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Temporal correspondence between pluvial lake highstands in the southwestern US and Heinrich Event 1

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ABSTRACT: Pluvial lakes were abundant in the southwestern United States during Pleistocene glaciations, particularly in the Great Basin. Many of these lakes occupied closed basins; therefore, fluctuations of their water surface elevations are valuable sources of paleoclimate information. Histories of the largest lakes are well constrained, whereas dozens of smaller lakes that were present in this region have received relatively little scientific attention. Given their dimensions, these smaller lakes were climatically sensitive and can offer important information about Quaternary climate variability. Here we present new ages for the highstands of three previously undated small lakes based on radiocarbon dating of gastropod shells recovered from beach ridges. These results are combined with other published and unpublished ^{14}C ages to yield an extensive compilation of highstand shoreline ages for lakes of all sizes throughout the southwestern US. The results indicate that although some lakes reached highstands during the Last Glacial Maximum, the strongest temporal correspondence is between highstands and Heinrich Event H1. These results are consistent with speleothem-based reconstructions of effective moisture in the southwestern US, which show increased precipitation during stadials of the last glacial cycle. Copyright © 2012 John Wiley & Sons, Ltd.

KEYWORDS: Great Basin; Heinrich events; pluvial lakes; radiocarbon dating; southwestern US.

Introduction

The southwestern United States, including the hydrographically closed Great Basin, features an arid climate, with many areas receiving <250 mm of precipitation per year (Houghton, 1969). This region includes several large and fast growing population centers, and is a premier example of a setting in which future climate change may exacerbate an already marginal situation (Karl and Melillo, 2009). Numerical climate modeling efforts have raised the sobering warning that global warming will cause modern drylands to become more arid as existing patterns of effective moisture are accentuated (Held and Soden, 2006). Evaluating this prediction with geologic data is important for making informed predictions about future water availability in dryland settings such as the southwestern US.

Because it is impossible to directly test a future warmer world scenario under current conditions, studying the degree to which modern drylands became *wetter* during past intervals of *colder* climate is a valuable exercise. The former presence of large lakes in the southwestern US during pluvial episodes of the last glacial cycle has been employed in this effort (Quade and Broecker, 2009). The existence of these lakes is revealed by shoreline landforms, many of which are exceptionally well preserved and easily traceable in this sparsely vegetated environment (Mifflin and Wheat, 1979). The largest lakes, such as Lake Bonneville in western Utah, and Lake Lahontan in western Nevada, had maximum surface areas of >20 000 km^2 and clearly indicate major changes in effective moisture during the last glacial cycle. However, the cause of this moisture increase remains unclear.

Recent studies of speleothems in this region indicate that increased effective moisture in the southwestern US during the late Pleistocene was correlated with cool, stadial conditions in marine and ice-core proxy records from the North Atlantic (Asmerom *et al.*, 2010; Wagner *et al.*, 2010). Although some lake-based studies reached the opposite conclusion (e.g. Zic *et al.*, 2002; Benson *et al.*, 2003), these results generally corroborate previously proposed connections between the largest Great Basin pluvial lakes and North Atlantic climate variability (e.g. Phillips *et al.*, 1994; Oviatt, 1997). However, there are reasons why these previously studied lakes might provide an incomplete story. For instance, Lake Bonneville overflowed at its highstand (Oviatt, 1997), so it is perhaps impossible to determine when the actual hydrologic maximum of the lake occurred, and how the timing of this event compares with the age of the Lake Lahontan highstand. Furthermore, modeling studies (Hostetler *et al.*, 1994) and glacial records (Munroe *et al.*, 2006) have demonstrated that Lake Bonneville influenced precipitation over its watershed. In doing so, this lake may have become partially self-sustaining, reducing its sensitivity to regional climate forcing. Inadequacies of age models in some core-based lake-level reconstructions, and uncertainties in connecting core-based data to actual shorelines, also make it difficult to elucidate the temporal relationships between lakes and other proxy records (Benson *et al.*, 2003). Thus, it is unclear how closely records from these largest lakes track effective moisture changes in the Great Basin during the latest Pleistocene.

Dozens of lakes with surface areas an order of magnitude less than Bonneville and Lahontan were also present in the Great Basin and surrounding region, but with few exceptions they have received little scientific attention. In many cases only the existence of shorelines delineating the dimensions of these former lakes has been reported (Mifflin and Wheat, 1979). These smaller closed-basin lakes should have responded more rapidly to climatic fluctuations than the much larger Lakes Bonneville and Lahontan. These smaller lakes also offer the benefit of recording conditions in spatially more restricted regions because their watersheds generally lacked major river systems that imported water from distal source areas. Therefore, the paucity of geochronologic control on highstands of small lakes represents a missed opportunity to evaluate models of how atmospheric circulation changed during late Pleistocene climate cycles.

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Here we compile a set of radiocarbon ages constraining the highstands of pluvial lakes of all sizes (Fig. 1). Some of these were previously published, but shorelines of three lakes, Clover, Franklin and Waring in northeastern Nevada, were not previously dated, and dates from many other lakes had not been reported in the literature. These results were evaluated to assess the reliability of the radiocarbon ages, and compared with records of sustained high water reconstructed for pluvial lakes elsewhere in the southwestern US, well-dated glacial chronologies from around the Great Basin, relevant speleothem-based paleoclimate records and marine proxies for conditions in the North Atlantic Ocean.

Methods

Highstand beach ridges were identified in the Clover, Franklin and Goshute Valleys of northeastern Nevada (representing Lakes Clover, Franklin and Waring, respectively) through field reconnaissance, consultation of relevant literature, and examination of aerial photography and 1:24 000-scale topographic maps. Ridges typically stand 1–5 m above the surrounding land surface and are laterally continuous for 100s of meters. In aerial imagery, ridge crests are often a distinctly lighter shade, due to a sparser cover of grasses compared with sagebrush on ridge side slopes. In many cases ridges are also bordered by linear playettes featuring unvegetated surfaces of light gray mud that are conspicuous in aerial imagery.

Radiocarbon dating of aquatic gastropod shells was employed to limit the ages of these ridges. Pits measuring ~1 m^3 were excavated by hand into the highstand ridge in all three valleys. Excavations were located in positions from the ridge crest to the upper backslope. These excavations consistently revealed a layer (10–50 cm thick) enriched in fine silt overlying deposits of rounded sandy gravel. To avoid this non-fossiliferous material, and to remain below the zone of pervasive bioturbation, efforts to find shells were focused on sediment from >75 cm depth. Once this depth was reached, undisturbed beach gravel was shoveled onto a shaker table incorporating two stacked screens with 1-cm and 0.1-cm mesh. After shaking, the sediment remaining on the lower screen was scrutinized visually and shells were collected using tweezers.

