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Late Pleistocene to early Holocene lake level and paleoclimate insights from Stansbury Island, Bonneville basin, Utah

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ABSTRACT

This paper reports on recent multiproxy research conducted to determine the chronology of lake-level fluctuations recorded in sediments from a natural exposure at a classic Bonneville basin site. Grain size, carbonate percentage, magnetic susceptibility, amount of charcoal, and diatom community composition data were collected from the 16 lacustrine units that compose the 122 cm stratigraphic column in Stansbury Gulch. Trends observed in the measured proxies reveal several significant changes in lake level, and thereby effective moisture, over the approximately 14,500 yr time span represented by the sediments. Results (1) verify the effectiveness of the multiproxy approach in Bonneville basin studies, which has been underutilized in this region, (2) reaffirm the double nature of Lake Bonneville's Stansbury oscillation, (3) suggest a previously undocumented post-Gilbert highstand of Great Salt Lake, and (4) identify possible teleconnections between climate events in the Bonneville basin and events in the North Atlantic at about 20,500 and 7500 ^{14}C yr BP.

Introduction and objective

The Bonneville lake basin of northwestern Utah, northeastern Nevada, and southeastern Idaho has been recognized as an important source of paleoenvironmental data for more than 135 yr because of widespread sedimentary and geomorphic evidence of late Pleistocene Lake Bonneville and its Holocene successor, Great Salt Lake (Sack, 1989) (Fig. 1). With a maximum depth of 372 m and area of 50,000 km^2 (Gilbert, 1890), Lake Bonneville was the largest of the scores of paleolakes that existed and fluctuated in subbasins of the Great Basin from about 30,000 to 12,000 ^{14}C yr BP. Because it was a closed-basin lake for most of its existence, Lake Bonneville responded sensitively to climate change through oscillations in water level and area, as has Great Salt Lake (e.g., Benson and Paillet, 1989; Currey, 1990; Oviatt et al., 1992). A thorough understanding of the record of climate change stored in the sediments of Lake Bonneville and Great Salt Lake is essential for accurately reconstructing the regional paleoenvironment and for predicting how Great Salt Lake and other large, climatically sensitive lake systems will be affected by future climate change.

The general chronology of Lake Bonneville and Great Salt Lake is well established (Fig. 2). According to previous work, Lake Bonneville originated sometime after 30,000 ^{14}C yr BP (Oviatt et al., 1992). Between 28,000 and 14,000 ^{14}C yr BP it underwent its protracted, transgressive phase, which was punctuated by at least a few comparatively low-amplitude oscillations (Currey and Oviatt, 1985; Oviatt, 1997; Sack, 1999). One of these, the Stansbury oscillation, with an amplitude of perhaps 45 m, occurred between about 22,000 and 20,000 ^{14}C yr BP and helped to create the Stansbury shoreline at an elevation of about 1370 m (Currey, 1980; Oviatt, 1997). The transgressive phase of Lake Bonneville culminated between 15,000 and 14,500 ^{14}C yr BP when the lake achieved open-basin conditions at 1552 m and constructed its highest shoreline, called the Bonneville shoreline (Gilbert, 1890; Oviatt et al., 1992). Failure at the lake's outlet about 14,500 ^{14}C yr BP instigated the Bonneville flood, which lowered the water level to the threshold-controlled Provo shoreline at 1444 m (Gilbert, 1890; Malde, 1968; Burr and Currey, 1988; Oviatt et al., 1992). Lake Bonneville regressed rapidly from the Provo shoreline, returning to closed-basin conditions beginning about 14,000 ^{14}C yr BP. By the end of the Bonneville lacustral cycle at 12,000 ^{14}C yr BP, the lake had fallen to very low levels, probably below 1280 m, which is the modern average elevation of Great Salt Lake (Oviatt et al., 1992). Great Salt Lake formed subsequently and rose to the Gilbert level at 1294 m between about 10,900 and 10,300 ^{14}C yr BP (Benson et al., 1992). It is believed to have remained well below that elevation since that time.

Most of the research that has been conducted on the oscillations of Lake Bonneville and Great Salt Lake has been undertaken to

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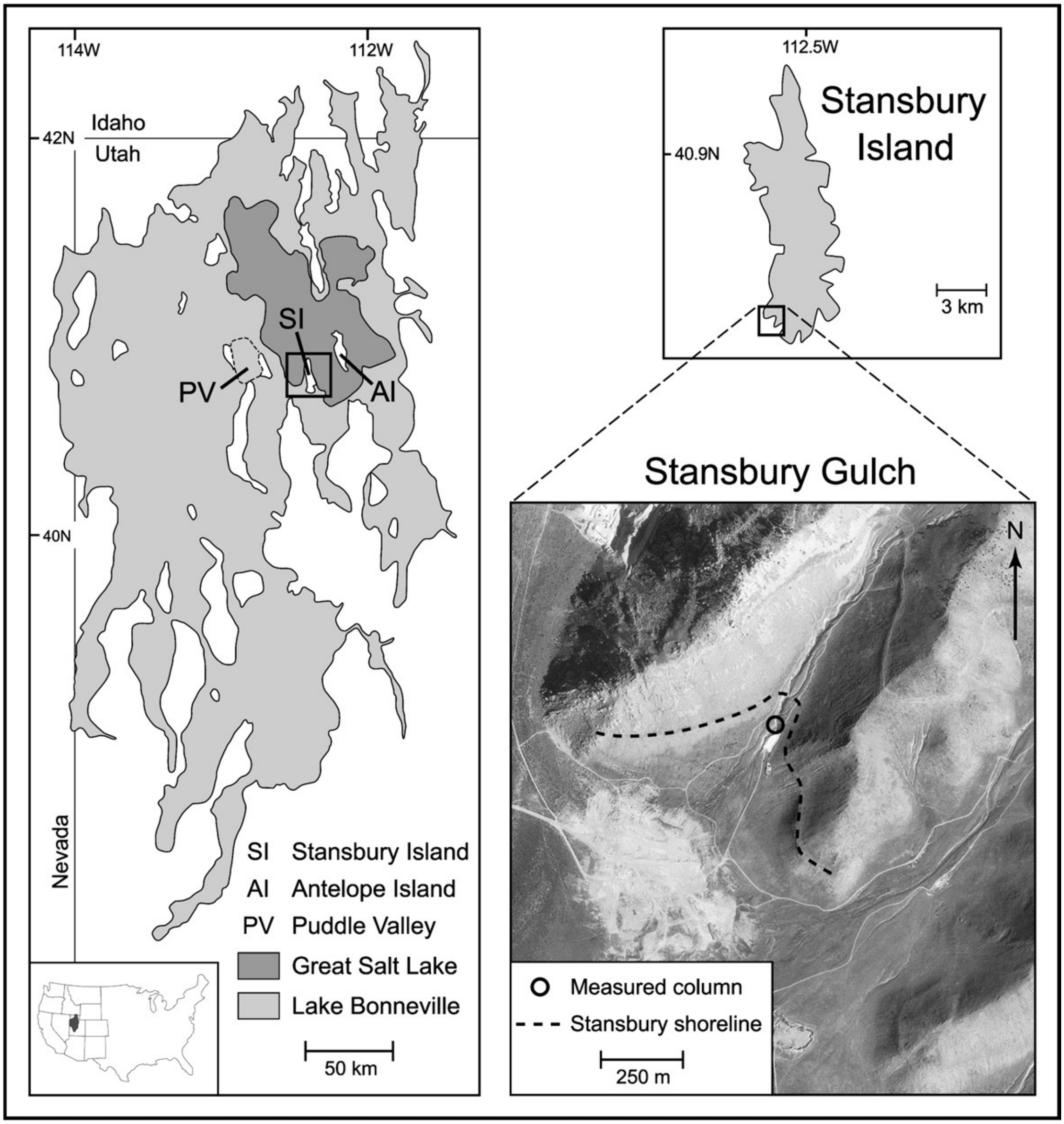


