1 Quantitative Identification of
2 Erosional Lake Bonneville Shorelines, Utah

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11

12 Abstract

13 Although the major shorelines of Pleistocene Lake Bonneville have been
14 recognized for more than 100 years, less prominent shorelines have proven
15 difficult to quantitatively identify and correlate since the time of G. K. Gilbert. By
16 applying the Savitsky-Golay filter and methodology of Hare et al. (2001) to high
17 resolution LiDAR data of selected erosional shorelines, five distinct, correlatable
18 shorelines between the well-described Bonneville and Provo shorelines on the
19 transgressive limb of the Lake Bonneville hydrograph are documented. The
20 results provide a framework for determining whether these transgressive features
21 represent lake oscillations or stillstands during the height of the Last Glacial
22 Maximum in the eastern Great Basin of the western United States with possible
23 attendant paleoclimate implications.

24
25 keywords: shorelines, Pleistocene, Lake Bonneville, Savitsky-Golay, LiDAR

1. Introduction

The shoreline record of lakes is a premier measure of important regional climatic and hydrologic variables (e.g., Krist and Shaetzl, 2001; Adams, 2003; Jewell, 2007; Knott et al., 2012). Cores from lake bottom sediments have traditionally been the repository of choice for long-term climate records, however they say little about the volumes and water balances of lakes in the way shorelines can. Unfortunately, lake shorelines are relatively short-lived features with very poor potential preservation into the long-term geologic record.

Identification of subtle, relatively old shorelines represents a particular challenge.

Among the most-studied and important lacustrine records of North America are the multiple shorelines of the Late Pleistocene Lake Bonneville in the Great Basin of western North America. Beginning with the seminal work of G. K. Gilbert (1890), the prominent Bonneville, Provo, and Stansbury shorelines (Fig. 1) have been described in considerable detail (e.g., Oviatt et al., 1990; 1992; Godsey et al., 2005, 2011). The very lowest recognizable shoreline (Gilbert) was first recognized throughout the basin by Currey (1990), but has since been relegated to relatively minor status (Oviatt, 2014).

More difficult to describe, much less categorize, are numerous shorelines between the three major shorelines. Gilbert (1890) devoted particular attention to the most prominent of these features between the Bonneville and Provo shorelines which he called “Intermediate shorelines and embankments” (Fig. 2). He surveyed and described a number of intermediate profiles throughout the

basin but was unable to establish consistent correlations. The issue has received relatively little attention since Gilbert's time.

1.1 Paleoclimate significance of intermediate shorelines

The intermediate shorelines formed during the transgressive phase of Lake Bonneville; a period corresponding with the peak of the Last Glacial Maximum (LGM). As such, they hold the important promise of identifying possible stillstands and oscillations in the transgressive record of the lake (Fig. 1) and their possible relationship to global climate cycles (Oviatt, 1997). Work to date suggests oscillations in the intermediate shoreline range representing as much as 25% loss in lake volume within the overall transgressive period (Nelson and Jewell, 2015 and associated references). Possible relationships of these and other oscillations to global climate events (e.g., Heinrich events) are speculative but an important first step must be positive identification and correlation of these transgressive features across the Bonneville basin.

1.2 Shoreline geomorphology

The geomorphic differences between the erosional and depositional features of lakes shorelines have long been recognized although it is difficult to precisely determine paleo-water-level elevations in many of these environments. Erosional shorelines typically are characterized by an eroding cliff and a lakeward shore platform (e.g., Bird, 2008) and have been classified as "high-relief erosional shorelines" by Ritter et al. (2011, p. 541). The best examples in

71 Lake Bonneville are typically covered by a veneer of boulders or other coarse
72 sediment from the erosional cliff face. In a transgressing shoreline, this material
73 can be significant and the term “depositional platform” has been proposed for this
74 particular environment (C.G. Oviatt, pers. Comm.).

75 By contrast, depositional features (“low relief depositional shorelines of Ritter
76 et al. (2011)) tend to be less topographically prominent and are often manifested
77 a wide variety of features such as spits, barrier bars, beach ridges, and tombolos.
78 Many of these features can form as much 2-5 m above or below water level (e.g.,
79 review in Schaetzl et al., 2002). As a result, literature as far back as Johnson
80 (1933) and Miller (1939) argues that erosional shorelines more faithfully
81 represent the water level of paleoshorelines.

