Synchronous millennial-scale climatic changes in the Great Basin and the North Atlantic during the last interglacial

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ABSTRACT

Stalagmites from Goshute Cave, located in the Great Basin of the western United States, preserve ~20,000 yr of millennial-scale oxygen isotopic variability during marine isotope stages 5c and 5b, similar in timing and structure to Dansgaard-Oeschger (D-O) events 23–21 from the Greenland Ice Sheet Project 2 record. That D-O interstades 23–21 were of longer duration than many of the later D-O events, coupled with the asymmetric shape of the D-O oxygen isotope curve, and the direct U-Th dating of the Goshute Cave stalagmites, allows for an improved understanding of the synchroneity of climatic changes between the western continental United States and the North Atlantic. Eastern Pacific–atmosphere interactions are a likely mechanism for transmission of millennial-scale climate variability into the Great Basin.

Keywords: speleothem, Great Basin, last interglacial, oxygen, Dansgaard-Oeschger event.

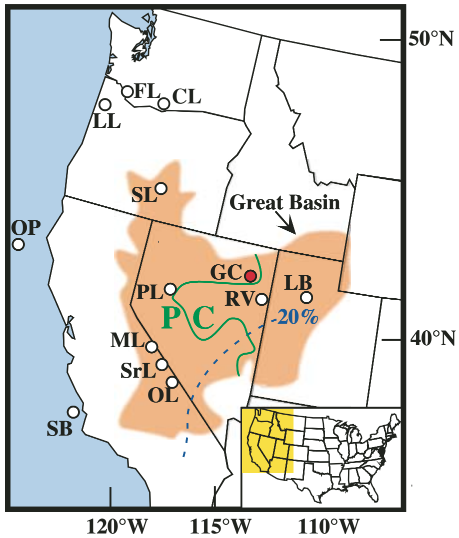

Figure 1. Map of western United States showing Great Basin (brown area), modern northern limit of Southwest Monsoon (blue line; as defined as <20% annual precipitation received during June–August) (Douglas et al., 1993), and modern boundary between continental-dominated and Pacific-dominated moisture (green line) (Houghton, 1969). Studies cited in text: CL—Carp Lake, GC—Goshute Cave, FL—Fargher Lake, LB—Pluvial Lake Bonneville, LL—Little Lake, ML—Mono Lake, OL—Owens Lake, OP—Ocean Drilling Program Site 1020, PL—Pyramid Lake, RV—Ruby Valley, SB—Santa Barbara Basin, SL—Summer Lake, SrL—Searles Lake.

INTRODUCTION

Evidence for synchronous millennial-scale climatic change between the Great Basin of the western United States and the North Atlantic exists mostly as records of Great Basin lake-level fluctuations (Benson et al., 1998; Lin et al., 1998; Oviatt, 1997) and alpine glacier advance and retreat along the west coast (Benson et al., 1996; Clark and Bartlein, 1995). However, robust dating that would allow detailed correlations has been problematic. Determining the phase relationships of Great Basin and North Atlantic records is complicated by uncertainties and limits of the radiocarbon method (including lake water reservoir effects), the difficulty in identifying deflation-related hiatuses in lake sediments, and the high frequency and short duration of Dansgaard-Oeschger (D-O) events.

Here we present an oxygen isotope record from stalagmites collected from Goshute Cave, Nevada, United States (40°2′N, 114°47′W), from the last interglacial period (Fig. 1). A robust U-Th chronology allows comparison with Greenland ice core sequences as well as other high-resolution records of climatic variability from western North America and the Northern Hemisphere.