Figure 1. Location of sites mentioned in the text in relation to Great Salt Lake and late Pleistocene Lake Bonneville at its maximum extent. Aerial imagery is from the USGS Corral Canyon, UT, 7.5-min orthophotoquad.

contribute to paleoclimate reconstruction. Fluctuations of the two lakes have been used along with paleoclimate evidence from nonlacustrine sources to help reconstruct regional patterns of effective moisture for the late Pleistocene and Holocene (e.g., Madsen et al., 2001). Regional paleoclimatic inferences drawn from the lacustrine evidence, however, have not always agreed with paleoclimatic data derived from other sources (Rhode and Madsen, 1995). These problems should diminish as continued refinements in the use of lacustrine-based paleoenvironmental proxies provide the means to evaluate the lacustrine record more thoroughly. One refinement in paleolake studies is the increasing use of combinations of multiple proxies to glean the maximum amount of information on water-level and paleoclimate fluctuations from the lacustrine sediment record (e.g., Holmes et al., 1999; Peck et al., 2002; Mayr et al., 2005). In the Bonneville lake basin, a multiple-proxy approach has previously been employed investigating sediments derived from Bonneville lake-basin cores (Spencer et al., 1984; Oviatt et al., 1994). A truly multiproxy approach employing a range of data sources, from grain size, carbonate content, and magnetic susceptibility to charcoal concentration and diatom communities, however, has not previously been undertaken at a natural stratigraphic exposure in the Bonneville basin. This paper reports on recent multiproxy research, combined with radiocarbon dating, conducted to determine the chronology of lake-level fluctuations recorded in sediments from a natural exposure at a classic Lake Bonneville site, the type locality of the Stansbury shoreline (Currey et al., 1983).

Stansbury Gulch study site

Stansbury Gulch is a large gully cutting through sediments at the south end of Stansbury Island, which is located on the southwestern margin of Great Salt Lake, Utah (Fig. 1). Stansbury Island consists of a ridge of Paleozoic bedrock with a variable cover of Quaternary sediments. Since European-American encroachment into the region in the early 1800s, the “island” has been connected to the mainland by mudflats except at infrequent highstands of Great Salt Lake. With a maximum elevation of 2025 m, a portion of Stansbury Island remained well above even the highest level of Lake Bonneville.

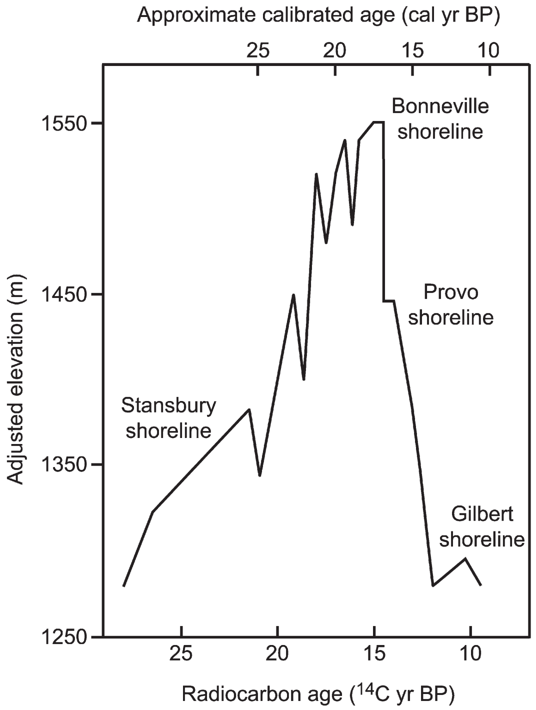


Figure 2. Generalized hydrograph of Lake Bonneville and Great Salt Lake (after Oviatt, 1997). Higher levels of Lake Bonneville are plotted at their approximate original elevations, obtained by correcting for differential postlake hydroisostatic rebound (Currey and Oviatt, 1985). Elevations of the major fluctuations between the Stansbury and Bonneville levels are schematic.

This study focuses on the 122 cm high, vertical sequence of lacustrine sediments exposed in the wall of Stansbury Gulch at 40°47.46′N, 112°31.05′W (Fig. 1). The top of the sediment column measured during this investigation lies at an elevation of 1360 m, which is approximately 8 m below the local elevation of the Stansbury shoreline (Currey et al., 1983). The minimum horizontal distance from the study site to the Stansbury shoreline is 53 m.

Significance

Stansbury Gulch was selected for this detailed investigation because of the significance and quality of the exposure of lacustrine sediments at this location. Gilbert (1890) first noted the potential importance of the Stansbury shoreline, which he named as one of the three principal shorelines of Lake Bonneville. He called it the Stansbury because of its strong development on Stansbury Island (Gilbert, 1890; Currey et al., 1983). Although Gilbert (1890, Fig. 34, p. 262) believed that the Stansbury shoreline represents a stillstand that occurred during Lake Bonneville's post-Provo regressive phase, rather than during the lake's transgression to the Bonneville shoreline, lingering questions about the possibility of an internal subbasin threshold control of the Stansbury caused him to characterize that shoreline as a “problem” (p. 187). Eardley et al. (1957) investigated the problematic lake level further, noting the occurrence of multiple minor stillstands above and below a single, dominant Stansbury shoreline that varies considerably in elevation around the basin. Eardley et al. (1957) concluded that the Stansbury water level was controlled by climatic factors and not by an internal Lake Bonneville subbasin threshold. Much later, Sack (1995) found evidence that Lake Bonneville spilled into its Puddle Valley subbasin (Fig. 1) at about the Stansbury level. Currey et al. (1983) were the first researchers to study the exposed lacustrine sediments at the location on Stansbury Island that they informally named Stansbury Gulch. They used stratigraphic evidence found in the gully walls to demonstrate that the Stansbury shoreline was formed during the transgressive, rather than the regressive, phase of Lake Bonneville (Currey et al., 1983; Green and Currey, 1988).

