of formation and the oxygen isotope ratio of the carbonate (e.g., Urey, 1947; Epstein et al., 1953; Emiliani, 1966). The fractionation between these two phases is temperature dependent (Kim and O'Neil, 1997). Unfortunately, the isotopic composition of the fluid from which the carbonate precipitated is nearly always unknown and must be estimated/guessed to solve the temperature equation with varying degrees of confidence. Recent work suggests this fractionation can also be affected by pH and growth rate (Watkins et al., 2014). All of these factors can further complicate the interpretation of oxygen isotope ratios in carbonate minerals and the paleotemperatures derived from them. Here, we apply the clumped isotope paleothermometer to lacustrine stromatolites in order to surmount some of the drawbacks of traditional $\delta^{18}O$ paleothermometry. With the temperature of formation and the isotopic composition of the mineral known, the $\delta^{18}O$ of ancient lake water can be uniquely calculated.

1.2. Stromatolites as terrestrial climate archives

Several studies have explored the use of lacustrine carbonates, and stromatolites in particular, to reconstruct past environment and climate (e.g., Petryshyn et al., 2012; Ibarra et al., 2013; Frantz et al., 2014; Petryshyn et al., 2015). Stromatolites, laminated sedimentary structures that are accretionary away from a point or surface (Semikhatov et al., 1979), typically accrete through the interplay of sediment, environment, and biology (e.g., Shapiro, 2007; Riding, 2011; Bosak et al., 2013; Frantz et al., 2015). As the structures form, they record chemical and physical information about their surroundings. Frantz et al. (2014), coupling trace element analysis, clumped isotope paleothermometry, and oxygen isotope modeling of stromatolites from the Eocene Green River Formation, was able to document several meter-scale changes in paleolake level, corresponding to several tens of kilometers of shoreline change over 30 cm of stromatolite accretion. This study demonstrated that stromatolites record the physical changes in their surroundings as lake level, water temperature, and environment fluctuates around them.

Petryshyn et al. (2015) also utilized clumped isotope thermometry while studying the carbonate tufas (microbialites) of Pavilion Lake, British Columbia. The stromatolites in this study, although thought to be mostly modern, were actually found to be up to 9 ka. The stromatolites also contained evidence of a historic drought in the region prior to 7 ka, followed by a period of lake level rise. These studies (and several others mentioned above) have demonstrated the utility of lacustrine stromatolites as a high-resolution climate archive.

2. Walker Lake

Walker Lake is a closed-basin, sodium bicarbonate lake with an area of ~100 km^2 and a maximum depth of 28 m in Summer 2015 (Fig. 1A). The lake was once part of the Pleistocene Lake Lahontan complex (e.g., Russel, 1885) and has been isolated from the remaining Lake Lahontan system for the last 12,000 years (Benson and Thompson, 1987; Benson et al., 1995). Walker Lake has seen a historic drawdown (over 50 m) since 1882 due to anthropogenic diversion of the Walker River, its main tributary (Benson et al., 1991; Yuan et al., 2006b; Adams, 2007). Currently, the lake surface is at an elevation of 1198 m above sea level.

Presently in Walker Lake, calcium carbonate precipitation is limited by the availability of dissolved calcium. While it is replete with carbonate (~20 mM; pH 9.5), the overall concentration of calcium is less than 0.2 mM (Berelson et al., 2008). Petryshyn et al. (2012) analyzed a number of Holocene carbonate stromatolites found currently exposed on the southwest corner of the lake. The stromatolites were dated, and laminations were counted to produce a record of lamination frequency. Surprisingly, Petryshyn et al. (2012) found that lamination rate was not yearly, or even seasonal, contrary to long-standing assumptions that stromatolite laminae represent biologically relevant diurnal, seasonal, or annual cycling. When lake level was high, laminae precipitated on average every 4 to 6 years with ENSO-like periodicity. This larger-scale climatic forcing was required to deliver enough calcium to the lake to produce a single lamination. When lake level was low (near present-day levels), yearly runoff was able to deliver enough calcium to promote precipitation. These structures hint that high-resolution terrestrial climate signals are captured by Walker Lake stromatolites.

In addition to the stromatolites studied by Petryshyn et al. (2012), several other discrete horizons of carbonate accretions of varying ages are found above current lake level (Newton and Grossman, 1988; Benson et al., 1996). The stromatolites studied here are found 55–60 m above the eastern shoreline (38°38′30″N, 118°40′21″W). The stromatolites crop out in large, meter-tall "heads," with arms or "petals" that protrude laterally out from the sides (Fig. 1B, C); that is, the structures grew upward and outward simultaneously.

2.1. Lake level and climate history

The history of Pleistocene Lake Lahontan and its remnants, including Walker Lake, has been documented and refined in many studies (e.g., Newton and Grossman, 1988; Benson et al., 1991, 1995 and 1996; Buetel et al., 2001; Yuan et al., 2006a; Yuan et al., 2006B; Adams, 2007; Berelson et al., 2008; Benson et al., 2013; Reheis et al., 2014). The majority of the carbonates (tufas) used to construct the record were deposited in the last 35 ka (Benson et al., 1995).

Generally, it is thought that Lake Lahontan was at a lowstand between 27,500 and 23,500 ybp (Benson et al., 1995, 2013). At this time, lake surface elevation was ~1156 m above sea level. Walker Lake would have been a separate, closed basin at this time, given the height of the sill that separates it from the rest of the Lahontan basin (Benson et al., 1995, 2013). Prior to ~30 ka, there are few constraints on lake level, although recently the use of volcanic tephra (interpreted at the outcrop scale) has been implemented in reconstruction of the Lake Lahontan record (Reheis et al., 2014). While the two proxies (tufa and tephra) produce similar lake level curves from 22 ka to the present, they diverge (often by tens of meters) at older dates (see Reheis et al., 2014, Fig. 12). Thus, the history of Lake Lahontan prior to 30 ka remains unresolved.

In this study, we aim to use the stromatolites found on the east shore of Walker Lake to derive a lake level history during this disputed time period by coupling carbon dating with clumped isotope thermometry and an oxygen isotope-based model of lake volume.

3. Methods

Full stromatolite heads were collected from the east side of Walker Lake (Fig. 1) at a paleoshoreline at 1288 m elevation, 58 m above