A record of mid- and late Holocene paleohydroclimate from Lower Pahranagat Lake, southern Great Basin

Kevin M. Theissen[a]*, Thomas A. Hickson[a], Ashley L. Brundrett[a], Sarah E. Horns[a], Matthew S. Lachniet[b]
[a]Department of Geology, University of Saint Thomas, Saint Paul, Minnesota 55105, USA
[b]Department of Geoscience, University of Nevada Las Vegas, Las Vegas, Nevada 89154, USA
*Corresponding author e-mail address: kmtheissen@stthomas.edu (K.M. Theissen).

Abstract

We present a continuous, sediment core-based record of paleohydroclimate spanning ∼5800 cal yr BP to recent from Lower Pahranagat Lake (LPAH), a shallow, alkaline lake in southern Nevada. We apply stable isotopes ($\delta^{18}O$ and $\delta^{13}C$) from fine-fraction authigenic carbonate, which are sensitive recorders of hydroclimatic variability in this highly evaporative region. Additional geochemical proxies (total organic carbon, C/N, and total inorganic carbon) provide supporting information on paleoecological change in and around the lake. Our data suggest progressively wetter conditions starting at the later part of the middle Holocene and extending into the late Holocene (∼5500–3350 cal yr BP) followed by a millennial-scale dry period from ∼3150 to 1700 cal yr BP. This latter interval encompasses the 'Late Holocene dry period' (LHDP) reported by other investigators, and our data help refine the area affected in this episode. Our data also show evidence for a series of century-scale fluctuations in regional hydroclimate, including wet and dry intervals between 2350 and 1600 cal yr BP, and drier conditions over the past few centuries. Paleohydroclimate trends in the LPAH record show correspondence with those from the central Great Basin to the north, suggesting that both areas were subject to similar climatic forcings.

Keywords: Middle Holocene; Late Holocene; Paleohydroclimate; Great Basin; Late Holocene dry period; Alkaline lake; Stable isotopic values; $\delta^{18}O$ and $\delta^{13}C$; Authigenic carbonate

INTRODUCTION

Continuous, high-resolution records of paleoclimate are rare for the arid Great Basin province of the United States. Such records provide valuable historical context for a region with high population growth and challenges to provide sufficient water to this growing population. An important finding from natural archives of Holocene paleoclimate in the Southwest is that droughts of far greater duration and magnitude than those experienced and documented for the past century—so-called megadroughts—are not unusual (e.g., Stine, 1994; Mensing et al., 2013; Cook et al., 2014).

Archives of Holocene paleoclimate for the Great Basin include cave deposits, tree rings, and pollen and geochemical indicators from lake sediments. Records from locations across the Great Basin (Fig. 1A) indicate a notably drier and warmer middle Holocene (starting between ∼7000 and 8000 cal yr BP and ending between 4000 and 5500 yr BP), followed by a relatively wetter and cooler late Holocene (Benson et al., 2002; Wigand and Rhode, 2002; Grayson, 2011; Lachniet et al. 2014; Salzer et al., 2014). In the southern Great Basin, Quade et al. (1998) note the complete absence of organic-rich deposits known as black mats in sedimentary outcrops across several sites in the Las Vegas Valley between 6300 and 2300 ^{14}C yr BP as evidence of general aridity, with the occurrence of black mats dated to 2300 ^{14}C yr BP and younger signaling the onset of generally wetter conditions. A high-resolution speleothem record from Leviathan Cave indicates drier and warmer conditions from 9000 to 5000 cal yr BP and relatively wetter and cooler conditions after this (Lachniet et al., 2014). In the western Great Basin, generally arid conditions are indicated in a pollen record from Pyramid Lake from 7600 to 5000 cal yr BP, followed by wetter conditions after 5000 cal yr BP (Mensing et al., 2004). A chironomid-based temperature record from Stella Lake in the central Great Basin shows generally warmer conditions from 6800 to 4200 yr BP and cooler conditions between 4200 and 1000 yr BP (Reinemann et al., 2009). A high-resolution, 4600-yr-long tree ring index from northern and central
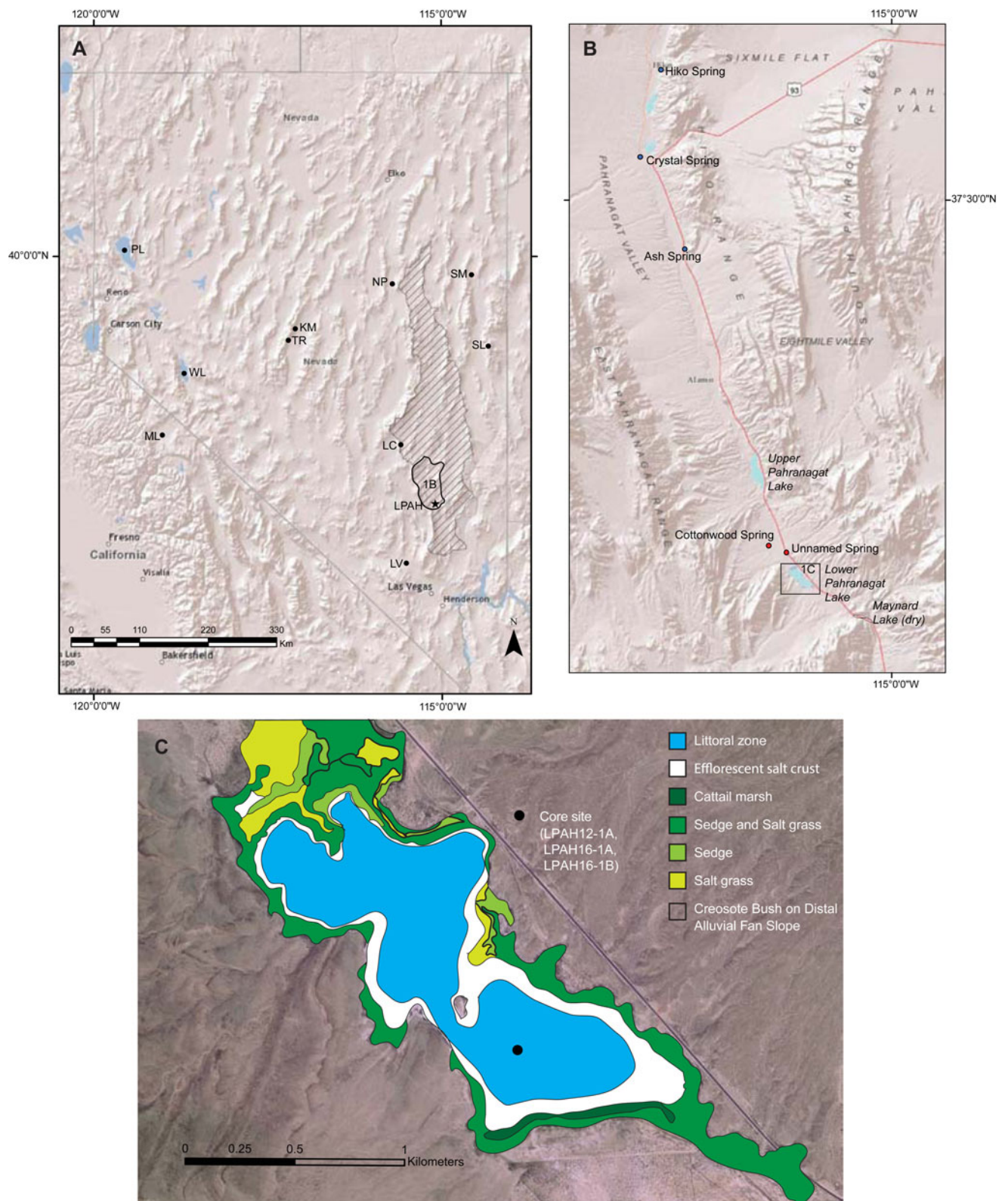
Figure 1. (A) Map of Nevada and neighboring states with sites discussed in this article indicated. Lower Pahranagat Lake (LPAH) indicated with star. KM, Kingston Meadow; LC, Leviathan Cave; LV, Las Vegas Valley; ML, Mono Lake; NP, Newark Valley Pond; PL, Pyramid Lake; SL, Stella Lake; SM, Stonehouse Meadow; TR, Toiyabe Range; WL, Walker Lake. Boundaries of the Pahranagat National Wildlife Refuge are indicated with thick black line. Area highlighted with diagonal lines is the regional carbonate aquifer as mapped by Eakin (1966). (B) Map of the Pahranagat Valley. Regional carbonate aquifer springs are indicated with blue dots. Local volcanic aquifer springs are indicated with red dots. (C) Map of LPAH, showing modern vegetation and coring site (modified from Hickson et al., 2018). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Great Basin sites indicates a long-term decline of approximately −1.1°C since the mid Holocene (Salzer et al., 2014). Although viewed as being generally wetter, there is clear evidence of significant drought during the late Holocene. The multicentury-long Medieval Climate Anomaly (MCA; ~1200–700 cal yr BP) was a dry period for much of the Great Basin (Stine, 1994), and more recently, evidence of a millennium-long "late Holocene dry period" (LHDP) from ~2800 to 1850 cal yr BP has been found at sites across the central Great Basin as well (Mensing et al., 2013).