Despite more than a century of study, the Stansbury remains the most poorly understood of Lake Bonneville's three principal shorelines (Oviatt et al., 1990). Its present geomorphic expression is such that at some locations it is large, well defined, and easy to identify, while at other locations it is vague, nonexistent, or impossible to pick out with confidence among several weakly expressed shorelines (Gilbert, 1890; Eardley et al., 1957; Oviatt et al., 1990). Mapping problems are enhanced by local and regional neotectonism and spatially variable postlake obliteration (Sack, 1995). These processes have left laterally isolated preserved segments of the shoreline at various modern elevations. Evidence for the amplitude of the related Stansbury oscillation likewise varies significantly around the basin (Oviatt et al., 1990). This detailed, multiple-proxy investigation of the stratigraphic section at Stansbury Gulch, therefore, was undertaken to help resolve puzzling aspects of this important interval. Results validate the multiple-proxy approach, suggest new details about water-level and climate fluctuations in the Bonneville basin, and afford the opportunity to better resolve the teleconnections between climate events in the western U.S. and the North Atlantic.

Methods

Proxies used

Grain size, percent carbonate, magnetic susceptibility, macroscopic charcoal, and diatom characteristics were all quantified at the Stansbury Gulch stratigraphic column. Each of these variables provides information on environmental conditions related to climate.

In lacustrine sediments, the percentage of sand tends to decrease with increasing distance from the shoreline (Sarmiento and Kirby, 1962; Picard and High, 1981). Horizontal as well as vertical distance between Stansbury Gulch and the paleolake shoreline would have increased as the lake level rose above the site, thus grain size (i.e., percentage sand) is considered an indicator of lake-level variations. During times of greater effective precipitation when the lake level was higher and the zone of wave action was therefore farther from the study site, relatively smaller particles would have dropped out of suspension to accumulate at the studied section (Menking, 1997). During drier climatic conditions, falling lake levels shifted the high-energy zone of wave action lower and closer to Stansbury Gulch, delivering more coarse sediment to the site (Menking, 1997).

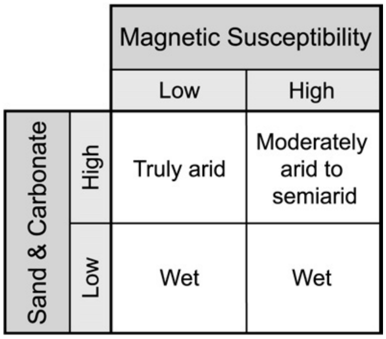
The percentage carbonate in closed-basin lacustrine sediment is a sensitive proxy of lake-level change (Bischoff et al., 1997) and is a useful indicator of temperature and humidity variations (Wetzel, 2001). The amount of autochthonous carbonate varies with lake productivity, which is related to temperature. As lake temperature increases, algal productivity increases, removing CO_2 from the water and favoring the carbonate form of dissolved inorganic carbon (Wetzel, 2001). As more water evaporates due to warmer and drier conditions, carbonates are concentrated in situ and precipitate more readily (Wetzel, 2001). An increase in percent carbonate in the lake sediments, therefore, indicates a lower lake level and a warmer and drier climate.

Magnetic susceptibility is commonly measured in stratigraphic studies of Quaternary lacustrine sediments (Sandgren and Snowball, 2001), yet thus far has been little utilized in the Bonneville basin. The susceptibility of sediments to magnetization increases with the amount of iron-bearing sediments present, and these are primarily transported into a closed-basin lake from allochthonous sources by surface runoff. Under the assumption of equal distribution of iron-bearing minerals in the drainage basin, comparatively higher values of magnetic susceptibility signal an increased input of terrestrial sediment into the lake (Zolitschka et al., 2001). Magnetic susceptibility, therefore, constitutes a proxy for sediment-charged surface runoff. Runoff and sediment yield are high in moderately arid to semiarid climates that have sufficient precipitation to produce substantial overland flow, but support only limited vegetation coverage (Langbein and Schumm, 1958). Sediment yield is typically lower in wetter climates because of the stabilizing effect of denser vegetative cover. Sediment yield is also low in more extreme arid climates because of insufficient runoff. Presence of a high percentage of carbonate with low magnetic susceptibility signals little runoff, as is the case of truly arid climates.

Fire episodes are inferred from fluctuations in macroscopic charcoal counts in lacustrine sediment (Long et al., 1998; Brunelle and Whitlock, 2003), and changes in fire regimes are linked to climate variations. Sediments with greater charcoal content reflect an increase in the number of fire episodes, which, in turn, point to an environment of decreased effective moisture and therefore lower lake level (Brunelle et al., 2005). A concentration of charcoal particles larger than 125 μm suggests nearby fires because charcoal particles are mechanically fragile and cannot remain this large if they travel far (Clark, 1988; Long et al., 1998; Brunelle and Whitlock, 2003).

Because various diatom species have different ecological requirements, the types of diatoms present in a sedimentary record constitute a useful indicator of the environmental conditions represented in the section (Smol, 1990). Climate fluctuations cause variations in lake level and lake chemistry that influence the species composition of the diatom community. Diatom community composition is affected by salinity, which increases in closed-basin lakes with decreasing lake level, and the salinity tolerances of lacustrine diatoms have been employed extensively to infer lake-level changes (Fritz et al., 1999). In closed-basin lakes, salinity is primarily controlled by the evaporation–precipitation ratio, although factors such as groundwater chemistry, surface water chemistry, and lake morphometry can also have an effect. In addition, poor preservation of diatoms signifies the high energy and saline environments of shallow and intermittently desiccated lakes (Flower, 1993; Bradbury, 1997).

In summary, in closed-basin lake sediments, like those from Stansbury Gulch, higher percentages of sand and carbonate, plus high values of magnetic susceptibility and a high concentration of charcoal, indicate drier periods with lower lake levels during which sufficient precipitation fell to cause significant surface runoff and terrestrial erosion. The same sediment evidence but with low magnetic susceptibility indicates a dry period of comparatively low lake level with insufficient precipitation to generate significant runoff, as would be the case in a truly arid climate regime. Conversely, sediments displaying low percentages of sand and carbonate and a low concentration of charcoal denote a high lake level and a wet climate regardless of magnetic susceptibility values (Fig. 3).



		Magnetic Susceptibility	
		Low	High
Sand & Carbonate	High	Truly arid	Moderately arid to semiarid
	Low	Wet	Wet

Figure 3. Climate signals represented by the different combinations of magnetic susceptibility values versus percentages of sand and carbonate. Lower percentages of sand and carbonate represent wetter conditions regardless of magnetic susceptibility values.

Data collection

Contiguous bulk sediment samples were collected throughout the 122 cm high, exposed stratigraphic column at Stansbury Gulch after scraping off the outer several centimeters to reveal the intact stratigraphy. Sediment samples were obtained from every distinct stratigraphic unit, as determined by visual assessment in the field. Samples were analyzed for percentage sand, percentage carbonate, magnetic susceptibility, amount of charcoal, diatom communities, and diatom preservation. Stratigraphic units are identified by their height above the base of the section, which is designated as 0 cm.