MILLENNIAL-SCALE CLIMATE VARIABILITY IN WESTERN NORTH AMERICA

D-O events, first identified in Greenland ice records (Dansgaard et al., 1993), have been documented in multiproxy records (e.g., gray scale and foraminiferal oxygen isotopic ratios) of marine sediments in the Santa Barbara Basin off the west coast of the United States (Fig. 1) (Hendy and Kennett, 1999). However, the connection from the marine to the continental realm is not necessary straightforward, and no record has unambiguously demonstrated the synchroneity of D-O events between the North Atlantic and the western United States. Evidence of rapid climate change in the Great Basin comes largely from lake sediments (Benson et al., 2003). Despite the benefits of multiple paleoenvironmental proxies from a number of lake basins, age-control limitations have hampered the ability to correlate variability in lake records from the western United States with the North Atlantic. For example, Grigg and Whitlock (2002) used palynological analysis of Fargher, Carp, and Little Lakes from the Pacific Northwest to demonstrate that temperatures oscillated every 1–3 k.y. during marine isotope stages (MIS) 2–3 (14–60 ka), although age uncertainties do not allow precise correlation among these lakes or with other regional climate records (Fig. 1). Zic et al. (2002) tied fluctuations in isothermal remnant magnetization signatures from sediments at Summer Lake, Oregon, to D-O and Heinrich events and Bond cycles, but their chronology is stretched around a single ^{14}C correlation point. Lin et al. (1998) applied U-Th methods to date interbedded muds and salts at Searles Lake, California, and found that lake levels rose and fell on time scales similar to D-O events from 35 to 24 ka; however, precise correlations were hampered by significant corrections for detrital ^{230}Th. Based on proxy glacial and hydrologic records of Owens Lake, California, and Pyramid Lake, Nevada, Benson et al. (2003) argued that D-O interstades corresponded to relatively warm and wet conditions in the Great Basin; however, the chronology was problematic. In general, these issues derive from the situation that (1) the duration of D-O events is roughly the same as the age uncertainties, and (2) the characteristic asymmetry of D-O events in the Greenland ice δ^{18}O record can be difficult to detect in lacustrine records from the Great Basin. The question has thus remained unresolved as to whether the millennial-scale climatic shifts of the western United States have been synchronous with those of the North Atlantic region.

METHODS

Three stalagmites, GC2, GC3, and GC4, were collected from Goshute Cave, sawed in half, polished, and visually inspected. The chronologies for the Goshute Cave stalagmites are derived from ^{238}U-^{234}U-^{230}Th disequilibrium mass spectrometry dates obtained at the University of New Mexico Radiogenic Isotope Lab. GC3 and GC4 are both small (12 and 15 cm, respectively), and were dated at their top and basal layers using thermal ionization mass spectrometry (TIMS). GC2 was dated at 12 points by TIMS and/or multicollector–inductively coupled plasma–mass spectrometry (Table 1). The U-Th dating and the visual stratigraphy suggest that GC2 and GC3 may be considered one stalagmite, with the drip position having shifted from GC2 to GC3. A missing interval of time between the top of GC2 and the bottom of GC3 may reflect calcite deposition on the flanks of GC2 as the drip switched position, by a basal portion GC3 not recovered during sampling, or by a hiatus (Fig. 2). The dates, reported at the two standard deviation level, are in stratigraphic order or within error of their correct stratigraphy-controlled age relations (see the GSA Data Repository[1]). The Goshute Cave data are compared to the Greenland Ice Sheet Project 2 (GISP2) record. Uncertainties in the GISP2 chronology are quoted as 5%–10% in sections older than 40 ka (Meese et al., 1997).

Stalagmites were microsampled for stable isotope ratios using a 0.3 mm bur, and δ^{13}C and δ^{18}O values of powdered carbonates (0.1 mg) mm were measured using a Finnigan MAT 252 with a Kiel III automated carbonate device at the University of Iowa's Paul H. Nelson Stable Isotope Laboratory. Daily analysis of NIST and in-house standards produced an analytical precision better than 0.1‰ (Table 1).