In this article, we reconstruct a sediment core–based paleohydroclimate record continuously spanning the past 5800 cal yr BP from Lower Pahranagat Lake (LPAH) in southern Nevada. Our multiproxy record builds on and extends a 3800 yr pollen-based record from LPAH showing evidence for century-scale hydroclimate variability (Wigand, 1996; Wigand and Rhode, 2002). Fifteen AMS radiocarbon age dates provide age control for our 12.4 m composite core record. LPAH is hydrologically closed and lies in a region with a very high ratio of evaporation to precipitation, making it sensitive to changes in water balance. We apply stable isotope analyses ($\delta^{18}O$ and $\delta^{13}C$) from fine-fraction (<63 μm) authigenic carbonates that record changes in isotopically sensitive lake waters through time. We also present down-core total organic carbon (TOC), C/N, and total inorganic carbon (TIC) results that refine interpretations of hydroclimate as well as sources of organic matter and productivity. Our analysis allows us to compare our record with others from the Great Basin on century to millennial timescales.

Site hydrology and climatology

LPAH is a small (1.2 km^2), shallow (average depth, <1 m; maximum depth, 1.5 m), alkaline lake in the Pahranagat National Wildlife Refuge (PNWR), a 17.7-km-long, 21.8 km^2 area of marshes, impoundments, and shallow lakes that lies at the southern end of the Pahranagat Valley in southern Nevada (Fig. 1B and C). Hickson et al. (2018) provide a detailed description of the LPAH site, including modern ecology, water chemistry, and geologic setting.

LPAH is spring-fed, receiving the majority of its water budget from a deep carbonate aquifer (Fig. 1A) and a smaller amount from more local and shallower aquifers in volcanic strata (Eakin, 1966). Water is discharged at a number of springs north of the lake, that then flow south through a series of connected marshes and small lakes through the Pahranagat Valley (Fig. 1B). Paleozoic carbonate strata comprise the deep regional aquifer and extend north to Great Basin National Park, east into Utah, and south to Death Valley and Lake Mead (Eakin, 1963, 1966). U.S. Geological Survey stream gauges for the two highest discharge springs, Crystal and Ash, discharged at 340 L/s and 510 L/s between 2004 and 2009 with discharge at a relatively constant rate throughout the year (Paces and Wurster, 2014). Tectonics also plays a role in Pahranagat Valley hydrology, with faults in the valley serving as conduits for groundwater flow. Movement along these faults, which include a series of east–northeast trending

strike-slip faults within the PNWR, would likely have some influence on groundwater flow in the valley, but there is relatively little known about Holocene activity on these faults. Through most of the Holocene, water would have flowed south and pooled at LPAH and in Paleolake Maynard, a now drained and dry lake bed at the south end of the Pahranagat Valley (Fig. 1B). Pahranagat Valley spring water is managed to support irrigation of pasture land and for domestic purposes. In the early 1930s, a dam was constructed at the south end of existing marshland to form an impoundment 7.1 km northwest of LPAH (Upper Pahranagat Lake). Since 1963, LPAH water volume has been managed by the U.S. Fish and Wildlife Service as part of a broader management plan for the hydrology in the PNWR. Water released from the Upper Pahranagat Lake has been the largest control on LPAH water volume since this time. Paces and Wurster (2014) used Sr and U isotopes as tracers and determined that surface water in the PNWR is composed of waters from the two regional carbonate aquifer springs and groundwater from the local volcanic aquifer source in a 65:25:10 mixture. Stable isotopic values for O in Pahranagat Valley surface waters are highly sensitive to hydroclimatic conditions and show a strong seasonal trend of evaporative enrichment from the wetter and less evaporative winter months to the drier and more evaporative summer months (Paces and Wurster, 2014; Fig. 2).

The climate of the Pahranagat Valley features low annual precipitation (157.7 mm/yr average at the PNWR) and high evaporation, with cold winters and hot summers. Data from the PNWR weather station (National Oceanic and Atmospheric Administration/National Weather Service Cooperative Observer Network station #265880) for the period 1964–2015 show average maximum/minimum monthly temperatures of 11.5/−3.0°C in December and 36.9/18.1°C in July (Western Regional Climate Center website [https://wrcc.dri.edu/cgi-bin/cliMAIN.pl?nv5880, accessed October 15, 2017]). Relative to the spring water from the regional carbonate aquifer, precipitation is a trivial source of moisture to the marshes and lakes of the Pahranagat Valley (Wurster, 2010; Paces and Wurster, 2014). As such, we interpret changes in the water balance at LPAH to be related to the evaporation/discharge (E/Q) ratio. The source of most precipitation is large winter storm systems from the Pacific Ocean. A somewhat smaller amount of precipitation comes from summer convective storms associated with a monsoon-like weather pattern from the Gulf of California (Tyler et al., 1996). The Pahranagat Valley is in a region with some of the highest evaporation rates in the United States. Wurster (2010) calculated that open water evaporation approaches 1676 mm/yr, greater than 10 times the average annual precipitation.

METHODS

Core collection and correlation

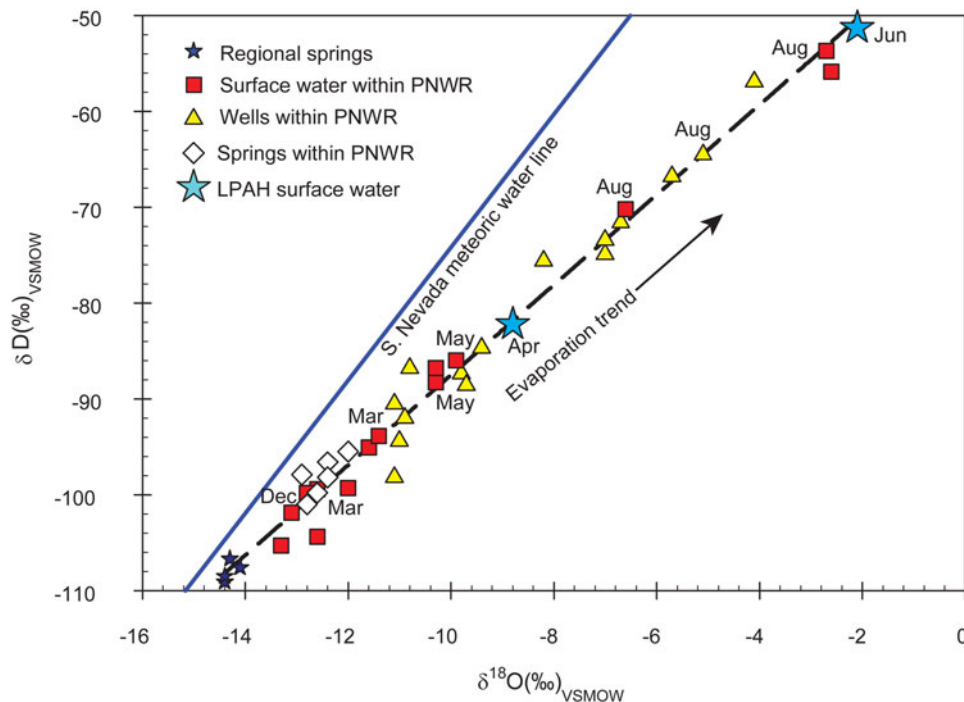We used a square-rod piston corer (Livingstone) aboard a floating coring platform with a winch and pulley system to

Figure 2. Plot of O and H water isotopic values and trend of evaporative enrichment from northern to southern sites. Dates (months) are labeled to illustrate seasonal isotopic enrichment from wetter winter/spring (December–April) to drier summer (June–August) conditions. O and H isotopic values for southern Nevada precipitation are indicated with the labeled blue line. With the exception of Lower Pahranagat Lake (LPAH) surface waters, all surface water and groundwater data are from Paces and Wurster (2014). PNWR, Pahranagat National Wildlife Refuge. VSMOW, Vienna standard mean ocean water. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

collect successive 1-m-long drives resulting in a 12.4-m-long overlapping core sequence (cores LPAH12-1B, LPAH16-1A, and LPAH16-1B) from southern LPAH in January 2012 and March and November 2016 (Fig. 1C). All cores were collected in the same location (37°13.001′N, 115°4.882′W). Cores were extruded into split tubing in the field and transported to the National Lacustrine Core Facility (LacCore) at the University of Minnesota where they were stored at 4°C. Cores were split, digitally imaged, and scanned at high resolution for magnetic susceptibility and color properties following standard laboratory protocols. We used the Corelyzer software (v. 2.0.4.rc5; available at https://csdco.umn.edu/resources/software/corelyzer) to examine the high-resolution core images, correlate the cores based on shared stratigraphic markers, and construct a composite depth profile.