Shells were prepared for radiocarbon dating by gentle scraping and sonification in distilled water to remove internally packed sediment and light carbonate coatings. This process was repeated until shells were visibly clean, at which point they were dried, weighed and submitted to the National Ocean Sciences Accelerator Mass Spectrometry facility. At the lab, all samples were subjected to standard acid/alkali/acid pretreatments to further remove carbonate coatings and the outer layers of shell material that are more susceptible to post-depositional contamination or recrystallization. Pretreatments resulted in a reduction of shell mass by 18–75%.

In addition to the new dates for these three valleys, existing radiocarbon dates for pluvial lake highstands were gathered from the published and unpublished literature. Most of these dates are for the mapped highstand ridge, although in three lake basins in northern Nevada (Carpenter, Railroad and Spring) dates were only available for beach ridges near (generally <10 m below) the elevation of the mapped highstand. These near-highstands were included in the compilation because no other data are available for these basins, and because these dates nonetheless record the existence of lakes nearly as large as those present at the pluvial maximum.

Where multiple radiocarbon ages were available for the *same* locality (i.e. the same horizon in a given shoreline) they were combined using the 'R_combine' function in OxCal 4.1

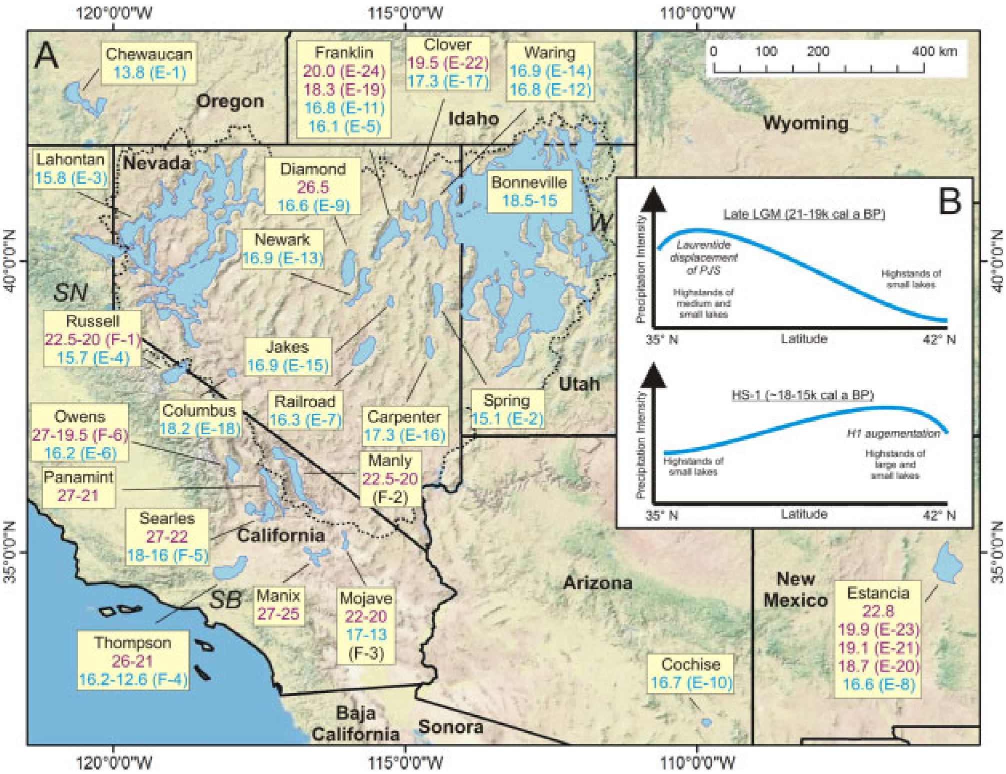

Figure 1. (A) Map of pluvial lakes in the southwestern USA. Lake names are given along with highstand ages (median probability of the 2-sigma calibration range) in k cal a BP. Codes in parentheses refer to Fig. 3 and Tables 1–3. Analysis focused on highstands after 21k cal a BP; older highstands are listed without codes, and are not plotted in Fig. 3. Dates shown in purple fall during the latter part of the LGM, whereas dates shown in cyan fall during Heinrich Stadial 1. For clarity, only dated lakes are shown. The outline of the Great Basin is dashed. The Sierra Nevada (SN), San Bernadino (SB) and Wasatch Mountains (W) are labeled. (B) Schematic model of changes in the mean position of the Polar Jet Stream (PJS) and corresponding pluvial lake levels across the Great Basin for the Late LGM (~21–18k cal a BP) and HS-1 (~18–15k cal a BP).

(Ramsey, 2006) before calibration. Where multiple non-overlapping dates were available for *different* localities in a given basin, they were assumed to represent discrete episodes of high water and were treated separately. All ^{14}C ages (both individual ages and combined ages) were calibrated into calendar years BP using Calib 6.0 (Stuiver and Reimer, 1993) and the Intcal09 calibration curve (Reimer *et al.*, 2009).

To address the reality that any effort to compile existing data from the literature is fundamentally vulnerable to issues regarding the quality of the original data, all radiocarbon ages constraining highstand ridges were assigned a confidence weighting from 1 to 3. Values of 3 were reserved for dates presented with abundant supporting information, including stratigraphic and species details, descriptions of processing techniques, and results of X-ray analysis to check for post-depositional recrystallization. In contrast, values of 1 were assigned to dates that were devoid of such supporting information, such as personal communications, and those presented as merely an age and associated error. Intermediate values of 2 were used for dates accompanied by some supporting information, but still lacking some of the critical components required for a higher confidence weighting. These weights were then applied to the probability density functions (PDFs) for the individual ages derived from OxCal 4.1 (Ramsey, 2006), and combined to yield a summed PDF illustrating the clustering of calibrated radiocarbon ages through time. The overall shape of the resulting PDF was very similar to a version generated from the unweighted ages, but this weighting approach, while still subjective, was considered preferable to treating all the dates in the compilation as if they carried equal import.