82 Prior to the formation of Lake Bonneville, the valleys and lower elevations of
83 mountains in the eastern Great Basin were dominated by bedrock and highly
84 incised alluvial channels and fans. As the lake transgressed, portions of pre-
85 existing bedrock and alluvial fans were eroded and the intervening alluvial
86 channels filled by a variety of sediment types. For this reason, purely erosional
87 shorelines are difficult to positively identify through simple field examination. For
88 this study, shorelines with as much erosional character as possible were chosen
89 on the basis of three criteria: (1) identifiable rock outcrops or steep bluffs (cliffs)
90 in the vicinity (Fig. 2b), (2) lack of nearby, clearly depositional features such as
91 spits and bars, and (3) lack of nearby alluvial fans that could have fed sediment
92 into the shoreline.

93 This latter criterion is significant because modern alluvial fan studies have
94 documented sediment fluxes ranging from 10^2 - 10^5 m³/yr (Korup et al., 2004;
95 Hornung et al. 2010), meaning the formation of depositional features such as
96 spits and bars fed by alluvial fans could take place over time spans as short as
97 decades. This is particularly relevant to a number of Gilbert's intermediate
98 embankments, spits, and bars that have clear associations with nearby,
99 prominent alluvial fans (Gilbert, 1890, p. 135-137). On the other hand,
100 documented erosion rates of modern cliff and platform shorelines are on the
101 order of 1 to 10s of mm/yr (Trehaile, 1987). Similar erosional shorelines in Lake
102 Bonneville must therefore have taken a significant time to develop and should
103 more faithfully reflect extended periods of static water level.

104 105 1.3 Purpose of this study

106 The widespread use and availability of airborne LiDAR-derived digital
107 elevation data present new opportunities to characterize well-known shorelines of
108 Lake Bonneville, to possibly identify and correlate lesser known shorelines, and
109 to examine the assertion by Gilbert (1890, p. 137-147) that the intermediate
110 shorelines are the result of localized, rather than basinwide factors. This study
111 employs LiDAR data in conjunction with methodologies employed previously on
112 late Pleistocene Lake Lahontan (Hare et al. 2001) to characterize the enigmatic
113 intermediate shorelines first described by G.K. Gilbert. This paper focuses on
114 erosional shorelines which are less likely than depositional shorelines to have the
115 complicated sediment source issues mentioned above. The framework of

erosional shorelines described here will be used as the basis for more comprehensive studies of depositional features in the Lake Bonneville basin.

2. Methodology

2.1 Data sources

High quality (~10 cm vertical resolution) digital elevation data derived from LiDAR surveys in the Lake Bonneville basin have been generated by the State of Utah (<http://gis.utah.gov/>). Additional LiDAR data were acquired for this study. Together they provide an opportunity to use generalized algorithms to quantitatively identify features that are difficult to categorize visually. The publically available LiDAR data sets are at horizontal resolutions of either 1.0-m or 0.5-m resolution. LiDAR data acquired for this study are 1.0-m horizontal resolution. All LiDAR data have vertical resolution of ~0.2 m.

2.2 Quantifying shoreline expressions

Quantifying the morphology of erosional shorelines involves identification of specific geomorphic features. Terminology that includes the riser inflection, riser crest, bench width, bench top, and knick point has been presented by Hare et al., (2001) for work on Lake Lahontan shorelines in the western Great Basin (Fig. 3) and is retained for this study.

The first step of the analysis involves approximating the overall slope of the composite shoreline with a polynomial of variable degree. Polynomial values are subtracted from the elevation data, resulting in a residual topography (Fig. 3b). A

Savitsky-Golay filter is then applied to the residual topography as well as its first and second derivatives (Bromba and Ziegler, 1981). For equally spaced data, the Savitsky-Golay filter functions similarly to a moving average filter in that a set of adjacent data points are used to filter noise from the data. Different coefficients for the adjacent data are applied depending on the number of adjacent points and whether they are being applied to the data or their derivatives. Values for the coefficients can be found in a number of textbooks or websites (e.g., Madden, 1978).

Because a shorezone encompasses a range of features over a vertical range, it is necessary to establish a single datum point on which to compare different shorezone profiles. The idealized shoreline morphology of Hare et al. (2001) contains one point where the second derivative is zero and the first derivative is a minimum within the bench width (BW) (Fig. 3c, d) and this point is used as a datum for the analyses included in this paper. It is important to emphasize that the purpose of this datum is correlation of shorelines and the datum is not meant to represent a paleo-water-level.

