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Research Article

Chronology of the early transgressive phase of Lake Bonneville

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Abstract

Radiocarbon and uranium-thorium dating of microbialites and penecontemporaneous cements in a microbialite mound at Death Point at Lakeside, Utah, on the shore of Great Salt Lake, Utah, call for a revision of the Lake Bonneville hydrograph. At about 30,000 cal yr BP, the lake experienced an abrupt rise of about 20 m, then dropped back down to levels near or slightly higher than the modern average elevation of Great Salt Lake. Over the ensuing ~6000 yr the lake experienced a series of fluctuations, up to levels a few tens of meters higher than the modern average Great Salt Lake, then down again. The exact timing and amplitudes of those fluctuations are not known, but importantly, the lake did not rise to levels near the Stansbury shoreline (~80 m higher than Great Salt Lake) until after about 24,000 cal yr BP. After the Stansbury shoreline, the lake rose almost 200 m to its highest level at the Bonneville shoreline by about 17,500 cal yr BP. This interpretation is different from previously published hydrographs, many of which show a relatively steady rise to near the Stansbury shoreline between 30,000 and 25,000 cal yr BP.

Keywords: Lake Bonneville, Great Basin, paleoclimate, chronology, hydrograph

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Introduction

Pleistocene Lake Bonneville in the eastern Great Basin of North America (Fig. 1) has been studied since the late 1800s (Gilbert, 1890), and the scientific understanding of the lake system has evolved considerably during that time (e.g., Sack, 1989; Oviatt and Shroder, 2016). As recognized long ago by G.K. Gilbert (1890), the rises and falls of Lake Bonneville in its hydrographically closed basin are closely tied to changes in climate. The major lake cycle itself is broadly correlated with Marine Oxygen Isotope Stage 2 (Atwood et al., 2016), and some lake-level oscillations during the Bonneville cycle were probably correlated with global or hemispheric and millennial-scale climate changes (Oviatt, 1997; Nelson and Jewell, 2015). The timing of lake-level changes has research implications in fields such as geology, geomorphology, archaeology, biology, paleoclimatology, and geochemistry. Hydrographs (plots of lake-level change through time) have been fundamental to those interpretations, and the form of the Lake Bonneville hydrograph has evolved along with the science. We do not attempt to review here the many published hydrographs of Lake Bonneville, but the interested reader can consult previous efforts in Eardley et al. (1957), Broecker and Orr (1958), Broecker and Kaufman (1965), Morrison and Frye (1965), Scott et al. (1983), Currey and Oviatt (1985), Oviatt et al. (1992), Godsey et al. (2005), and Oviatt (2015).

Geochronologic data are limited for the early transgressive phase of the Lake Bonneville hydrograph. New radiocarbon (^{14}C) and uranium-thorium (U-Th) ages from a detailed study of a microbialite ("tufa") mound at Death Point (Pedone et al., 2023; Fig. 1) call for a new interpretation of the early history of Lake Bonneville. The microbialite mound is located about 2 km east of Lakeside, UT, at the northern tip of the Lakeside Mountains, where the Union Pacific Railroad causeway intersects the mainland on the west side of Great Salt Lake, with an elevation range between ~1280 and 1285 m, a few meters higher than the historic average lake level. The aragonite microbialite formed in the wave zone, within a few meters of lake level, episodically over a minimum time range of 3600 yr. Episodic exposure resulted in formation of large dissolution pores, which were partly to completely filled by multiple generations of penecontemporaneous prismatic aragonite cement during re-submergence of the mound.

As part of the continuing evolution of the hydrograph of Lake Bonneville, we present in Figure 2A a new version of the early transgressive part of the Bonneville cycle, modified from the hydrograph of Oviatt (2015; Fig. 2). Figure 2B shows the hydrograph for the entire Bonneville cycle, modified from Oviatt (2015) using the curve from Figure 2A and the shift in the age of the Bonneville flood discussed in Oviatt (2020).

Materials and methods

This paper relies on previously published observations and interpretations in Pedone et al. (2023). No new methods or procedures are used here. The ^{14}C ages used in this paper were calibrated with CALIB 8.2 using calibration data set IntCal20 (Stuiver and Reimer, 1993; Reimer et al., 2020). Elevations of samples for locations higher than 1300 m are adjusted for isostatic deformation using the Currey equation (Oviatt, 2015).

