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Millennial-scale variations in western Sierra Nevada precipitation during the last glacial cycle MIS 4/3 transition

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A B S T R A C T

Dansgaard–Oeschger (D–O) cycles had far-reaching effects on Northern Hemisphere and tropical climate systems during the last glacial period, yet the climatic response to D–O cycles in western North America is controversial, especially prior to 55 ka. We document changes in precipitation along the western slope of the central Sierra Nevada during early Marine Oxygen Isotope Stages (MIS) 3 and 4 (55–67 ka) from a U-series dated speleothem record from McLean's Cave. The timing of our multi-proxy geochemical dataset is coeval with D–O interstadials (15–18) and stadials, including Heinrich Event 6. The McLean's Cave stalagmite indicates warmer and drier conditions during Greenland interstadials (GISs 15–18), signified by elevated $\delta^{18}O$, $\delta^{13}C$, reflectance, and trace element concentrations, and less radiogenic $^{87}Sr/^{86}Sr$. Our record extends evidence of a strong linkage between high-latitude warming and reduced precipitation in western North America to early MIS 3 and MIS 4. This record shows that the linkage persists in diverse global climate states, and documents the nature of the climatic response in central California to Heinrich Event 6.

Introduction

Irregular, millennial-scale climate fluctuations known as Dansgaard–Oeschger (D–O) cycles are prominent features of Marine Oxygen Isotope Stages (MIS) 4, 3, and 2 (73.5–17.8 ka). First identified in the Greenland ice-core records (e.g. Dansgaard et al., 1984; Johnsen et al., 1992), D–O cycles are characterized by abrupt temperature increases of up to 10°C in as little as 50 yrs, followed by gradual cooling, and terminating in brief periods of accelerated cooling and cold conditions in the North Atlantic (Steffensen et al., 2008; Wolff et al., 2010). The most prominent of these abrupt terminal coolings are associated with Heinrich Events, large discharges of icebergs that are inferred from an influx of detrital grains in North Atlantic sediment cores (Heinrich, 1988).

High-resolution paleoclimate proxy records document the response of the Intertropical Convergence Zone (ITCZ) (Peterson et al., 2000) and East Asian (Wang et al., 2001; Cheng et al., 2009) and South American monsoons (Wang et al., 2007; Kanner et al., 2012) to D–O cycles and Heinrich Events across MIS 2 through 4 and beyond. However, few continuous records with sufficient resolution to capture D–O variability have been developed for terrestrial mid-latitude regions outside the direct influence of the ITCZ and monsoon systems (Voelker and workshop participants, 2002; Genty et al., 2003; Harrison and Sanchez Goñi, 2010; Jo et al., 2014). Two speleothem $\delta^{18}O$ records from the southwestern United States reveal a strong regional correlation with D–O events during MIS 2 and 3, interpreted to reflect elevated winter precipitation during Greenland stadials (cold periods) and reduced winter precipitation during interstadials (warm periods) (Asmerom et al., 2010; Wagner et al., 2010). Less is known about the relationship between D–O cycles, Heinrich events and western North American climate prior to MIS 3 (~55 ka), a time period that is especially difficult to investigate given that it is beyond radiocarbon age control. Lake records from the Great Basin suggest shifts to colder and wetter conditions during Heinrich Events, including the oldest Heinrich Event 6 (H6) (Bischoff and Cummins, 2001; Jiménez-Moreno et al., 2007). In contrast, the Devils Hole $\delta^{18}O$ record, which apparently has resolution adequate to capture D–O events during MIS 3 and 4, does not display millennial-

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scale variability consistent with D–O cycles and Heinrich Events (Winograd et al., 2006). Thus, it remains unclear how (and if) climate in western North America varied in response to these events prior to 55 ka.

Stalagmites from caves on the western slope of the central Sierra Nevada provide proxy records of past precipitation (Oster et al., 2009, 2010) with sufficient continuity and temporal resolution to assess climatic responses to D–O cycles and Heinrich Events. Here, we present U-series-dated records of growth rate, reflectance, stable isotope and $^{87}Sr/^{86}Sr$ ratios, and trace elements from a stalagmite from McLean's Cave, California (Fig. 1), a ~290 mm segment of which grew from 67 to 55 ka. Stable and radiogenic isotope and reflectance records from McLean's Cave share many features coincident with millennial-scale climate events, including D–O cycles, documented in time-equivalent Greenland ice-core records (Dansgaard et al, 1984; NGRIP Members, 2004), Cariaco Basin sediments (Peterson et al., 2000), and Chinese, Brazilian, and European speleothems (Wang et al., 2001, 2004, 2007; Genty et al., 2003). Our new record also documents a significant climate response in central California to H6 and provides new constraints on the timing and duration of the effects of H6 in the mid latitudes. The McLean's Cave stalagmite provides the first precisely dated record of the dynamic and variable climate in western North America that prevailed during MIS 4 and early MIS 3.

Site and sample description

McLean's Cave (Fig. 1) is developed within the Columbia carbonate lens, one of several discrete metamorphosed pre-Jurassic limestone and dolomite masses in the Sierra Nevada foothills that are tectonically intercalated with other metasedimentary and metavolcanic rocks of the Calaveras Complex (Clark and Lydon, 1962; Bowen, 1973). The Columbia carbonate lens is oriented NE–SW and is 6.5 km long by 2.4–4 km wide (Clark and Lydon, 1962). The cave entrance, which is 300 m above sea level (asl), is located near the bottom of the South Fork Stanislaus River canyon. Speleothem ML-2, a ~400 mm long stalagmite, 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 construction of the New Melones Dam.