Elemental and stable isotopic analysis

We subsampled LPAH cores at 5 cm intervals and split each subsample into two separate portions for C and N elemental analysis. Samples were ground with a mortar and pestle for homogenization and weighed with a microbalance. One portion of each subsample was placed into a tin capsule for analysis to determine total C (TC). A second portion was placed into silver capsules and then acidified with 6% sulfurous acid to remove carbonate to determine TOC following Verardo et al. (1990). Because LPAH sediments are consistently carbonate-rich

(often >50% by wt.), we followed the recommendations of Phillips et al. (2011) and added a minimum of 1280 µL of acid prior to analysis to ensure that all inorganic C was removed. Untreated and acidified samples were then analyzed using a Thermo Electron Flash EA 1112 elemental analyzer in the Geology laboratory at the University of St. Thomas. TIC was calculated for each sample by taking the difference between untreated (TC) and acidified (TOC) results. We replicated 5% of our samples with average standard deviations of 0.088% and 0.038% for TOC and TIC, respectively. We also collected five samples at 10 cm intervals from an organic-rich layer near the base of the LPAH core (12.28 to 11.78 m depth) and determined percent organic matter by loss-on-ignition following standard procedures (Heiri et al., 2001).

We subsampled LPAH12-1B at 5 cm intervals and LPAH16-1A at 10 cm intervals for O and C stable isotopic analysis of fine-fraction (<63 µm) authigenic carbonate. Sample preparation and analysis are described in Hickson et al. (2018). Analysis was primarily completed in the Stable Isotope Laboratory at the University of Minnesota where replicate analysis of 37% of 128 samples showed average standard deviations of 0.029‰ for $\delta^{13}C$ and 0.147‰ for $\delta^{18}O$. A smaller number of samples (n = 27) were analyzed in the Las Vegas Isotope Science Laboratory at the University of Nevada, Las Vegas. Comparison of results for seven samples run at both laboratories showed average standard deviations of 0.124‰ $\delta^{13}C$ and 0.264‰ for $\delta^{18}O$.

Mineralogy

We characterized the mineralogy of the LPAH sediments in detail (10 cm spacing), using a finely ground portion of each <63 μm fraction for analysis with a PANalytical X'Pert Pro MPD X-ray Diffractometer (XRD) in the Keck Laboratory at Macalester College. We also examined mineralogy in a semiquantitative fashion using smear slides at the same spacing throughout the core.

Chronology

In order to develop a full chronology for the LPAH record, we sampled the core record at 15 intervals for age dating by ^{14}C analysis. Where sufficient plant remains were available, this was used for age dating. For most samples, this included a mixture of aquatic, emergent, and terrestrial plant materials. For eight of our age-dated samples, it was necessary to use bulk organic matter. Subsamples were placed into baked glass containers and sent to Beta Analytic Laboratories for dating by accelerator mass spectrometry. All carbonates were removed from samples through acid washes. To develop our age model, we used Bacon v. 2.2, Bayesian age-depth modeling software (Blaauw and Christeny, 2011), which uses the IntCal13 database (Reimer et al., 2013) for age calibration.

RESULTS

Chronology

All radiocarbon age dates, associated errors, and corrections are shown in Table 1. Old carbon is often found in freshwater springs emerging from ancient carbonate rocks such as the regional spring sources to LPAH. Subaqueous plants incorporate this old carbon from the available pool of dissolved inorganic carbon (DIC), resulting in erroneously old dates. To test for the presence of this reservoir effect, we dated both bulk and plant fractions from a surface sample (0–3 cm depth). These produced significantly different dates with charred plant remains giving a postmodern age (−390 pMC), whereas bulk organic material at the same depth showed a 590 ± 30 ^{14}C yr BP age. Based on these results, we assume that the sediment surface is modern and use the year of collection of LPAH12-1B (2012, $= -62$ cal yr BP) as an upper age in our chronology. We assume that the regional spring-water source has remained in constant proportion through time and subtracted 590 yr from 10 of the 15 dates used in our age model to account for the influence of the reservoir effect, producing adjusted radiocarbon ages (Table 1). The exceptions were the postmodern surface sample discussed previously and samples with measured δ^{13}C values of the organic material that indicate they are largely composed of terrestrial/emergent plants and are less likely to be affected by the reservoir effect (Table 1). We applied the Bacon software package to adjusted, uncalibrated dates, giving an age-depth model based on the resulting calibrated

ages that spans approximately the past 5800 cal yr (Fig. 3). Age dates progress in a fairly steady, linear fashion with sedimentation rates ranging from 0.07 to 0.37 cm/yr. One age date (Beta 458303 at 1046 cm depth) is older than the two dates stratigraphically below it and is largely ignored in the age-depth model. Overall, we are confident that our age model is useful for discussion of paleohydroclimate at a century-scale resolution.

Sedimentology and mineralogy

Hickson et al. (2018) described several sedimentary facies for LPAH12-1 cores representing the last ~2000 cal yr. LPAH sediments are primarily carbonate muds and silts with some intervals showing wavy laminations and other fabrics that are interpreted as microbial in origin. Peloidal textures dominate the carbonate sediments, with some millimeter-scale irregular and wavy laminae at irregular intervals that we interpret as thin microbial mat material based on modern analogs that have been identified in the lake (see figs. 6 and 7 in Hickson et al., 2018). These microbial features imply deposition in a very shallow, yet calm setting. Evidence of wave activity is almost completely lacking, probably because of the small fetch of LPAH and concomitantly low wave activity, coupled with the cohesion imparted by benthic aquatic plants and microbial exocellular polymeric substance. Our down-core XRD analyses of the <63 μm fraction indicate that the carbonates are a mixture of high- and low-Mg calcite and dolomite with high-Mg calcite as the dominant carbonate mineralogy through much of the core. Magnetic susceptibility (MS) shows low values throughout the majority of the core, consistent with carbonate-rich sediments. Several small deviations in MS occur along with two notable jumps centered on approximately the base of the core and 5.2 m depth (~5820 and 2418 cal yr BP, respectively). We interpret each of these intervals as periods of greater terrestrial input from the surrounding alluvial fans. The fossil remains of charophytes are a pervasive feature throughout much of the LPAH record. These macroscopic green algae most commonly grow and thrive in clear, alkaline, freshwater lakes (Hutchinson, 1975) such as LPAH, and *Chara* spp. occur in the modern lake in dense meadows. In both our macroscopic and microscopic investigation of down-core materials, we regularly found two distinct calcified parts of charophytes: gyrogonites (reproductive zygotes) and calcite encrustations (Fig. 4). The ubiquitous nature of these remains supports the long-term persistence of a clear, alkaline, and freshwater condition for the majority of the lake's history. Here we describe two additional facies found at the base of the longer record under investigation.

Clay unit (12.28 to 12.40 m depth)

At the base of the core, we captured the top 12 cm of a distinct clay facies. The unit is a gray to dark-gray, clay to fine-silt-sized material. Smear slides from this interval show a high proportion of clastic materials with magnetic

Table 1. Details of the radiocarbon-dated samples used in this study.