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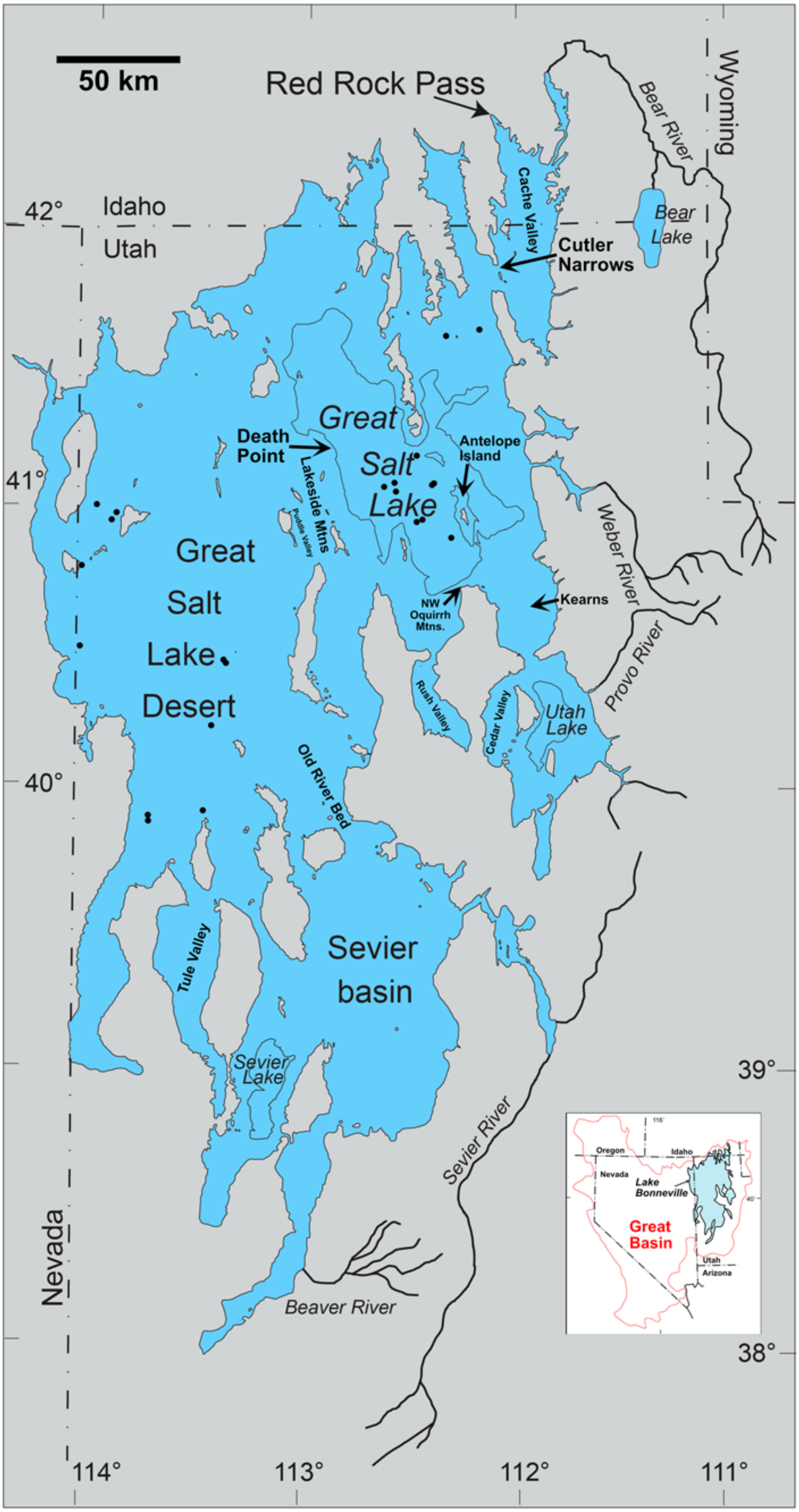

Figure 1. Map showing Lake Bonneville at its highest level (the Bonneville shoreline). Inset map shows the location of Lake Bonneville in the eastern Great Basin of North America. Black dots mark locations where algal-laminated marl (ALM) has been observed.