TABLE 1. URANIUM AND THORIUM ISOTOPIC RATIOS AND ^{238}U-^{234}U-^{230}TH AGES

Sample	Distance from bottom (mm)	^{238}U (ng/g)	^{232}Th (ng/g)	δ^{234}U* (measured)	^{230}Th/^{238}U (activity)	^{230}Th/^{232}Th (activity)	Uncorrected age (yr B.P.)	Corrected age*† (yr B.P.)	Instrument
GC4	145	1550	0.83	729 (5)	0.071 (1)	401 (16)	4550 (60)	4540 (60)	TIMS
GC4	22	1120	1.13	730 (6)	0.093 (1)	283 (7)	6030 (100)	5990 (100)	TIMS
GC3	102	470	6.46	691 (5)	0.952 (9)	212 (5)	84,330 (1220)	84,120 (1220)	TIMS
GC3	5	400	19.2	738 (6)	0.283 (2)	63 (0.5)	86,870 (1070)	86,140 (1120)	TIMS
GC2	450	360	29.7	756 (9)	1.06 (1)	40 (0.5)	93,080 (1910)	91,870 (1980)	TIMS
GC2	438	420	18.9	740 (1)	1.04 (0.4)	70 (0.3)	91,440 (550)	90,770 (650)	MC-ICP-MS
GC2	438	420	18.6	743 (11)	1.04 (1)	71 (0.9)	91,980 (1910)	91,300 (1920)	TIMS
GC2	404	340	22.1	760 (1)	1.05 (0.4)	49 (0.2)	91,090 (520)	90,130 (700)	MC-ICP-MS
GC2	404	440	28.1	765 (9)	1.05 (1)	50 (0.5)	90,560 (1570)	89,580 (1630)	TIMS
GC2	381	430	20.4	782 (5)	1.07 (1)	69 (0.8)	92,690 (1170)	91,990 (1210)	TIMS
GC2	329	430	28.7	756 (1)	1.04 (0.4)	47 (0.2)	91,040 (520)	90,040 (710)	MC-ICP-MS
GC2	329	430	28.6	754 (6)	1.05 (2)	48 (0.7)	92,350 (2040)	91,340 (2090)	TIMS
GC2	267	390	9.76	728 (1)	1.08 (0.4)	130 (0.6)	97,580 (560)	97,200 (590)	MC-ICP-MS
GC2	198	480	16.6	749 (1)	1.08 (0.4)	95 (0.4)	96,260 (550)	95,760 (600)	MC-ICP-MS
GC2	175	430	11.5	727 (1)	1.07 (0.4)	122 (0.6)	96,600 (580)	96,200 (610)	MC-ICP-MS
GC2	175	430	11.4	726 (6)	1.08 (1)	124 (1)	98,350 (1510)	97,940 (1520)	TIMS
GC2	144	400	6.91	700 (5)	1.07 (0.5)	189 (1)	98,920 (850)	98,660 (860)	TIMS
GC2	100	560	6.45	668 (0.7)	1.05 (0.4)	281 (2)	99,500 (580)	99,630 (590)	MC-ICP-MS
GC2	100	564	6.32	667 (6)	1.07 (2)	291 (7)	102,280 (3270)	102,100 (3270)	TIMS
GC2	62	760	7.72	645 (1)	1.04 (0.3)	314 (2)	100,670 (590)	100,510 (590)	MC-ICP-MS
GC2	7	790	4.20	666 (5)	1.06 (1)	608 (7)	100,610 (1470)	100,530 (1470)	TIMS

Note: TIMS—thermal ionization mass spectrometry; MC-ICP-MS—multicollector–inductively coupled plasma–mass spectroscopy.

*$\delta^{234}U_{meas'd} = [(^{234}U/^{238}U)_{meas'd}/(^{234}U/^{238}U)_{eq} - 1] \times 10^3$, where $(^{234}U/^{238}U)_{eq}$ is the secular equilibrium atomic ratio: $\lambda_{238}/\lambda_{234} = 5.472 \times 10^{-5}$.

*The initial ^{230}Th/^{232}Th ratio of $4.5 \times 10^{-6} \pm 2.25 \times 10^{-6}$ was subtracted from measured ^{230}Th/^{232}Th ratios.

†Values in parentheses represent 2σ errors in the last significant figure.

