THE GILBERT EPISODE IN THE GREAT SALT LAKE BASIN, UTAH

by Charles G. Oviatt

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Cover photo: View to the north of the southeast side of the Silver Island Mountains, northeast of Wendover, Utah; Lamus Peak is the high point on the skyline. The upper limit of the Gilbert-episode lake was at about the edge of the white sediment on the valley floor in the center of the photograph (the white sediment is the Bonneville marl and efflorescent salts). The Provo shoreline of Lake Bonneville is marked by the prominent tufa-cemented gravel rim on the flank of the mountains. The photo was taken from the Provo shoreline on a nearby hill, and tufa is visible on quartzite bedrock in the left foreground.

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CONTENTS

ABSTRACT ... 1
KEYWORDS ... 1
INTRODUCTION ... 1
PREVIOUS WORK ... 2
OBSERVATIONS ... 7
GEOCHRONOLOGY ... 15
ISOSTATIC REBOUND ... 16
DISCUSSION ... 16
CONCLUSIONS ... 18
ACKNOWLEDGMENTS ... 18
REFERENCES ... 18

FIGURES

Figure 1. A. Map of Lake Bonneville showing the Gilbert shoreline as mapped by Currey; B. Generalized hydrograph for Lake Bonneville; C. Enlargement of the part of figure 1B that shows the Gilbert episode ... 3
Figure 2. Map of the Gilbert shoreline as mapped by Currey ... 4
Figure 3. Schematic cross section through Magna spit ... 7
Figure 4. Schematic cross sections to show stratigraphic relationships between the Lake Bonneville marl and lacustrine gravel... ... 9
Figure 5. Satellite image of an area near Currey site 22 ... 10
Figure 6. Schematic diagram showing Currey's interpretation of the stratigraphy of the deposits at Public Shooting Grounds ... 10
Figure 7. Photo of core segment GSL96-6 2B, percent TIC, and δ^{18}O for endogenic carbonate. ... 11
Figure 8. Data from core BL04-4, from Blue Lake in western Utah ... 13
Figure 9. A. Photo of the wall of a gravel pit on Stansbury Island; B. Part of the USGS 1968 Corral Canyon topographic quadrangle ... 14
Figure 10. Photo composite of the northeast wall of the backhoe trench below Juke Box Cave, northeast of Wendover, Utah ... 15
Figure 11. Diagram showing the upper part of the stratigraphic section in the West(N) trench at the Baileys Lake site ... 16
Figure 12. Summary of some of the radiocarbon ages of Gilbert-episode deposits ... 17

TABLES

Table 1. Radiocarbon, luminescence, and PSV ages from Gilbert-episode sites ... 5
Table 2. Gilbert shoreline sites of Currey (1982) ... 8
Table 3. Information about Gilbert and non-Gilbert sites mentioned in the text. ... 12

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ABSTRACT

The Gilbert shoreline has been regarded as one of the major named paleolake shorelines in the Great Salt Lake basin, however, stratigraphic and geomorphic data suggest that the Gilbert shoreline should be reinterpreted. Stratigraphic evidence indicates that Lake Bonneville had regressed to altitudes at least as low as those of modern Great Salt Lake (about 1280 m; 4200 ft) by 13,000 calibrated yr B.P.; the lake remained at low altitudes for about 1400 yr, then transgressed to a maximum altitude of 1295 to 1297 m (4250–4255 ft) at 11,600 calibrated yr B.P. This lake transgression is referred to as the Gilbert episode, and it has been presumed that features previously identified as being part of the Gilbert shoreline formed at this time. In two areas where the Gilbert shoreline had been previously mapped at altitudes close to 1305 m (4280 ft), neither sediments nor shorelines of the Gilbert-episode lake have been found. Geomorphic conditions (wave energy, sediment supply and grain size, reconstructed water depth) in these areas were favorable for shoreline formation and preservation, so if no shoreline is present at these places, it is likely the lake did not transgress across this part of the basin floor. The Gilbert-episode lake covered less of the basin floor than was previously thought, and isostatic rebound in response to the removal of the earlier Lake Bonneville water load may have been completed by Gilbert-episode time. The relative ages of lacustrine barriers at previously mapped Gilbert-shoreline sites can be classified as (1) older than the deep-water phase of Lake Bonneville (not related to the Gilbert episode), (2) younger than the deep-water phase of Lake Bonneville (but not independently dated as Gilbert), (3) indeterminate (whether the barrier is older than or younger than the deep-water phase of Lake Bonneville cannot be, or has not been determined). There is no internal basin threshold, or other potential non-climatic reason for the lake to stabilize in the Gilbert-episode altitude range, so the transgression to the Gilbert-episode high must have been caused by a shift in water budget associated with climate change, but the regional paleoclimate context is not clear. The Gilbert episode occurred very late in the Northern Hemisphere Younger Dryas paleoclimate event (13,000 to 11,500 calibrated yr B.P.). Until more of the uncertainty has been resolved in understanding the Gilbert-episode lake, the Gilbert shoreline, as it has been previously mapped, should not be regarded as a well-defined altitude datum in the lacustrine chronology of the basin.

KEYWORDS

Lake Bonneville; Great Salt Lake; Gilbert shoreline; Gilbert episode; isostatic rebound; Younger Dryas

INTRODUCTION

The purposes of this paper are to present new data and interpretations of the age of the Gilbert episode (the high-lake event during which the Gilbert shoreline formed), to show that no shoreline of unequivocal Gilbert age has been found in the basin (although several possibilities exist), and to report stratigraphic and geomorphic data that suggest the hypothesized Gilbert lake may have covered less of the basin floor than is shown on previous maps. Stratigraphic evidence shows that Lake Bonneville had dropped to altitudes at least as low as those of modern Great Salt Lake by about 13,000 calibrated yr B.P. (13.0 cal ka) (Oviatt and others, 2005). The lake remained low for about 1400 yr before transgressing to the Gilbert-episode high (an altitude of 1295–1297 m; 4250–4255 ft), about 15 m (50 ft) higher than modern average Great Salt Lake, at about 11.6 cal ka. Previous workers (Currey, 1982; Bills and others, 2002) have inferred that the Gilbert shoreline (the shoreline that was presumed to have formed during the Gilbert episode) was deformed by isostatic rebound in response to the removal (evaporation) of the Lake Bonneville water load. However, because no stratigraphic evidence of sediments of Gilbert-episode age has been found higher than ~1295 m (4250 ft) in two of the areas where the Gilbert shoreline has been mapped at altitudes of about 1305 m (4280 ft; in the areas of Currey [1982] sites 9, 20, and 21; figures 1 and 2), the shoreline that formed during the Gilbert episode may be horizontal and not isostatically deformed. Some of the barriers or other shoreline features previously identified as Gilbert (Currey, 1982) may be related to the Gilbert episode, but others probably are not. The Gilbert-episode shoreline has not been unequivocally identified at any location in the basin. In post-Gilbert time Great Salt Lake has fluctuated within about ± 6 m of its average historic altitude (~1280 m; 4200 ft).

As described in previous literature, the Gilbert shoreline has been viewed as a Lake Bonneville shoreline (e.g., Currey and others, 1984; Hylland and others, 2012) or as a Great Salt Lake shoreline (e.g., Currey, 1990; Oviatt and others, 2005). In this paper, the Gilbert-episode lake is regarded as distinct from both Lake Bonneville and Great Salt Lake because it occurred long after the regression of Lake Bonneville from the Provo shoreline and it contained brackish water, not the hypersaline water of Great Salt Lake.

The shoreline for an existing lake is the boundary line between the lake water and the land, and thus is an ephemeral feature that shifts constantly in vertical and horizontal positions with changes in weather, climate, tectonics, and geomorphic processes. For an ancient lake where the water evaporated long ago, the shoreline is defined as a line that connects depositional and erosional landforms that were produced simultaneously at the edge of the ancient lake, and that mark the highest altitude attained by that lake. Ancient shorelines might vary in altitude from place to place by 2 to 3 m (6–9 ft), depending on variations in geomorphic processes. Examples of ancient shorelines that have been defined in the Bonneville basin are the Bonneville and Provo shorelines (Gilbert, 1890). The Bonneville shoreline marks the highest altitude reached by Lake Bonneville, where the lake first reached the low point on the basin rim and began to overflow into the Snake River drainage basin in southern Idaho about 18 cal ka. The Provo shoreline marks the highest altitude of the overflowing lake about 15 cal ka. Numerous other shorelines were formed before and after Lake Bonneville overflowed and are visible at various places in the basin above and below the Provo shoreline. Some of these (e.g., the Stansbury shoreline of Gilbert, 1890) have been named, although mapping these shorelines has been problematic because they formed while the lake occupied a closed basin and its surface altitude was not stable for an extended period. Sedimentary deposits that were laid down in or near the surf zone or within wave base of ancient lakes, do not define shorelines in the sense the term is used here, but they can be useful in attempts to limit ancient-lake dimensions in basins where landforms are not preserved.

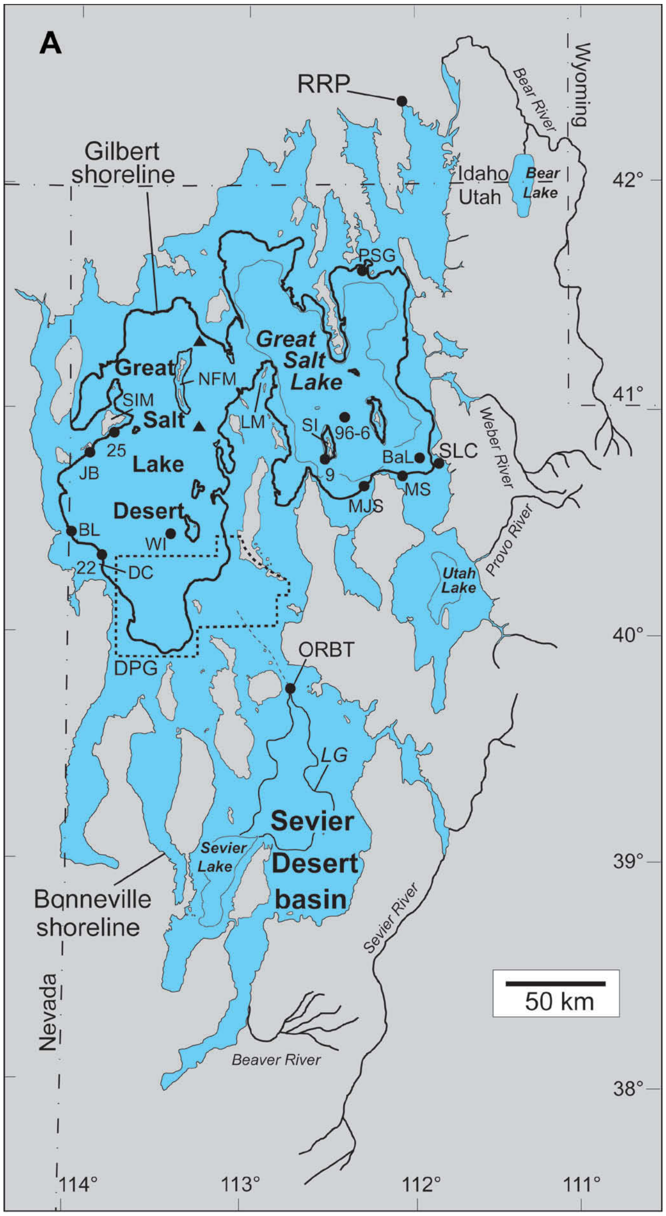
So far, no landform in the Bonneville basin has been positively and exclusively identified as marking the highest shoreline of the Gilbert-episode lake. A number of geomorphic features that seem to have reasonable altitudes and relative ages for potentially being the Gilbert-episode shoreline, however, have been identified at various places around the basin (see the discussion below), and others likely exist. One of the purposes of this paper is to point out that there is more uncertainty in our knowledge of lake-surface altitude during the Gilbert episode than a line drawn on a map would suggest. Future geologic work in the basin should not be based on the assumption that the chronology and altitude of the Gilbert lake is known with certainty. Additional detailed work on the Gilbert episode and its shoreline should be pursued to clarify the upper altitudinal limit of the Gilbert lake and to determine its paleoclimatic significance.