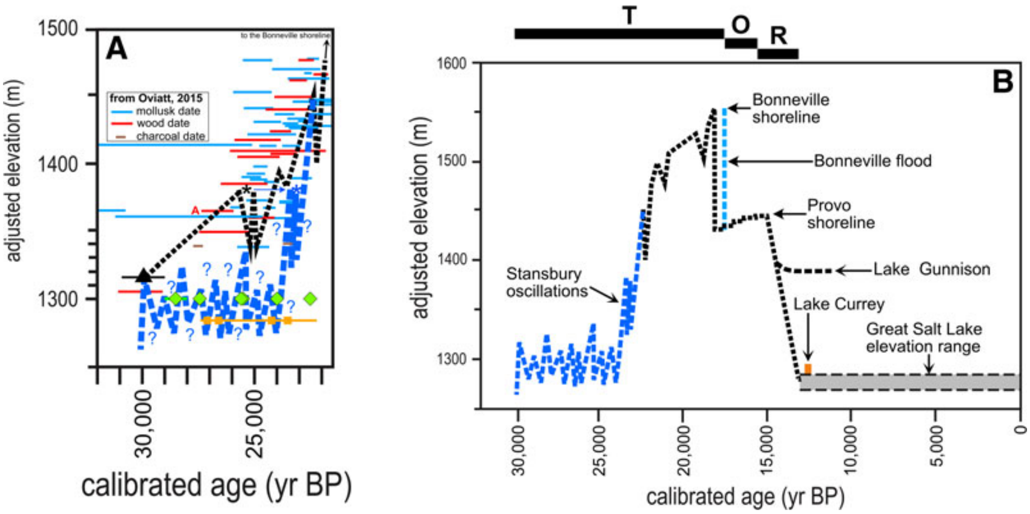

Figure 2. Hydrograph of Lake Bonneville. (**A**) The early transgressive phase with revisions discussed in this paper; the lake-level curve of Oviatt (2015) is shown by the dashed black line, and mollusk, wood, and charcoal ages used by Oviatt (2015) are shown. Mollusk-shell ages are not considered in this revision (see text for an explanation). New interpretation of the lake-level curve is shown by the blue dashed line. Orange squares are calibrated ^{14}C and U-Th ages of microbialite samples from Death Point (Table 1). The black triangle marks the age and elevation of the eruption of the Hansel Valley basaltic ash (Oviatt et al., 1992). Green diamonds are ^{14}C and U-Th ages of cement in pores in microbialite precipitated when lake level was higher than the microbialite. The red "A" refers to a wood date discussed in the text (W-4898 from Scott et al. 1983). The two asterisks mark the high point of the Stansbury oscillation and the shift to a younger age in the revision (blue and black, respectively). (**B**) The entire Lake Bonneville cycle, modified from figure 2 of Oviatt (2015), with revisions discussed in this paper, and adjustment to the age of the Bonneville flood discussed in Oviatt (2020). T, transgressive phase; O, overflowing phase; R, regressive phase. The vertical axes (elevation) of both **A** and **B** are adjusted for the basin-wide effects of isostatic rebound using the Currey equation (Oviatt, 2015).

Results

Discussions of new interpretations of previously published data are given in the following sections. Table 1 is a list of pertinent ^{14}C and U-Th ages, and Figure 2 provides graphical depictions of the revisions.

Discussion

In this paper, we reinterpret many of the ^{14}C ages that were used to construct previous versions of the Lake Bonneville hydrograph and discuss the reasoning behind the reinterpretations. A major aspect of our revision of the hydrograph is tied to the meanings of ^{14}C ages for wood and charcoal samples.

Ages derived from wood and charcoal

Wood and charcoal generally yield excellent analytical results for radiocarbon; in addition, plants from which wood and charcoal were derived (trees, shrubs, herbs, grasses) receive the carbon that ends up in their tissues directly from the atmosphere, not from some other carbon reservoir, such as water, thus satisfying one of the fundamental principles of radiocarbon dating (Trumbore, 2000). The geologic context of those samples is also extremely important, however, and must be incorporated into interpretations of individual ages in terms of lake history. In most cases, if they could be quantified, the uncertainties resulting from the geologic context of ^{14}C samples would probably exceed the analytical uncertainties of the reported ages. In Figure 2A, only the analytical uncertainties are plotted, because we cannot quantify the geologic uncertainties.

A number of factors could result in the age of the wood or charcoal being older than the Lake Bonneville sediment in which they are enclosed. In most cases, the dated wood fragments or logs were derived from trees that grew before the rise of Lake Bonneville to the elevation of the sample; in some cases, lacustrine deposits bury stumps of trees that grew before the rise of the lake. Furthermore, trees can live for hundreds to thousands of years, so a sample from a tree might be significantly older than the death of the tree. The time span from the growth of wood to the deposition of that wood in the lake sediments could easily be thousands of years. For instance, it is possible, and likely in many cases, that dated wood was preserved in wet environments for a long period before lake transgression and wave erosion and deposition at that site. In some cases (not involving in situ stumps), older wood fragments might have been transported to the site of deposition by fluvial and/or colluvial processes, and the transport time also needs to be considered.

