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Stalagmite records of hydroclimate in central California during termination 1

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ABSTRACT

The last deglaciation is marked by large and abrupt hydroclimatic changes in the Great Basin and the American Southwest. However, comparatively little is known about how hydroclimate varied on the western side of the Sierra Nevada. We present new evidence for abrupt changes in precipitation amount in the central Sierra Nevada during the last deglaciation. Our new record from McLean's Cave overlaps with a previously published record from nearby Moaning Cave (Oster et al., 2009), and extends the record of hydroclimatic change in the region through Heinrich Stadial 1. McLean's Cave speleothem $\delta^{18}O$, $\delta^{13}C$, Mg/Ca, and Sr/Ca indicate a shift to drier conditions at the beginning of Heinrich Stadial 1 from 16.1 to 17.5 ka followed by wetter conditions at the end of Heinrich Stadial 1 when the majority of Great Basin lakes reached their deglacial highstands. During the last deglaciation, coincident shifts in the Moaning and McLean's Cave proxy records indicate drier conditions in the western Sierra Nevada during millennial-scale intervals of warming at high latitudes such as the Bölling and Alleröd, and wetter conditions during cooler intervals such as the Older and Younger Dryas. Thus, the Sierra Nevada speleothem records are consistent with other regional records that document increased winter rainfall during millennial-scale cold periods of the last deglaciation. However, regional differences exist in the hydroclimatic response to the Younger Dryas, with central Californian and interior southwestern sites indicating an increase in winter storms that is not apparent in southern California. Dynamic simulations of atmospheric circulation indicate that wetter conditions during the Younger Dryas relative to the Bölling at McLean's Cave may have resulted from a stronger storm track in the north Pacific at the latitude of northern California.

1. Introduction

The Late-Pleistocene to Holocene transition in the western United States was punctuated by rapid hydroclimatic changes that significantly influenced the geomorphology and ecology of this semi-arid region. Such changes include the growth of pluvial lakes to post-Last Glacial Maximum highstands (Munroe and Laabs, 2013), and changes in the amount and sources of rainfall as recorded in speleothem proxy records, alluvial fan aggradation, and pollen records from the California coast (Oster et al., 2009; Wagner et al., 2010; Asmerom et al., 2010; Lyle et al., 2012; Antinao and McDonald, 2013). Approximately synchronous shifts in several western US proxy records and time series of Greenland temperature indicate that robust teleconnections exist between the two regions. Likely mechanisms include changes in winter and summer insolation (Lachniet et al., 2014), the thickness and extent of continental ice sheets and sea ice (COHMAP Members, 1988; Hostetler and Benson, 1990; Oster et al., 2015), and variations in meridional temperature gradients (Asmerom et al., 2010) that in turn drove changes in atmospheric circulation and influenced the strength, position, and moisture sources of the winter westerly storm track in western North America.

Despite numerous and diverse proxy records of deglacial change in this region, questions remain about the spatial pattern of

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hydroclimatic change during this interval and its driving mechanisms. Disparities in the timing and sometimes the sense of hydroclimate change noted in various proxy records have led to multiple hypotheses about how the westerly storm track evolved from the Last Glacial Maximum to the Holocene, and the variable impacts of that evolution across the western United States (Hostetler and Benson, 1990; Asmerom et al., 2010; Lyle et al., 2012). Given the presently marginal water resources in this region (Griffin and Anchukaitis, 2014), and the potentially dire though uncertain projections of hydroclimatic change expected with continued global warming (Seager and Vecchi, 2010; Diffenbaugh et al., 2013), understanding the pattern and causes of past hydroclimate change in the region is essential.

Stalagmites from caves on the western slope of the central Sierra Nevada provide proxy records of past precipitation and temperature changes during the last glacial cycle (Oster et al., 2009, 2010, 2014), including a multi-proxy record of precipitation change at decadal-to centennial-resolution from Moaning Cave over the range of 8.7–16.5 ka (Oster et al., 2009). Here, we present an improved chronology for the Moaning Cave record and a new multi-proxy record from a stalagmite from nearby McLean's Cave (ML1) that grew from 12 to 19 ka. Sub-decadally to decadally-resolved stable isotope records from ML1 reproduce centennial-to millennial-scale shifts evident in the lower-resolution Moaning Cave record and extend the central Sierra Nevada record to include Heinrich Stadial 1 (~14.5–18 ka). The two Sierra Nevada speleothem records indicate significant hydroclimate changes that are consistent with several other regional paleoclimate records (e.g. Wagner et al., 2010; Asmerom et al., 2010; Street et al., 2012) but display differences relative to others (e.g. Kirby et al., 2013). The hydrologic changes noted in the Sierra Nevada speleothem records are consistent with the results of recent models of changes in the strength of the westerly storm track on millennial timescales during the last deglaciation (Wong et al., in revision).

2. Site and sample description

Moaning Cave (MC) and McLean's Cave (ML) are developed in the same metamorphosed carbonate lens within the Calaveras Complex of the central Sierra Nevada foothills (Fig. 1). The cave entrances are located approximately 4 km apart. MC, situated at 520 m above sea level, is presently a tourist cave. The entrance to ML at 300 m above sea level lies below the historic level of the New Melones reservoir, though the entrance has recently reemerged in the present drought. Complete descriptions of both cave systems can be found in Oster et al. (2009) (for MC) and Oster et al. (2014) (for ML). Collection of the Moaning Cave stalagmite (MC3) has been described previously (Oster et al., 2009, 2010). The stalagmite from McLean's Cave used in this study (ML1) is a 24 cm stalagmite that was collected in 1979 from the upper passage of McLean's Cave, below 30–60 m of carbonate bedrock (Fig. 1C), just prior to cave inundation following dam construction.