PREVIOUS WORK

Eardley and others (1957, p. 1155–1157) first proposed the idea that a shoreline could be mapped around the Great Salt Lake basin that was lower in altitude than Lake Bonneville shorelines, but relatively high in altitude compared to modern Great Salt Lake. They named this shoreline the Gilbert beach or Gilbert level. These authors described Gilbert-beach features at four localities around the lake, and mentioned similar shorelines at several other sites. Their map (Eardley and others, 1957, figure 7, p. 1158–1159) depicts the Gilbert level at an altitude of 4245 ft (1294 m) east of Great Salt Lake but does not show the shoreline in the Great Salt Lake Desert. Eardley and others (1957) regarded the Gilbert level as having been produced during the expansion of Great Salt Lake into the Great Salt Lake Desert. They reasoned that there should be a shoreline at or close to the altitude of the topographic threshold between the Great Salt Lake and the Great Salt Lake Desert (4220 ft; 1286 m; figure 1A) because at that altitude the surface area would expand so that output by evaporation would be roughly equal to input by precipitation and runoff. The Gilbert-level altitude used by Eardley and others (1957) (1294 m; 4245 ft) is about 8 m (26 ft) higher than the topographic threshold, but they did not identify other mappable shorelines at altitudes closer to the threshold altitude, and they regarded the Gilbert level as the most likely candidate to fit the Great Salt Lake-expansion hypothesis. Later, Eardley (1962) abandoned the idea that the Gilbert level was related to the threshold between Great Salt Lake and the Great Salt Lake Desert.

Antevs (1955, figure 92) showed the Mills Junction spit (figure 2, site 8) to have an altitude of 4262 ft (1299 m) and an age slightly older than 3000 yr, but he did not indicate what this age estimate was based on. Eardley and others (1957) mapped the Mills Junction spit as part of the Gilbert beach. Although Morrison (1966, p. 101) did not use the term “Gilbert shoreline,” he thought there might have been several lake rises to about 4260 ft (1298 m) in Neoglacial (late Holocene) time, however, he did not present evidence for this conclusion. Van Horn (1979, p. C10) thought the Gilbert shoreline was either 3000 or 1700 yr old, depending on which isostatic-rebound model he used for age calculation.

Currey (Currey, 1980; Currey and James, 1982) dated gastropod shells collected from wetland sediments at the Magna spit (figure 1A, site 5, altitude 1299 m; 4262 ft) at 10.29 ± 0.27 and 10.30 ± 0.31 ^{14}C ka B.P. Later he obtained an age of 10.57 ± 0.06 ^{14}C ka B.P. for material he referred to as peat in a sewer trench at the Magna spit (Currey, unpublished information, not dated) (table 1). The stratigraphic relationships between the two shell ages and the peat age are not known, but the two shell samples were collected from wetland sediments on the mainland (south) side of the Magna spit (figure 3). Currey (1980) interpreted the wetland sediments as having been deposited in a lagoon of the same age as the spit gravels, and the spit as part of the Gilbert shoreline. If this is correct, these



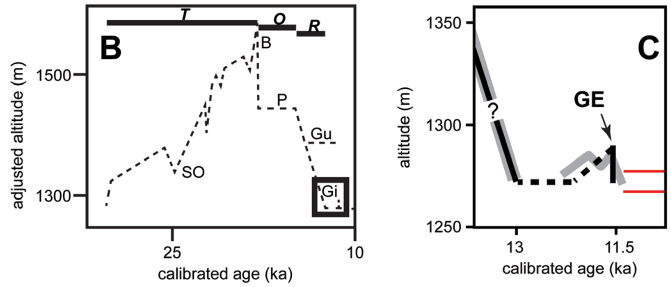


Figure 1. A. *Map of Lake Bonneville showing the Gilbert shoreline as mapped by Currey (1982). 9 = Stansbury Island Gilbert-shoreline site (Currey, 1982, site 9); 96-6 = site of core GSL96-6; BaL = Baileys Lake; BL = Blue Lake; DC = Deep Creek; DPG = Dugway Proving Ground (boundary shown by dotted line); JB = Juke Box trench; LG = approximate outline of Lake Gunnison, the late-Pleistocene shallow lake in the Sevier Desert basin that overflowed along the Old River Bed into the Great Salt Lake basin; LM = Lakeside Mountains; MJS = Mills Junction spit; MS = Magna spit; ORBT = Old River Bed threshold, the topographic divide between the Sevier basin and the Great Salt Lake Desert; PSG = Public Shooting Grounds; RRP = Red Rock Pass, the overflow threshold of Lake Bonneville in southern Idaho; SI = Stansbury Island; SIM = Silver Island Mountains; SLC = Salt Lake City; WI = Wild Isle site.* ***B.*** *Generalized hydrograph for Lake Bonneville, modified after Oviatt and others (2005) and Reheis and others (in press). SO = Stansbury oscillation; B = Bonneville shoreline; P = Provo shoreline; Gu = Gunnison shoreline (in the Sevier Desert basin); Gi = Gilbert shoreline. T = transgressive phase; O = overflowing phase; R = regressive phase. The dark rectangle shows the area enlarged in figure 1C.* ***C.*** *Enlargement of the part of figure 1B that shows the Gilbert episode. The gray line is the interpretation of Oviatt and others (2005); the solid black line is the interpretation presented in this paper; the dashed line represents uncertainty in lake-level chronology during the pre-Gilbert interval; and the two horizontal red lines younger than the Gilbert episode represent the upper and lower altitude limits of Holocene Great Salt Lake fluctuations. GE = Gilbert episode.*

are the only radiocarbon ages in the basin directly related to the Gilbert shoreline.

Currey's (1980) interpretation is speculative, however, because no available observations show that the wetland sediments at Magna interfinger with the spit gravels. It is not clear whether the wetland sediments were deposited in a lagoon that formed at the same time as the gravel barrier, or in groundwater-fed wetlands in the topographic depression behind the spit. The hypothesis that the wetland sediments are groundwater-fed depression fill is consistent with modern-day shallow groundwater in the Magna area, which is fed by recharge in the nearby Oquirrh Mountains (Lowe and others, 2005; Castleton and others, 2011). If the wetlands at Magna were not formed at the same time the barrier-spit gravel was deposited, the spit may have formed during the regressive phase of Lake Bonneville, or at an earlier time, and is unrelated to the Gilbert episode. More data from the Magna spit are needed to resolve this question.

Sediments of the Gilbert episode have been studied and dated at the Public Shooting Grounds, north of Great Salt Lake (figure 1A; Miller and others, 1980; Murchison, 1989; Currey, 1990; Benson and others, 1992; Oviatt and others, 2005). At the Public Shooting Grounds a ripple-laminated sand bed thickens upslope toward gravel barriers that Currey (1982) mapped as the Gilbert shoreline in this area (figure 2; table 2; Currey, 1982, sites 1 and 48), so Oviatt and others (2005) inferred that the ripple-laminated sand and the barrier gravel were the same age. Based on radiocarbon ages of organic wetland sediments at the base of and within the ripple-laminated sand, Oviatt and others (2005) thought the Gilbert episode occurred sometime between 12.9 and 11.2 cal ka (between 11 and 9.8 ^{14}C ka B.P.). The inference that the

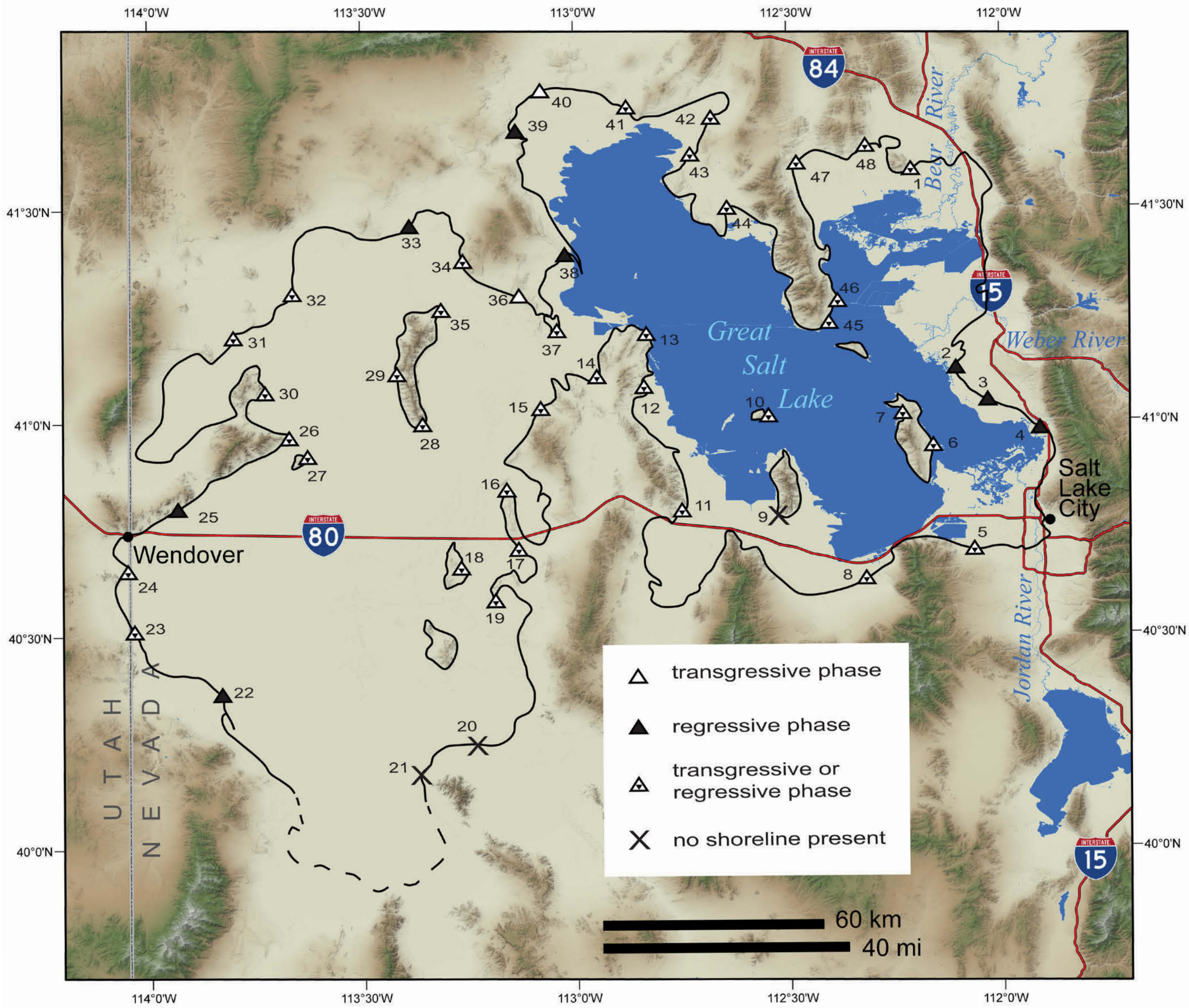


Figure 2. *Map of the Gilbert shoreline as mapped by Currey (1982). Numbers refer to Currey's sites (table 2). Note that the map is plotted on a square (not projected) grid. Open triangles are used for sites where barrier gravel stratigraphically underlies Lake Bonneville marl, and therefore was deposited during the transgressive phase. Closed triangles are used for sites where barrier gravel stratigraphically overlies the marl, and therefore the gravel was deposited during the regressive phase of Lake Bonneville, or in post-Bonneville time. Open triangles with black-triangular centers are used for sites where the relative age of the barrier gravel (that is, whether it is transgressive or regressive) has not been determined. Xs are used for sites where no shorelines (sites 20 and 21), or no Gilbert-age sediments (site 9), are present. The shoreline of the Gilbert-episode lake was probably similar to Currey's mapping of the Gilbert shoreline (at this map scale) where slopes are relatively steep around Great Salt Lake, but would have much less extensive on the mudflats and salt flats in the western part of the basin.*