Similar uncertainties apply to processes that deposit charcoal fragments. Carcaillet (2001) documented that charcoal fragments in most soils and colluvium may be thousands of years older than the soil. Charcoal fragments could easily have been incorporated in pre-Bonneville soils or other surficial deposits that later were eroded by waves in rising Lake Bonneville. The charcoal fragments that were deposited with other clastic sediments in the lake would retain the age of their formation (the age of the burning bush or tree) and would be older than the lacustrine deposition. Once formed, charcoal can persist for long periods (even for tens of millions of years; Herring, 1985) in suitable geochemical environments and undergo one or more episodes of transport, so the age difference between charcoal fragments and lacustrine deposition could range from zero years (in appropriate settings) to many thousands of years.

Therefore, in constructing a hydrograph for Lake Bonneville, the ^{14}C ages of samples of wood and charcoal should be regarded as maximum limiting ages rather than closely limiting ages. Scott et al. (1983, p. 273) recognized that wood and charcoal in transgressive-phase deposits should be regarded as yielding maximum limiting ages, but in their figure 5 (the hydrograph) and in their text, they assumed that wood and charcoal ages closely

Table 1. ^{14}C and U-Th ages from Death Point, Utah[a] (Pedone et al., 2023).[b]

Lab no.[c]	Sample no.	^{14}C or U-Th age	^{14}C 1-σ error	U-Th 2-σ error	Cal med. prob.	Cal min.	Cal max.	Material dated
AA-112719	DP14A	19,580	92	—	23,520	23,300	23,810	Microbialite
RT-002C	**DP14A**	**24,166**	**—**	**1880**	**—**	**—**	**—**	**Microbialite**
RT-002E	**DP14C**	**27,100**	**—**	**730**	**—**	**—**	**—**	**Microbialite**
RT-DP-9-1	**97-DP-9-1**	**26,720**	**—**	**600**	**—**	**—**	**—**	**Microbialite**
AA-112720	DP14B	24,350	170	—	28,560	28,000	28,990	Cement
RT-002D	**DP14B**	**27,380**	**—**	**140**	**—**	**—**	**—**	**Cement**
AA-112718	97-DP-9-2	21,360	120	—	25,730	25,350	25,920	Cement
RT-DP-9-2	**97-DP-9-2**	**25,450**	**—**	**120**	**—**	**—**	**—**	**Cement**
RT-DP-9-3	**97-DP-9-3**	**22,570**	**—**	**110**	**—**	**—**	**—**	**Cement**
?[d]	97-DP-9	19,800	?	—	~24,000	—	—	Cement

[a] All samples were collected at Death Point within a few meters of elevation 1283 m; the isostatically adjusted elevations are identical to the collection elevations in all cases, because they were below 1300 m (Oviatt, 2015).

[b] Calibrations ("cal") using CALIB 8.2 and IntCal20 (Stuiver and Reimer, 1993; Reimer et al., 2020). U-Th ages are listed in bold type.

[c] Three pairs of ages (AA-112719 and RT-002C, AA112720 and RT-002D, AA112718 and RT-DP-9-3) each consists of one age based on ^{14}C analysis and the other based on U-Th analysis, each pair for the same sample; the analytical uncertainties overlap for two of the pairs. For one pair (AA-112720 and RT-002D), the ^{14}C age range is ~480 yr younger than the U-Th age range.

[d] This sample was extracted from hand sample DP-9 in 1997, and information about the exact site of extraction and uncertainties of the analysis are no longer available; it is designated "DP-9" in Pedone et al. (2023).

matched the time of deposition of the enclosing sediment. Currey and Oviatt (1985) and Oviatt et al. (1992) also assumed that wood and charcoal ages were closely limiting, and most other previously published hydrographs were based on that assumption.

An example from Scott et al. (1983) illustrates this point. They dated a wood sample (W-4898, labeled A in Fig. 2A) collected from transgressive-phase Bonneville deposits in a gravel pit near Kearns, Utah, in Salt Lake Valley (Fig. 1). Specifically, the sample was collected "near [the] base of [a] 0.5-m-thick lens of bluish-gray mud in [a] gravel-bar complex [which overlies] 2.5 m of lake gravel that buries soil formed in deposits of an older lake cycle" (Scott et al., 1983, table 4). The collection elevation was 1379 m, isostatically adjusted to 1365 m (1364 m in Scott et al., 1983). In figure 5 of Scott et al. (1983), they show the transgression of Lake Bonneville to the elevation of the sample as being fairly close in age to the radiocarbon date. However, we show the transgression as being much younger than the date (Fig. 2A). Wood in mud interbedded with lacustrine gravel could easily be older than the lake transgression to that elevation. Our interpretation of that age as a maximum limiting age does not violate the original description of the sample or the analytical results.