ORIGINS OF GOSHUTE CAVE STALAGMITE ISOTOPIC VARIABILITY

The structure of D-O cycles in Greenland ice is asymmetric, with gradual cooling (decreasing δ^{18}O values) followed by rapid warming (increasing δ^{18}O values) (Dansgaard et al., 1993). The magnitude of these temperature shifts and the frequency of their occurrence are typically higher from 70 to 20 ka than from 100 to 70 ka. Three D-O events, 23–21, occurred during the interval spanned by the Goshute Cave stalagmites (ca. 100–80 ka). Of these, event 22 is characterized by reduced oxygen isotopic variability and events 23 and 21 were particularly long (Fig. 3). The same sense of asymmetry and scale is apparent in the oxygen isotopic sequences of the Goshute Cave stalagmites. While we recognize that age errors in both the Goshute Cave and GISP2 records (<2 and >5 k.y., respectively) make an exact temporal correlation indefinite, the numerical ages of each proxy record taken at face value result in similar oxygen isotopic trends in both records, and this makes a plausible argument for synchroneity of dominant features in the two records. The only significant mismatch in the two records exists at the rapid decrease in δ^{18}O values following D-O interstade 22. The Goshute Cave stalagmite age model precedes GISP2 by 1500 yr, although this is well within the combined ice and stalagmite age uncertainties.

The variability in Goshute Cave stalagmite δ^{18}O values could have resulted from changes in the isotopic composition of precipitation, secondary effects that fractionate oxygen isotopes during calcite crystallization, or postcrystallization alteration. A comparison of δ^{13}C and δ^{18}O values from the Goshute Cave stalagmites reveals only a limited correlation ($r^2 = 0.3$; n = 111), and both stalagmites exhibit no signs of secondary alteration (loss of fine crystalline fabric, high porosity, interruption of banding) (Polyak, 1992), suggesting that environmental conditions are responsible for the observed isotopic variation (Table 1).

Variation in oxygen isotope ratios in the Goshute Cave stalagmite record reflects paleoenvironmental conditions, and thus these changes are tied to cave temperature and the δ^{18}O values of cave dripwater, which is derived from meteoric precipitation and may also be linked to atmospheric temperature. However, the effect of temperature on the oxygen isotopic ratio of meteoric precipitation can be complex, particularly at middle and low latitudes (Fricke and O'Neill, 1999, and references therein). The impacts on water vapor δ^{18}O values by millennial-scale changes in sea surface temperatures, seawater isotopic composition (Lea et al., 2002), or wind

[1]GSA Data Repository item 2007154, DR1, analytical methods, is available online at www.geosociety.org/pubs/ft2007.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

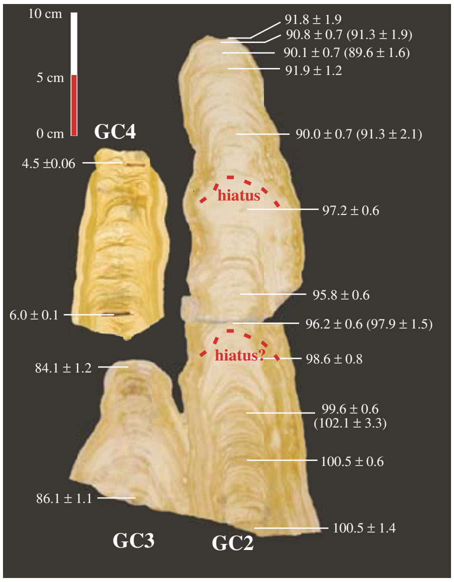

Figure 2. Photographs GC2, GC3, and GC4 showing location of areas sampled for U-Th dating. Where two dates are listed for same interval, first is by multicollector–inductively coupled plasma–mass spectroscopy and second date, shown in parentheses, is by thermal ionization mass spectrometry.