ripple-laminated sand is the same age as the barrier-beach gravel cannot be tested without better exposures in the Public Shooting Grounds area, but the barrier altitudes at sites 1 and 48 (1297 and 1296 m; 4255 and 4252 ft) are within the range suggested in this paper for the Gilbert episode.

Figure 2 shows Currey's (1982) map of the Gilbert shoreline. The numbered points on the map are keyed to Currey's (1982) list of sites (table 2), which includes horizontal and vertical coordinates of the shoreline feature at each site (the precision of Currey's [1982] measurements, as noted in his table, was ± ~1 km horizontally and ± 1–3 m vertically, although careful reading of his 1:500,000-scale map in comparison with the 1:24,000-scale maps available to Currey in the early 1980s permits higher horizontal precision in estimating the coordinates of his sites). At most sites, Currey estimated the altitude of the crest of a well-defined barrier beach that he had identified as being of Gilbert age. According to footnotes in Currey's (1982) table of data, he made on-the-ground visits to 22 of his 48 Gilbert-shoreline points, and he studied others remotely using aerial photographs and topographic maps. Currey's (1982) map shows the 48 points connected by a line

__Table 1.__ Radiocarbon, luminescence, and PSV ages from Gilbert-episode sites

lab number	^{14}C age (yr)	^{14}C error[1] (yr)	cal min[2] (yr)	cal mid[2] (yr)	cal max[2] (yr)	cal error[2] (yr)	material	method[3]	stratigraphy	location	reference
WW-4145	9850	40	11200	11300	11300	50	plant fragments	radiocarbon AMS	channel-fill sand	Public Shooting Grounds	Oviatt and others, 2005
WW-2773	9980	40	11300	11400	11600	200	humate	radiocarbon AMS	channel-fill sand	Public Shooting Grounds	Oviatt and others, 2005
WW-2759	10040	70	11300	11600	11900	300	plant fragments plus sediment	radiocarbon AMS	wetland deposits; mid unit 2	Public Shooting Grounds	Oviatt and others, 2005
WW-4261	10105	45	11400	11700	12000	300	plant fragments	radiocarbon AMS	wetland deposits; base unit 2	Public Shooting Grounds	Oviatt and others, 2005
WW-3680	10195	35	11800	11900	12100	150	humic acid	radiocarbon AMS	wetland deposits; base unit 2	Public Shooting Grounds	Oviatt and others, 2005
WW-2760	10440	70	12100	12300	12600	250	plant fragments	radiocarbon AMS	wetland deposits; base unit 2	Public Shooting Grounds	Oviatt and others, 2005
WW-3681	10500	35	12200	12400	12600	200	plant fragments	radiocarbon AMS	wetland deposits; base unit 2	Public Shooting Grounds	Oviatt and others, 2005
GX-6614	10285	265	12300	12000	12700	700	gastropods	radiocarbon radiometric	wetland deposits	Magna spit	Currey, 1980; Currey and others, 1983; Benson and others, 1992
GX-6949	10300	310	11200	12000	12800	800	gastropods	radiocarbon radiometric	wetland deposits	Magna spit	Currey, 1980; Currey and others, 1983; Benson and others, 1992
Beta-159195	10570	60	12400	12500	12700	150	“peat”	radiocarbon AMS	wetland deposits	Magna spit	Currey, unpublished
WW-4617	10600	270	11500	12300	13100	800	wood fragment	radiocarbon AMS	core GSL96-6-2B-16.0	Great Salt Lake sediment core	Thompson and Oviatt, unpublished
PSG-125B	----	----	----	10030	----	510	sand	OSL	Gilbert sand, upper	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125B	----	----	----	9870	----	630	sand	IRSL	Gilbert sand, upper	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013

Table 1. *continued*

lab number	^{14}C age (yr)	^{14}C error[1] (yr)	cal min[2] (yr)	cal mid[2] (yr)	cal max[2] (yr)	cal error[2] (yr)	material	method[3]	stratigraphy	location	reference
PSG-125B	----	----	----	10950	----	850	sand	TL	Gilbert sand, upper	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125C	----	----	----	11160	----	570	sand	OSL	Gilbert sand, middle	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125C	----	----	----	10635	----	530	sand	IRSL	Gilbert sand, middle	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125C	----	----	----	10670	----	730	sand	TL	Gilbert sand, middle	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125D	----	----	----	13240	----	910	sand	OSL	Gilbert sand, lower	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125D	----	----	----	11660	----	1080	sand	IRSL	Gilbert sand, lower	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
PSG-125D	----	----	----	11040	----	1090	sand	TL	Gilbert sand, lower	Public Shooting Grounds	Oviatt and others, 2005; S. Mahan, written communication, 2013
BL-L14	----	----	----	11510	----	2610	sand	OSL	Gilbert sand, middle	Baileys Lake trench	Hylland and others, 2012
BL-L13	----	----	----	12530	----	910	sand	OSL	Gilbert marl, lower	Baileys Lake trench	Hylland and others, 2012
-----	----	----	----	11500-10700	----	----[4]	PSV	PSV	base and top of TIC spike	Blue Lake core	Benson and others 2011, supplementary data

[1] *Radiocarbon error is 1-sigma, reported by laboratory.*
[2] *Radiocarbon ages calibrated using CALIB7.0 (Stuiver and Reimer, 1993; Reimer and others, 2013). cal min = lower limit of 2-sigma calibrated range; cal max = upper limit of 2-sigma calibrated range; cal mid = average of cal min and cal max; cal error = ± years from cal mid to the limits of the 2-sigma range. Calibrated radiocarbon ages are rounded to the nearest 100 cal yr; calibrated-age errors are rounded to the nearest 50 cal yr. Luminescence and PSV (paleomagnetic secular variation) ages are not calibrated.*
[3] *Luminescence ages (OSL = optically stimulated luminescence; IRSL = infrared stimulated luminescence; TL = thermoluminescence) from the Public Shooting Grounds are re-calculated from ages reported in Oviatt and others (2005) using the following water contents: PSG-125B 7%, PSG-125C 13%, PSG-125D 14% (S. Mahan, personal communication, 2013. AMS = accelerator mass spectrometer.*
[4] *No errors were reported for PSV ages (Benson and others, 2011).*

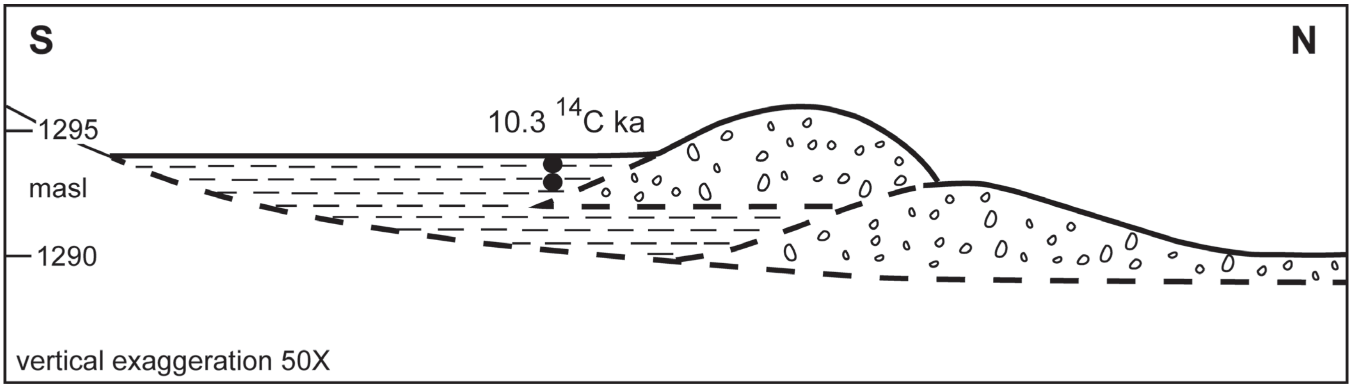


Figure 3. *Schematic cross section through Magna spit (Currey, 1982, site 5). Modified from Currey and others (1983, figure 13). The two black circles are a schematic representation of the two shell ages from this site (see text and table 1).*

on the map, but no shoreline exists on the ground connecting these points; because there is no independent evidence that landforms at all 48 points are the same age, it is difficult to interpret Currey's map.

At some of Currey's (1982) Gilbert-shoreline sites the stratigraphic relationship of the barrier gravel to the fine-grained deep-water deposits of Lake Bonneville (the Bonneville marl) can be determined in the field. If remnants of the Bonneville marl are found resting on the barrier gravel (figure 4A), the barrier at that location was formed prior to the deep-water phase of the lake, and may be early-transgressive-phase Bonneville or older, and not of Gilbert age. If the marl is beneath the barrier gravel (figure 4B), the barrier is younger than the marl and was deposited during the regressive phase of the lake or in post-Lake Bonneville time. Using these and other field observations, the relative age of landforms at Currey's (1982) Gilbert-shoreline sites can be classified as (A) transgressive-phase Bonneville (the Bonneville marl overlies the barrier gravel at that site), (B) regressive-phase Bonneville or post-Bonneville (the Bonneville marl underlies the barrier gravel at that site), or (C) indeterminate—the relative age of the barrier gravel cannot be determined (exposures are insufficient to reveal the stratigraphic relationships between the gravel and the marl), or has not been determined (table 2). In three cases no Gilbert-age shoreline features or sediments are present (Currey [1982] sites 9, 20, and 21).