An important aspect of our revision of the early portion of the hydrograph is the recognition that previously published ^{14}C ages of samples of wood and charcoal from the early transgressive phase of Lake Bonneville should be regarded as maximum limiting ages rather than closely limiting ages. We view this as a more scientifically conservative approach and one that is compatible with reconciling previously published results with newly acquired data.

Mollusk samples

The interpretations of ^{14}C ages of aragonite in mollusk samples are more complicated than those for wood or charcoal samples, because mollusk shells have the potential to be older than, the same age as, or younger than the sediment deposition, depending on local geologic contexts. Local geologic contexts include such processes as reworking of shells, radiocarbon reservoir effects from the water from which the shells precipitated, and postdepositional diagenesis and addition of ^{14}C-enriched carbon. These processes are difficult to assess, and insufficient information is available to evaluate potential problems for individual samples from Lake Bonneville deposits.

An additional observation is consistent with the interpretation that ^{14}C ages of aragonite in mollusk samples (mostly gastropods) have large geologic uncertainties. Mollusk 2σ calibrated age ranges form a scatter on Figure 2A in which similar ages are plotted over a broad elevation range (roughly ~1350 to ~1500 m). All these mollusk samples were obtained from sediments that were interpreted as having been deposited in Lake Bonneville. However, even allowing generous interpretations of the age ranges, they cannot all be correct, unless some very rapid and high-amplitude lake-level fluctuations are postulated, all older than the trend of maximum limiting wood ages shown in Figure 2A. No stratigraphic evidence exists for fluctuations of this type and age.

For this paper, we have chosen to interpret ^{14}C ages of mollusks from the early transgressive phase as being of uncertain usefulness in determinations of depositional age. Published ages of mollusk shells from deposits of the early transgressive phase are shown in Figure 2A, but they are not used in the placement of the dashed blue line in the revised hydrograph.

Microbialite ages

Microbialites in the early transgressive phase of Lake Bonneville have been dated using ^{14}C and U-Th dating techniques (Hart et al., 2004; Bouton et al., 2016; Vennin et al., 2019; Pedone et al., 2023). The ^{14}C ages of $CaCO_3$ in microbialite samples could be influenced by radiocarbon reservoirs in the water from which the $CaCO_3$ precipitated and/or by diagenetic alteration that adds younger $CaCO_3$.

Microbialites might contain detrital grains that include older carbon-bearing minerals, such as reworked fragments of older carbonate deposits. Unlike $CaCO_3$-bearing mollusks, however, the in situ microbialites discussed here cannot have been reworked or transported from their firmly attached locations on solid substrates. U-Th ages are independent of possible radiocarbon reservoirs in water, but inclusion of detrital U- or Th-bearing minerals or loss of U by diagenetic alterations could impact the accuracy of the measured age.

Ages of the microbialite from Death Point are fundamental to the revision of the Lake Bonneville hydrograph that is presented here, so it is important to detail why we are confident in these samples and ages. Pedone et al. (2023) presented strong evidence that these microbialites were formed in a wave-agitated, shallow-water shoreline setting in the lake. Another strength of the Pedone et al. (2023) study is that they obtained a total of 17 radiometric ages on one microbialite complex at Death Point: 10 ages for early transgressive microbialite and 7 ages for younger stratigraphic units that are not discussed in this paper. Hence, they established a good stratigraphic context for understanding the geologic history of the complex. The meaning and reliability of an isolated radiometric age can be difficult to evaluate if it has limited stratigraphic and geologic context within the basin.

To help assess the applicability of microbialite samples for both ^{14}C and U-Th analyses, microbialite samples from Death Point were thoroughly examined in thin-section and by X-ray diffraction (XRD). Methods used to assess initial ^{230}Th are detailed in Pedone et al. (2023). Paired ^{14}C and U-Th ages for one sample of microbialite (dates AA-112719 and RT-002C; Table 1) provide assessment of a radiocarbon reservoir at the time and place that particular microbialite was precipitated. The ^{14}C and U-Th analytical uncertainties overlap. Because U-Th age analysis is independent of carbon, similarity of the paired ^{14}C and U-Th ages provides a reasonable test that a radiocarbon reservoir was not significant at the time of precipitation and provides added confidence in evaluating the accuracy of the ages.

