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Mid-Holocene drying of the U.S. Great Basin recorded in Nevada speleothems

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ABSTRACT

Lake level records point to dramatic changes in Great Basin water balance over the last 25 ka, but the timing and pace of Holocene drying in the region remains poorly documented. Here we present stable isotope and trace metal data from two Lehman Caves, NV speleothems that provide a well-dated record of latest Pleistocene to mid-Holocene hydroclimate in the U.S. Great Basin. Together the stalagmites span the interval between 16.4 ka and 3.8 ka, with a hiatus from 15.0 ka to 12.7 ka. Mg/Ca and $\delta^{13}C$ covary throughout the records, consistent with control by the extent of degassing and prior calcite precipitation (PCP); measurements of modern cave and soil waters support PCP as the primary control on drip-water trace-element composition. We therefore interpret Mg/Ca and $\delta^{13}C$ as reflecting infiltration rates, with higher values corresponding to drier periods. Both Mg/Ca and $\delta^{13}C$ indicate a wet period at the beginning of the record (12.7–8.2 ka) followed by pronounced drying after 8.2 ka. This mid-Holocene drying is consistent with records from around the western United States, including a new compilation of Great Basin lake-level records. The strong temporal correspondence with the collapse of the Laurentide ice sheet over Hudson Bay suggests that this drying may have been triggered by northward movement of the winter storm track as a result of ice sheet retreat. However, we cannot rule out an alternative hypothesis that wet early Holocene conditions are related to equatorial Pacific sea-surface temperature. Regardless, our results suggest that Great Basin water balance in the early Holocene was driven by factors other than orbital changes.

1. Introduction

The Great Basin is a large internally drained region in the western United States that covers large areas of Nevada, Utah, California, and Oregon (Fig. 1). Modern climate over much of the Great Basin is arid, with most of its sub-basins unable to sustain permanent lakes; however, the spectacular paleoshorelines and lake deposits in the Great Basin have long been recognized as evidence of dramatic hydrologic changes in the past. The Great Basin has fascinated geologists since the late 19th century, when G. K. Gilbert and I.C. Russell began to unravel the histories of the region's massive paleo-lakes. More recently, developments in the application of radiocarbon, and later, U-series, dating methods have yielded improved chronologies of hydrologic change from the Great Basin.

Despite years of research, well-dated Holocene records of hydrological change from the Great Basin remain sparse. Most existing records of past Great Basin hydrology utilize either shoreline and sediment deposits from closed-basin lakes or biological archives like packrat middens. Although they offer valuable

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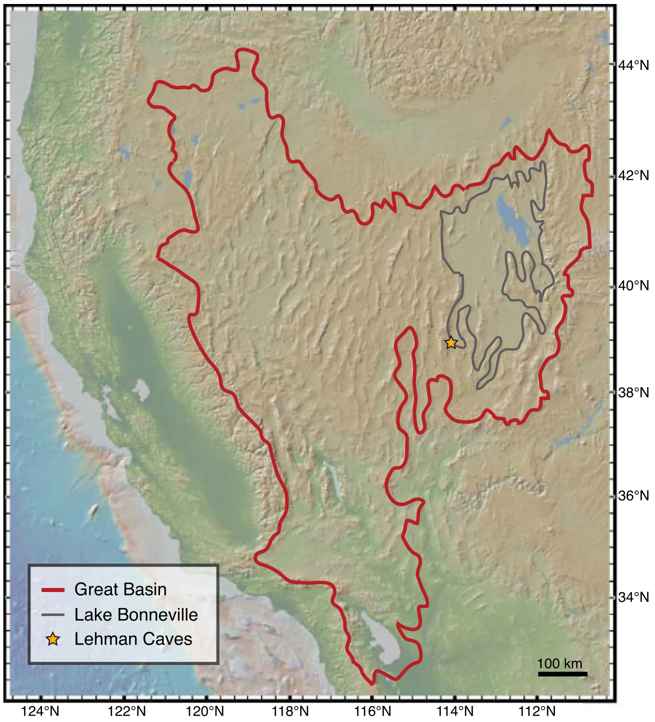

Fig. 1. Map of the Great Basin (red outline) showing the largest extent of Lake Bonneville (gray outline), and the location of Lehman Caves (yellow star) on the western edge of the Bonneville Basin. Map modified from GeoMapApp (http://www.geomapapp.org/); base map from Ryan et al. (2009); Great Basin outline adapted from HydroSHEDS (http://hydrosheds.cr.usgs.gov; Lehner et al., 2008); Bonneville Basin outline adapted from Currey et al. (1984). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

information, these types of records do not always provide the temporal resolution necessary to make inferences about mechanisms of climate change. In addition, lake deposits commonly record wetter conditions during the Last Glacial period but offer incomplete records of drier conditions during the Holocene.