For a shoreline feature to be of Gilbert age, the feature should be demonstrably younger than the Bonneville marl, associated with independent geochronological or stratigraphic data that link it to the Gilbert episode, and, as discussed below in this paper, have an altitude within the approximate range of 1295–1297 m (4250–4255 ft). Although there is clear stratigraphic evidence for the Gilbert episode at a few places (for example, at the Public Shooting Grounds and in sediment cores from Great Salt Lake), and landforms at some of Currey's (1982) sites could possibly be of Gilbert age (see table 2 and descriptions below), there is no place in the basin where a shoreline landform of unequivocally Gilbert age has been found. Note that barriers and other lacustrine landforms are common in the Bonneville basin at altitudes slightly higher than features Currey (1982) mapped as part of the Gilbert shoreline (figure 5). These barriers are most likely unrelated to the Gilbert episode and are either transgressive-phase or regressive-phase Bonneville in age.

OBSERVATIONS

Currey (1990, p. 201) described reddish sediments directly beneath Gilbert-age deposits at a number of low-altitude locations in the Great Salt Lake basin, and referred to those sediments as the "pre-Gilbert red beds" (figure 6). He envisioned the origin of the red beds as fine-grained, sulfide-rich sediments of Lake Bonneville that were reworked by waves and oxidized in the water column by "receding brines" as the lake regressed. An alternative interpretation is that the pre-Gilbert red beds are regressive-phase Lake Bonneville deposits that were oxidized in place in a soil-forming environment in pre-Gilbert time.

Pre-Gilbert red beds are not found at every place where deposits that are presumed to be of Gilbert-episode age are present, and this is not surprising because soil-forming factors and rates of sediment erosion and deposition vary considerably across landscapes. A site northeast of Wendover, Utah, along the east side of the Silver Island Mountains (about 12 km northeast of Currey site 25; figures 1 and 2) provides a typical example of sediments that have been referred to as the pre-Gilbert red beds. At this site, lacustrine gravel, which was deposited in a low barrier or beach, forms a protective cap on fine-grained sediments that include Lake Bonneville marl and pre-Bonneville oolitic sand. The gravel and underlying marl stand 3 or 4 m higher than the surrounding flats at an altitude of 1296 m (4252 ft) in a smooth, elongate erosional landform referred to informally as a "lozenge" (D.B. Madsen, verbal communication, 1980s). The gravel overlies reddish sediments that Currey correlated with the pre-Gilbert red beds (Currey, verbal communication, 1980s).

Table 2. *Gilbert shoreline sites of Currey (1982).*

Site number, figure 2	altitude (m)	altitude (ft)	locality name	Currey level of investigation[1]	Category[2]	possible Gilbert-episode shoreline[3]
1	1297	4255	Little Mountain E shore	1	C	X
2	1294	4245	Hooper Canal beach	2	C	X
3	1294	4245	Bluff Road shore	3	C	X
4	1293	4242	Haight Creek bluff	2	C	X
5	1296	4252	Magna spit	3	C	X
6	1300	4265	Sea Gull Point V bar	1	C	
7	1305	4281	White Rock bay	3	C	
8	1299	4262	Mills Junction spit	2	C	
9	1305	4281	Tabbys Canyon V bar	2	D	
10	1309	4295	Carrington Island SE spit	1	C	
11	1308	4291	Poverty Point V bar	3	C	
12	1311	4301	Hill 4718 N cove	1	C	
13	1311	4301	Little Valley bayhead beach	1	C	
14	1310	4298	Homestead Knoll SW Bay	1	C	
15	1311	4301	Grassy Mountains NW V bar	1	C	
16	1306	4285	Hill 4654 SW coves	1	C	
17	1308	4291	Grayback Hill SE spit	2	C	
18	1306	4285	Knolls SE Cove	1	C	
19	1306	4285	Hill 4426 SE spits	1	C	
20	1306	4285	Old River Bed delta	1	D	
21	1305	4281	Granite Peak NW beach	1	D	
22	1300[4]	4265	Deep Creek N beach	1	B	X
23	1299	4262	Lead Mine Hills NE headland	1	C	
24	1300	4265	Salt SE tombolo	1	C	
25	1297	4255	Volcano Peak SE cove	2	B	X
26	1300	4265	Cobb Peak SE V bar	2	C	
27	1302	4272	Floating Island E V bar	1	C	
28	1306	4285	Newfoundland Mountains SE V bar	1	C	
29	1304	4278	Newfoundland Mountains W V bar	1	C	
30	1302	4272	Crater Island SE tombolo	1	C	
31	1299	4262	Lemay Island SE spit	1	C	
32	1302	4272	Little Pigeon Mountains NE beach	1	C	
33	1299	4262	Terrace Mountain SE spit	1	B	
34	1303	4275	Crescent Spring cove	2	C	

Table 2. *continued*

Site number, figure 2	altitude (m)	altitude (ft)	locality name	Currey level of investigation[1]	Category[2]	possible Gilbert-episode shoreline[3]
35	1304	4278	Newfoundland Mountains NE V bar	1	C	
36	1306	4285	Hogup NW beach	2	A	
37	1309	4295	Hogup Ridge S V bar	1	C	
38	1304	4278	The Fingerpoint W bay	2	B	
39	1300	4265	Peplin Flats NE beach	2	B	
40	1304	4278	Bar F Ranch beach	2	A	
41	1299	4262	Locomotive Springs NE spit	2	C	
42	1300	4265	Lake Ridge N beach	2	C	
43	1306	4285	Black Mountain NE cove	2	C	
44	1306	4285	Rozel Flat beach	2	C	
45	1305	4281	Promontory Point NE V bar	2	C	
46	1305	4281	Pokes Point V bar	2	C	
47	1301	4268	Blue Creek Ponds SW beach	1	C	
48	1296	4252	Penrose S cove	1	C	X

[1]*Currey level of investigation (Currey, 1982): 1 aerial photo and map interpretation; 2 interpretation augmented by field reconnaissance; 3 interpretation augmented by spirit leveling.*
[2]*Categories: A. transgressive-phase barrier beach (cannot be of Gilbert age); B. regressive-phase barrier beach (could be of pre-Gilbert or Gilbert age); C. barrier beach (the relative age – whether it is transgressive-phase or regressive-phase – has not been, or cannot be determined); D. no shoreline at the site.*
[3]*The landform at this location has an altitude that is close to the possible range of the Gilbert-episode lake (i.e., 1295-1297 m), and the landform age is regressive-phase Bonneville or post-Bonneville, so although it is not known whether the Gilbert-episode lake was responsible for the formation of the landform, it is possible.*
[4] *Altitude re-measured by differential GPS on June 4, 2013, at 1297 m, with the assistance of Adam McKean and Don Clark, Utah Geological Survey.*

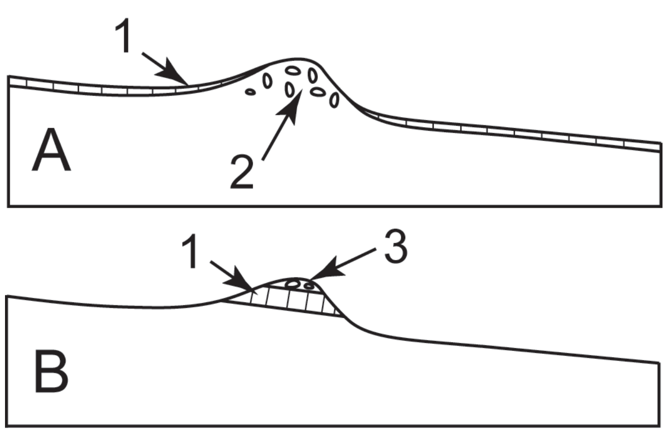


Figure 4. *Schematic cross sections to show stratigraphic relationships between the Lake Bonneville marl and lacustrine gravel in barriers that have been mapped as part of the Gilbert shoreline (Currey, 1982).* **A**. *The gravel is older than the marl (1), and therefore was deposited prior to the deep-water phase of Lake Bonneville, and the barrier (2) is not of Gilbert age.* **B**. *The gravel is younger than the marl (1), and therefore the barrier (3) was deposited either during the regressive phase of Lake Bonneville or in post-Bonneville time and could be of Gilbert age.*

At this site the reddish sediments are composed of poorly sorted calcareous mud and fine sand. A possible interpretation of these sediments is that they were deposited in shallow water during the late regressive phase of Lake Bonneville and were oxidized and bioturbated by soil-forming processes prior to the deposition of the gravel. If this interpretation is correct, the gravel at this site could be of Gilbert-episode age (the altitude and the presence of the pre-Gilbert red beds are consistent with this interpretation), although no numerical ages or other geochronological data are available from this site to test this correlation.

The pre-Gilbert red beds at the Public Shooting Grounds contain undisturbed ostracodes that are typical of the regressive phase of Lake Bonneville (Oviatt and others, 2005), suggesting that the sediments were deposited with no reworking (reworking would have caused ostracode shells to be broken, frosted, or coated with mud). Oxidation (reddening) of these sediments, and mudcracks at their stratigraphic top, suggest weathering in place during the period of low lake levels during pre-Gilbert time.

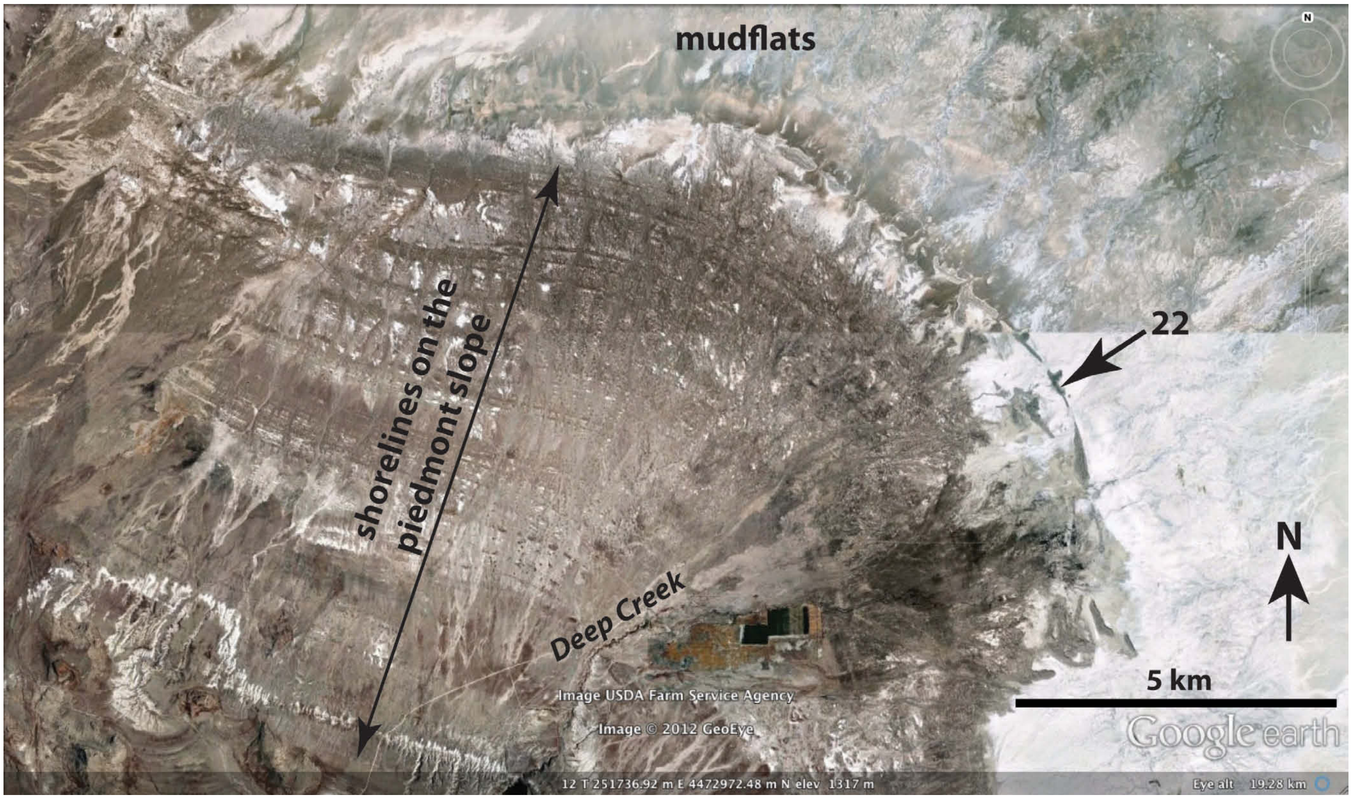


***Figure 5.** Satellite image of an area near Currey (1982) site 22 (see figure 2; table 2). Site 22 is on the features Currey (1982) mapped as the Gilbert shoreline. Note the numerous shorelines (gravel barriers) above Currey's Gilbert shoreline on the piedmont slope (which has an average gradient of 0.0070). Although these shorelines have not been examined in detail in the field, based on observations at many other places in the basin it is likely that there are both transgressive-phase and regressive-phase shorelines here.*