Three other ^{14}C ages for transgressive-age microbialites in the Great Salt Lake basin of Lake Bonneville have been published: (1) ~25,700 cal yr BP from "tufa" (microbialite) near the entrance of Lakeside Cave in the Lakeside Mountains (Fig. 1) at an elevation of 1295 m (AA-20955; Hart et al., 2004); (2) ~26,100 cal yr BP from microbialite crust on Antelope Island (Fig. 1) at an elevation of 1281 m (sample POZ-77888 in Bouton et al. 2016; Vennin et al. 2019); and (3) ~25,700 cal yr BP from microbialite crust on Antelope Island at an elevation of 1378 m (isostatically adjusted elevation of ~1357 m) (sample POZ-77887 in Vennin et al., 2019). The sample from near Lakeside Cave, AA-20955, was examined by J. Quade (personal communication, 2022) and found to be free of contamination from either older detrital grains or younger additions of carbon. Bouton et al. (2016) and Vennin et al. (2019) reported that microbialite samples collected on Antelope Island (including POZ-77888) were examined by thin section and XRD, but specifics for these samples were not reported. These three samples were collected at locations far from the microbialites investigated by Pedone et al. (2023), so undocumented radiocarbon reservoirs in those locations could have affected the radiocarbon ages reported by Vennin et al. (2019) and Hart et al. (2004).

The ages of AA-20955 and POZ-77888 indicate low lake elevations during the early transgressive phase of Lake Bonneville, similar to those indicated by microbialites from Death Point (Pedone et al., 2023; Fig 2A), and support the revision of the hydrograph presented in this paper. Date POZ-77887 (Vennin et al., 2019), however, suggests Lake Bonneville was at least 60 m higher about 25,700 cal yr BP than AA-20955, POZ-77888, and the ages from Death Point. Without further information about sample POZ-77887 (including its precise location and stratigraphic connections), it is difficult to interpret the age, and we have chosen not to use it in our reconstruction of lake history.

Carbonate cement

$CaCO_3$ cement also has the possibility to form from a fluid not in equilibrium with atmospheric ^{14}C, to include mineral inclusions, and/or to undergo diagenesis. Hence, as with samples of microbialite, selection of samples of cement for ^{14}C and/or U-Th dating should include thin-section and XRD examination. This was done by Pedone et al. (2023).

Because accuracy of ^{14}C and U-Th ages can be affected by different factors, paired results with overlapping uncertainties provide added confidence in evaluating the ages. Table 1 and Figure 2A include ages of prismatic aragonite cement that partly or completely fills solution-enlarged pores in the microbialite at Death Point. Samples appear pristine, with no indication of diagenetic alteration, and consist of 100% aragonite in XRD analysis. Two cement samples have paired ^{14}C and U-Th ages (Table 1). One pair has overlapping uncertainties, and one pair has ranges separated by ~480 yr (AA-112720 and RT-002D; Table 1).

The ~6000-yr-long time span defined by ages measured in prismatic aragonite cement samples from the Death Point microbialite (Table 1) indicate that prismatic aragonite precipitated a number of times during the formation of the microbialite. For example, two samples from a multilayer, 2-cm-thick prismatic cement are separated by 3000 yr (97-DP-9-2 inner layer, 97-DP-9-3 outer layer, Table 1). Although we cannot quantitatively define the time between deposition of the microbialite and precipitation of the prismatic aragonite cement in all cases, the U-Th ages of aragonite microbialite 97-DP-9-1 and aragonite cement 97-DP-9-2 (Table 1) are separated by ~1100 yr and 1 cm along the growth direction. This indicates a relatively short time for the shallow-water microbialite to become exposed and experience subaerial meteoric dissolution and enlargement of the pores, then to be resubmerged, and for aragonite cement to precipitate (Pedone et al., 2023). None of the pores that contain prismatic aragonite cement also contain geopetal sediment, an observation that also supports a minimal time lapse between formation of the pore and precipitation of cement. Although we cannot quantify the depth of water when the prismatic aragonite cement precipitated, the multiple times of formation of aragonite cement during the microbialite history and the relatively short time between secondary pore formation and fill suggest that water depth was likely not more than 10 m, similar to maximum fluctuations for historic Great Salt Lake.

Another age for cement precipitated during the early transgressive phase of Lake Bonneville was reported by Vennin et al. (2019; sample POZ-79032; calibrated ^{14}C age ~27,000 cal yr BP; NW Oquirrh Mountains; isostatically adjusted elevation of 1343 m). The specific description and mineralogy of POZ-79032 was not given by Vennin et al. (2019), although the sample might be some of the botryoidal cement in their figure 7H. The age and elevation of this sample suggest the lake was ~60 m higher than the elevation suggested by samples of similar age at Death Point as presented in this paper and in Pedone et al. (2023). Without further information, interpretation of

POZ-79032 is problematic, and it was not used in the revision of the hydrograph.