In recent decades, high-precision U–Th dating of speleothems, combined with trace element and stable isotope measurements, has allowed for the development of detailed chronologies of climate change. To date, there are few published speleothem records from in and around the Great Basin (Polyak et al., 2004; Asmerom et al., 2007; Denniston et al., 2007; Oster et al., 2009; Wagner et al., 2010; Shakun et al., 2011; Lundeen et al., 2013; Lachniet et al., 2014), and only a small number of these offer substantial coverage of the Holocene. Well-dated terrestrial records from this region are necessary to better understand the response of Great Basin hydroclimate to changing boundary conditions over the late Quaternary and to assess the representation of regional precipitation patterns in general circulation models simulating past climates.

This study presents geochemical (Mg/Ca and Sr/Ca) and stable isotope ($\delta^{18}O$, $\delta^{13}C$) records spanning much of the deglaciation and Holocene from two speleothems from Lehman Caves, Nevada. We interpret these data – and in particular, the Mg/Ca and $\delta^{13}C$ records – as primarily reflecting infiltration rates above the cave, and we present evidence that local infiltration rates are well correlated with water balance changes over a large portion of the Great Basin during the early to mid Holocene. These records provide important constraints on the potential drivers of relatively wet early Holocene conditions and of mid-Holocene drying in the Great Basin.

2. Regional setting

2.1. Lehman Caves

Lehman Caves is situated on the east flank of the southern Snake Range on the western margin of the Bonneville Basin, at 39°00′20″N, 114°13′13″W and 2130 m elevation (Fig. 1). Average annual precipitation above the cave is approximately 33 cm/year (National Park Service). Seasonal recharge in Lehman Caves is dominated by winter precipitation, as evidenced by seasonal changes in drip rates and cave pool levels; dripwater response time is 1–4 weeks (Ben Roberts, National Park Service, personal communication). The cave is situated within a local topographic high in the Pole Canyon limestone such that the great majority of water entering the cave is from infiltration directly above the cave, not from infiltration or run-off from the higher elevations of the Snake Range. Most of the cave network is situated between 30 and 60 m from the surface (National Park Service). HOBO data loggers (Onset Computer Corporation, Bourne, MA) placed in the cave in 2009–2010 indicate that air temperature and relative humidity in the cave remain approximately constant year round, at 11.0 °C and approximately 100%, respectively.

The Bonneville Basin enclosed a very large (~55,000 km^2) lake during the Last Glacial Maximum (LGM) and early deglaciation that lay just to the east of the cave site (Fig. 1), reflecting significantly more positive water balance in the region at these times. The rise of Lake Bonneville leading into the LGM has been suggested by a number of studies to reflect the southward displacement of the mean winter storm track by the Laurentide and Cordilleran ice sheets (Antevs, 1952; COHMAP Members, 1988; Bromwich et al., 2004), although Lyle et al. (2012) used coastal precipitation records to suggest that post-LGM precipitation entered the Great Basin from the tropical Pacific. Superimposed on this response to ice sheet topography, the basin experienced its wettest conditions during ice-rafting events in the North Atlantic, in particular Heinrich events 1 and 2 (Oviatt, 1997; McGee et al., 2012; Munroe and Laabs, 2013b). Although the Bonneville Basin is well studied, relatively little is known about the precise timing of hydrological changes in the Great Basin during the latest Pleistocene and early-to-mid-Holocene. Lake levels dropped considerably around 15 ka, approximately at the time of the Bølling/Allerød warming in the Northern Hemisphere (Oviatt et al., 1992; Godsey et al., 2011; McGee et al., 2012). The work of Murchison (1989) and Oviatt et al. (2005) on lacustrine deposits indicates a modest rise of the lake known as the Gilbert highstand between ~12.9 and 11.2 ka, a time which is roughly correlative with the Younger Dryas cold event in the Northern Hemisphere (12.9–11.7 ka; Rasmussen et al., 2006). Other studies from the Bonneville Basin, reviewed in Section 5.4 below, document the drying of the basin during the early-to mid-Holocene, but the timing and drivers of this drying remain unclear (Madsen et al., 2001; Patrickson et al., 2010).

3. Materials and methods

3.1. Sample collection

Two Lehman Cave stalagmites, WR11 and CDR3, were analyzed for this study (Fig. 2). WR11 was collected from the West Room of the cave, located approximately 50 m below the surface (Ben Roberts, National Park Service, personal communication), where it originally precipitated on a piece of flowstone that had been broken during cave development over the past century. CDR3 had been broken during previous cave vandalism and was collected from the part of the cave known as the Civil Defense Room (Fig. 2) that is used for storage of broken stalagmites; the original growth location