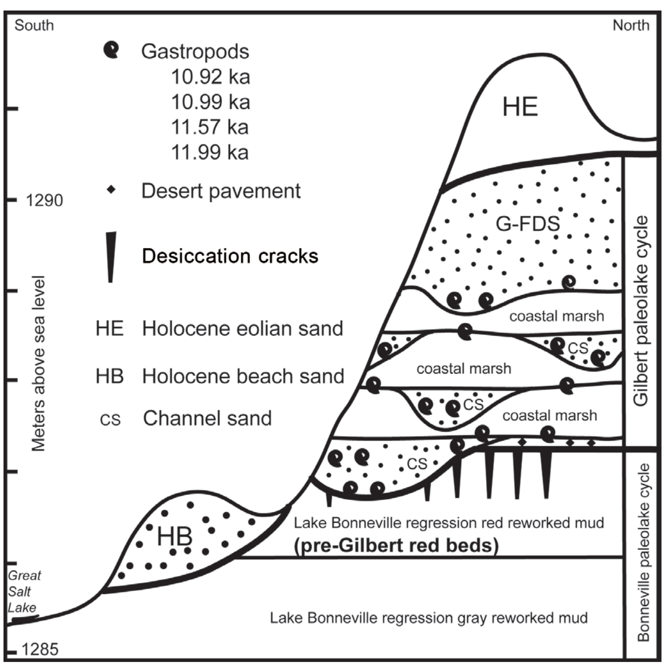


***Figure 6.** Schematic diagram modified from Oviatt and others (2005, figure 3A), which was modified from Currey (1990, figure 15), showing Currey's interpretation of the stratigraphy of the deposits at Public Shooting Grounds, including the pre-Gilbert red beds. G-FDS = "Gilbert shoreline fluviodeltaic fine sand," as interpreted by Currey (1990).*

Currey (1982) site 22 is near the mouth of Deep Creek on the western edge of the Great Salt Lake Desert (figure 2). At this site lacustrine gravel overlies Lake Bonneville marl with no intervening reddish unit (that is, no pre-Gilbert red beds). The altitude of the crest of the gravel is about 1297 m (4255 ft), an altitude that is reasonable for being related to the Gilbert episode (table 3; altitude rounded to the nearest meter, measured using a differential GPS unit; Currey [1982] reported an altitude of 1300 m [4265 ft] for this site).

In sediment core GSL96-6 from the floor of Great Salt Lake (figures 1 and 7; Thompson and Oviatt, unpublished work on Great Salt Lake sediment cores), the interval interpreted to represent the Gilbert episode (between about 18 and 13 cm; figure 7) is at an altitude of approximately 1263 m (4144 ft) and consists of carbonate mud that contains reworked and mud-coated ostracodes and un-reworked ostracodes. No brine shrimp cysts are present in the Gilbert or pre-Gilbert sediments in GSL96-6-2B, but cysts are abundant in the finely laminated mud directly above Gilbert sediments (above 13 cm). The absence of brine shrimp and the presence of un-reworked ostracodes (including the species *Limnocythere sappaensis*) indicate that the Gilbert-lake water was not hypersaline, but may have been brackish based on the presence of *L. sappaensis*. *L. sappaensis* suggests total dissolved solids were between about 500 and 10,000 mg/L (Smith, 2013); hy-

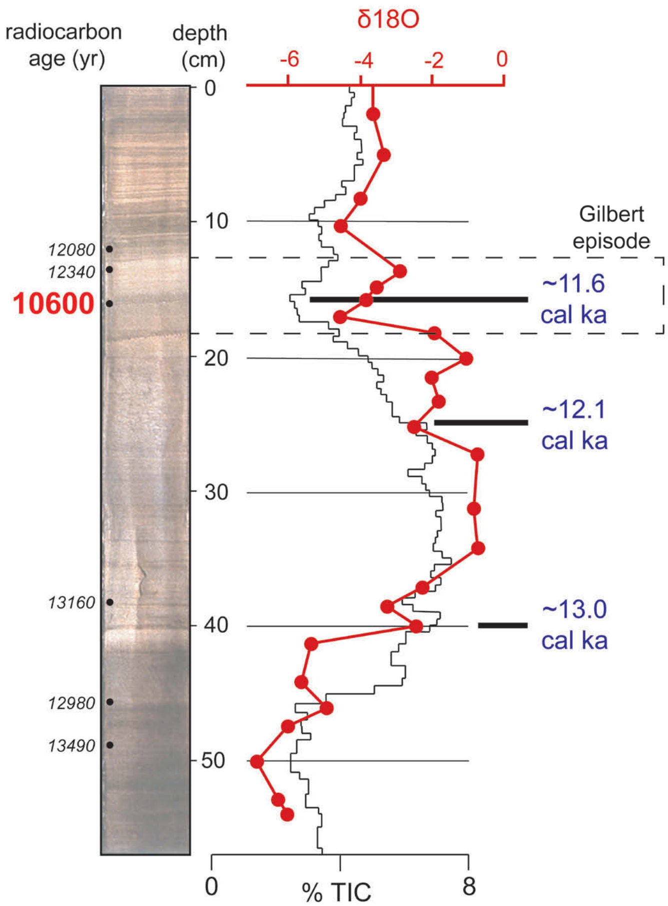


Figure 7 (left). *Photo of core segment GSL96-6 2B, percent TIC, and $\delta^{18}O$ for endogenic carbonate; core taken in 1996 from the floor of Great Salt Lake (core site shown on figure 1A; information from Thompson and Oviatt, unpublished work on Great Salt Lake sediment cores). The Gilbert episode is interpreted to be represented by sediment between about 18 and 13 cm. Numbers in italics are radiocarbon ages for bulk-organic samples from the core. The bold-red number (10600) marks a radiocarbon age (in radiocarbon yr B.P.) for a small piece of wood (table 1). Note that the wood age is younger than the bulk-carbon ages; it should be interpreted as a maximum-limiting age for the Gilbert episode (the enclosing sediments are younger than 10.6 ^{14}C ka B.P.). The bulk-organic radiocarbon ages should be adjusted by subtracting 1800 yr prior to calibration, based on data from higher in the core and comparison of the wood age (10.6 ^{14}C ka B.P.) to the bulk-carbon ages (Thompson and Oviatt, unpublished work on Great Salt Lake sediment cores; the cause of the 1800-yr offset is not known but may be related to radiocarbon-dead organic matter mixed in the sediment). Three approximate calibrated-age calls (~13.0, ~12.1, and ~11.6 cal ka) are shown. The low points in the TIC and $\delta^{18}O$ values at 16 to 17 cm are interpreted to mark the culmination of the Gilbert episode (maximum freshening), which has been independently dated at the Public Shooting Grounds at about 11.6 cal ka (see text). Using a deposition rate of 0.014 cm/yr (calculated from the radiocarbon ages in the core), the age of the beginning of the decline in TIC at 25 cm is about 12.1 cal ka, and TIC reaches its lowest value at about 16 cm; $\delta^{18}O$ begins to decline higher in the core (at about 20 cm) and reaches its lowest value at about 17 cm (the differences between the TIC and $\delta^{18}O$ curves for this core have not been studied). The finely laminated sediments above 13 cm contain brine shrimp cysts – no brine shrimp cysts are present below this depth. Note the two inclined laminations, which contain mud-coated ostracodes, at depths of ~18 and 16 cm. The inclination of these laminations is interpreted to represent wave agitation or earthquake disruption of the Great Salt Lake bottom during the Gilbert episode.*

persaline water (or brine) typically has total dissolved solids significantly greater than that of average seawater, ~35,000 mg/L (Drever, 1988).

In GSL96-6-2B, total inorganic carbon (TIC) in the sediments, and oxygen isotopes ($\delta^{18}O$) in the endogenic carbonate, begin to decrease at 25 and 20 cm, respectively (figure 7). If the beginning of the decline in total inorganic carbon (TIC) is interpreted as the beginning of freshening of the lake water at the end of the pre-Gilbert low-lake interval, its age is approximately 12.1 cal ka (assuming a constant sedimentation rate in this part of the core). If $\delta^{18}O$ is used instead of TIC, the age of the beginning of freshening is between 12.1 and 11.6 cal ka.

A small piece of carbonized wood collected from a depth of 16 cm in GSL96-6-2B has provided a radiocarbon age of 10.6 ± 0.27 ^{14}C ka B.P. (12.3 ± 0.8 cal ka) (figure 7; tables 1 and 3). The wood fragment was collected from a 0.5-cm-thick sediment sample that also contained mud-coated ostracodes in a lamination that is slightly inclined relative to the beds below it in the core. The inclined lamination may represent slight truncation of the lake-bottom muds by increased wave agitation in deep water (15 to 30 m [30 to 100 ft] deep), or it could mark disruption of the lake bottom by an earthquake that occurred at about Gilbert episode time (Hylland and others, 2012, in press). There is no evidence in the core that the lake bottom at this site was subaerially exposed prior to the Gilbert episode (possible evidence for exposure would include roots, mud cracks, or oxidation in the sediments underlying the inclined lamination). The wood fragment was probably entrained by waves from the gently sloping ground at the lake edge, and the radiocarbon age should be regarded as a maximum-limiting age for the Gilbert episode.