Revision of the hydrograph for the early transgressive phase

The Bonneville deep-lake cycle was initiated by an abrupt rise about 30,000 cal yr BP (Fig. 2A). The level of the lake just before 30,000 cal yr BP, when the transgression of the deep-lake cycle began, is not known precisely, but the lake was likely to have been near its modern levels at that time, possibly close to 1300 m (Oviatt, 2015). The lake experienced an abrupt rise of 20 m, or possibly slightly more, and was near an isostatically adjusted elevation of 1320 m when the Hansel Valley basaltic ash was erupted (Oviatt et al., 1992; Miller et al., 2008). The eruptive source of the ash has not been identified (Miller et al., 2008), but its age in sediment cores from Great Salt Lake is ∼30,000 ± ∼1000 cal yr BP (Thompson et al., 1990, 2016; Thompson, R.S., and Oviatt, C.G., unpublished information; Fig. 2A).

In Figure 2A, the dashed blue line includes multiple schematic lake-level fluctuations (the precise timing and amplitude of those fluctuations are not known) between about 30,000 and 24,000 cal yr BP. The approximate ages of some of those fluctuations have been determined from the ^{14}C and U-Th ages of cement and microbialite at Death Point (Table 1), although the analytical uncertainties for those ages probably exceed the durations of the fluctuations; and it is likely that not all fluctuations have been determined at this point. The youngest age for the microbialite at a low elevation is about 24,000 cal yr BP.

One of the major implications of the revised hydrograph we are presenting here is that the age of the Stansbury shoreline will have to be reconsidered. We suggest that the Stansbury shoreline might be roughly 2000 cal yr younger than the age proposed by Currey et al. (1983; i.e., ∼23,000 rather than ∼25,000 yr BP).

The interpretation that Lake Bonneville remained at low and fluctuating levels before the Stansbury oscillation is consistent with what little is known about the stratigraphy of algal-laminated marl (ALM) in the Bonneville basin (Oviatt et al., 1990, 2018; Thompson et al., 1990, 2016; Rey et al., 2016). ALM is found at very low elevations in the Bonneville basin (Fig. 1) and low in the Lake Bonneville stratigraphic sequence, where it forms part of the laminated-marl subfacies of the Bonneville marl (Oviatt et al., 1994, 2018). ALM is composed of well-preserved algal filaments in finely laminated calcareous mud. The alga is probably a species of *Cladophora* (Oviatt et al., 1990; Thompson et al., 1990), a benthic taxon that requires light for photosynthesis. Thus, the lake had to be shallow enough for sunlight to reach the bottom, likely no more than 50 m (Thompson et al., 1990; Pedone et al., 2023)—this interpretation is different from that of Oviatt et al. (1990), who thought ALM was deposited only once during a short-lived interval, in deep water while the Stansbury shoreline was forming. More work is necessary to understand the spatial and temporal variations in the deposition of ALM, but it is likely to have formed over an extended period, and possibly more than once in different areas, before the Stansbury shoreline formed. ALM appears to be stratigraphically lower than deposits of Stansbury age, and contrary to the interpretations of Oviatt et al. (1990), the lake would have been too deep during Stansbury time and during the subsequent lake-level rise for sunlight to reach the bottom.

Dated organic matter (calibrated ^{14}C dates) from a total of nine samples of ALM from different parts of the Bonneville basin (Oviatt et al., 1990; Thompson et al., 1990, 2016; Rey et al., 2016) are collectively consistent with its relative age at the base of the Bonneville stratigraphic sequence. All but one of the ages for ALM fall within the time interval 30,000-22,500 cal yr BP. The one anomalous age of ∼19,000 cal yr BP (sample PVC22-1012-8 in Rey et al., 2016,) cannot be correct, because by 19,000 cal yr BP, Lake Bonneville would have been more than 200 m deep in the area where the ALM sample was accumulating, and benthic photosynthetic algae would not have been growing at that depth. The stratigraphic position and approximate age range of ALM support the interpretation of deposition at relatively shallow water depths during the early transgressive phase of Lake Bonneville and a start of transgression to the Stansbury shoreline after 24,000 cal yr BP.