An idealized morphology of Lake Bonneville that incorporates the prominent Bonneville and Provo shorelines would display four inflection points where the second derivative changes sign for the two bench widths (Fig. 4). For the Bonneville-Provo interval the idealized topographic trend is thus a 5th order polynomial (four second order inflection points) with two inflection points bracketing each shoreline.

The chosen filter length for the Savitsky-Golay method is a matter of some serendipity (Hare et al., 2001) that depends among other factors on horizontal resolution of the data and the desired accuracy. For this study, a filter width of 12 m was found to yield good results. Following coding in a Matlab script, expressions of the filtered residual shoreline data and its first and second derivatives were plotted and examined.

After the regional slope was established and the Savitsky-Golay filter applied to the data, deviations from the overall trend of the profile could be identified. These are termed “wave-cut slopes” and are defined as the tangent of the angle between the regional slope and the shoreline bench width (Fig. 5) and will form the basis for much of the following discussion. Only portions of the profiles with wave-cut slopes > 0.05 are included in further analysis.

Applications of this method produced easily identifiable Bonneville and Provo shorelines (Fig. 6) including the “double Provo” shoreline first recognized by Gilbert (1890, p. 130-131) and described in detail by Miller et al. (2013) (Fig. 6b). The double Provo shoreline was identified in ~90% of the profiles of the study. Where two Provo shorelines could not be identified, the single Provo was assumed to be the upper Provo shoreline, since this one has the most distinct topographic expression (Gilbert, 1890; Miller et al., 2013).

2.3 Isostatic rebound correction

Gilbert (1890) and subsequent researchers have recognized significant (>70 m) isostatic rebound associated with Lake Bonneville shorelines; a feature that

has led to understanding lithosphere and upper mantle dynamics of the eastern Great Basin (Bills and May, 1987; Bills et al., 1994, 2002) while also complicating methods of shoreline correlation. Quantitative correction for isostatic rebound has previously been accomplished with the following relationship (Currey and Oviatt, 1985; Oviatt et al., 1992):

$$Z_a = Z_r - [(Z_r - 1200)/(Z_b - 1200)] * [Z_b - 1552] \quad (1)$$

Where Z_a is the adjusted altitude, Z_r is the modern altitude at a given location, and Z_b is the modern Bonneville shoreline altitude. 1552 m is the assumed altitude of the unrebounded Bonneville shoreline, and 1200 m is the approximate altitude of the lowest point in the Bonneville basin. Note that $Z_a = 1552$ for $Z_r = Z_b$ (i.e., the Bonneville shoreline is fixed at 1552 m). The effect of Equation (1) is to evenly apportion the effect of isostatic rebound over the entire altitude range of Lake Bonneville shorelines (Fig. 1).

2.4 Methodology for this study

Whereas Equation (1) was intended to make approximate isostatic corrections from the Bonneville shoreline to the bottom of the lake basin, this study is intended to identify the altitudes of intermediate shorelines relative to the measured altitudes of Bonneville and Provo shorelines. A uniform vertical distance between the Bonneville and Provo shorelines is thus required and for this purpose, the shortcomings of Equation (1) become evident. Suppose the

Bonneville shoreline (Z_b) was measured at 1600 m, an intermediate shoreline at 1560 m, and the Provo shoreline at 1485 m (Fig. 7). Vertical separation between the two would be 115 m, a reasonable value for localities with significant isostatic rebound (Miller et al., 2013). However, the isostatically adjusted Provo shoreline using Equation (1) would be 1451 m or a Bonneville-Provo separation of only 101 m which is an unrealistically low value for a location with significant rebound.

For this study, a simpler equation (setting the $(Z_r - 1200)/(Z_b - 1200)$ term in Equation (1) to unity) is the first step in for dealing with relative isostatic rebound of the intermediate shorelines:

$$Z_a = Z_r - Z_b + 1552 \quad (2)$$

The effect of Equation (2) is to preserve the vertical distance between measured Bonneville and Provo shorelines (Fig. 7). As in the case of Equation (1), if $Z_r = Z_b$, $Z_a = 1552$ m. If $Z_r = 1485$ m (the measured Provo altitude), $Z_a = 1437$ m thus retaining the known 115 m between the Bonneville and Provo shorelines. The intermediate shoreline in this hypothetical example is thus adjusted to an altitude of 1512 m (Fig. 7b).