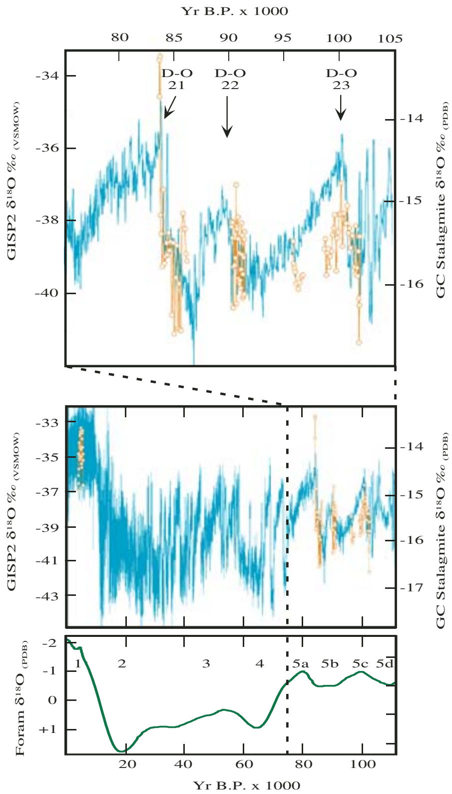

Figure 3. Top: Oxygen isotopic values of Goshute Cave stalagmites (GC, orange) and Greenland Ice Sheet Project 2 (GISP2; blue) (National Snow and Ice Data Center, 1997) for interval 105–75 ka. Ages for Goshute Cave stalagmite stable isotope data are determined using linear interpolation between radiometric dates and do not involve any tuning. Dansgaard-Oeschger (D-O) events 21, 22, and 23 are identified. Middle: Oxygen isotopic values of Goshute Cave stalagmites (orange) and GISP2 (blue) for interval 110–0 ka. Bottom: SPECMAP oxygen isotope profile (Imbrie et al., 1991) with marine isotope stages. Interval denoted by dashed line represents time period in top panel. PDB—Peedee belemnite; VSMOW—Vienna Standard Mean Ocean Water.

speeds (Grootes, 1993) would have affected precipitation $\delta^{18}O$ values at Goshute Cave. However, the magnitude of these effects would have likely been small relative to air mass and temperature effects in the Great Basin. The relation between the $\delta^{18}O$ value of precipitation and mean annual temperature has been elusive in parts of the Great Basin; Benson and Klieforth (1989) found no reliable relation between air temperature and precipitation $\delta^{18}O$ values in southern Nevada. However, measurements made at Ruby Valley, located near Goshute Cave (Fig. 1), indicate a +0.5‰/°C relationship (n = 10; r^2 = 0.53) (L. Benson, 2006, personal commun.) (Table 1), close to the high-latitude Northern Hemisphere average $\delta^{18}O$/mean annual temperature relationship of +0.7‰/°C (Dansgaard, 1964). The seasonality of precipitation must also be considered, but cool-season precipitation is the dominant input to groundwater systems across much of the modern Great Basin (Benson and Klieforth, 1989), and this situation has probably not changed significantly over the past several glacial cycles (Winograd et al., 1988). The amount effect, in which ^{18}O is partitioned into condensing moisture at a rate faster than is predicted by temperature effects alone, is observed in modern precipitation associated with monsoon systems around the globe, including the Southwest monsoon (Higgins and MacFadden, 2004). Goshute Cave is located north of the area receiving significant Southwest monsoon moisture today (Benson and Klieforth, 1989), and the monsoon system probably extended further south during glacial stadials.

Alternatively, chemical evolution of pore fluids prior to their reaching the cave could play a role. Evaporative enrichment of ^{18}O in meteoric waters during infiltration through the soil and epikarst has been demonstrated (Gazis and Feng, 2004), as has its effects on speleothem $\delta^{18}O$ values (Denniston et al., 1999). These changes can be significant; soil water $\delta^{18}O$ values were elevated by >6‰ by evaporation in a soil study in Hawaii (Hsieh et al., 1998). Although systematic offsets in speleothem $\delta^{18}O$ values due to evaporative effects may play a role, they still reflect paleoenvironmental conditions (air temperature, effective moisture, wind speed).