These results were compared with records of sustained high water reconstructed for pluvial lakes elsewhere in the southwestern US. Many of these highstands are based on multiple lines of evidence, rather than just ^{14}C dating of the highstand beach ridge. Furthermore, many of these lakes overflowed at their hydrologic maxima, so that the elevation of the highstand was geologically controlled, and highstands in one lake directly impacted the hydrologic balance of lakes downstream. The watersheds of some of these lakes along the east side of the Sierra Nevada also contained extensive glaciers, which may have altered their hydrologic balance with respect to lakes that lacked glacierized headwaters. Because of these fundamental differences, these records were included for comparison, but were not included in the summed PDF.

Results

Ten new radiocarbon ages were obtained from the highstand beach ridge in the Clover ($n=5$), Franklin ($n=4$) and Goshute ($n=1$) Valleys (Table 1). When calibrated, seven of the ten ages cluster with medians between 17.0 and 16.0k cal a BP (Fig. 2). Multiple ages from the same locality exhibit strong convergence. Samples OS-89976 and OS-92401, both from the same horizon exposed in an excavation on the highstand ridge in the Franklin Valley, yielded ages of 13 250 ± 55 and 13 150 ± 55 ^{14}C a BP. Sample OS-90241 from a location 4.5 km further north along the same shoreline yielded an age of 13 600 ± 45 ^{14}C a BP. When calibrated, these three ages overlap at 16.5k cal a BP. Similarly, three samples from the highstand ridge at the north end of Lake Clover (OS-90532, OS-85506 and OS-85537) yielded ages of 13 900 ± 90, 14 200 ± 50, and 14 400 ± 60 ^{14}C a BP, respectively. When calibrated, these results overlap at 17.0k cal a BP. The lone sample from the highstand ridge in the Goshute Valley (OS-92149) yielded an age of 13 650 ± 75 ^{14}C a BP, which calibrates to between 17.0 and 16.5k cal a BP. Thus, all three valleys yielded highstand

Table 1. New radiocarbon dates for pluvial lake highstands in northeastern Nevada from this project

Code*	Lake	Lab. code	Radiocarbon age (^{14}C a BP)	δ^{13}C (‰)	Min. age (k cal a BP)	Max. age (k cal a BP)	Median prob.	Latitude (°N)	Longitude (°W)	Elevation (m)	Material dated
–	Franklin	OS-92025	19 000 ± 70	0.20	22 317	22 997	22 601	40.28145	115.34398	1850	Lymnaeid, *Pisidium*, *Gyraulus*
E-22‡ (OS-85505 and OS-90527 combined in OxCal†)											
–	Clover	OS-85505	16 400 ± 60	−2.95	19 408	19 598	19 516	40.78841	114.84103	1727	*Gyraulus*
–	Clover	OS-90527	16 300 ± 75	−3.28	19 253	19 594	19 456	40.78841	114.84103	1727	*Gyraulus*
E-17‡ (OS-85537, OS-85506 and OS-90532 combined in OxCal†)											
–	Clover	OS-85537	14 400 ± 60	−0.09	17 178	17 847	17 519	40.96100	114.67429	1726	*Gyraulus*
–	Clover	OS-85506	14 200 ± 50	−3.72	16 974	17 578	17 274	40.96100	114.67421	1726	*Gyraulus*
–	Clover	OS-90532	13 900 ± 90	−7.23	16 750	17 230	16 973	40.96100	114.67421	1726	Unknown
E-12‡	Waring	OS-92149	13 650 ± 75	−0.96	16 576	17 000	16 796	40.76948	114.54800	1735	Lymnaeid, *Pisidium*, *Gyraulus*
E-11‡	Franklin	OS-90241	13 600 ± 45	1.72	16 558	16 944	16 752	40.28145	115.34398	1850	Lymnaied
E-5‡ (OS-92041 and OS-89976 combined in OxCal†)											
–	Franklin	OS-92041	13 250 ± 55	−8.73	15 530	16 709	16 231	40.24779	115.34629	1848	Lymnaeid
–	Franklin	OS-89976	13 150 ± 55	−7.65	15 282	16 528	15 992	40.24779	115.34629	1848	Lymnaeid

*Referenced to Fig. 3. †B. Ramsey, 2001: Development of the radiocarbon calibration program OxCal. *Radiocarbon* 43, 355. ‡Assigned a weight of 3 in calculating the summed PDF.

Table 2. Pre-existing radiocarbon dates for pluvial lake highstands in the southwestern US.

Code[*]	Lake	Lab. code	Radiocarbon age (^{14}C a BP)	Min.	Max.	Med. prob.	W[†]	Note	Source[‡]
E-24	Franklin	Beta-50766	16 800 ± 130	19 570	20 288	19 959	3	–	Lillquist, 1994
E-23	Estancia	CAMS-18041	16 730 ± 170	19 476	20 271	19 884	3	H5 highstand	Allen and Anderson, 2000
E-22	Clover	–	16 361 ± 94	19 296	19 613	19 506	3	See Table 1	This study
E-21	Estancia	CAMS-18607	15 880 ± 60	18 837	19 361	19 100	3	H6 highstand	Allen and Anderson, 2000
E-20	Estancia	CAMS-18611	15 480 ± 60	18 564	18 849	18 695	3	H7 highstand	Allen and Anderson, 2000
E-19	Franklin	Beta-50765	15 070 ± 100	18 007	18 583	18 255	3	–	Lillquist, 1994
E-18	Columbus	WW-3724	14 860 ± 50	17 795	18 519	18 186	2	–	Kurth *et al.*, 2011
E-17	Clover	–	14 228 ± 71	16 978	17 629	17 310	3	See Table 1	This study
E-16	Carpenter	Beta-50773	14 210 ± 100	16 938	17 649	17 294	1	near highstand	Lillquist, 1994
E-15	Jakes	Beta-182377	13 870 ± 50	16 775	17 143	16 944	2	–	Garcia and Stokes, 2006
E-14	Waring	Unknown	13 800 ± 50[§]	16 730	17 063	16 901	1	From K. Adams	Garcia and Stokes, 2006
E-13	Newark	Beta-148046	13 780 ± 50	16 730	17 063	16 889	2	–	Kurth *et al.*, 2011
E-10	Cochise	–	13 561 ± 60	16 474	16 921	16 730	3	–	Combined in Oxcal from:
		AA-1985	13 750 ± 120	16 609	17 150	16 870	–		Waters, 1989
		AA-1988	13 610 ± 150	16 123	17 094	16 732	–		Waters, 1989
		AA-1986	13 590 ± 120	16 324	17 025	16 730	–		Waters, 1989
		AA-1984	13 400 ± 130	15 824	16 875	16 479	–		Waters, 1989
		AA-1987	13 380 ± 150	15 527	16 878	16 405	–		Waters, 1989
E-9	Diamond	Beta-50776	13 500 ± 180	15 599	16 988	16 562	2	Highest closed shoreline	Tackman, 1993
E-8	Estancia	CAMS-18609	13 420 ± 100	15 877	16 892	16 556	3	H8 highstand	Allen and Anderson, 2000
E-7	Railroad	Beta-29026	13 300 ± 120	15 479	16 821	16 276	1	Near highstand	Lillquist, 1994
E-6	Owens	–	13 240 ± 34	15 547	16 676	16 220	2	Last time to sill	Combined in Oxcal from:
		WW-4782	13 340 ± 40	15 897	16 826	16 483	–		Bacon *et al.*, 2006
		Unknown	13 000 ± 60	15 134	16 315	15 627	–		Orme and Orme, 1993
E-5	Franklin	–	13 200 ± 39	15 451	16 635	16 121	3	See Table 1	This study
E-4	Russell	n/a	13 100 ± 50[§]	15 231	16 443	15 869	2	Interpolated	Benson *et al.*, 1998
E-3	Lahontan	NSRL-3014	13 070 ± 60	15 200	16 413	15 800	3	–	Adams and Wesnousky, 1998
E-2	Spring	Beta-50776	12 710 ± 90	14 548	15 605	15 054	1	Near highstand	Lillquist, 1994
E-1	Chewaucan	AA-13588	11 930 ± 90	13 569	14 000	13 780	3	–	Licciardi, 2001