In a sediment core (BL04-4) taken at Blue Lake in far western Utah (figure 1A; core-site altitude 1297 m; 4255 ft) Benson and others (2011, figure 2) interpreted the Gilbert interval to be between paleomagnetic secular variation (PSV) ages of 13 and 11.5 cal ka (between depths of 305 and 288 cm; Benson and others, 2011, supplementary data). This age range is the same as the age range of the Younger Dryas as it has been identified in ice cores from Greenland (Bradley and England, 2008), but in the context of the other information from the Bonneville basin, the Blue Lake site would have been subaerially exposed during this time period. There are

Table 3. *Information about Gilbert and non-Gilbert sites mentioned in the text.*

site[1]	specific site information	closest Currey (1982) sites[2]	Gilbert shoreline altitude (Currey, 1982)	ground surface altitude (m)[3]	distance to base of Gilbert (m)	base of Gilbert sediments altitude (m)[3]	age of Gilbert sediments (cal yr ka)	reference	notes
Public Shooting Grounds	outcrop site 3 of Oviatt and others, 2005	1, 48	1297, 1296	1295	-5	1290	<11.7 base; 11.6 middle of section	Oviatt and others, 2005; this paper	nearshore sediments of Gilbert age
Baileys Lake	trench West(S) of Hylland and others, 2012	4, 5	1293, 1296	1288	-1	1287	OSL 11.5; 12.5	Hylland and others, 2012	nearshore sediments, including tufa, interpreted to be of Gilbert age
Great Salt Lake	core GSL96-6-2B	7, 10	1305, 1309	1271	-7	1264	<12.1	Thompson and Oviatt, unpublished	offshore sediments interpreted to be of Gilbert age
Deep Creek	near mouth of Deep Creek, far western Utah	22	1300	1297[4, 7]	---	---	no ages available	this paper	possible Gilbert shoreline; gravel lens in barrier over marl
Blue Lake	core BL04-4	23	1299	1297[7]	-3	1294	~11.5–10.7	Benson and others, 2011	nearshore sediments of Gilbert age
Dugway Proving Ground	landforms and sediments at Currey sites 20 and 21	20, 21	1306, 1305	1306, 1305	---	---	<13	Oviatt and others, 2003; Madsen and others, in press	Gilbert shoreline not present at either site; 20 = fluvial gravel; 21 = eolian dunes
north of Dugway Proving Ground	Wild Isle, north of Dugway Proving Ground	---	---	1295	---	1295	numerical ages not available	this paper	sediments of possible Gilbert age at this site
Stansbury Island	gravel-pit exposure	9	1305	1293[6, 7]	+3[5]	1296[5]	numerical ages not available	this paper	no sediments of Gilbert age at this site
backhoe trench at Jukebox Cave	backhoe trench	24, 25	1300, 1297	1297[7]	-1	1296	stratigraphically above Bonneville marl; below early Holocene wetland deposits	Murchison, 1989; this paper	discontinuous gravel lens of probable Gilbert-episode age

[1]*See figure 1A.*
[2]*See figure 2.*
[3]*Altitudes rounded to the nearest meter above sea level.*
[4]*Crest of gravel barrier.*
[5]*Top of Bonneville sediments; no Gilbert sediments present here.*
[6]*Floor of gravel pit.*
[7]*Altitude measured using differential GPS with the assistance of Adam McKean and Don Clark, Utah Geological Survey.*

few ostracodes in samples from the depth interval 305 to 288 cm, and these ostracodes are typical of regressive-phase Lake Bonneville sediments (*L. ceriotuberosa*, *Candona caudata* or a species similar to *C. caudata*; Oviatt, unpublished data on ostracodes from BL04-4; Forester, 1987; Thompson and others, 1990; Oviatt, 1991; Oviatt and others, 1994; Forester verbal and written communications with Oviatt, 1980s through 2000s). An alternative interpretation of the BL04-4 core interval 305-288 cm, which is consistent with the ostracodes and the data presented by Benson and others (2011), is that these sediments were deposited during the late regressive phase of Lake Bonneville, that they were exposed subaerially and rooted by wetland vegetation during the pre-Gilbert low-lake period, and that there is an unconformity at core depth 288 cm.

As interpreted in this paper, the Gilbert episode appears to be represented by sediment between 288 and 258 cm in core BL04-4. This core interval contains gastropod shells, carbonate pellets, and mud intraclasts (Benson and others, 2011, figure 7). Ostracodes in this core interval are typical of shallow-lake environments in this basin (including *L. ceriotuberosa*, *Candona rawsoni*, *Cypridopsis vidua*; Oviatt, unpublished data on ostracodes from BL04-4; Forester, 1987; Thompson and others, 1990; Oviatt, 1991; Oviatt and others, 1994; Forester verbal and written communications with Oviatt, 1980s through 2000s). TIC and aragonite abruptly increase, and calcite decreases at core depth 288 cm, then both return to more typical values at core depth 258 cm; $\delta^{18}O$ varies only slightly in this depth interval (figure 8). The PSV age for interval 288 to 258 cm is 11.5 to 10.7 cal ka (table 1; Benson and others, 2011, supplementary data). The PSV time range of 800 yr may have been derived from an assumption of a linear sediment-accumulation rate, similar to that of the underlying Bonneville sediments, but the shallow-water Gilbert-episode sediments (288–258 cm) were likely deposited more rapidly than the older Bonneville sediments. The reasons for this are (1) the rate of endogenic carbonate precipitation is likely to be higher in shallow water than in deep water because in shallow water the temperature is generally higher, wave agitation greater, and photosynthetic removal of dissolved CO_2 is greater; and (2) the rate of input of clastic sediment (pebbles, sand, silt, and clay) is likely to be greater in shallow water than in deep water in offshore settings. Without more information about the PSV age estimates, including the core depths of the PSV-age calls and their uncertainties, variations in sedimentation rates in core BL04-4 cannot be determined.

Currey (1982) mapped the Gilbert shoreline at site 9 on the south end of Stansbury Island (figure 2), where he reported a “SW trending cuspate foreland” (a V-shaped barrier) at the mouth of Tabbys Canyon having an altitude of 1305 m (4281 ft). Currey (1982) listed the location of site 9 as 40.78 °N, 112.52 °W, but the precise location is not known (coordinates given to the nearest 0.01 of a degree of latitude and longitude at this latitude on Earth are approximately ± 1 km, so Currey’s [1982] coordinates are for small areas, not point locations). Holocene alluvium from Tabbys Canyon, and eolian deposits derived from the nearby mudflats, have covered the lacustrine deposits in this area (figure 9A), and although V-shaped barriers are faintly visible on the 1968 USGS Corral Canyon 7.5-minute topographic quadrangle near the mouth of Tabbys Canyon (figure 9B), a V-shaped barrier is not pres-

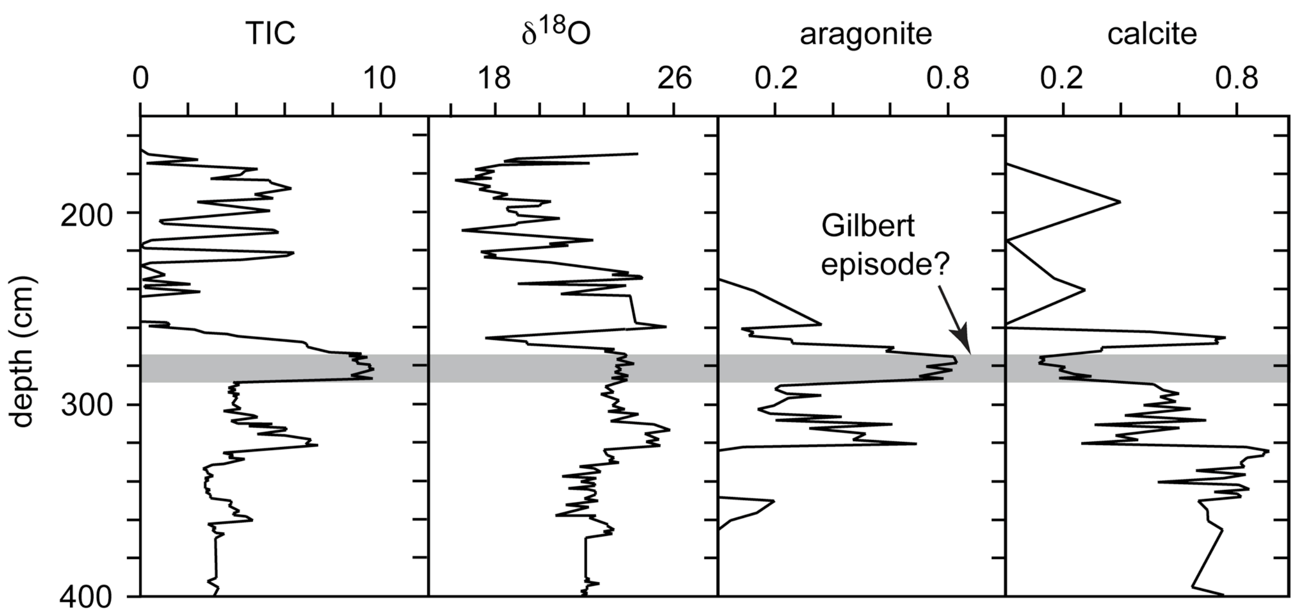


Figure 8. *Data from core BL04-4, from Blue Lake in western Utah (figure 1A; Benson and others, 2011, supplementary data). The gray band marks the Gilbert episode as interpreted in this paper. TIC = total inorganic carbon, in percent; $\delta^{18}O$ = oxygen isotopes, per mil, relative to SMOW (standard mean ocean water); aragonite = proportion of aragonite in the sediments; calcite = proportion of calcite in the sediments.*

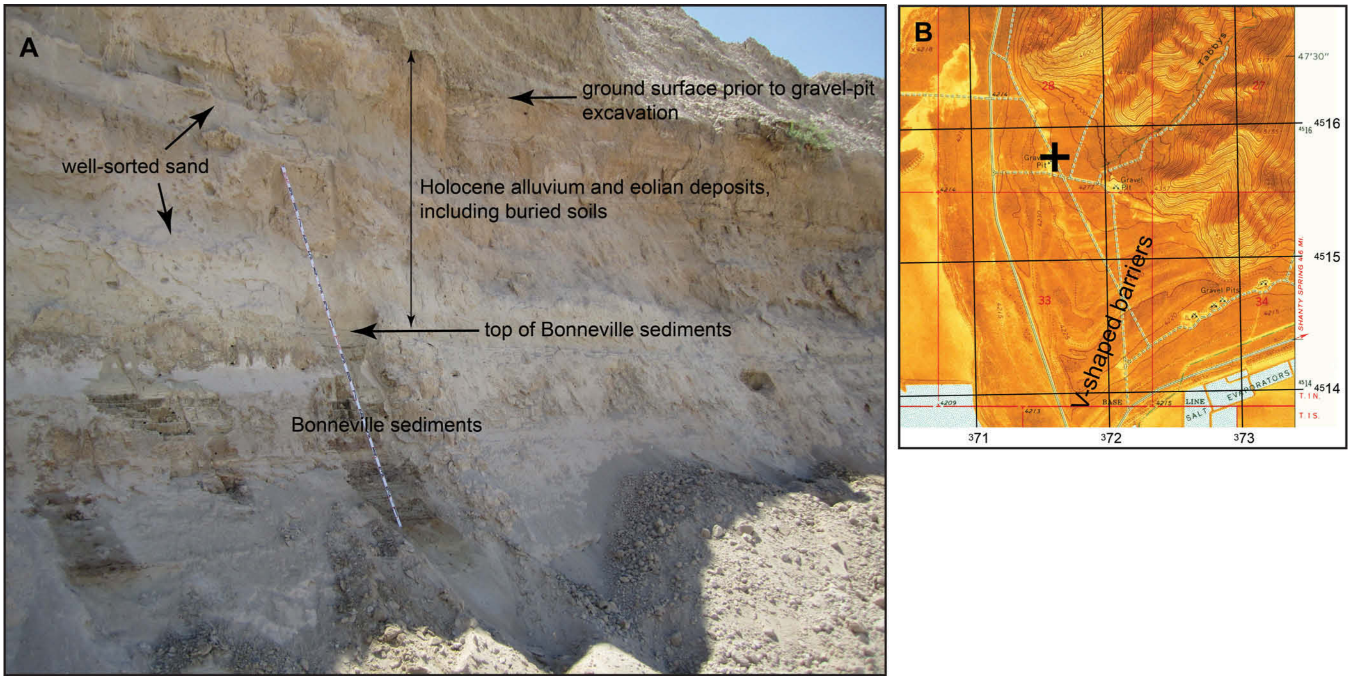


***Figure 9. A.** Photo of the wall of a gravel pit on Stansbury Island, near Currey's (1982) site 9 (site 9 has not been identified on the ground). The measuring stick is 2 meters in length. **B.** Part of the USGS 1968 Corral Canyon topographic quadrangle showing the approximate location of the gravel pit shown in figure 9A (at the black cross) and V-shaped barriers. UTM coordinates relative to NAD27.*

ent at an altitude of 1305 m (4281 ft).