The final step used in this study is to retain the Bonneville shoreline altitude of 1552 m and normalize all other measurements to an arbitrary but uniform Bonneville-Provo vertical separation of 107 m. For the example given above, the Bonneville elevation remains at 1552 m, but the Provo elevation becomes 8 m

higher (1445 m). The modified hypothetical intermediate shoreline of 1512 m is now adjusted proportionately upward to 1515 m (Fig. 7c).

Given the varying rates of water loading during transgressive phase of the lake, as well possible post-Bonneville tectonic complications (Jewell and Bruhn, 2013), the method described here is admittedly imperfect. However, unlike Equation (1), the purpose of the method outlined here is simply to identify relative shoreline altitudes between the Bonneville and Provo shorelines by negating the complication of spatially variable isostatic rebound. To that end, the method works reasonably well.

3. Field localities

Forty-eight profiles were measured at eight locations in the basin (Fig. 8). Individual profiles in a given location were 200-500 m apart and if possible located where nearby erosional features were identifiable (Fig. 2b). Localities covered by 1.0-m LiDAR surveys included Bear River, Little Mountain, Promontory Mountains, Antelope Island, Table Mountain; 0.5 m resolution surveys included Clarkson, West Mountain, Lake Mountain (Table 1).

4. Results

4.1 Bonneville and Provo shorelines

For a given locality (Fig. 8), the method outlined here produced results with variances of approximately ± 1.5 m for both Bonneville and upper and lower Provo erosional shorelines (Table 1). The scatter in the data can attributed to a

number of factors, including fetch-controlled wave run-up (e.g., Atwood, 2002; Carling et al., 2011), LiDAR error, differential rebound within a given locality, Holocene modification of the shoreline, and post-Bonneville tectonic activity (Jewell and Bruhn, 2013).

The relative amount of isostatic rebound is clearly visible for Bonneville and Provo shorelines (Fig. 9) and approximates the results presented in Bills et al. (2002). Differences with the findings of Bills et al. (2002) include large horizontal rebound differences between the Promontory and Little Mountain localities and greater Provo rebound in the southeastern corner of the Bonneville basin. Future studies will clearly be necessary to resolve these differences as well as expanding the results into the western side of the basin.

Altitude separation between the Bonneville and upper Provo shorelines is similar to that documented by Miller et al. (2013) and varies from 105 to 115 m (Fig. 10). The double Provo was not visible on all 48 profiles and the separation between the upper and lower Provo shorelines (1-3 m) was not as pronounced as documented by Miller et al. (2013) (Table 1).

Although the emphasis of this study is erosional shorelines, it is worthwhile to compare the Bonneville and Provo erosional shoreline elevations determined here with published values of depositional shorezone features (Table 2). Currey's (1982) elevation data were derived by examination of published paper topographic maps and were primarily taken from beach ridges. Miller et al.'s (2013) elevation data (Table 2) consist of the high crest of the upper Provo shoreline identified from 5 m DEMs published by the State of Utah Automated

Geographic Resource Center. In general, the published depositional Bonneville elevations are higher than the erosional shorelines of this study, sometimes significantly so (13-15 m). Differences between published depositional Provo shorelines and erosional Provo shorelines are more variable (Table 2).

A variety of factors may account for these differences. 1) The datum choice in this study is near the lower part the entire erosional shorezone system (Fig. 4, 5). 2) The published vertical accuracy of the AGRC 5 m DEMs used by Miller et al. (2013) is ± 5 m. 3) Considerable horizontal and vertical errors may be associated with Currey's (1982) use of topographic maps. In some cases a clearly identifiable Lake Bonneville depositional feature was not visible in the LiDAR data at the UTM coordinates given in Currey's (1982) data. 4) Discrepancies ≥ 10 m are a feature of locations on Antelope Island and the Promontory Mountains (Table 3). Both ranges are bounded on the western side by portions of the Great Salt fault system which has published vertical slip rates of ~ 0.6 mm/yr (Lund, 2005). As such, there could be as much as 10 m of fault block rotation since the time of the transgressive phase of Lake Bonneville (e.g., Jewell and Bruhn, 2013).