Laboratory procedures included standard hydrometer and loss-on-ignition techniques for determining percentage sand and percentage total carbonate, respectively. Magnetic susceptibility was measured with the Bartington MS2 magnetic susceptibility instrument.

Macroscopic charcoal was collected by washing sediments through nested sieves of mesh sizes 250 and 125 μm. Charcoal particles were counted under a stereomicroscope, and charcoal concentration (number of particles/cm^3) was calculated for each sample (Whitlock and Millspaugh, 1996).

Diatom analyses were conducted on 0.5 g of all units. At least 500 diatom valves were counted for each sample, and diatom preservation characteristics were noted. *Mastogloia elliptica*, an epiphytic diatom species common in hyposaline to mesosaline waters (3–50 g/L) (Cumming et al., 1995), was used as an indicator of more saline conditions resulting from lower lake levels.

Any material appropriate for AMS radiocarbon dating was collected from the column and submitted for analysis. One relevant numeric age from the study site is available from a previous investigation (Currey et al., 1983). Calendar dates of analyzed samples were calculated using the radiocarbon calibration program of Stuiver and Reimer (1993).

Graphical and statistical analyses

For purposes of describing relative values of the various proxies, a measurement derived from a given stratigraphic unit is classified as a "peak" if it exceeds the mean of that variable determined from all sampled units. An increase in the value of the proxy compared to that obtained from the underlying unit is termed a "semi-peak" if the value does not exceed the mean of that variable determined from all sampled units. Statistical tests of association between percentage sand, percentage carbonate, magnetic susceptibility, charcoal concentration, and percentage of *M. elliptica* were conducted with Spearman's correlation at the 0.05 level of significance. These tests were used to verify that the proxies used covary as outlined in the above description. In addition, a direction of change analysis was performed on the observed up-section trends in the sand, carbonate, and charcoal variables.

Results

Stratigraphic column

Sixteen distinct lacustrine units constitute the studied exposure of sediments at Stansbury Gulch (Fig. 4). The units display mixed composition dominated by clastic sediments. No erosional unconformities were observed in the studied column.

Proxy variation

The 16 stratigraphic units consist of 35% to 85% sand, with a mean of 58%. Five of the units display a peak and two a semi-peak in percentage sand (Fig. 5). These seven units lie in the lower portion of the sediment column, with the sand peaks at 0–9 cm, 28–31 cm, 33–38 cm, 54–55 cm, and 59–63 cm, and semi-peaks at 25–28 cm and 40–41 cm. In

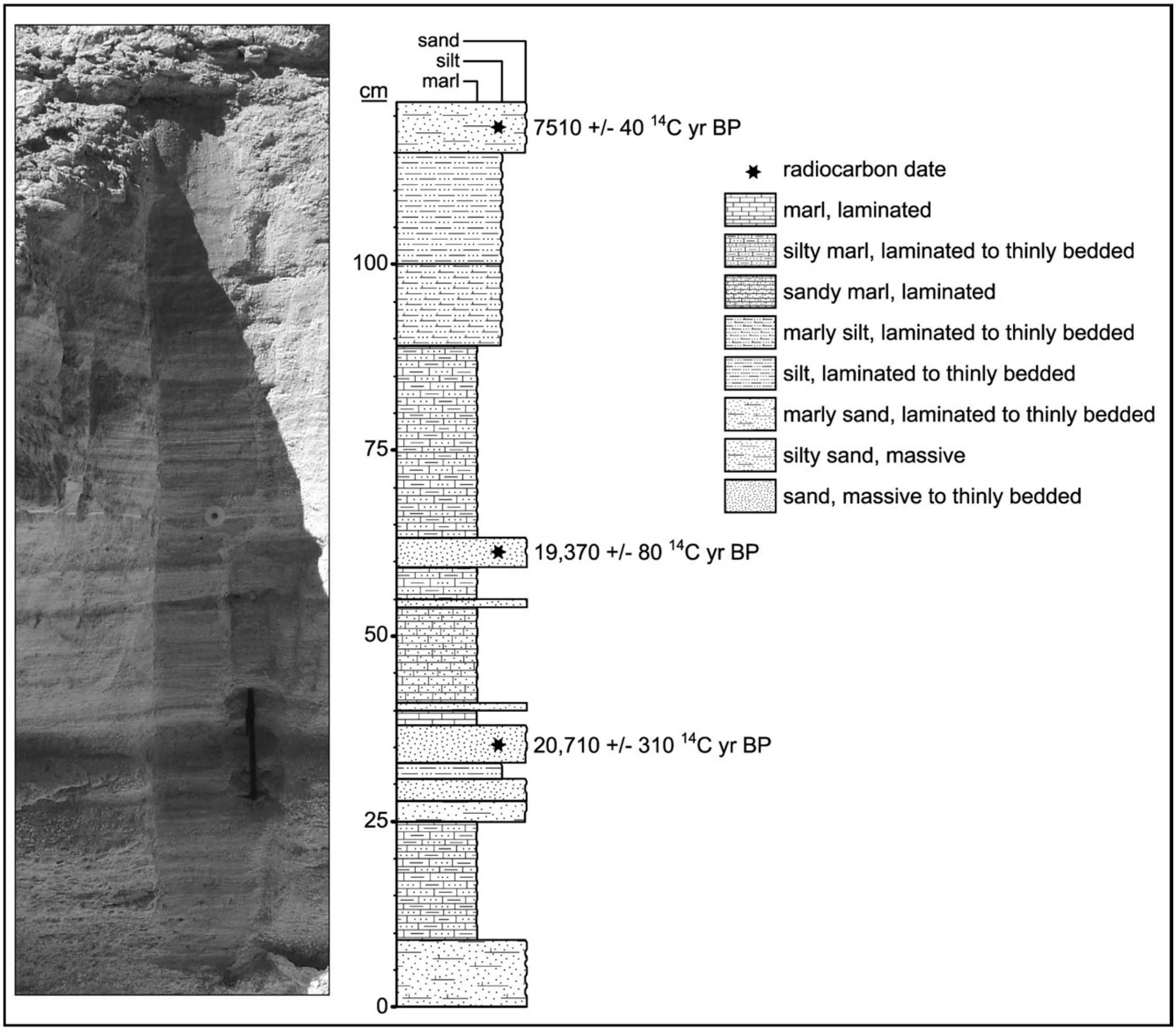


Figure 4. Stansbury Gulch stratigraphic column with field description of measured units and showing the stratigraphic position of radiocarbon-dated material.

contrast to the varied lower portion, the upper part of the column exhibits a comparatively consistent, or flat, grain-size signal.

Carbonate content varies from 5% to 34% in the different units, with a mean carbonate content of 15%. Carbonate percentage peaks in six stratigraphic units and semi-peaks in one unit, all in the lower part of the section in the same units that contain the percentage sand peaks and semi-peaks (Fig. 5). As with grain size, the carbonate signal flattens out in the higher part of the column, indicating much greater homogeneity in carbonate content among the units there.