New gravel pits have been opened near site 9 since Currey mapped there, so that a view of the internal stratigraphy of the deposits is now available. In one of the gravel pits fine-grained Lake Bonneville sediments (marl, fine sand) are overlain by well-sorted medium to coarse sand, which is overlain by muddy alluvium (figure 9A). Weakly developed buried soils are present in the alluvium. One interpretation of the well-sorted sand is that it has a lacustrine origin and therefore could be related to the Gilbert episode. The well-sorted sand, however, is poorly bedded, contains pebbles, pinches out laterally in a distance of about 10 m, and interfingers with sediments interpreted to be alluvium. Most likely the well-sorted sand was deposited in a fluvial environment, and may consist of reworked lacustrine sand. Other deposits that could potentially be of Gilbert-episode age are not exposed in this gravel pit, despite its favorable location for deposition and preservation of near-shore sediments. The altitude of the top of the Lake Bonneville marl is approximately 1296 m (4252 ft) (table 3), and considering the uncertainty in the altitude estimate (at least ± 1 m), the Gilbert lake may not have reached this altitude at this site.

Below the mouth of Juke Box Cave in the Silver Island Mountains northeast of Wendover, Utah (figures 1 and 2), a backhoe trench was opened in the 1980s (Murchison, 1989) to reveal deposits of Lake Bonneville overlain by deposits of a Holocene spring or wetland (figure 10). The trench was enlarged in 2009 (Pigati and Oviatt, unpublished data). An unconformity exposed in the trench between the Bonneville sediments and the Holocene wetland deposits is directly overlain by well-sorted fine gravel and sand as much as 40 cm thick. The gravel and sand unit is lens shaped; it pinches out upslope and downslope within the trench and on both sides of the trench. The gravel was interpreted by Murchison (1989) to be the Gilbert gravel because it is well sorted and likely lacustrine, and it is younger than Lake Bonneville deposits and older than early Holocene wetland deposits; this is a reasonable interpretation although numerical ages for the gravel are not available. The altitude of the upper limit of the gravel in the trench is approximately 1296 m (4252 ft; table 3). This altitude coincides with an upturn in the slope of the unconformity surface (figure 10), which could mark the shoreline angle of the Gilbert-episode lake at this locality.

At Dugway Proving Ground (Oviatt and others, 2003; Madsen and others, in press), no lacustrine deposits or shorelines that could be interpreted as Gilbert in age have been found. Two of Currey's (1982) Gilbert-shoreline sites were located on Dugway Proving Ground (figure 2; sites 20 and 21), but no evidence of a Gilbert-aged lake occupation has been observed at these sites. Access to Dugway Proving Ground was limited at the time Currey did his work, and he did not visit these sites. All deposits in this area that are younger than Lake Bonneville were deposited in fluvial, eolian, or wetland environments (Oviatt and others, 2003; Madsen and others, in press). Geomorphic conditions, such as wave energy, sediment supply and grain size, and reconstructed water depth, are favorable at Dugway for barrier beach formation

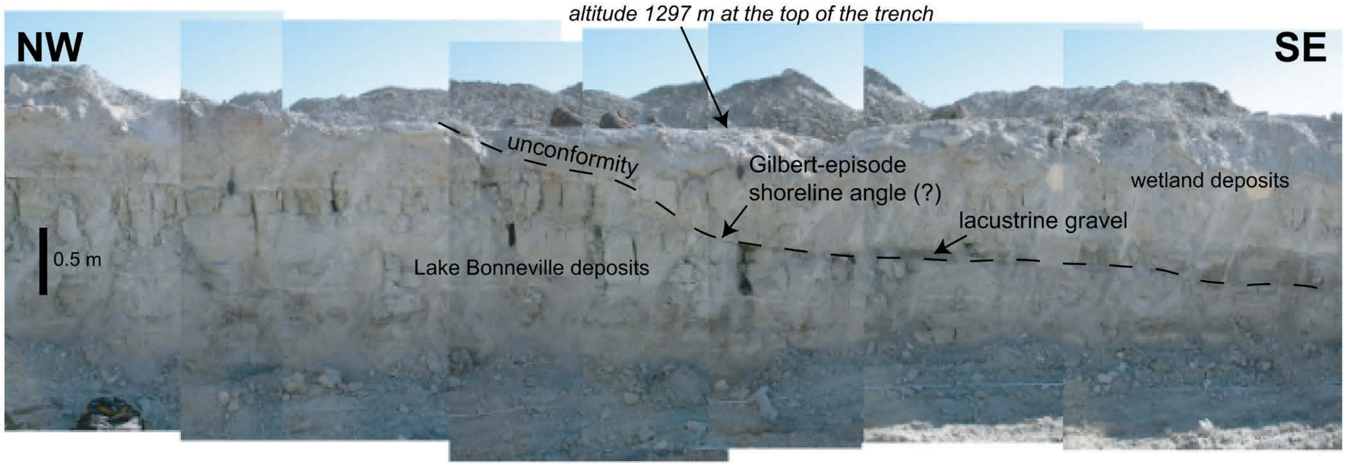


Figure 10. *Photo composite of the northeast wall of the backhoe trench below Juke Box Cave, northeast of Wendover, Utah, along the east side of the Silver Island Mountains (figure 1A). The lacustrine gravel (interpreted to be of Gilbert age) grades into lacustrine sand toward the southeast, and pinches out against the steeply sloping unconformity in the center of the photo (this may be the shoreline angle of the Gilbert-episode lake). The Lake Bonneville deposits contain an ostracode faunal sequence typical of Lake Bonneville sediments elsewhere in the basin (Oviatt, unpublished data), and the wetland deposits contain the Mazama ash and organic-rich beds dated to the early Holocene (Murchison, 1989).*

and preservation. Since the middle Holocene the landscape at Dugway has been lowered as much as 3 to 4 m by wind deflation, but the fine gravel delivered to the Dugway area by late Pleistocene and early Holocene rivers (Oviatt and others, 2003), which is present in topographically inverted fluvial landforms, would have been easily redistributed by waves into beaches and barriers if a lake had been present. If no barriers or offshore sediments are present here, the Gilbert lake likely did not transgress across this landscape.

At Wild Isle, just north of Dugway Proving Ground (figure 1A), about 20 cm of sand and muddy sand directly overlie Lake Bonneville marl at an altitude of about 1295 m (4250 ft), and underlie reddish mud that may have been deposited in either a fluvial or lacustrine environment (unpublished field observations and interpretations by Oviatt, 2003). The sand is possibly of Gilbert-episode age, but more work needs to be done in this area before the age and depositional environment of the sand can be definitely determined. The mud flats near Wild Isle at altitudes lower than 1295 m (4250 ft) have not yet been thoroughly examined for the presence of Gilbert sediments or shorelines.

Gilbert-episode sediments were exposed and dated in backhoe trenches dug across fault scarps at the Baileys Lake trench site, west of Salt Lake City International Airport (figures 1 and 11; table 3; Hylland and others, 2012, in press) (Murchison, 1989, discussed the sediments in borehole samples and exposed in the walls of drainage ditches in this area). At the Baileys Lake site the Gilbert episode is represented by a 0.5-m-thick sequence of basal tufa and overlying marls and sands; the tufa overlies a prominent unconformity cut into regressive Bonneville sediments. Possible evidence for a mid-Gilbert lake-level oscillation consists of a well-sorted sand bed (figure 11) that can be traced in the trench exposures across the site. The sand may represent a mid-Gilbert transgression at this altitude (1287 m; 4222 ft; Hylland and others, 2012), correlative with similar evidence observed at the Public Shooting Grounds at a slightly higher altitude (1290 m; 4232 ft; Oviatt and others, 2005).

GEOCHRONOLOGY

The age of the Gilbert episode is determined by radiocarbon ages at several localities (tables 1 and 3). Luminescence and PSV ages are consistent with the radiocarbon ages, although luminescence-age errors are large (table 1). At the Public Shooting Grounds, perhaps the best sedimentological evidence in the basin for the Gilbert episode—a ripple-laminated sand—is exposed just below the Gilbert shoreline of Currey (1982; Oviatt and others, 2005). As interpreted here, the age of the initial Gilbert transgression is younger than the youngest of four radiocarbon ages of samples of carbonized fragments of emergent aquatic plants collected from black mats beneath the ripple-laminated sand (figure 12; table 1; 11.7 ± 0.3 cal ka [10.1 ± 0.05 ^{14}C ka B.P.]). This interpretation of these basal ages is different from that of Oviatt and others (2005), who suggested that the Gilbert transgression occurred sometime between 12.9 and 11.2 cal ka (between 11 and 9.8 ^{14}C ka B.P.) following the thought that the older basal radiocarbon ages also might closely limit the age of the transgression, and in recognition of the analytical uncertainty of the calibrated radiocarbon ages. However, the interpretation presented in this paper is that the youngest basal radiocarbon age places the closest limit on the age of the transgression, and that some carbonized plant fragments could have persist-

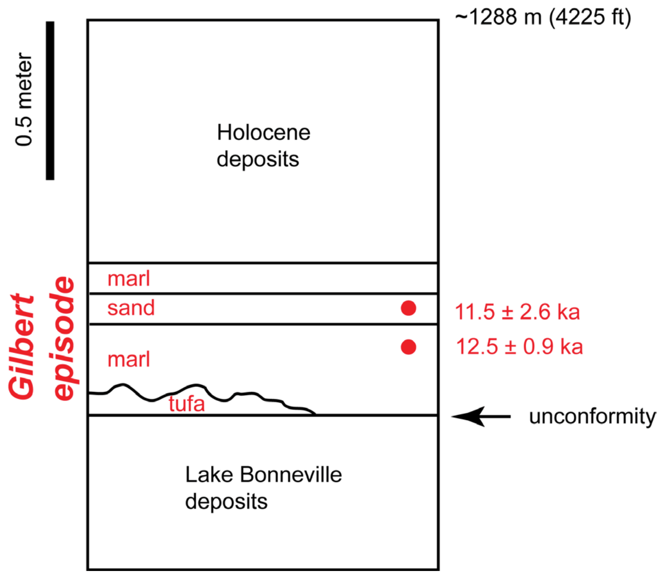


Figure 11. *Diagram showing the upper part of the stratigraphic section in the West(N) trench at the Baileys Lake site, west of the Salt Lake City International Airport (figure 1A) (modified from Hylland and others, 2012). The sediments interpreted as representing the Gilbert episode consist of tufa, which directly overlies an unconformity at the top of Lake Bonneville deposits, and marl, a well-sorted sand bed, and more marl that overlie the tufa. Two OSL ages are marked on the diagram (table 1). Holocene deposits consist of poorly sorted muddy sand, interpreted to be of eolian origin.*

ed in the sediment for hundreds of years while the pre-Gilbert wetlands were developing at this site.