Lab ID#	Core section and section depth (cm)	Composite depth (cm) and material	δ^{13}C (‰)	^{14}C age (^{14}C yr BP)	Adjusted ^{14}C age, reservoir corrected (^{14}C yr BP)	^{14}C error (^{14}C yr)	2σ Calibrated age range (cal yr BP)	Median age (cal yr BP)
Beta-324209	LPAH12-1B-1L-1-W, 1–4	0–3, Bulk organic C	−20.1	590	Modern	30	—	Modern
Beta-474576	LPAH12-1B-1L-1-W, 1–4	0–3, Charred plant	−13.9	Postmodern	—	30	—	Modern
Beta-324210	LPAH12-1B-1L-1-W, 51.5	68.5, Bulk organic C	−18.9	760	170	30	1–290	180
Beta-324211	LPAH12-1B-2L-1-W, 22.5	120.5, Bulk organic C	−26.4	1150	560	30	522–642	593
Beta-324212	LPAH12-1B-3L-1-W, 67.5	276, Bulk organic C	−22.1	1920	1330	30	1184–1301	1273
Beta-324213	LPAH12-1B-4L-1-W, 80.5	357.5, Bulk organic C	−15.3	2370	1780	40	1574–1819	1700
Beta-458298	LPAH16-1A-5L-1-A, 61–62	420, Plant macro.	−15.3	2480	1890	30	1735–1893	1840
Beta-458299	LPAH16-1A-6L-1-A, 50–51	500, Plant macro.	−24.1	2500	—	30	2485–2736	2587
Beta-458300	LPAH16-1A-7L-1-A, 76–77	628, Plant macro.	−8.9	3090	2500	30	2485–2736	2587
Beta-458301	LPAH16-1A-9L-1-A, 70–71	801, Bulk organic C	−22.1	3530	2940	30	2991–3206	3098
Beta-458306	LPAH16-1B-9L-1-A, 14–15	888, Bulk organic C	−31.6	4160	3570	30	3729–3971	3871
Beta-464214	LPAH16-1A-11L-1-A, 20–22	949, Plant macro.	−25.3	4460	—	30	4970–5285	5143
Beta-458303	LPAH16-1A-12L-1-W, 24–25	1046, Plant macro.	−29.5	5220	—	30	5913–6170	5966
Beta-458304	LPAH16-1B-12L-1-W, 7–8	1181, Charred plant	−24.1	4780	—	30	5468–5590	5518
Beta-458305	LPAH16-1B-12L-1-W, 61–62	1235, Bulk organic C	−21.2	5650	5060	30	5738–5902	5820

susceptibility reaching the highest values for the record. This unit also has a small number of diatom microfossils, indicating the presence of an aqueous environment. This clay unit appears to be associated with an interval of silici-clastic sedimentation, derived from the surrounding Tertiary volcanic carapace that temporarily shut off carbonate production. This may be related to a period of increased local runoff and/or wind transport from the surrounding alluvial fans in the basin. This unit is centered on an age of 5792 cal yr BP.

Peat unit (11.78 to 12.28 m depth)

In sharp contact with the underlying clay unit is an olive brown to black, 50-cm-thick organic-rich layer. The high organic matter content (32.9–78.7%) and TOC (10.8–27.1%) measured from samples in this unit are characteristic of peat. Smear slides and thin sections reveal that the sediment ranges from clay to very fine sand grain sizes with abundant plant fragments, calcite, and, in some intervals, rare diatoms. The plant fragments range from reddish brown to black in color, show a layered or blocky structure, and sometimes have visible cell structure. A low δ^{13}C value (−24.1‰) measured from plant fragments in this unit suggests they are largely composed of C_3 plants like trees, shrubs, grasses, and sedges (Deines, 1980). Intermediate to high C/N values (17.3 to 78.7) measured from this unit fall in the range of measured modern aquatic and terrestrial plants from LPAH. The characteristics of this unit suggest a palustrine setting where generally water-saturated and low oxygen conditions were prime for peat formation. The observed blackened plant fragments and general absence of diatoms suggest periodic drying and oxidation during the formation of this unit.

Stable isotopes

Both δ^{18}O and δ^{13}C show a wide range of values in the LPAH record, with δ^{18}O values ranging from −11.44‰ to +1.14‰ and δ^{13}C values ranging from −5.22‰ to 10.28‰ (Fig. 5). There is a statistically significant positive covariation between δ^{18}O and δ^{13}C values in LPAH samples (n = 155, $P \leq 0.0001$; t-test). This is a typical phenomenon in hydrologically closed lakes (Talbot, 1990) and is the result of evaporative enrichment of ^{18}O in water and ^{13}C in DIC (e.g., Horton et al., 2016). Between 5250 and 4000 cal yr BP, stable isotopic values are especially low (−11.4‰ to −9‰ for δ^{18}O and −5‰ to −4‰ for δ^{13}C). Values for both δ^{18}O and δ^{13}C increase sharply to the highest levels in the record (+1.14‰ for δ^{18}O and +10.28‰ for δ^{13}C) and remain high between 3150 and 2500 cal yr BP and again between 2100 and 1700 cal yr BP, indicating two distinct periods of evaporative enrichment. Between these two multicentury evaporative periods is a shorter period centered on 2350 cal yr BP during which isotopic values for both drop significantly (−8.7‰ for δ^{18}O and −4.9‰ for δ^{13}C). Stable isotopic values also vary on centennial timescales over the past 1600 cal yr of the LPAH record with periods of low values centered on ~1600 and 600 cal yr BP and periods of high values (dry intervals) centered on 1100 cal yr BP and over the past few centuries (Fig. 5).

TOC, C/N, and TIC content

TOC values range widely with most values being relatively low (<3%) (Fig. 5). One exception to this is the peat unit near the base of the record, where values increase by an order of magnitude, reaching up to 27.1%. LPAH organic C/N reflects changing mixtures of terrestrial and aqueous plant sources of organic matter. Modern terrestrial plants
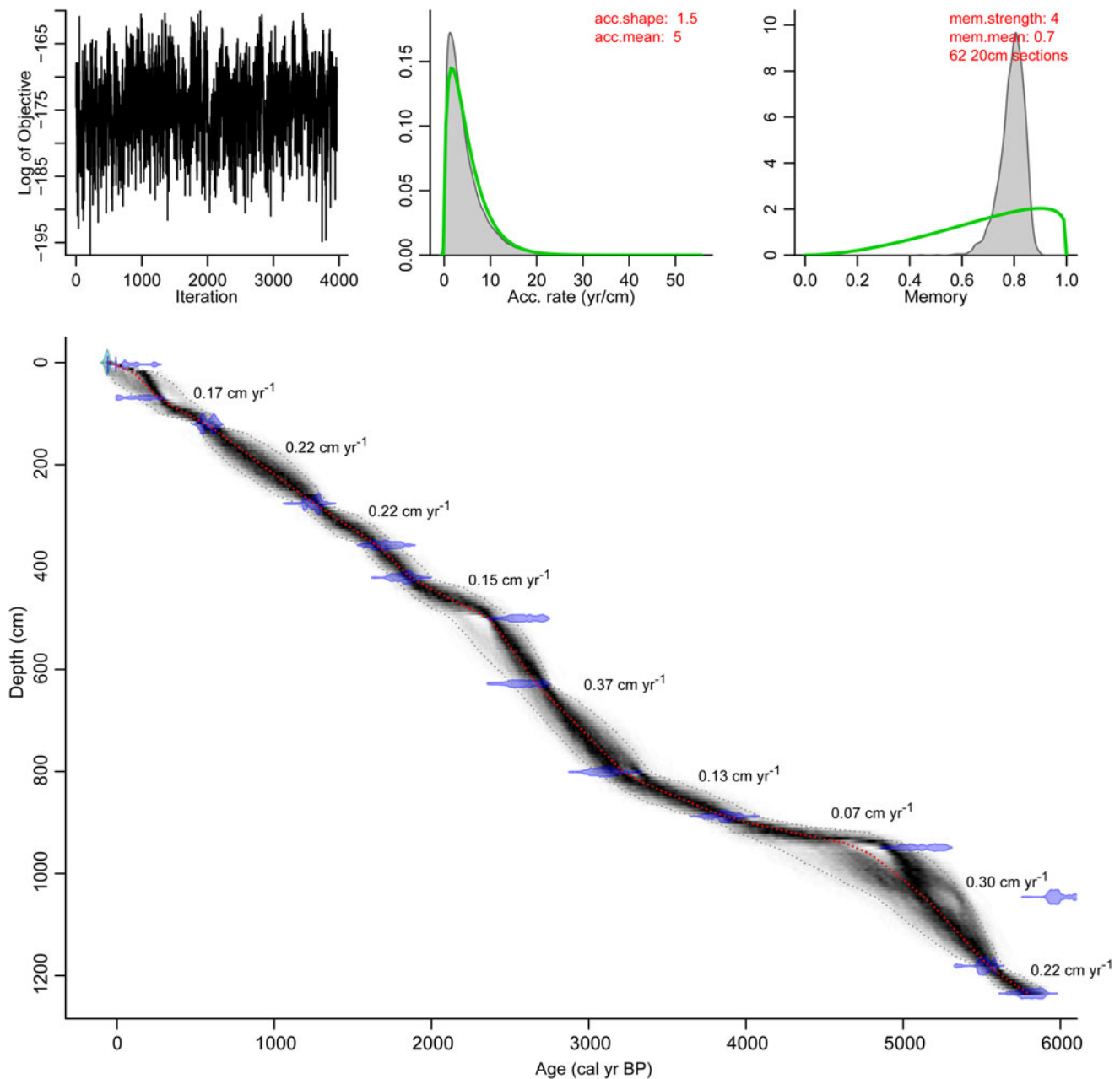
Figure 3. Age model for Lower Pahranagat Lake composite core record based on Bayesian modeling of data from Table 1. Red dotted line indicates the best fit. Blue bars represent calibrated radiocarbon ages with 2-sigma error. The darkened area indicates the 95% confidence interval. The default Bacon model parameters were used in all cases except for one of the accumulation rate parameters ("acc. mean"), which was changed to 5, and the section thickness parameter, which was changed to "res = 20." The average sedimentation rate between radiocarbon ages is indicated, except for intervals with overlapping dates. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