Magnetic susceptibility measurements range from 0 to 5.0, with a mean of 1.6. The plot of magnetic susceptibility reveals three peaks and three semi-peaks (Fig. 5). Strata with the highest values of magnetic susceptibility lie at the top of the column, in stratigraphic units with below average sand and carbonate percentages.

Charcoal concentration averages 8.3 particles/cm^3; values per unit range from 0 to 57 particles/cm^3. Peak units lie at 8–31 cm, 33–38 cm, 54–55 cm, and 59–63 cm, with semi-peaks at the 25–28 cm and 40–41 cm units (Fig. 5). The lowest unit (0–9 cm) displays high percentages of sand and carbonate, but low macroscopic charcoal. Upper units that contain small percentages of sand and carbonate, however, also have small amounts of sedimentary charcoal.

All of the stratigraphic units measured at Stansbury Gulch contain fossil diatoms typical of freshwater lakes, and unit 63–89 cm contains a lamina at 65.0–65.5 cm consisting almost entirely of diatoms. Although 31 diatom species were identified in the column, their reported ecological constraints vary tremendously, suggesting that many of the diatoms are generalists. Because of its abundance and more clearly defined ecology, *M. elliptica*, which lives in saline waters, was selected as the principal bioindicator in this study.

M. elliptica abundance in the studied column varies from 0% to 11% (Fig. 5), and peaks coincide with those for sand and carbonate percentages. The units at 0–9 cm, 28–31 cm, 33–38 cm, 59–63 cm, 89–100 cm, and 100–115 cm contain many broken diatoms with low-quality preservation. The lower four of these six strata are units with higher percentages of sand, carbonate, and *M. elliptica* abundance. The remaining two samples are from the upper units 89–100 cm and 100–115 cm that are characterized by low values for all variables except magnetic susceptibility.

Associations among proxies

Spearman's correlation reveals that the climate proxies used in this study tend to change together, as initially hypothesized (Table 1). Percentage sand has a statistically significant positive correlation with percentage carbonate, charcoal concentration, and abundance of *M. elliptica*. Likewise, percentage carbonate correlates with charcoal

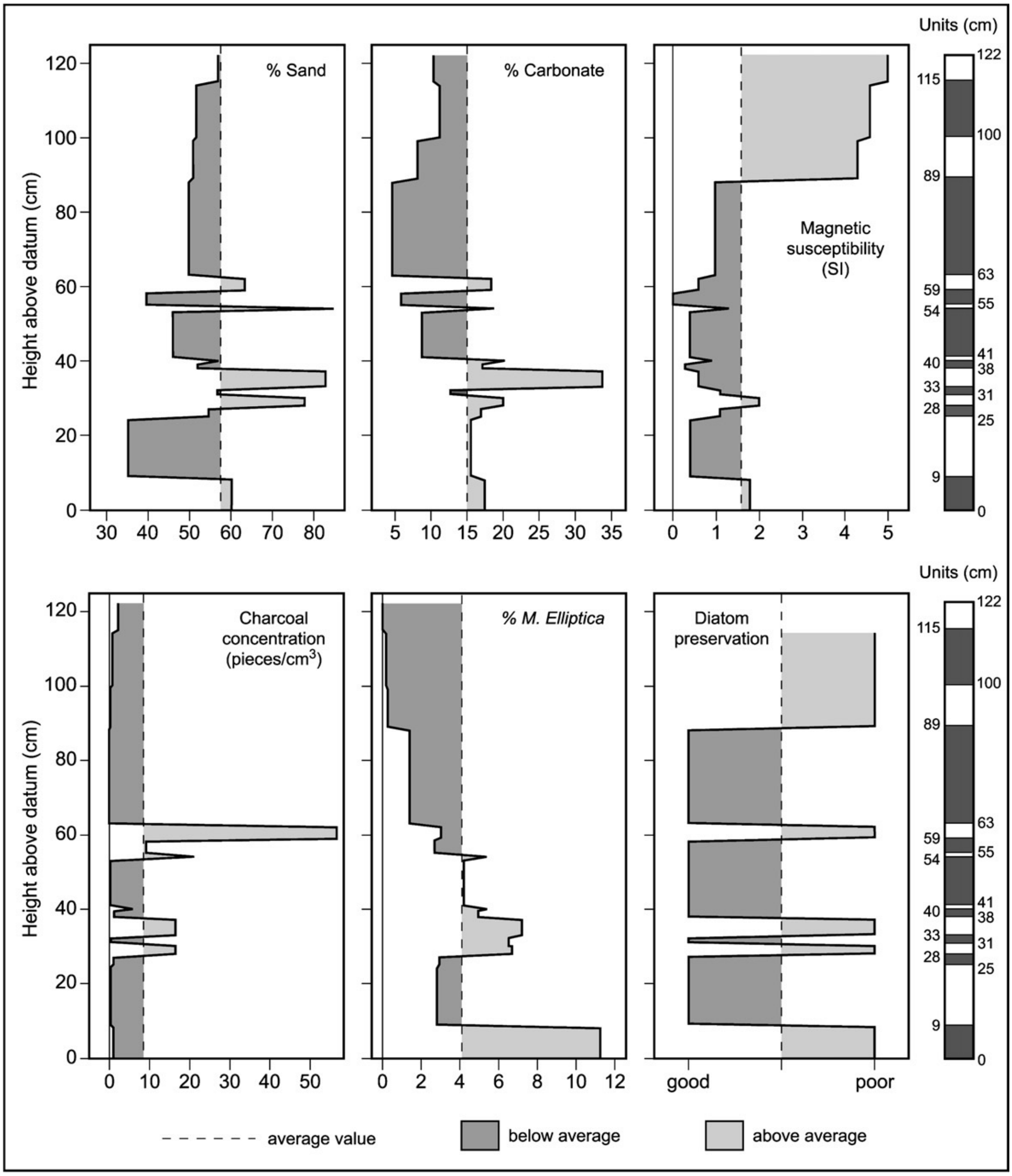


Figure 5. Up-column variations in each of the six proxies displayed over the complete sequence of 16 stratigraphic units. Each of the graphs is plotted so that trends to the right represent drier conditions and lowering lake levels, while trends to the left indicate wetter conditions and rising lake levels.

concentration and with abundance of *M. elliptica*. Magnetic susceptibility does not correlate significantly with any of the other variables. This lack of association is not surprising because either high or low magnetic susceptibility can point to an arid climate (Fig. 3); its role as a proxy helps to refine details of aridity when considered along with the values of the other proxies. The remaining set of proxies, charcoal concentration versus abundance of *M. elliptica*, failed to show a meaningful bivariate correlation at the 0.05 level.

A simplified plot of the direction of variable change dataset illustrates that percentage sand, percentage carbonate, and charcoal

Table 1
Spearman's correlation coefficients and probabilities (in parentheses) for the measured proxies (n = 16).