A radiocarbon age for plant fragments in an organic-rich bed within the ripple-laminated sand at Public Shooting Grounds is 11.6 ± 0.3 cal ka (10.0 ± 0.07 ^{14}C ka B.P.) (table 1); this age is statistically indistinguishable from the youngest basal age (11.7 ± 0.3 cal ka [10.1 ± 0.05 ^{14}C ka B.P.]). Ages for plant fragments and humates collected from a sandy channel-shaped body that represents lowering, then raising, of base level (lake level in this case) during or after the deposition of the ripple-laminated sand are 11.3 ± 0.05 and 11.4 ± 0.2 cal ka (9.85 ± 0.04 and 9.98 ± 0.04 ^{14}C ka B.P.) (table 1), and are also statistically indistinguishable from the other ages (figure 12). From this and other information presented above, I conclude that the Gilbert episode culminated at approximately 11.6 cal ka and consisted of two lake-level rises near its upper altitudinal limit. The PSV age estimates in the BL04-4 core, and the luminescence ages from the Baileys Lake trench and Public Shooting Grounds, are consistent with the radiocarbon age approximation from the Public Shooting Grounds (table 1).

The Gilbert-episode lake is likely to have fluctuated within about 5 m of its highest altitude for a very short time, a period that was probably shorter than the time range of a typical 1-sigma analytical error for an accelerator-mass-spectrometry radiocarbon age (less than a century). The Gilbert lake was probably similar to modern closed-basin lakes in its response to weather and climate changes in the basin. Great Salt Lake has constantly fluctuated in altitude during historic time (U.S. Geological Survey, 2013), and there is no reason to think the Gilbert lake would have behaved differently.

ISOSTATIC REBOUND

In selecting the landforms that he collectively mapped as the Gilbert shoreline, Currey (1982, 1990) apparently assumed that the Gilbert shoreline had been isostatically deformed by the lingering effects of the much larger Lake Bonneville water load. Currey's (1982) map shows the Gilbert lake occupying all of the area of Great Salt Lake and the Great Salt Lake Desert (figure 2), with the highest altitudes on the Gilbert shoreline (1311 m) in the vicinity of the Lakeside Mountains, near the center of the Lake Bonneville water load. Currey's (1982) data on the Gilbert shoreline have been used in geophysical modeling efforts that included estimates of mantle viscosity and crustal rigidity in the Bonneville basin (Bills and May, 1987; Bills and others, 1994, Bills and others, 2002, Karow and Hampel, 2010).

It is possible, however, that rebound of the isostatic depression caused by the Bonneville and Provo water loads may have been complete, or nearly complete, prior to the Gilbert episode (for instance, Miller and others, 2013, thought all isostatic rebound in response to the instantaneous removal of over 100 m of water during the Bonneville flood had been completed by the end of Provo shoreline time, a time span of 1500 to 3000 yr). The time period under consideration for the Gilbert episode is from the end of formation of the Provo shoreline (probably 15 cal ka; Godsey and others, 2011; Miller and others, 2013) to the culmination of the Gilbert episode (11.6 cal ka), a period of approximately 3400 yr. Further modeling of the isostatic response of the crust and mantle in the Bonneville basin, which is not based on Currey's (1982) Gilbert-shoreline data set, is needed to help test this hypothesis. If it were possible to determine the upper altitudinal limit of sediments or shoreline landforms of the Gilbert episode in the vicinity of the Lakeside Mountains (figure 1), in the area of the maximum Lake-Bonneville water load, this would provide a test of whether isostatic rebound in response to Lake Bonneville had been completed by Gilbert-episode time.

DISCUSSION

The available evidence suggests that the Gilbert-episode lake probably did not cover all of the Great Salt Lake Desert. Prior to the Gilbert episode, the lake dropped to altitudes below the lowest outcrops at the Public Shooting Grounds (lower than ~1285 m; 4216 ft), but did not reach an altitude as low as 1263 m (4144 ft), the altitude of Gilbert-age sediments in Great Salt Lake core GSL96-6. The Gilbert lake supported ostracodes but not brine shrimp, so the lake was brackish and not hypersaline, probably because of insufficient time for

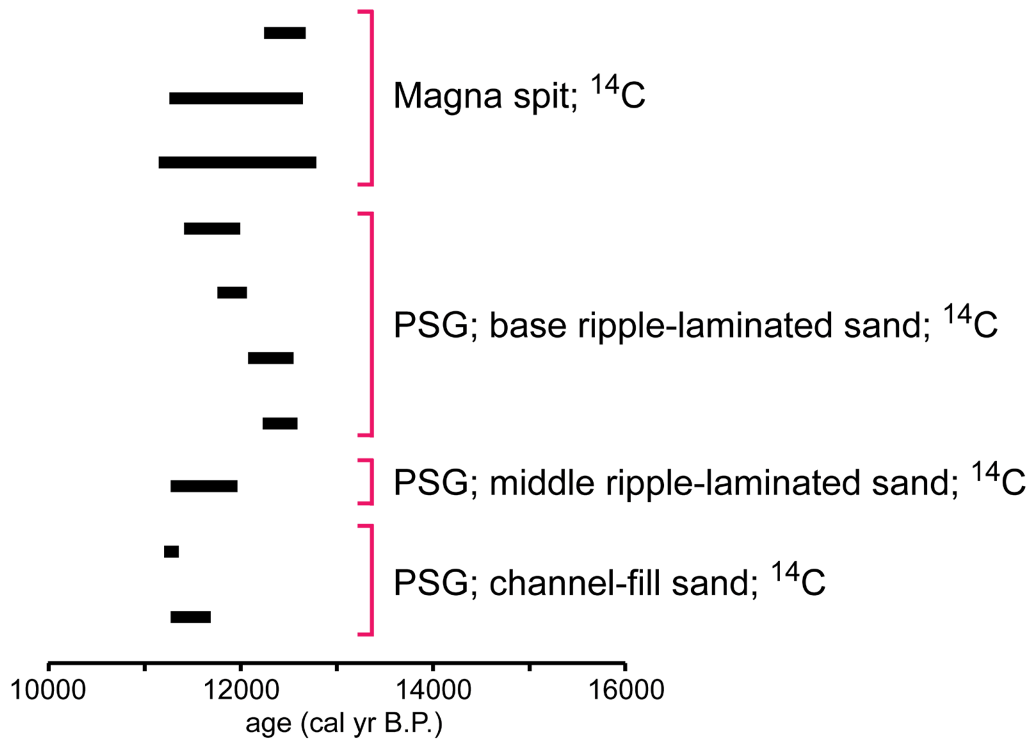


Figure 12. *Summary of some of the radiocarbon ages of Gilbert-episode deposits. Two-sigma calibrated age ranges are shown by the black bars. Refer to tables 1 and 3 for more information.*

evaporation and concentration of dissolved solids, combined with an inferred large volume of inflow of fresh groundwater from mountain and piedmont aquifers during the pre-Gilbert interval. One large area of enhanced groundwater discharge and river flow was in the Sevier Desert and at Dugway Proving Ground in the southern part of the basin (Oviatt and others, 2003, Madsen and others, in press), and groundwater discharge during this time period has been documented in other areas on the basin floor (Public Shooting Grounds, Oviatt and others, 2005; Blue Lake, Benson and others, 2011; Baileys Lake, Hylland and others, 2012). Groundwater continued to discharge on the basin floor for several thousand years after the Gilbert episode, and may have led to lake stratification as low-density fresh water floated on the hypersaline water of the lake (Oviatt, 2012).

The Gilbert episode has paleoclimatic significance, but the specific paleoclimate cause of the lake transgression is not known. The Gilbert-episode lake occupied a hydrographically closed basin, and there is no external or internal topographic threshold in the altitude range of 1295–1297 m (4250–4255 ft) that might have caused the lake to stabilize at those altitudes during transgressions or regressions. The Gilbert episode was most likely caused by a shift in water balance (an increase in input and/or decrease in output) brought on by climate change in the basin. The Gilbert-episode rise of about 15 m (50 ft) was greater than that of any Holocene lake rises, all of which were less than 6 m (20 ft) above average modern Great Salt Lake altitudes.

The shoreline landforms that were produced during the short-lived Gilbert episode are unlikely to have been composed of huge volumes of gravel or sand. The Gilbert-episode shoreline, where it can be identified, is probably a relatively minor feature on the landscape, and may consist of a discontinuous, thin skim of gravel, which in some places may have been added to a pre-existing gravel barrier, and in other places may have been easily eroded away in post-Gilbert time. The Gilbert-episode lake probably did not have time to produce extensive wave-cut platforms and bluffs. Wave-cut platforms in such places as along the west side of Stansbury Island, which have been mapped as the Gilbert shoreline (Currey, 1982), may be regressive-phase Bonneville or older erosional landforms that were reoccupied more than once as the lake transgressed and regressed in the basin during the late Quaternary. The altitude of the Gilbert-episode shoreline could vary by up to several meters because of local geomorphic controls (Atwood, 2006).

Based on the observations and interpretations presented in this paper, the Gilbert episode occurred at the very end of the Northern Hemisphere Younger Dryas cooling event (~13–11.5 cal ka; 11–10 ^{14}C ka B.P.; Bradley and England, 2008). The lake in the Bonneville basin fluctuated at relatively low altitudes, probably not much different than those of modern Great Salt Lake, during most of the post-Provo, pre-Gilbert time period that coincided with the Younger Dryas.

CONCLUSIONS

The Gilbert shoreline has been regarded, since at least the early 1980s when Currey (1982) mapped it throughout the basin, as one of the primary mappable shorelines of Lake Bonneville or Great Salt Lake. There is no doubt that there was a significant lake transgression during the early Holocene (Oviatt and others, 2005), an event referred to in this paper as the Gilbert episode. However, since the early 1990s questions have been raised about the maximum extent of the lake during the Gilbert episode, and that information is summarized here.

This paper should be regarded as a progress report. Further observations of sediments and landforms related to the Gilbert episode, and the paleoclimatic implications of the timing and extent of the Gilbert lake, are needed. Future geologic work in the Bonneville basin below an altitude of about 1300 m (~4260 ft) should be undertaken with a critical approach to the previously mapped Gilbert shoreline. An assumption that the lake reached altitudes higher than about 1297 m (4255 ft) during the Gilbert episode may not be valid. Lacustrine sediments and landforms in the Gilbert altitude range should be carefully described and put into context with other information from the basin before interpretations of lacustrine history are relied on as the chronologic basis for other geologic events such as faulting or mass wasting.

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