[*] Referenced to Fig. 3. [†] W is the weight used in calculating the summed PDF. See text for details. [‡] "Combined in Oxcal" refers to ages generated using the R_Combine function. Where listed, these are averages of the ages grouped with vertical bars on the subsequent rows. B. Ramsey, 2001: Development of the radiocarbon calibration program OxCal. *Radiocarbon* 43, 355. [§] Assumed.

beach ridge ages that calibrate to between 17.0 and 16.5k cal a BP.

The remaining three dates fall outside this grouping (Fig. 2). Two samples from the highstand beach ridge at the southern end of the Clover Valley (OS-90527 and OS-85505) returned ages of 16 300 ± 75 and 16 400 ± 60 ^{14}C a BP, which overlap at 19.5k cal a BP when calibrated. The final sample from the base of the highstand beach ridge in the Franklin Valley (OS-92025) returned the oldest age of 19 000 ± 70 ^{14}C a BP, which calibrates to 23.0–22.3k cal a BP.

The compilation of ages ($n = 24$) for radiocarbon-dated highstands of large and small lakes throughout the southwestern US is presented in Fig. 3. The dates span a range of 20–13.8k cal a BP, with extremely strong clustering (13 of the 24 dates, 54%) between 17.5 and 16k cal a BP. Considering the full width of the calibration ranges for these ages, nearly two-thirds of the dated highstands overlap with this interval, and the summed PDF of all available ages, weighted to reflect confidence in each age, features a significant maximum at 16.9k cal a BP (Fig. 3).

Two ages appear as outliers at the young end of the distribution. Sample E-1, representing the highstand of Lake Chewaucan (Licciardi, 2001), yielded an age of 11 930 ± 90 ^{14}C a BP, which calibrates to 14.0–13.6k cal a BP. And sample E-2, from a beach ridge 3 m below the highstand beach of Lake Spring (Lillquist, 1994), yielded an age of 12 710 ± 90 ^{14}C a BP, which calibrates to 15.6–14.6k cal a BP.

Table 3. Other dated lake highstands in the southwestern US.

Code[*]	Lake	Age range (k cal a BP)	Source
F-6	Owens	27–19.5	Bacon *et al.*, 2006
F-5	Searles	17–16	Lin *et al.*, 1998
F-4	Thompson (late)	16.2–12.6	Orme, 2008
F-3	Mojave-I	22–20	Wells *et al.*, 2003
F-3	Mojave-II	17–13.5	Wells *et al.*, 2003
F-2	Manly	22.5–20	Anderson and Wells, 2003
F-1	Russell	22.5–20	Benson *et al.*, 1998

[*] Referenced to Fig. 3.

Discussion

Considerations when interpreting pluvial highstands from radiocarbon ages

Radiocarbon ages for aquatic gastropod shells isolated from beach ridge sediments are frequently used to constrain the age of former pluvial lakes (e.g. Oviatt *et al.*, 1992; Licciardi, 2001; Godsey *et al.*, 2005, 2011). This reliance is due to these shells being generally well preserved in beach ridges, and the fact that terrestrial macrofossils are usually absent in these sediments. Attempts to date beach ridges with cosmogenic nuclides and U-series techniques have reported some success (e.g. Kurth *et al.*, 2011), although efforts to apply a combination of methods to a single ridge have yielded a confusing and troubling range of age assessments (e.g. Owen *et al.*, 2007). Radiocarbon dating was used in this study because of the

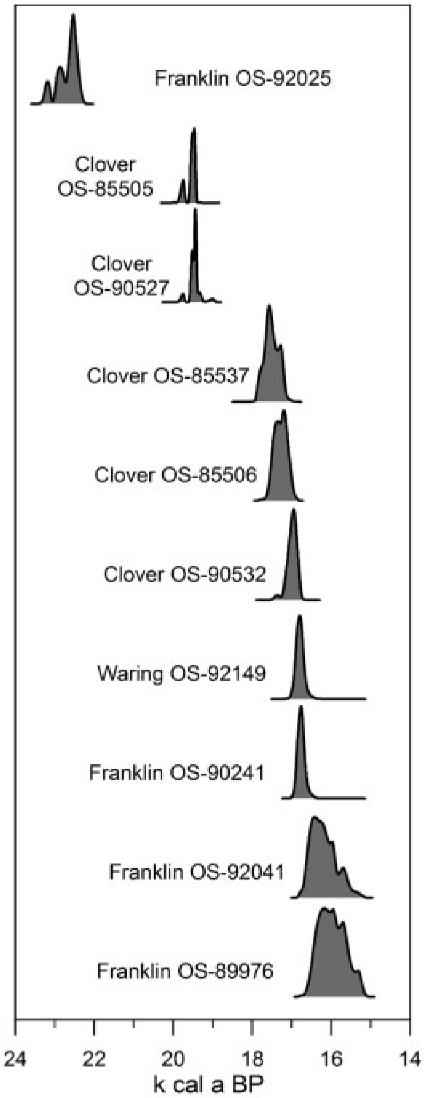

Figure 2. Calibration ranges for new radiocarbon ages obtained for Lakes Clover, Franklin and Waring in northeastern Nevada.

presence of shells in the targeted beach ridges (which are otherwise devoid of organic material), and the abundance of pre-existing radiocarbon ages from the southwestern US in the published and unpublished literature, which permitted the widest possible compilation of highstand ages.