The modern climate above both caves is characterized by cool, wet winters and warm, dry summers. On average, 90% of rainfall occurs between the months of October and April. These months are characterized by winter storms carrying moisture to the Sierra from the central and northern Pacific (Dettinger et al., 2004). However, storms that produce the most intense rainfall are often associated with atmospheric rivers, narrow bands of water vapor that can travel long distances in the lower atmosphere (Ralph and Dettinger, 2011). Such storms often tap vapor sources from the subtropical Pacific, and are frequently associated with flooding in southern and central California (Dettinger, 2011; Ralph and Dettinger, 2011).

The tourist operation, which alters water flow within MC, and the perennial flooding of ML, prevents monitoring of modern drip water chemistry and ventilation in these caves. However, a study of the modern cave system was conducted over five years at a third nearby cave, Black Chasm Cavern (BL) (Fig. 1B). BL is located 45 km to the northwest of MC and ML and has a similar vertical, fracture-oriented geometry and should provide a modern analogue to the response of central Sierra Nevada caves to environmental change. The results of that study are detailed in Oster et al. (2012). We note here that BL is ventilated during the cold winter months, during which drip rates also increase substantially. Monthly measurements of rain and drip water $\delta^{18}O$ at Black Chasm Cavern documented that rainwater $\delta^{18}O$ is significantly positively correlated with surface air temperature, but shows no significant relationship

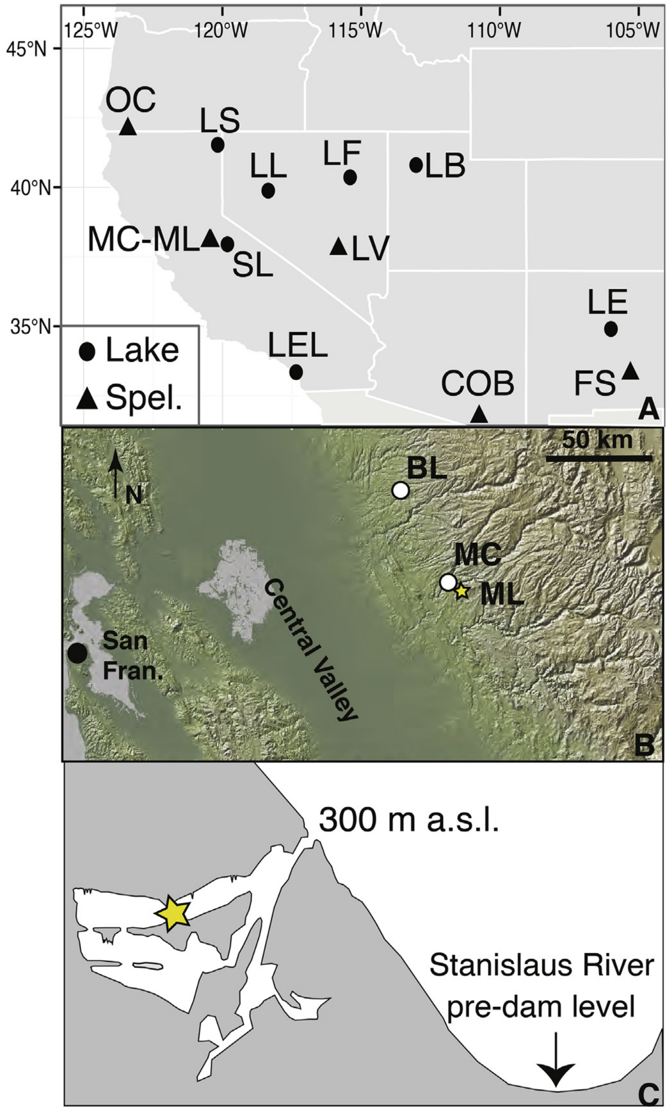

Fig. 1. A) Map of paleoclimate records discussed in the text: OC = Oregon Caves (Vacco et al., 2005); LS = Lake Surprise (Ibarra et al., 2014): LL: Lake Lahontan (Benson et al., 1995; Adams et al., 2008); LF = Lake Franklin (Munroe and Laabs, 2013); LB = Lake Bonneville (McGee et al., 2012); MC = Moaning Cave; ML = McLean's Cave; SL = Swamp Lake (Street et al., 2012); LV = Leviathan (Lachniet et al., 2014); LEL = Lake Elsinore (Kirby et al., 2013); COB = Cave of the Bells (Wagner et al., 2010); LE = Lake Estancia (Broecker and Putnam, 2012); FS = Fort Stanton Cave (Asmerom et al., 2010). B) Location of McLean's Cave (ML; 38°4.20′N, 120°25.20W; elevation of 300 m above sea level) in the western foothills of the Sierra Nevada with location of Black Chasm Cavern (BL; Oster et al., 2012) and Moaning Cave (MC; Oster et al., 2009). C) Cross-sectional view of McLean's Cave (adapted from McEachern et al., 1978). Star shows location of sample ML1 at time of collection.

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