	% Sand	% Carbonate	Magnetic susceptibility	Charcoal concentration
% Carbonate	0.81 (<0.001)			
Magnetic susceptibility	0.36 (0.18)	−0.01 (0.97)		
Charcoal concentration	0.69 (0.003)	0.70 (0.003)	−0.12 (0.67)	
M. elliptica abundance	0.61 (0.01)	0.74 (0.001)	−0.19 (0.49)	0.35 (0.19)

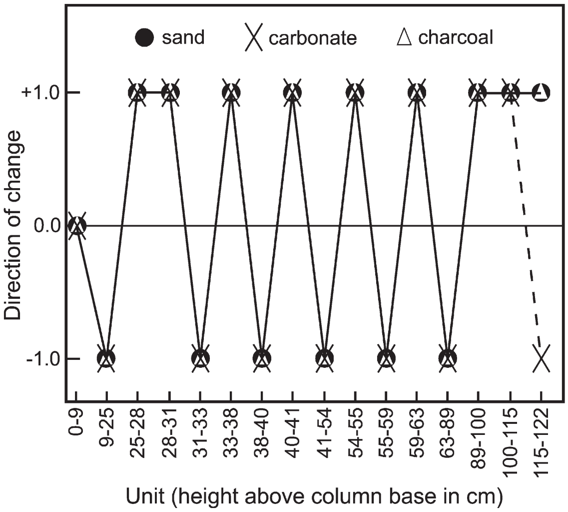


Figure 6. Simplified graph illustrating that the amounts of sand, carbonate, and charcoal have almost identical patterns of directional change from unit to unit within the column. Divergence occurs only in the uppermost stratum (115–122 cm), where percentage carbonate decreases while sand and charcoal values continue an increasing trend.

concentration have almost identical patterns of directional change throughout the stratigraphic column (Fig. 6). The only exception is within the uppermost unit, where percentage carbonate decreases but percentage sand and charcoal concentration increase.

Radiocarbon ages

Three radiocarbon ages have been determined on material collected from three separate units at the study site (Table 2). Currey et al. (1983) obtained a conventional radiocarbon age on gastropod shells collected from the unit designated 33–38 cm in this study (Currey, D.R., personal communication, 2003). During the course of the present investigation, charcoal was found in sufficient quantity for numeric age analysis near the middle of the column in unit 59–63 cm and within the highest unit, 115–122 cm.

Evaluation and interpretation

Verification of proxies

Because sand and macroscopic charcoal were transported to the studied sedimentation site from elsewhere, it is possible that some of the up-column changes measured in these variables might be partly influenced by variations in the delivery system, such as changes in the lacustrine currents or terrestrial drainage system. Major alterations in the delivery system, however, were unlikely given the protected setting of the gulch in a reentrant on Stansbury Island, its distance from the mainland, and its bedrock ridge-controlled drainage area. Furthermore, the nature and size of the charcoal (>250 μm) indicate little secondary transport of those particles (Clark, 1988; Long et al., 1998; Brunelle and Whitlock, 2003). The carbonate content of the sediments varies with climate-induced changes in lake level, and the fact that the amounts of sand, charcoal, and carbonate fluctuate together in the column (Fig. 6) further substantiates the notion that climate determined the trends in sand and charcoal as well as in carbonate at this site. These results, moreover, agree with those of Bischoff et al. (1997) and Menking (1997), who found that fine grain size and low carbonate content correlated with freshwater and low productivity in Owens Lake, California, and with those of Oviatt et al. (1994) and Bischoff et al. (1997), who detected an inverse relationship between calcium carbonate and lake level, and suggested that percentage calcium carbonate is therefore a useful proxy of lake-level change.

Variations in lake level

With the utility of the proxies as lake-level indicators established, the trends observed in the variables were analyzed in conjunction with the three radiocarbon ages to suggest a chronology of lake-level changes represented by the Stansbury Gulch study site. Despite limited numeric age control, the derived chronology fits well with established interpretations of Lake Bonneville oscillations.

Trends observed in the measured proxies indicate that significant changes in lake level occurred over the time span represented by the Stansbury Gulch sediments, particularly in the lower half of the column. During its transgressive phase, Lake Bonneville rose above the modern elevation of 1360 m sometime before about 21,000 ^{14}C yr BP and began depositing the lowest unit (0–9 cm) of the measured column. At this time, Lake Bonneville was probably undergoing its initial transgression toward the Stansbury shoreline (Oviatt, 1997) (Fig. 7). Higher than average values of sand, carbonate, magnetic susceptibility, and *M. elliptica* abundance, and the common occurrence of broken diatoms (Fig. 5), indicate that deposition of this unit occurred in shallow water. The second unit (9–25 cm) displays low values of sand, carbonate, magnetic susceptibility, macroscopic charcoal, and *M. elliptica*, as well as better diatom preservation than in the layer below, thus denoting an environment of relatively deeper water and greater effective precipitation, which is interpreted as approximately marking initial occupation of the Stansbury shoreline. Unit 25–28 cm shows a return to high values of sand, carbonate, magnetic susceptibility, charcoal, and *M. elliptica*, all of which peak in the fourth unit (28–31 cm) that also contains numerous broken diatoms. Units 25–28 cm and 28–31 cm, therefore, represent a major drying interval with a falling lake level. The climate was wetter and lake level higher during subsequent deposition of unit 31–33 cm, as evidenced by the low values of sand, carbonate, charcoal, and magnetic susceptibility as well as good preservation of diatoms in that layer.

This second fluctuation to wetter conditions and higher lake level, interpreted as a second occupation or near-occupation of the Stansbury shoreline, had ended by about 20,710 ± 310 ^{14}C yr BP (Table 2), a radiocarbon date determined from unit 33–38 cm and which Oviatt et al. (1990, p. 297) interpret as representing “the age of the low point on the Stansbury regression.” Indeed in unit 33–38 cm, very high amounts of sand, carbonate, charcoal, and *M. elliptica*, and low magnetic susceptibility reveal a drier environment with fire episodes and the return to a lower lake level. Low magnetic susceptibility points to reduced sediment yield from the drainage basin and very dry

Table 2
Radiocarbon ages discussed in this paper.

^{14}C age yr BP	2σ calibrated[b] age BP	Lab no.	Material	Locality, or unit at study site	Reference
7510 ± 40[a]	8285-8400	Beta-208,972	Charcoal	115–122 cm	This paper
7650 ± 90	8300-8600	Beta-25,290	Humates	Antelope Island	Murchison & Mulvey (2000)
19,370 ± 80[a]	22,640-23,430	Beta-195,845	Charcoal	59–63 cm	This paper
20,710 ± 310	24,030-25,660	Beta-5566	Gastropod shells	33–38 cm	Currey et al. (1983)

[a] AMS radiocarbon.
[b] (CALIB 5.0.1; Stuiver and Reimer, 1993).