Despite these benefits, some concerns with radiocarbon dating of aquatic gastropods from beach ridges need to be considered. One potential issue is the possibility that radiocarbon-reservoir effects could skew the ages of shells, making them appear older than they actually are (e.g. Lin *et al.*, 1998). This situation could arise if the former pluvial lake were fed by large volumes of groundwater that took considerable time to travel from upland recharge areas. Upon emerging in the lake, the $^{14}C/^{12}C$ ratio of this water would be very different from the equilibrium value of the atmosphere due to radioactive decay of ^{14}C in the water while underground. A similar issue would result if water in the former pluvial lake contained significant amounts of dissolved carbon derived from ancient carbonate rocks, which would be much older than the half-life of ^{14}C. Either way, gastropods building their shells from carbon in this water would appear artificially old when measured for their ^{14}C content. Springs and carbonate bedrock are present in many of the watersheds that hosted pluvial lakes considered in this study, so it is possible that some of the ^{14}C ages considered to represent pluvial lake highstands are too old by an unknown amount.

In the absence of independent age control, it is not possible to determine whether this effect is an issue, or to quantify its possible magnitude. However, in one test radiocarbon dating of a modern snail from a spring in the Franklin Valley yielded an age of 770 ^{14}C a BP (J.S. Munroe, unpublished data), indicating that the $^{14}C/^{12}C$ ratio of discharging spring water is lower than the modern equilibrium value. On the other hand, the upper end of such an effect would probably be significantly less given that these lakes were voluminous (Lake Franklin, for instance, contained $\sim$24 km^3 of water), and the relatively small amount of spring inflow would have been substantially diluted by surface water runoff from the large watersheds surrounding the lakes. Prior studies have estimated reservoir effects in the vicinity of a few hundred years, similar to analytical uncertainties (e.g. Benson *et al.*, 1990; Oviatt *et al.*, 1992; Lin *et al.*, 1998). In the context of the compilation presented here, shifts of age of this magnitude are insignificant.

Perhaps the most compelling argument against the operation of pervasive radiocarbon-reservoir effects in this dataset is the strong clustering of the ages themselves. If hard-water effects were significant, they would be expected to differ from basin to basin, reflecting the unique geology of each watershed. If this varying effect was superimposed on a set of lakes that actually attained synchronous highstands, the result would be a random scattering of apparent ages. Similarly, if radiocarbon-reservoir effects unique to specific basins were superimposed on a set of ages representing asynchronous highstands, it is unlikely that the result would be apparent convergence of the ages. Overall, the strong clustering of dates from separate basins between 17.5 and 16.0k cal a BP is best explained by synchronous highstands of multiple lakes. Radiocarbon-reservoir effects, where applicable, were probably insignificant compared with the width of the calibration ranges for these dates, although they may have contributed to apparent duration of the highstand cluster.

Another set of issues pertains to post-depositional modification of gastropod shells. Previous studies have noted that shells are vulnerable to leaching by percolating water in the vadose zone after deposition, and recrystallization of aragonite to calcite, both of which can skew their apparent radiocarbon ages (e.g. Benson *et al.*, 1990; Oviatt *et al.*, 1992; Benson, 1993). However, in the case of the new dates obtained in this study from the Franklin, Clover and Goshute Valleys, samples were intentionally collected from depths of >75 cm where evidence for leaching was minimal. Although secondary carbonate coatings were present on some of these shells when they were extracted from the sediment, physical and chemical treatments removed these coatings until the shells universally exhibited a clean mother-of-pearl luster. X-ray diffraction (XRD) analysis of these shells revealed a dominantly aragonite signature, with strong peaks at 2.69, 3.40 and 1.98 Å, which rules out extensive recrystallization to calcite. Thus, for the new dates, the effects of these processes are considered negligible. The possibility that these processes impacted the radiocarbon ages gathered from the literature cannot be fully eliminated. However, the confidence weighting process applied in generating the summed PDF was designed to reduce reliance on ages for which the potential effects of these processes is less well constrained.

Finally, it is possible that even if the ^{14}C ages on shells accurately reflects the age of the enclosing beach ridge sediment, some lake highstands may have lagged climatic shifts toward greater effective moisture. For the largest lakes, this delay may simply reflect the time necessary to fill an extensive basin, especially if rising water overtopped divides and flooded