from LPAH have organic C/N values ranging from 46.6 to 142, submerged aquatic plants have values ranging from 14.6 to 29.1, and modern algae values are 5.99 to 6.96. Down-core C/N values range widely from 12.2 to 98.2 (Fig. 5). Values are generally higher (median = 33.2) and largely reflect a mixture of terrestrial and submerged aquatics between the oldest part of the record and 4950 cal yr BP. Between 4900 and 3400 cal yr BP, values are lower (median = 11.8) and reflect a mixture of submerged aquatic plants and

algal sources of organic matter. Values again rise (median = 24.8) to reflect mainly submerged aquatic sources with some terrestrial input between 3400 and 1700 cal yr BP. The most recent 1700 yr of the record indicates consistent low values (median = 9.3) and a mixture of algal and submerged aquatic sources. TIC concentrations are high throughout the record and are especially so (up to 10.9%) between 5450 and 4900 cal yr BP. Variation in TIC values is generally in phase with the stable isotopic data discussed previously (Fig. 5).
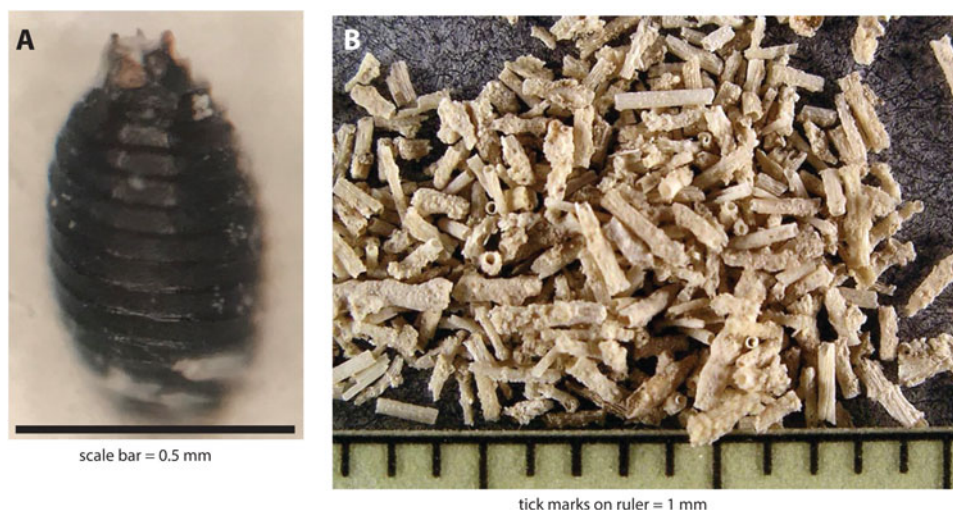
Figure 4. (color online) Evidence of the aquatic plant *Chara* spp., which is found extensively throughout the Lower Pahranagat Lake core record. (A) Close-up photograph of an individual fossil gyrogonite from core sediments. (B) Photograph of calcite-encrusted plant stems.

DISCUSSION

Paleohydroclimate overview

The LPAH record suggests that a shallow lake or wetland has continuously existed (or nearly so) in this area since 5800 cal yr BP. The earliest part of the LPAH record (~5800–5700 cal yr BP) is represented by the uppermost portion of the siliciclastic clay unit with diatom microfossils, representing the existence of a shallow lake. The absence of carbonate suggests that surface runoff from adjacent alluvial fans may have dominated sedimentation and, hence, water supply to
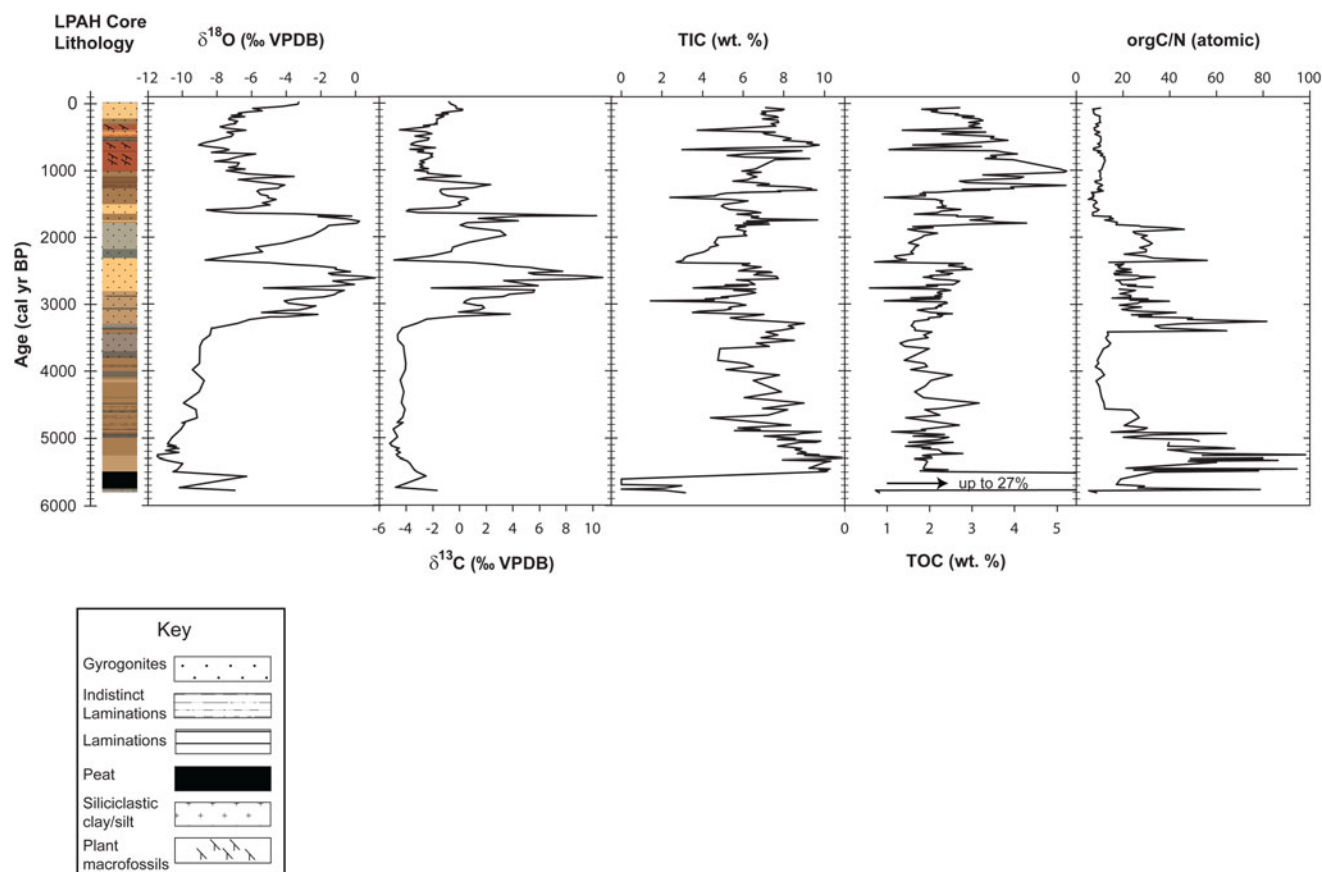

Figure 5. (color online) Stable isotopic and elemental results for the Lower Pahranagat Lake (LPAH) composite core record. Core lithology is shown near the age (left) axis. TIC, total inorganic carbon; TOC, total organic carbon; VPDB, Vienna Pee Dee belemnite.

the lake. The clay unit lies in sharp contact with the overlying peat layer, suggesting that LPAH water level dropped abruptly after ~5700 cal yr BP.

What might account for this abrupt depositional change? One possibility is the onset of drought conditions. The LPAH record shows a sharp and brief rise to a higher $\delta^{18}O$ value near this time, but this is only a single value (little available carbonate in the peat unit), and that value (−6.30‰) at 5564 cal yr BP and in the upper 10 cm of the peat unit is still relatively low for the record overall (Fig. 5). There is little evidence for a trend toward drought elsewhere in the region at this time. The high-resolution speleothem record from nearby Leviathan Cave suggests an important step toward wetter rather than drier conditions at this time, with a trend toward lower $\delta^{13}C$ values and an increase in cave drip rates (Lachniet et al., 2014). Other regional records show relatively muted hydroclimatic responses during this time period (Fig. 6).