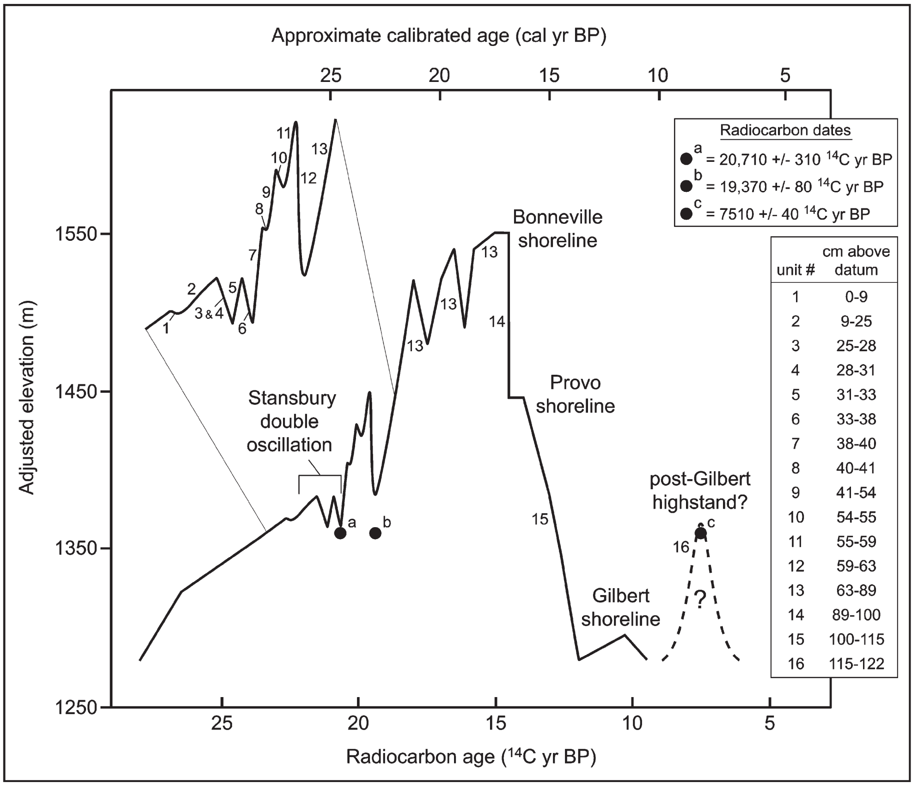


Figure 7. Chronologic interpretation of the lake-level changes indicated by multiple-proxy evidence from the Stansbury Island study site (compare with Fig. 2). Evidence derived from the measured column suggests considerable detail regarding the middle transgressive phase of the Lake Bonneville chronology. Elevation and timing of the stillstands and oscillations inferred from the lower 12 units are depicted in a relative and largely schematic fashion, with interpretations being anchored by the elevation of the stratigraphic column and two radiocarbon dates (a and b). Units 13, 14, and 15 are interpreted as representing the subsequent segments of the Bonneville lacustrine chronology (after Oviatt, 1997). If reliable, data from the uppermost unit of the column point to a previously unidentified highstand of Great Salt Lake that reached an elevation of at least 1360 m about 7500 ^{14}C yr BP.

conditions at this time. In addition, the large number of broken and abraded diatoms observed in this unit indicates sediment deposition in the high-energy nearshore lacustrine zone and probably reworking of sediment as the lake fell.

A return to greater effective wetness and higher lake level is signaled by lower values of all measured proxies and the notably better preservation of diatoms in unit 38–40 cm. This expansion is interpreted as the transgression of Lake Bonneville out of the Stansbury oscillation. Evidence at the measured column therefore corroborates the concept that the Stansbury consisted of a double oscillation, a possibility noted by Oviatt (1987) and Oviatt et al. (1990). Although the 45 m amplitude previously inferred for the Stansbury oscillation (Oviatt et al., 1990) would have lowered the level of Lake Bonneville below the elevation of the sediments studied here, the event could be represented by disconformities in the measured section, rather than unconformities.

Lake-level fluctuations have also been previously postulated for the post-Stansbury part of the Lake Bonneville transgression (Currey and Oviatt, 1985; Oviatt, 1997; Sack, 1999), and evidence from this study supports that notion as well. After the post-Stansbury transgression, which is represented by unit 38–40 cm, unit 40–41 cm indicates an only marginally drier interval, as evidenced by slightly elevated values for grain size, carbonate, charcoal, magnetic susceptibility, and *M. elliptica*. Decreased proxy values in the 41–54 cm layer, along with good diatom preservation, designate a subsequent return to lake expansion and increased effective precipitation. This was apparently followed by a cycle of lower, then higher, lake level represented by proxy values in units 54–55 cm and 55–59 cm, respectively (Fig. 5). All proxies indicate that effectively drier conditions returned about 19,370 ^{14}C yr BP (Table 2) in unit 59–63 cm, the midpoint of the measured column. Occurrence of a very high charcoal concentration and a large number of broken diatoms in this stratum suggests that this was a significant oscillation, with the shoreline again in close proximity to the elevation of the Stansbury Gulch study site.

Unit 63–89 cm denotes a return to wetter conditions and higher lake levels, as marked by a decrease in sand, carbonate, charcoal concentration, and *M. elliptica*, and an increase in magnetic susceptibility. This thick unit may represent the later transgressive phase of Lake Bonneville, including Bonneville shoreline time. It is unique from the others in the column because it contains the diatom lamina at 65.0–65.5 cm. In long cores retrieved from Great Salt Lake for the GLAD800 project (Moser, K. A., unpublished data, 2007), millimeter-scale layers composed almost exclusively of diatoms are observed sporadically throughout the core, indicating that the events are not uncommon. The cause of these events, however, remains unknown.

The upper three sedimentary units differ markedly from those in the lower part of the column by having little directional change in proxy values (Figs. 5 and 6). First, relative to the layer below, unit 89–100 cm exhibits only small increases in sand, carbonate, and charcoal values but a substantial jump in magnetic susceptibility and a decrease in *M. elliptica*. These values suggest only slightly drier conditions than in the preceding interval. The catastrophic 104-mm fall in lake level from the Bonneville to the Provo shoreline (Malde, 1968; Burr and Currey, 1988) left former areas of the lake bottom subaerially exposed and initially devoid of vegetation. Erosion of the exposed lacustrine and underlying nonlacustrine sediments at and above the Provo shoreline could account for the observed jump in magnetic susceptibility in unit 89–100 cm, which is interpreted as deposits of Provo shoreline time.

Next, compared to unit 89–100 cm, unit 100–115 cm exhibits a slight increase in sand along with increases in carbonate, charcoal, magnetic susceptibility, and broken diatoms, and a decrease in the abundance of *M. elliptica*. These data signify a drier climate with continued terrestrial erosion. After Provo shoreline time, high rates of sediment delivery to the lake continued as the rapidly regressing water level left additional former lake-bed sediments subaerially exposed. This unit, therefore, may have accumulated during the post-Provo regressive phase of Lake Bonneville before the water level fell past the elevation of the study site at 1360 m to very low levels, ending the Bonneville lake cycle.