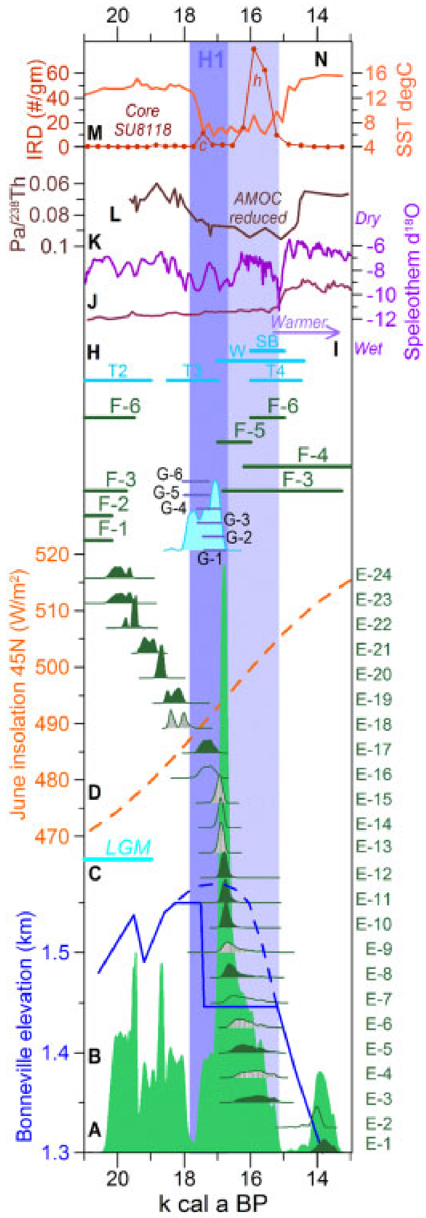

Figure 3. Calibrated radiocarbon dates for the last pluvial lake highstand in the Great Basin, in comparison with other climate proxy records spanning 21–13k cal a BP. (A) Summed probability density function (PDF) of calibrated ^{14}C ages for dated highstand beach ridges, weighted to reflect confidence. (B) Hydrograph for pluvial Lake Bonneville (Oviatt, 1997; Benson *et al.*, 2011; Godsey *et al.*, 2011). Dashed line represents a hypothetical trajectory had overflow not occurred. (C) Latter part of the global Last Glacial Maximum (LGM) (Clark *et al.*, 2009). (D) Insolation curve (Berger, 1978) illustrating correspondence between the summer insolation minimum, the LGM and some pluvial lake highstands. E-1 to E-24 are calibration curves for individual ^{14}C dates constraining the highstand beach ridge in multiple lake basins. Solid fill reflects highest confidence, stipple fill represents intermediate confidence and open represents lowest confidence. Abbreviations are keyed to Fig. 1 and Tables 1 and 2. F-1 to F-6 are extended intervals of high water in other southwestern US lake basins. Abbreviations are keyed to Fig. 1 and Table 3. G-1 to G-6 are calibrated ^{14}C ages constraining the onset of Heinrich Event 1 with a summed PDF. G-1 from Core V23-81 (Bond et al., 1992, 1993); G-2 from Core HU75-55 (Vidal *et al.*, 1997); G-3 from Core NA87-22 (Andrews *et al.*, 1994); G-4 from Core DSDP609 (Bond et al., 1992, 1993); G-5 from Core SU90-09 (Grousset *et al.*, 2001); G-6 from core V23-81 (Bond and Lotti, 1995). (H) Glacier advances (Tioga 1–4) in the Sierra Nevada (Phillips *et al.*, 2009), in the San Bernadino Mountains (Owen *et al.*, 2003), and the onset of ice retreat (W) in the Wasatch Mountains (Laabs *et al.*, 2011). (I) Onset of warmer conditions noted in a speleothem record from Pinnacle Cave, NV (Lachniet *et al.*, 2011). δ^{18}O records from (J) Cave of the Bells, AZ (Wagner *et al.*, 2010) and (K) Fort Stanton Cave, NM (Asmerom *et al.*, 2010). (L) Record of Pa/^{238}Th from the subtropical North Atlantic as a proxy for strength of the Atlantic Meridional Overturning Circulation (AMOC) (McManus *et al.*, 2004). Note inverted axis. (M) Record of ice-rafted debris (IRD) in Core SU8118 from the northeastern Atlantic (Bard *et al.*, 2000). Layers rich in carbonate assumed to have been sourced in Hudson Strait are marked by '*c*' while '*h*' represents a layer rich in hematite-stained grains of northeastern Atlantic provenance that was deposited later in Heinrich Stadial 1. (N) Reconstructed sea-surface temperature (SST) from Core SU8118 showing dramatic depressions corresponding to episodes of increased IRD (Bard *et al.*, 2000). Heinrich Event H1 (Bond *et al.*, 1992) is shown with a vertical shaded bar. Lighter shading highlights the duration of Heinrich Stadial 1 (GS-2a) (Bjorck *et al.*, 1998) during which the influence of the H1 ice discharge persisted in the North Atlantic.

adjacent valleys, creating near-instantaneous jumps in the surface area available for evaporation. A highstand could also lag increased effective moisture if the majority of water entering the lake traveled slowly as groundwater from distant recharge areas in the surrounding mountains. However, at their maximum extents most of these lakes had pluvial indices (lake area/watershed area) of <0.25 (Mifflin and Wheat, 1979), indicating that they were surrounded by large source areas for surface runoff, and the extensive surface areas of the lakes themselves would have functioned as efficient collectors of precipitation. Results of numerical modeling experiments also suggest that runoff was greatly increased during pluvial periods (Menking *et al.*, 2004; Matsubara and Howard, 2009). Thus, it seems likely that at least the smaller lakes responded rapidly to increases in effective moisture, and any lag between climate change and resultant lake highstands would have been minimal.

Overall, the possibility that some of the ages compiled in this study fail to directly reflect the true timing of highstands cannot be completely discounted. However, the stratigraphic position of the shells collected for this study, and their dominantly aragonite composition, strongly suggest that the new ^{14}C ages are accurate. Furthermore, the strong convergence of weighted ages from multiple basins in the summed PDF suggests that the ^{14}C results represent the timing of lake highstands with sufficient precision to support the interpretations made here. Accordingly, all ^{14}C dates are considered direct recorders of the age of their corresponding shoreline.

Timing of the last lake highstand in the Clover, Franklin and Goshute Valleys

The strong clustering of seven of the ten new dates indicates that Lakes Clover, Franklin and Waring were at their highstand elevations simultaneously between 17.0 and 16.5k cal a BP (Fig. 2). Two of the dates (OS-89976 and OS-92041) from the same locality in the Franklin Valley are ~400 ^{14}C a younger than the third (OS-90241), yet the 2-sigma calibration ranges of all three dates overlap. Because the shells exhibited an aragonite composition in XRD analysis and were collected from within 1 m of the crest of the beach ridge, the age difference probably reflects the duration of the highstand rather than later recrystallization influencing the youngest age. The age for Lake Waring (OS-92149) is almost identical to another reported for the highstand beach at an unspecified location in the Goshute Valley (Garcia and Stokes, 2006), providing confirmation that this highstand is accurately dated. The three younger dates from the highstand ridge of Lake Clover

(OS-90532, OS-85506 and OS-85537) are from the same locality in the northeast Independence Valley. The older two of these are from separate excavations along the back slope of the highstand beach ridge, and the youngest age (OS-90532) is from 55 cm stratigraphically higher in the same excavation that yielded sample OS-85506. This pair of results differs by 300 ^{14}C years, suggesting that the duration of the highstand may have been on the order of a few centuries, similar to the results from Lake Franklin.