The climate above McLean's Cave is characterized by cool, wet winters and warm, dry summers. From 1951 to 2011, a University of California weather station located 11.2 km southeast of McLean's Cave at 533 m asl, experienced an average annual precipitation of ~850 mm. On average, 93% of this precipitation occurred between October and April. Only 2% of annual precipitation fell between July and September, suggesting minor influence by localized summer convective storms. McLean's Cave is not significantly influenced by precipitation related to the North American Monsoon (Higgins et al., 1999).

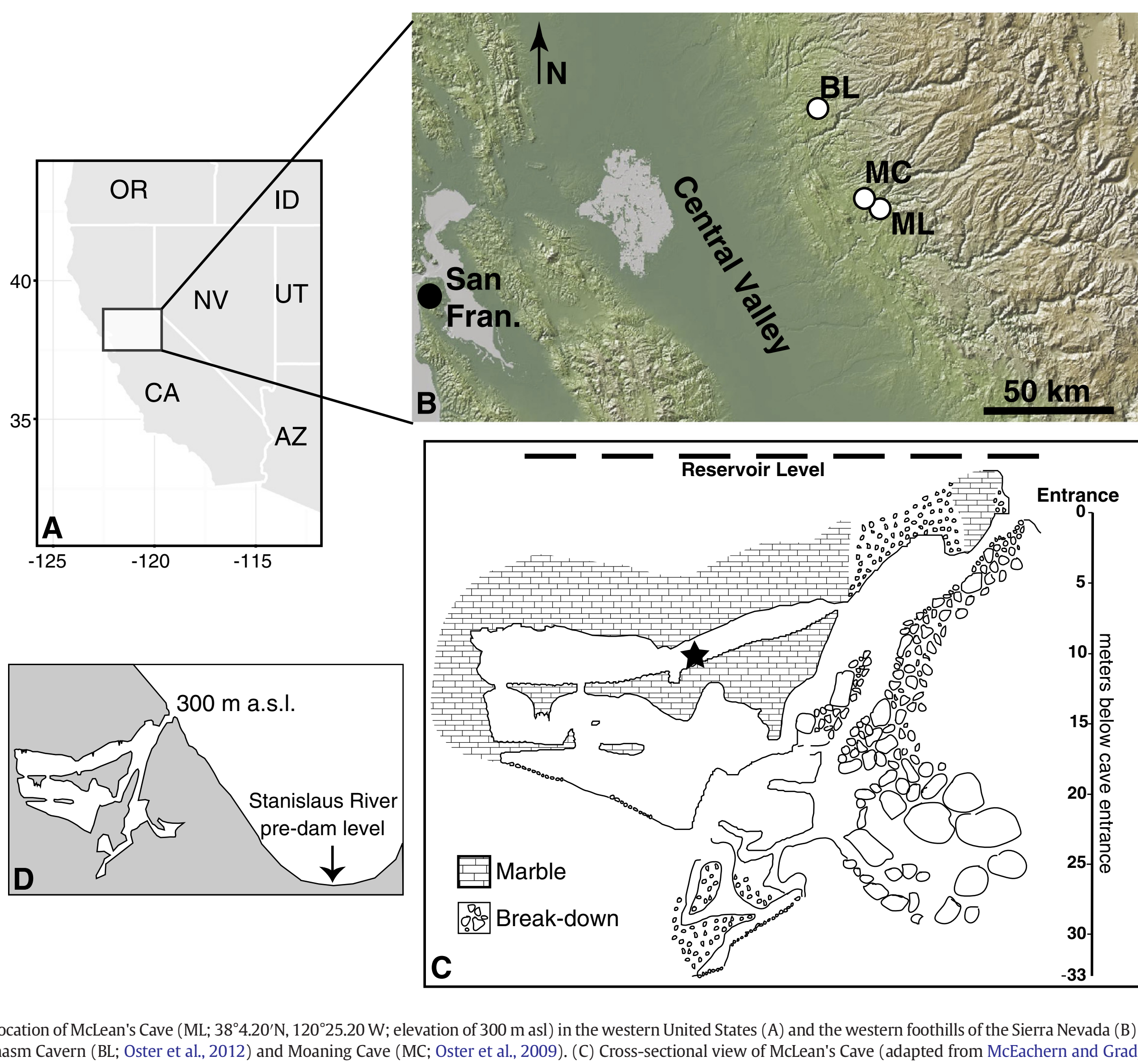

Figure 1. Location of McLean's Cave (ML; 38°4.20′N, 120°25.20 W; elevation of 300 m asl) in the western United States (A) and the western foothills of the Sierra Nevada (B) with location of Black Chasm Cavern (BL; Oster et al., 2012) and Moaning Cave (MC; Oster et al., 2009). (C) Cross-sectional view of McLean's Cave (adapted from McEachern and Grady, 1978). Star shows location of sample ML-2 at time of collection. (D) Cross-sectional location of the cave in relation to level of the Stanislaus River prior to construction of the New Melones Dam.