We speculate that there may be a nonclimatic reason for this change. One possibility is the movement of alluvial fans that are adjacent to LPAH. Fan surfaces near both the northern and southern ends of the lake show evidence of being relatively young with few incised channels. Perhaps one or more fan lobes near the lake or farther north moved or were breached, with a resulting change in the hydrology of the valley. A second possibility is that tectonic activity might have modified the topography and surface hydrology of LPAH. The Pahranagat Valley is cut by a series of east–northeast trending left-lateral strike-slip faults that include the Buckthorn Fault just to the north of LPAH and the Maynard Lake Fault (MLF) just to the south of the lake. Recent geophysical work has indicated that this Pahranagat Shear Zone (PSZ) accommodates up to 1.8 mm/yr of east–west basin and range extension (Kreemer et al., 2010). Quaternary fault scarps have been mapped in the PSZ including at least one along the MLF (Muhammad, 2016). Perhaps fault movement along the MLF resulted in the destruction or modification of a sill at the south end of LPAH, abruptly shifting the depocenter farther south and into Maynard Lake after 5700 cal yr BP. However, there is no direct, dated evidence of mid- to late Holocene activity on these faults (Taylor, W., personal communication, 2018).

Deposition of the 50-cm-thick peat layer indicates a shallow water table to support a marsh that may have periodically desiccated. Stable isotopic values for this earliest part of the record are moderate to low. The drop to low stable isotopic values at ~5500 cal yr BP and the sharp depositional change from peat to carbonate mud signal a transition from a peatland/marsh to an alkaline shallow lake. High organic C/N values at this time suggest that terrestrial plants were the dominant organic input at this time. As the lake continued to fill and expand, organic C/N values dropped, indicating decreasing terrestrial inputs and increasing in-lake sources of organic matter. For the period between 5500 and 3350 cal yr BP, stable isotopic values are at their lowest in the entire record, suggesting generally wetter and/or less evaporative conditions in the Pahranagat Valley.

Between ~3150 and 2600 cal yr BP, a distinct multicentury period is indicated by a sharp rise to the highest $\delta^{18}O$ and

$\delta^{13}C$ values in the LPAH record (Fig. 5). Viewed purely as an indicator of paleohydroclimate, the anomalous isotopic enrichments of approximately +10‰ for $\delta^{18}O$ and +14‰ for $\delta^{13}C$ during the transition into this period suggest that unusually dry and evaporative conditions were affecting the area at this time. This period is also indicated by a distinct rise in organic C/N values and a less pronounced rise in TOC, as lake margins neared our coring site in the desiccating lake. Within the longer period of drought, a century-scale interval centered on 2350 cal yr BP shows low TOC values, higher organic CN, low TIC, and low stable isotopic values. Smear slides from this interval show a high proportion of clastic materials with unusually coarse grain sizes (up to fine-grained sand size) and magnetic susceptibility reaching anomalously high values for the record. All of this can be explained by increased input of terrestrial materials during a wetter interval. This wet period was followed by a second multicentury dry period, centered on 1750 cal yr BP, with nearly the same level of isotopic enrichment as the earlier dry episode. There is also some evidence of a century-scale wet interval from 2800 to 2700 cal yr BP. This is most clearly seen in a well-defined drop in TIC but is also indicated by a sharp drop in stable isotopic values. After 1700 cal yr BP, stable isotopic values drop sharply to lower levels before a more gradual drop in values starting at ~1500 and reaching a minimum at about 600 cal yr BP. Multidecadal- to century-scale wet periods at 1600 and 600 cal yr BP are indicated by sharp drops in stable isotopic and TIC values. The most recent 400–500 yr of the record show a trend toward increasing aridity as indicated by rising stable isotopic values and high TIC values.

Comparison with other Great Basin records

The deposition of siliciclastic clay and peat, accompanied by relatively lower stable isotopic values, suggests relatively humid or wetter conditions in the latter part of the middle Holocene in the Pahranagat Valley, followed by the filling of a shallow, alkaline lake after ~5500 cal yr BP. The timing of increasingly wet conditions at LPAH is consistent with evidence from around the Great Basin. In the western Great Basin, pollen evidence from Pyramid Lake suggests rising lake level and somewhat wetter conditions starting at ~6300 cal yr BP with evidence for clearly wetter conditions and the end of middle Holocene aridity at ~5000 cal yr BP (Mensing et al., 2004). In the central Great Basin north of LPAH, pollen and elemental evidence imply that Stonehouse Meadow was well established and may have even had standing water from 7300 to 3000 cal yr BP (Mensing et al. 2013). Closer to LPAH, the speleothem record from Leviathan Cave suggests that generally wetter conditions started at ~5000 cal yr BP (Lachniet et al., 2014). In contrast, farther to the south in the Las Vegas Valley, the absence of black mats indicates that this area remained relatively dry following the last clear wet period near the end of the Younger Dryas interval (Springer et al., 2015).

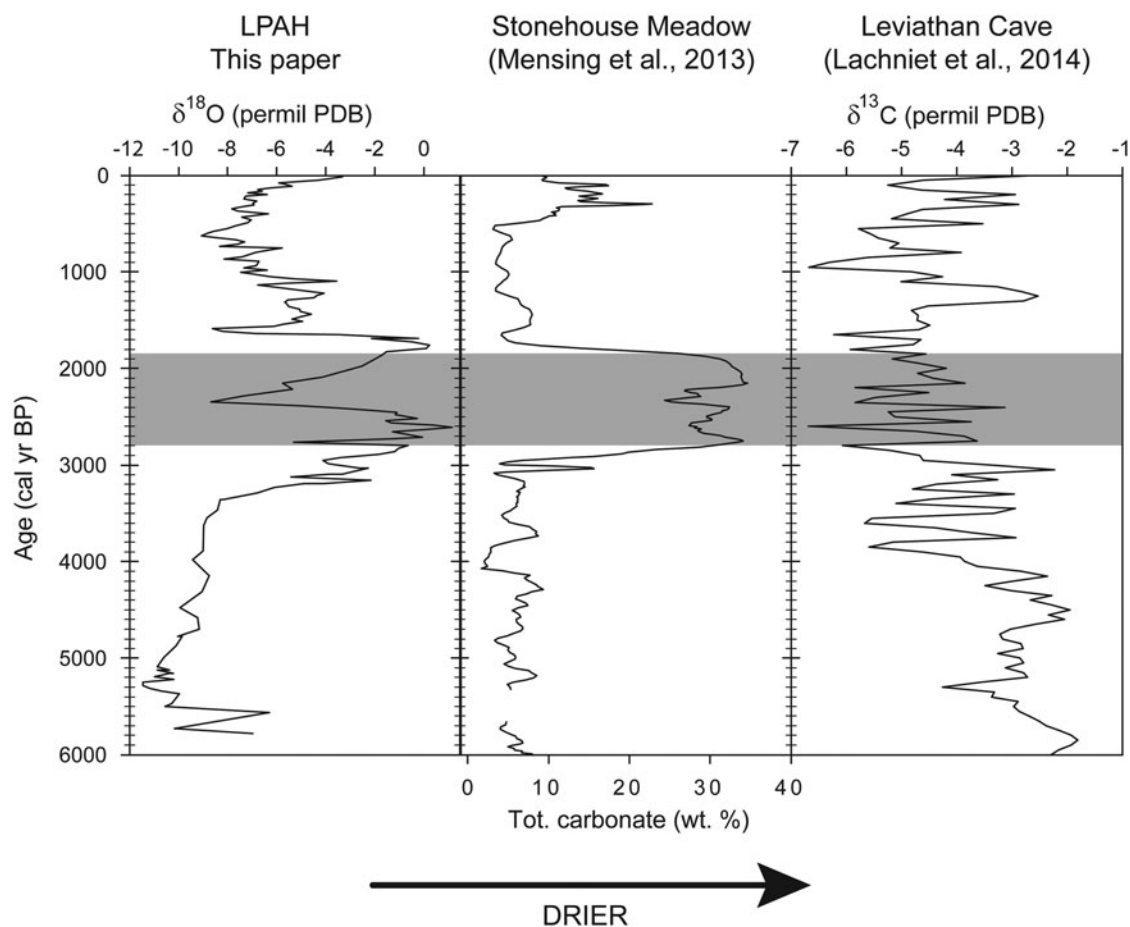The two distinct multicentury-scale dry periods between 3150 and 1700 cal yr BP at LPAH are significant in terms