The two outlying ages from the Clover Valley (OS-90527 and OS-85505) are ~2500 years older than this cluster, and the two groupings fail to overlap even at the distal ends of their 2-sigma calibration ranges (Fig. 2). The shells that yielded these older ages were collected from a locality along the highstand beach ridge 25 km from the northeast Independence Valley site that yielded the younger three ages. The ages, which were determined on separate collections of shells from the same excavation, are identical, suggesting a legitimate offset in the age of the highstand ridge at these two locations. Given the magnitude of this offset, it seems unlikely that the difference could be due to a local reservoir effect that artificially increased the ages of shells in this part of the lake. The more logical interpretation is that Lake Clover reached this elevation at least twice: first at ca. 19.5k cal a BP and again at ca. 17.0k cal a BP. This interpretation requires a more complicated lake-level history, but better fits the available data.

The outlying age from the Franklin Valley (OS-92025) can be explained by critical consideration of its stratigraphic setting. The gastropods in this sample were collected from the base of the highstand ridge in an excavation that penetrated through the beach gravel and into a fine-grained unit resembling the material forming the surface of the surrounding playettes. While the intent in collecting this sample was to obtain an age for the basal layer of the beach ridge, shells from the underlying silt may have been reworked into the sand at the onset of beach formation. Given the stratigraphic position of this sample, and its great age compared with the nine other new dates from highstand ridges, this age is assumed to represent a lagoonal environment that existed prior to construction of the highstand ridge and will not be discussed further.

Clustering of lake highstands and correlations with Heinrich Event 1

The dramatic clustering of ^{14}C ages between 17.5 and 16.5k cal a BP is well expressed in both the pattern of individual ages and the weighted summed PDF (Fig. 3). This pattern clearly illustrates that although some lakes reached highstands during the latter part of the Last Glacial Maximum, the majority of lakes simultaneously reached high levels a few millennia later, requiring a shift toward regionally enhanced effective moisture at this time.

This cluster of highstand ages is notable for its striking coincidence with the age of Heinrich Event 1 (H1) in the North Atlantic. Heinrich Events were colossal releases of icebergs from the Laurentide Ice Sheet (Heinrich, 1988; Hemming, 2004), which induced dramatic millennial-scale climate changes of at least hemispheric extent. Several studies have presented ^{14}C ages from marine sediment cores for the base of the interval enriched in ice-rafted debris (Bond *et al.*, 1992, 1993; Andrews *et al.*, 1994; Bond and Lotti, 1995; Vidal *et al.*, 1997; Grousset *et al.*, 2001). After adjustment for a standard 400-year reservoir effect, these dates range from 14 600 to 13 930 ^{14}C a BP. Combining these results in OxCal yields an estimate of 14 250 ^{14}C a BP for the onset of H1, which calibrates to 17.6–17.0k cal a BP. This is close to the age of 16.8k cal a BP presented in a comprehensive overview of Heinrich Events (Hemming, 2004), but is slightly older than the estimate of 16.1k cal a BP determined from the onset of the weak monsoon event in the Hulu Cave δ^{18}O record, assumed to be correlative with H1 (Wang *et al.*, 2001). Because the exact magnitude of the marine reservoir correction is unknown, and may have varied in both space and time (Broecker *et al.*, 2009), precise determination of the onset of the H1 iceberg discharge is difficult. However, the convergence of evidence indicates that H1 occurred at ca. 17k cal a BP, immediately before the strong clustering of lake highstands.

The close relationship between lake highstands and the start of H1 strongly suggests that changes in atmospheric circulation induced by the H1 ice discharge into the North Atlantic increased precipitation in the southwestern US. Melting of the H1 ice is known to have suppressed Atlantic Meridional Overturning Circulation (AMOC) (McManus *et al.*, 2004), resulting in cooling (Bard *et al.*, 2000) and tremendous sea-ice expansion (Denton *et al.*, 2005) in the North Atlantic. Global Circulation Models and paleoclimate data also reveal that AMOC curtailment corresponds to lowering of North Pacific sea surface temperatures and winter enhancement of the Aleutian Low (Okumura *et al.*, 2009). The exact nature of this interbasin connection is unclear, although it may involve eastward advection of cold air from the North Atlantic across Eurasia (Manabe and Stouffer, 1988), perhaps aided by sea-ice expansion in the North Pacific (Cheng *et al.*, 2007), or an atmospheric teleconnection related to suppression of precipitation in the tropical Atlantic (Okumura *et al.*, 2009). Whatever the cause, enhancement of the Aleutian Low would steer large amounts of moisture into the southwestern US, and is considered to be the source of δ^{18}O shifts seen in some speleothem records sensitive to Pacific-derived winter precipitation (Asmerom *et al.*, 2010). Our results, which indicate that effective moisture in the Great Basin and surrounding region was increased to unprecedented levels for the late Pleistocene immediately following the onset of H1, are consistent with these hypotheses linking the North Atlantic and western US paleohydrology.

This direct connection between H1 and lake highstands differs from a previous interpretation that H1 occurred near the start of a millennial-scale dry episode in the Great Basin that was followed by an increase in effective moisture at ca. 16k cal a BP that drove the highstand of Lake Lahontan (Broecker *et al.*, 2009). That interpretation was based primarily on data from the Estancia Basin in central New Mexico and Lake Lahontan. Yet although there is clear stratigraphic evidence for desiccation of Lake Estancia between 14 900 ± 100 and 13 840 ± 60 ^{14}C a BP (Allen and Anderson, 2000), the younger end of that age range overlaps with estimates for the onset of H1. Thus, from these dates it is equally possible to infer that the desiccation event ended with the start of extensive ice rafting. Data from the Lahontan Basin include δ^{18}O measurements from cores dated through application of paleomagnetic secular variations, as well as ^{14}C ages constraining the water surface elevation at different times. The former suggest that Lake Lahontan was low between 17.2 and 15.7k cal a BP, before reaching a highstand at ca. 15.5k cal a BP (Benson *et al.*, 2012). However, radiocarbon-dated tufa deposits indicate that the various sub-basins of Lake Lahontan coalesced into a single water body at ca. 17k cal a BP (Benson and Thompson, 1987; Benson *et al.*, 2012), implying a rising water level at that time. Similarly, ^{14}C dates on gastropod shells from transgressive shorelines within ~10 m of the ultimate highstand elevation are as old as 13 280 ± 110 ^{14}C a BP (Adams and Wesnousky, 1998), which calibrates to 16.8–15.5k cal a BP, with a maximum probability age of 16.5k cal a BP. Together, this collection of shore-based age estimates suggests that the rise of Lake Lahontan to its ultimate highstand may have been a short-lived and rapid event superimposed on a long interval of relatively high water that began at ca. 17k cal a BP. The cause of the disagreement between the shore and core-based reconstructions is unclear, yet consideration of the available shore-based data suggests that high water in the Lahontan basin may have followed H1 more closely than was previously suggested (Broecker *et al.*, 2009). Given the more comprehensive dataset presented here, we propose the alternative interpretation that smaller lakes responded rapidly to an increase in effective moisture related to H1, and that the protracted high water phase of Lake Lahontan was a function of the inherent lag time involved in filling its much larger, physiographically complex, basin.