Another indication that lake level was generally low early in the transgressive phase of Lake Bonneville comes from an interpretation of a layer of mirabilite found in shallow cores along the Southern Pacific railroad causeway that crosses Great Salt Lake (Currey, 1988). Mirabilite is hydrated sodium sulfate and precipitates in saline lake water when temperatures are low (Jones, 1965). Currey (1988, table 1) reported an estimated radiocarbon age of about 20,900 yr BP (about 25,000 cal yr BP) for the mirabilite layer. Oviatt et al. (1990, p. 302) noted that the age (∼25,000 cal yr BP) was similar to the presumed age of the Stansbury shoreline and devised an elaborate interpretive scheme for the deposition of the mirabilite in deep water. However, it makes more sense to interpret that mirabilite layer as having been precipitated in shallow water, and that interpretation fits well with the interpretation of the lake cycle presented in this paper. The mirabilite bed, about 25,000 cal yr old, reported by Currey (1988) has not been found in other places in the Bonneville basin—further work is needed on that mirabilite.

The dashed blue line in Figure 2A, representing the revision suggested in this paper, intersects with the dashed black line of the hydrograph of Oviatt (2015) between about 22,000 and 23,000 cal yr BP at an isostatically adjusted elevation of about 1450 m. The part of the chronology between about 22,000 cal yr BP and the Bonneville flood at about 17,500 cal BP (Oviatt 2020) has not been reviewed critically, and no new information is currently available for that time interval.

Paleoclimate implications

The abrupt lake rise after about 24,000 cal yr BP to elevations roughly equal to or higher than the Stansbury shoreline has not been thoroughly studied at this point. If taken at face value from the revised hydrograph (Fig. 2A) and not including fluctuations, such as those associated with the Stansbury oscillation (Oviatt et al., 1990), the average rate of lake-level rise would be about 90 m/1000 yr (rise from ∼1300 to ∼1450 m between ∼24,000 and 22,300 cal yr BP). This is a much higher rate of transgression than previously suggested for Lake Bonneville. For comparison, part of the hydrograph of Lake Lahontan in the western Great Basin shows a rise of about 95 m/1000 yr (estimated from fig. 12 in Reheis et al. [2014] between about 17,500 and 16,500 yr BP), and part of the hydrograph of Pleistocene Lake Lisan (Dead Sea basin in Israel and Jordan) shows a rise of >130 m/1000 yr (estimated from fig. 2 in Torfstein et al. [2013] between about 31,500 and 30,500 yr BP). Therefore, although the estimated transgressive rate we present here for Lake Bonneville is rapid, it is not unprecedented in reconstructions of the histories of other large Pleistocene lakes on Earth.

The cause of the post–24,000 yr abrupt rise of Lake Bonneville has not been determined, but perhaps it was connected in some way to the increase in the volume of glacial ice that led to the global last glacial maximum (LGM; Clark et al., 2009) or to the beginning of the local LGM in the Bonneville basin (Laabs and Munroe, 2016). Hemming (2004) has reported the age of Heinrich event 2 as about 24,000 cal yr BP, and the changes in climate associated with that event may be involved in some way. The relationship between lake-level change in Great Basin Pleistocene lakes and Heinrich events in the North Atlantic Ocean, however, has not been well deciphered (Nelson and Jewell, 2015); both lake-level rises and lake-level falls have been attributed to hemispheric climate changes associated with Heinrich events and other iceberg-rafting events (Oviatt, 1997; Munroe and Laabs, 2013; McGee et al., 2018).

Antevs (1948) hypothesized that the Northern Hemisphere ice sheets (Laurentide and Cordilleran) attained sufficient elevation during the LGM to influence atmospheric circulation and thus to divert storm tracks toward the Great Basin, although the relationship between Northern Hemisphere ice sheets and global circulation is not simple (Oster et al., 2015). Temperatures were lower when lakes reached their maximum sizes (Ibarra et al., 2014; Belanger et al., 2022). Belanger et al. (2022) show that a decrease in temperature was probably more important than an increase in precipitation with regard to causes of the changing levels of Lake Bonneville. The currently available evidence from the Bonneville basin, as presented in this paper, indicates rapid lake-level changes occurred; they should be included in future attempts to decipher the paleoclimate and the climatic controls on lake-level changes.

Summary

After an initial abrupt rise in lake level of about 20 m about 30,000 cal yr BP, Lake Bonneville experienced a series of low-level fluctuations during the ensuing 6000 yr before abruptly rising by more than 100 m after about 24,000 cal yr BP. Subsequently, the lake rose to its highest level, more than 270 m higher than the modern Great Salt Lake, and culminated in the formation of the Bonneville shoreline. The Stansbury shoreline formed during the transgressive phase sometime after about 24,000 cal yr BP. This scenario is different from that presented in previous hydrographs, and future work will undoubtedly test and expand upon these revisions.

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