Figure 6. Comparison of the Lower Pahranagat Lake (LPAH) $\delta^{18}O$ record with paleohydroclimate indicators from the southern and central Great Basin for the mid-Holocene to recent. Total carbonate from Stonehouse Meadow (Mensing et al., 2013) and $\delta^{13}C$ values from Leviathan Cave deposits (Lachniet et al., 2014). The gray area indicates the timing of the late Holocene dry period as proposed by Mensing et al. (2013). PDB, Pee Dee belemnite.

of their magnitude and duration. This is consistent with the pollen-based record from LPAH (fig. 18 in Wigand and Rhode, 2002), which generally indicates drier than current conditions over much of this interval. The pollen record shows three multidecadal- to century-scale wet periods (centered on 2700, 2300, and 2000 cal yr BP) over this time. Our record shows strong evidence of the 2300 cal yr BP event and some evidence for the 2700 cal yr BP event in a brief, sharp drop to lower stable isotopic and a more fully developed drop in TIC values. We expect some difference between the two records because of sampling resolution with the pollen record having an average sampling resolution (~14 yr) that ranges from 1.5 to 3 times higher than the sampling resolution for our elemental and stable isotopic analyses. The 3150–1700 cal yr BP interval encompasses an extended period of drought noted for the Great Basin that was termed the LHDP by Mensing et al. (2013). Tausch et al. (2004) reported evidence of a "post-Neoglacial drought" between 2600 and 1600 cal yr BP based on packrat midden and pollen records collected from the Toyiabe Range of the central Great Basin. Mensing et al. (2006) found evidence of aridity over much of this interval in a sediment record from Newark Valley Pond. More

recently, Mensing et al. (2013) reported their evidence for dry conditions spanning 2800–1850 cal yr BP at Stonehouse Meadow in the central Great Basin. These authors also gave a thorough review of the evidence for the LHDP at a number of additional sites across the central and southern Great Basin, including (1) Homestead Cave in the east central Great Basin; (2) Pyramid, Walker, and Mono Lakes in the west-central Great Basin; and (3) the Las Vegas Valley in the southern Great Basin (see figs. 7 and 8 in Mensing et al., 2013).

Overall, there appears to be a compelling similarity between the paleohydroclimatic trends revealed in the LPAH stable isotopic and some of the central Great Basin sites, especially the Stonehouse Meadow record of the past 6000 cal yr (Fig. 6). Comparison of these two records suggests that dry conditions began a few centuries earlier at LPAH than at the Stonehouse Meadow location, but given the uncertainty in the radiocarbon chronologies of these records, the timing may have been more or less synchronous. This indicates a consistent atmospheric forcing of evaporation both at LPAH and to the north in the central Great Basin. In contrast, the Leviathan Cave speleothem record, located

closer to LPAH than any of the central Great Basin sites, shows general correspondence with the LPAH record for some intervals, but little evidence for drought during the LHDP, instead indicating increased growth of cave deposits and a shift to relatively wetter conditions during that time (Fig. 6). We think the important differences between these two records are explained by the different spatial and seasonal signals that are being recorded by the two archives. The LPAH water balance is strongly influenced by input from a regional aquifer with a large recharge area and near constant spring discharge throughout the year (Fig. 1A), whereas the Leviathan Cave deposits are not connected to or influenced by a regional aquifer and are instead recording only water infiltration from directly above the cave site. Evaporation clearly has a significant influence on water balance at LPAH as well. Carbonate production and stable isotopic values are strongly influenced by evaporative enrichment, following a distinct trend line for Pahranagat Valley surface water and groundwater that deviates sharply from the southern Nevada meteoric water line (Fig. 2). This $\delta^{18}O$ enrichment peaks in the late summer and early fall months. In contrast, Leviathan Cave speleothem stable isotopic values are not influenced by evaporation, and $\delta^{18}O$ values fall directly on the southern Nevada meteoric water line. Given these differing influences, one possibility is that the LPAH record was strongly affected by extreme summer evaporation during the LHDP, whereas the winter-sensitive record from Leviathan may not have registered the enhanced summer season dry conditions.

The LPAH record indicates several century-scale oscillations in hydroclimate over the last 2500 cal yr BP as well. Evidence for multidecadal- to century-scale drought has been found in paleohydroclimate records across the Great Basin (e.g., Stine, 1994; Benson et al., 2002). The pronounced century-scale wet interval centered on 2350 cal yr BP in the LPAH record is consistent and synchronous with events indicated in the LPAH pollen record (Wigand and Rhode, 2002) and with evidence from the Leviathan Cave isotopic data and the Stonehouse Meadow carbonate data (Fig. 6). Drought intervals centered on 1750 and 1200 cal yr BP in the LPAH record correspond to lake level declines at Mono and Pyramid Lakes (Stine, 1990, 1994; Benson et al., 2002) and at Kingston Meadow (Mensing et al., 2008). However, in contrast with many Great Basin records, LPAH data indicate little evidence of notable aridity during dry intervals associated with the MCA (930–780 cal yr BP). This may simply be a matter of insufficient sampling or chronological resolution in the LPAH record. However, the higher-resolution record from Leviathan Cave also shows little evidence for aridity during the MCA (Fig. 6), suggesting hydroclimate variability across the west. A wet interval centered on 600 cal yr BP in the LPAH record falls at the earliest part of the Little Ice Age. The record from LPAH suggests a trend toward drier conditions over the last ~500 cal yr. The record from nearby Leviathan Cave shows evidence of this trend toward drier conditions as well. The most recent century of this trend is at least in part because of human controls on the distribution of the Pahranagat Valley water supply, which have diverted and impounded some of the water that would have naturally flowed into LPAH and thereby reducing its volume.

Regional paleohydroclimate forcings

Across the southern and central Great Basin, there is evidence of the influence of the Pacific Ocean over interannual to multidecadal timescales. Historical data on precipitation in the Pahranagat Valley show that above-average precipitation occurred during many El Niño–Southern Oscillation (ENSO) positive phase (El Niño) years (Western Regional Climate Center, https://wrcc.dri.edu/ [accessed October 15, 2017]). This correspondence is consistent with the findings of Hevesi et al. (2003) for a broader set of watersheds within the southern and central Great Basin. These authors also note good correspondence with the Pacific Decadal Oscillation (PDO), a multidecadal phenomenon associated with North Pacific Ocean sea surface temperatures, with above-average precipitation during the positive phase of the PDO and below-average precipitation during the cool phase. Just as modern Great Basin hydroclimate variability is influenced by conditions in the Pacific Ocean, a number of previous investigations have shown evidence that this likely holds true over the century- and millennial-scale time periods discussed in this article as well. Barron and Anderson (2011) reported that numerous proxy records from the northeastern Pacific indicate a more La Niña–like condition during the dry middle Holocene (8000–4000 cal yr BP) than in the relatively wetter late Holocene. Mensing et al. (2013) reviewed evidence of a north–south dipole for sites influenced by ENSO, with a boundary zone near 40–42°N for the Great Basin. During the LHDP, sites south (north) of this zone, which includes the central and southern Great Basin, show evidence for dry (wet) conditions. Overall, we are confident that the climatic forcings affecting the recharge area of the regional aquifer are the dominant control on the water balance in the Pahranagat Valley and likely exhibit similar controls on neighboring north-to-south-oriented valleys in the central to southern Great Basin.

Our findings of multiple century- to millennial-scale episodes of past drought are consistent with a large and growing body of paleohydroclimate research across the Great Basin. Given the apparent frequency of these events in the past, and the potential impacts of climate change on hydroclimate in the Southwest and across North America, we should expect and be prepared for more dry conditions (Cook et al., 2014).

CONCLUSIONS

We found evidence that LPAH has existed continuously, or nearly so, as a shallow lake, wetland, or marsh for at least the past 5800 cal yr. Our data show evidence of distinct millennial trends over the later part of the middle Holocene and into the late Holocene. The data indicate the establishment of a shallow, alkaline lake after ~5500 cal yr BP and relatively wet conditions until ~3350 cal yr BP. From 3150 to 1700 cal

yr BP, our data show evidence for a period dominated by drought with maximum aridity at ~2600 cal yr BP. This drought is consistent with the LHDP described by Mensing et al. (2013). Our results suggest that this was the most significant drought affecting the Pahranagat region over the period of record, though the absence of a record prior to ~5800 cal yr BP indicates the possibility for even drier conditions during the middle Holocene. The results also provide evidence that this millennial-scale drought had impacts farther to the south than have previously been recognized. We also note several century-scale climate episodes in the LPAH record. Most importantly, this includes drought intervals centered on 1750 and 1200 cal yr BP and wet intervals centered on 2350 and 600 cal yr BP. The past few centuries indicate progressively drier conditions.