The derived chronology of lake-level fluctuations becomes more problematic at the top of the measured section, which, as noted above, displays some conflicting trends in the measured proxies. According to the radiocarbon data, deposition of the highest lacustrine sediment layer of the measured column, unit 115–122 cm, occurred about 7510 ^{14}C yr BP (Table 2), after formation of Great Salt Lake. Compared to unit 100–115 cm, this layer exhibits slightly greater values of sand, charcoal, and magnetic susceptibility, which indicate a somewhat drier climate, but a slightly lower percentage of carbonate which points to wetter conditions than in unit 100–115 cm. These seemingly conflicting proxy signals may be an artefact of comparing the two different lacustrine systems (Oviatt et al., 1994); it is possible that the exact nature of the relationships between the various proxies used differ in Great Salt Lake than in Lake Bonneville, and therefore the direct comparison of measured proxies may not be entirely appropriate between the two lake systems, that is, between unit 115–122 cm and unit 100–115 cm. It is also possible that the radiocarbon date from the uppermost unit is unreliable or that the unit has been misinterpreted as being lacustrine.

If the data reported here are reliable, the occurrence of lacustrine sediments deposited about 7500 ^{14}C yr BP at an elevation of 1360 m would indicate the existence of an expanded Great Salt Lake and greater effective precipitation at this time. This highstand conflicts dramatically with traditional reconstructions of the fluctuations of Great Salt Lake, which place the highest level of that water body at the Gilbert shoreline (Currey, 1990) (Figs. 2 and 7). That shoreline formed between about 10,900 and 10,300 ^{14}C yr BP and lies more than 60 m below the column measured at Stansbury Gulch (Currey, 1990; Oviatt et al., 1992). The only other known support for a possible post-Gilbert readvance at approximately this time is a radiocarbon date of 7650 ± 90 ^{14}C yr BP (Beta 25,290) obtained on organic material from lagoon deposits at 1283 m on Antelope Island (Murchison and Mulvey, 2000) (Fig. 1).

Discussion and conclusions

Proxies

This study demonstrates that a multiple climate-proxy approach, which thus far has been underutilized in Bonneville basin lacustrine research, can be of great value in paleoenvironmental studies of Lake Bonneville and Great Salt Lake stratigraphic exposures. Contrary to some previous ambiguous conclusions regarding the covariation of sand, carbonate, and lake level in the Bonneville basin (Oviatt et al., 1994; Oviatt, 1997), this study confirms the notion that grain size and carbonates are useful in determining past variations of lake level, at least for sites with some proximity to the lake margin. Statistically significant positive correlations exist between percentage sand, percentage carbonate, charcoal concentration, and abundance of *M. elliptica* at the Stansbury Gulch study site. In agreement with physical processes and previous ecological, geomorphic, and sedimentological research elsewhere, higher values of these variables represent a lower lake level and an effectively drier climate while lower values indicate a higher lake level and an effectively wetter climate. Excluding the uppermost unit, additional verification of these signals comes from comparing the proxy-derived interpretation of relative lake level to the established chronology of Lake Bonneville. Although not as directly applicable as a climate proxy, when used in combination with the other variables, magnetic susceptibility helps identify hyperarid conditions. Relative amount of broken diatoms contributes to interpreting shoreline proximity.

Lake-level chronology

Results of this investigation help resolve some of the uncertainties about the nature of the Stansbury shoreline, the most problematic of Lake Bonneville's three major shoreline intervals. With higher lake levels represented by the 9–25 cm and 31–33 cm units and lower levels represented by the 28–31 cm and 33–38 cm strata, multiple-proxy evidence from Stansbury Gulch strongly supports the hypothesis that the Stansbury was a double oscillation (Oviatt, 1987; Oviatt et al., 1990) (Fig. 7). The water level thus traversed a range of elevations five times over the time period of the Stansbury oscillation. Within this range, shoreline evidence would have been formed and preserved at different elevations around the basin, reflecting spatially variable local conditions. This helps explain why a single well-developed Stansbury shoreline has proven so difficult to trace around the Bonneville basin.

Analysis of the Stansbury Gulch sedimentary column shows that, after the Stansbury double oscillation, in addition to a stillstand and comparatively small oscillation, a significant oscillation occurred during the overall transgressive phase of Lake Bonneville. This later oscillation reached its minimum level close to 19,370 ^{14}C yr BP. This event, and the subsequent late Pleistocene lake-level changes interpreted from the study site, correlate well with the generally established chronology of Lake Bonneville (Oviatt et al., 1992; Oviatt, 1997; Sack, 1999).

More controversial is the lacustrine sediment and radiocarbon evidence found at the top of the Stansbury Gulch column suggesting a rise of Great Salt Lake to an elevation of at least 1360 m by about 7510 ^{14}C yr BP (Fig. 7). This is 60 m above the established highstand of Great Salt Lake at the Gilbert shoreline, which was occupied between about 10,900 and 10,300 ^{14}C yr BP (Currey, 1990; Oviatt et al., 1992) and which was preceded by a period of general drought in the Great Basin (Smith and Street-Perrott, 1983). The only corroboration found for the notion of a post-Gilbert readvance at about 7500 ^{14}C yr BP is evidence of a transgression of Great Salt Lake at about 7650 ± 90 ^{14}C yr BP, reported by Murchison and Mulvey (2000). However, if a Great Salt Lake highstand did occur at about this time, it may be related to a global temperature anomaly about 8200 years ago known as the “8.2k event” (Alley et al., 1997), when a regional winter low pressure appears to have increased snowpack in the mountains adjacent to the Bonneville lake basin (Dean et al., 2006). Clearly the notion of a post-Gilbert highstand of Great Salt Lake at least merits further investigation.

Teleconnections

On a global scale, the Stansbury oscillation may coincide with the second oldest (H2) of six known Heinrich events (Bond et al., 1992, 1993). Global paleoclimatic records document the occurrence of H2 at 20,500 ± 3500 ^{14}C yr BP (Hemming, 2004). Heinrich events are marked by anomalous ice-rafted debris in the North Atlantic, and the array of sites suggesting cool conditions at this time indicate that this was at least a Northern Hemisphere, if not a global, phenomenon (Broecker, 1994; Hemming, 2004).

Mechanisms that drove the Heinrich events are still not fully resolved, but changes in solar insolation, wind, and volcanic events have been suggested (Hemming, 2004). Climatic responses to those mechanisms, moreover, are spatially variable (Hemming, 2004). Stansbury Gulch reveals evidence of four effectively dry periods from about 20,710 through 19,370 ^{14}C yr BP, and two others before 20,710 ^{14}C yr BP. Zic et al. (2002) also found evidence for a dry climate in the Great Basin during the H2 period. Temporal correlation indicates that these may reflect the same climate trends broadly responsible for the H2 signal in the North Atlantic. Further close examination of multiple-proxy evidence from sites like Stansbury Gulch should provide opportunities to hypothesize, verify, and better resolve teleconnections between climate events in the North Atlantic and the western U.S.

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