Paleoclimatic significance of lake highstands

Many lakes that experienced highstands following the H1 ice discharge were also high during the latter part of the LGM (Fig. 3), which has been attributed to southward displacement of the Polar Jet Stream (PJS) due to the influence of the Laurentide Ice Sheet (Antevs, 1948). This theory, which has been supported by general circulation modeling experiments (Bartlein *et al.*, 1998), predicts that highstands should be time-transgressive events following the northward migration of the PJS as the Laurentide Ice Sheet retreated. However, the data reported here reveal overlapping highstand ages for pluvial lakes at a variety of latitudes (Figs. 1 and 3), thereby presenting a challenge to this model by seemingly requiring the PJS to be in multiple places at the same time.

A solution to this dilemma is offered by refocusing on the 'mean position' of the PJS. In this view, the LGM highstands of southern lakes resulted from a PJS that was primarily focused over southern latitudes, but made short-lived northward excursions. With the average position of the PJS deflected to the south, most southern lakes reached highstands, while large northern lakes such as Bonneville and Lahontan exhibited relatively low water. Some small, sensitive lakes at northern latitudes, such as Clover and Franklin, also reached high levels (for unknown durations) during this time because they could respond more quickly to pulses of enhanced precipitation induced by temporary northward PJS migrations (Figs 1B and 3).

As the Laurentide influence waned during deglaciation, the mean position of the PJS shifted northward, inducing a rising, but still fluctuating, water level in Lakes Bonneville (Oviatt, 1997) and Lahontan (Benson *et al.*, 2012), as well as short-lived highstands of Lakes Clover and Franklin. Shortly before H1 the mean position of the PJS reached a latitude centered over the Bonneville and Lahontan basins (~41°N), raising the water level in both lakes, initiating Bonneville overflow at ca. 18.5k cal a BP (Oviatt, 1997; Benson *et al.*, 2011) and causing sub-basins of Lake Lahontan to coalesce (Benson *et al.*, 2012). This arrangement preconditioned the hydrology of the northern Great Basin so that augmentation of westerly moisture flow in response to H1-induced strengthening of the Aleutian Low at ca. 17.0k cal a BP was sufficient to drive most northern lakes to record-high levels (Fig. 3).

Lingering influence of the H1 ice discharge through Heinrich Stadial 1 (GS-2a, Bjorck *et al.*, 1998) sustained the overflow of Lake Bonneville and supported advances of alpine glaciers (Fig. 3) in the Wasatch (Laabs *et al.*, 2011) and San Bernadino (Owen *et al.*, 2003) Mountains, and in the Sierra Nevada (Phillips *et al.*, 2009). At the same time, occasional southward excursions of the PJS raised the water level in relatively small southern lakes (Figs. 1 and 3). Some southwestern lakes might also have been influenced by proximity to the coast (i.e. Thompson) and additions of glacier meltwater (Owens, and by downstream connection, Searles).

Final decay of the H1 influence on the Aleutian Low at the transition from GS-2a to GI-1 (the Bølling/Allerød) ended the enhanced delivery of Pacific moisture, as shown clearly in speleothem records from Arizona and New Mexico (Asmerom *et al.*, 2010; Wagner *et al.*, 2010). This shift terminated Bonneville overflow at 15.0k cal a BP (Godsey *et al.*, 2011), and caused Lake Lahontan to drop and become saline by 14.4k cal a BP (Benson *et al.*, 2012). If the Laurentide effect persisted despite the reduced extent of the ice sheet, the end of GS-2a may have allowed the mean position of the PJS to resume shifting northward, generating the northernmost highstand in the compilation, Lake Chewaucan, at ca. 14k cal a BP (Licciardi, 2001).

It is important to note that local factors probably played a role in controlling the water level in individual lakes. For instance, the response time or climatic sensitivity of specific lakes could vary based on differences in physiography, pluvial index and hydrogeologic setting. In addition, atmospheric factors such as El Niño–Southern Oscillation, orographic controls over precipitation in this region of complicated topography and convergence of moisture delivery from different directions (Houghton, 1969) could add variability in effective moisture at sub-regional scales (Licciardi, 2001). Therefore, wholesale shifts in the mean position of the PJS are not required to explain every highstand in the compilation. Nonetheless, the model proposed here focusing on the mean PJS position is more effective at explaining the simultaneous lake highstands identified in the regional comparison than the traditional concept of a PJS that migrated steadily northward during deglaciation.

Conclusions

The results of this study corroborate prior interpretations of effective moisture changes in the southwestern US during the last glacial cycle (Asmerom *et al.*, 2010), and identify H1 as the trigger for pluvial lake highstands throughout the Great Basin and surrounding region at ca. 17k cal a BP. New radiocarbon dates from highstand beach ridges of small pluvial lakes, combined with existing dates from other lakes of various sizes, clearly indicate that the southwestern US was much wetter when the North Atlantic region was cold in response to H1 and its slowing of AMOC. Reports of elevated lake levels in some pluvial lakes during the Younger Dryas interval, for instance in Lake Bonneville (Oviatt, 1997), Lake Owens (Orme and Orme, 2008) and the Pyramid Lake basin of Lake Lahontan (Benson *et al.*, 2012), provide further support for the conclusion that stadial conditions in the North Atlantic induce increased effective moisture in the southwestern US. Overall, the paleoclimate record of the latest Pleistocene in the southwestern US supports the prediction that this region will become more arid with continued global warming, adversely affecting its already stressed water supply (Held and Soden, 2006; Quade and Broecker, 2009).

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Abbreviations. AMOC, Atlantic Meridional Overturning Circulation; H1, Heinrich Event 1; PDF, probability density function; PJS, Polar Jet Stream; XRD, X-ray diffraction.

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