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REFERENCES

Barron, J.A., Anderson, L., 2011. Enhanced Late Holocene ENSO/PDO expression along the margins of the eastern North Pacific. *Quaternary International* 235, 3–12.

Benson, L., Kashgarian, M., Rye, R., Lund, S., Paillet, F., Smoot, J., Kester, C., Mensing, S., Meko, D., Lindström, S., 2002. Holocene multidecadal and multicentennial droughts affecting Northern California and Nevada. *Quaternary Science Reviews* 21, 659–682.

Blaauw, M., Christeny, J.A., 2011. Flexible paleoclimate age-depth models using an autoregressive gamma process. *Bayesian Analysis* 6, 457–474.

Cook, B.I., Smerdon, J.E., Seager, R., Cook, E.R., 2014. Pancontinental droughts in North America over the last millennium. *Journal of Climate* 27, 383–397.

Deines, P., 1980. The isotopic composition of reduced organic carbon. In: Fritz, P., Fontes, J.C. (Eds.), *Handbook of Environmental Isotope Geochemistry*, Vol 1. Elsevier, New York, pp. 329–406.

Eakin, T.E., 1963. Ground-Water Appraisal of Pahranagat and Pahroc Valleys, Lincoln and Nye Counties, Nevada. Ground-Water Resources – Reconnaissance Series Report 21. Nevada Department of Conservation and Natural Resources, Carson City, NV.

Eakin, T.E., 1966. A regional interbasin groundwater system in the White River area, southeastern Nevada. *Water Resources Research* 2, 251–271.

Grayson, D.K., 2011. The Great Basin: *A Natural Prehistory*. University of California Press, Berkeley.

Heiri, O., Lotter, A.F., Lemcke, G., 2001. Loss on ignition as a method for estimating organic and carbonate content in sediments: reproducibility and comparability of results. *Journal of Paleolimnology* 25, 101–110.

Hevesi, J.A., Flint, A.L., Flint, L.E., 2003. Simulation of Net Infiltration and Potential Recharge Using a Distributed-Parameter Watershed Model of the Death Valley Region, Nevada and California. Water Resources Investigations Report 03-4090. U.S. Geological Survey, Sacramento, CA.

Hickson, T.A., Theissen, K.M., Lamb, M.A., Frahm, J., 2018. Lower Pahranagat Lake: modern analogue for extensive carbonate deposition in paleolakes of the Late Oligocene to Miocene Rainbow Gardens and Horse Spring Formations. *Journal of Paleolimnology* 59, 39–57.

Horton, T.W., Defliese, W.F., Tripati, A.K., Oze, C., 2016. Evaporation induced ^{18}O and ^{13}C enrichment in lake systems: a global perspective on hydrologic balance effects. *Quaternary Science Reviews* 131B, 365–379.

Hutchinson, G.E., 1975. A Treatise of Limnology. *Vol. 3, Limnological Botany*. John Wiley and Sons, New York.

Kreemer, C., Blewitt, G., Hammond, W.C., 2010. Evidence for an active shear zone in southern Nevada linking the Wasatch fault to the Eastern California shear zone. *Geology* 38, 475–478.

Lachniet, M.S., Denniston, R.F., Asmerom, Y., Polyak, V.J., 2014. Orbital control of western North America atmospheric circulation and climate over two glacial cycles. *Nature Communications* 5, 3805.

Mensing, S., Livingston Reno, S., Barker, N.P., 2006. Long-term fire history in Great Basin sagebrush reconstructed from macroscopic charcoal in spring sediments, Newark Valley, Nevada. *Western North American Naturalist* 66, 64–77.

Mensing, S., Smith, J., Norman, K.B., Allan, M., 2008. Extended drought in the Great Basin of western North America in the last two millennia reconstructed from pollen records. *Quaternary International* 188, 79–89.

Mensing, S.A., Benson, L. V., Kashgarian, M., Lund, S., 2004. A Holocene pollen record of persistent droughts from Pyramid Lake, Nevada, USA. *Quaternary Research* 62, 29–38.

Mensing, S.A., Sharpe, S.E., Tunno, I., Sada, D.W., Thomas, J.M., Starratt, S., Smith, J., 2013. The Late Holocene Dry Period: Multiproxy evidence for an extended drought between 2800 and 1850 cal yr BP across the central Great Basin, USA. *Quaternary Science Reviews* 78, 266–282.

Muhammad, M.M., 2016. Structural Evolution of the Maynard Lake Fault within the Left-Lateral Pahranagat Shear Zone, Nevada USA. *Master's thesis*, University of Nevada, Las Vegas.

Paces, J.B., Wurster, F.C., 2014. Natural uranium and strontium isotope tracers of water sources and surface water–groundwater interactions in arid wetlands – Pahranagat Valley, Nevada, USA. *Journal of Hydrology* 517, 213–225.

Phillips, S.C., Johnson, J.E., Miranda, E., Disenhof, C., 2011. Improving CHN measurements in carbonate-rich marine sediments. *Limnology and Oceanography Methods* 9, 194–203.

Quade, J., Forester, R.M., Pratt, W.L., Carter, C., 1998. Black mats, spring-fed streams, and late-glacial-age recharge in the southern Great Basin. *Quaternary Research* 49, 129–148.

Reimer, P.J., Bard, E., Bayliss, A., Beck, J.W., Blackwell, P.G., Ramsey, C.B., Buck, C.E., *et al.*, 2013. IntCal13 and Marine13 radiocarbon age calibration curves 0–50,000 years cal BP. *Radiocarbon* 55, 1869–1887.

Reinemann, S.A., Porinchu, D.F., Bloom, A.M., Mark, B.G., Box, J.E., 2009. A multi-proxy paleolimnological reconstruction of Holocene climate conditions in the Great Basin, United States. *Quaternary Research* 72, 347–358.

Salzer, M.W., Bunn, A.G., Graham, N.E., Hughes, M.K., 2014. Five millennia of paleotemperature from tree-rings in the Great Basin, USA. *Climate Dynamics* 42, 1517–1526.

Springer, K.B., Manker, C.R., Pigati, J.S., 2015. Dynamic response of desert wetlands to abrupt climate change. *Proceedings of the National Academy of Sciences of the United States of America* 112, 14522–14526.

Stine, S., 1990. Late Holocene fluctuations of Mono Lake, eastern California. *Palaeogeography, Palaeoclimatology, Palaeoecology* 78, 333–381.

Stine, S., 1994. Extreme and persistent drought in California and Patagonia during mediaeval time. *Nature* 369, 546–549.

Talbot, M.R., 1990. A review of the palaeohydrological interpretation of carbon and oxygen isotopic ratios in primary lacustrine carbonates. *Chemical Geology: Isotope Geoscience section* 80, 261–279.

Tausch, R., Nowak, C., Mensing, S., 2004. Climate change and associated vegetation dynamics during the Holocene: the paleoecological record. In: Chambers, J.C., Miller, J.R. (Eds.), *Great Basin Riparian Ecosystems: Ecology, Management and Restoration*. Island Press, Covelo, CA, pp. 24–28.

Tyler, S.W., Chapman, J.B., Conrad, S.H., Hammermeister, D.P., Blout, D.O., Miller, J.J., Sully, M.J., Ginanni, J.M., 1996. Soil-water flux in the southern Great Basin, United States: temporal and spatial variations over the last 120,000 years. *Water Resources Research* 32, 1481–1499.

Verardo, D.J., Froelich, P.N., McIntyre, A., 1990. Determination of organic carbon and nitrogen in marine sediments using the Carlo Erba NA-1500 analyzer. *Deep Sea Research Part A: Oceanographic Research Papers* 37, 157–165.

Wigand, P.E., 1996. A Late-Holocene pollen record from Lower Pahranagat Lake, southern Nevada, USA: high resolution paleoclimatic records and analysis of environmental responses to climate change. In: *Proceedings of the Thirteenth Annual Pacific Climate (PACLIM) Workshop*. Interagency Ecological Program for the Sacramento–San Joaquin Estuary, Sacramento, CA, pp. 63–77.

Wigand, P.E., Rhode, D., 2002. Great Basin vegetation history and aquatic systems: the last 150,000 years. In: Hershler, R., Madsen, D.B., Currey, D.R. (Eds.), *Great Basin Aquatic Systems History*. Smithsonian Contributions to the Earth Sciences 33. Smithsonian Institution Press, Washington, DC, pp. 309–367.

Wurster, F.C., 2010. *Pahranagat National Wildlife Refuge Hydrologic Analysis Report*. U.S. Fish and Wildlife Service, Sacramento, CA.