A change in moisture source dominance could also explain the Goshute Cave $\delta^{18}O$ variability. Goshute Cave is located near the boundary between continental- and Pacific-dominated precipitation, and each moisture source imparts a distinctive oxygen isotopic signature (Benson and Klieforth, 1989). Therefore, shifts from Pacific-dominated to continental-dominated moisture could account for the observed shift in oxygen isotopic values in Goshute Cave stalagmites.

Using the general approach of Dorale et al. (1992), we can combine the relationship between air temperature and precipitation $\delta^{18}O$ values of +0.5‰/°C with the temperature-dependent calcite-water fractionation of –0.2‰/°C (Friedman and O'Neil, 1977) to yield a net temperature dependence of ~+0.3‰/°C for Goshute Cave speleothem calcite. The $\delta^{18}O$ values of GC4, a middle Holocene stalagmite, average –14‰, ~1.5‰ heavier than $\delta^{18}O$ values for GC2 and GC3. If ascribed solely to temperature (and without considering ice-volume effects on moisture source $\delta^{18}O$ values), this 1.5‰ rise translates to a ~5 °C increase in mean annual temperature relative to MIS 5b and 5c, a seemingly unlikely conclusion given that plant macrofossil assemblage–based reconstructions from southern Nevada have been interpreted as reflecting last glacial maximum mean annual temperatures ~5 °C lower than today (Thompson et al., 1999). The rate of temperature change is also higher than reconstructed for the latest Pleistocene. Oxygen isotopic shifts between D-O stades and interstades 22 and 23 are ~1.0‰, corresponding to 3 °C mean annual temperature shift in 2–3 k.y. In comparison, the reconstructions of Thompson et al. (1999) suggest rates of ~2 °C in 6 k.y. (a decrease from 27–23 to 20.5–18 ka and an increase from 20.5–18 to 14–11.5 ka). In addition, the unusually large (>3‰) increase in $\delta^{18}O$ values associated with D-O event 21 (84 ka) would translate to a 10 °C mean annual temperature rise in only 1 k.y. This latter event therefore likely reflects a combination of temperature and some other phenomenon, such as changes in air mass dominance and/or evaporative enrichment of ^{18}O.

However, the magnitude of temperature change suggested by Goshute Cave stalagmite oxygen isotopic ratios is not out of the question, and is much less than large warmings (~5 °C) of surface waters in the Santa Barbara Basin documented by Hendy and Kennett (1999) and that occurred in only a few decades (50–70 yr) in association with D-O events. These authors argued for northward shifts of the North Pacific high-pressure patterns (and thus in the cool, south-flowing California Current) that occurred synchronously with a reduction in the production of North Pacific Intermediate waters and warming over Greenland through contractions of the Aleutian low and Polar gyre. Collapse of the California Current has also been tied to regional warming in advance of the penultimate glacial-interglacial transition (Termination II) in western North America (Herbert et al., 2001). Alkenone records of sea surface temperature from the northern California margin (Ocean Drilling Program Site 1020) also suggest changes in water temperature of 2–3 °C on a millennial scale (Herbert et al., 2001).

It therefore seems plausible that East Pacific–atmosphere interactions allowed the Great Basin climate to respond synchronously with the North Atlantic, but it remains unclear whether the nature of Great Basin responses was changes in temperature, source of precipitation, or some combination of the two. Temperature or changes in moisture source, reflecting atmospheric circulation in response to ocean-atmosphere interactions, seem to play a more dominant role.

CONCLUSIONS

Stalagmites from Goshute Cave contain $\delta^{18}O$ variability similar to that of the GISP2 record. Relatively high stalagmite $\delta^{18}O$ values during D-O interstades support previous inferences for relative warmth during D-O interstades, although changes in precipitation moisture source could also be important. Previous reports demonstrating the connection between eastern Pacific sea surface temperatures and Great Basin air temperatures, coupled with the observation that ocean temperatures varied significantly during MIS 5b and 5c, suggest that Great Basin temperatures were driven by ocean-atmosphere interactions.

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