4.2 Intermediate shorelines

Wave-cut slopes > 0.05 and > 0.1 were recorded between the Bonneville and upper Provo shorelines for all 48 profiles. Wave-cut slopes > 0.1 are taken to represent more aggressive wave action that produced a more visible and potentially important intermediate shoreline.

298 Given the ± 1.5 m error found in characterizing the Bonneville and Provo
299 shorelines (Table 1), a moving window of 3 m at 0.25 m intervals was used to
300 identify wave-cut slopes > 0.05 and > 0.1 . After applying the methodology
301 documented above for normalizing shoreline elevations, clear peaks are
302 observed at (in descending order) 1515 m, 1529 m, and 1493 m (Fig. 11). A
303 distinct shoreline at 1479 m is identified in the > 0.1 slope data but appears as
304 two diffuse shorelines (1474 m and 1482 m) in the > 0.05 slope data. Wave-cut
305 slopes > 0.05 identify an additional shoreline at 1464 m (Fig. 11a). Thus, a total
306 of five previously unrecognized intermediate shorelines are identified.

307 The 1529 m, 1515 m, 1493 m, 1479 m, and 1464 m shorelines were
308 identified in 48%, 42%, 40%, 21%, and 21% respectively, of the 48 profiles
309 examined. Additionally, lesser shorelines might be interpreted from the data but
310 are either relatively subdued or hidden in the noise of the more prominent peaks
311 (Fig. 11).

312 The degree to which the intermediate shorelines exhibit a topographic
313 expression is reflected by the degree of wave-cut slope (i.e., the difference
314 between the regional slope and the slope of the shoreline) (Fig. 5). Although
315 there are considerable scatter in the data (Fig. 11, 12), the Bonneville and Provo
316 shorelines clearly have the greatest shoreline expressions, which of course has
317 long been known from visual examination of the Bonneville basin. The
318 intermediate shorelines have slightly greater shoreline expressions at the higher
319 elevations although the differences are not statistically robust (Fig. 12). A

possible implication of this observation is that Lake Bonneville wave power increased as water level increased to its highest level.

The five identified intermediate shorelines are often seen in hillshades of the LiDAR data such as the example from Antelope Island (Fig. 13), although it is rare to identify all five intermediate shorelines in a given topographic profile. However, given the subtlety and number of shorelines seen in the field, it is not surprising that correlating the intermediate erosional shorelines has not been possible prior to the acquisition of high-quality, high-resolution elevation data.

5. Discussion

5.1 Intermediate shoreline implications, terminology, and caveats

Although the relatively poor expression of the intermediate shorelines, first recognized by Gilbert (1890), is confirmed by this study, the precise reason is less clear. Occupation of any given intermediate shoreline for a short time relative to the amount of time occupied by the Bonneville and Provo shorelines is certainly one possible factor although it is also possible that oscillations within the vertical range of intermediate shorelines (e.g., Nelson and Jewell, 2015) obscured or obliterated shorezone features after they were first formed. Variability of the underlying substrate is not considered a factor since identification of a specific intermediate shoreline was highly variable at a given location, even where the profiles were relatively closely spaced (Table 1).

The intermediate shoreline terminology adopted in this paper (1529 m, 1515 m and so forth) is intended to be a framework for conducting more detailed work,

such as identifying lake level oscillations or gaining a better understanding of isostatic rebound. Future researchers wishing to relate these intermediate shorelines to specific elevation differences relative to the Bonneville and Provo shorelines (Table 3) will need to recognize that these differences are based on a uniform Bonneville-Provo separation of only 107 m as well as the other aspects of the methodologies outlined in this paper.

It should also be emphasized that the datum for altitudes of the erosional shorelines in this study are within a vertical range of possible water elevations (Fig. 5) and these do not necessarily represent presumed mean water-level at the time of shoreline formation.

5.2 Paleoclimate implications

Clearly one important aspect of this study is its use as the beginning of studies to determine whether the intermediate shorelines are the result of lake oscillations or simply represent lake still stands during a continuous transgression. This, in turn, might answer the question of whether the shorelines can be related to regional climate of the Great Basin and thus global climate cycles.

Existing literature gives hints as to how the paleoclimate questions might be addressed. Oviatt (1997) suggested three oscillations (termed U1, U2, and U3) during the transgressive of Lake Bonneville followed the well-documented and older Stansbury oscillation (Fig. 1). Recent radiocarbon measurements and stratigraphic studies in the Hogup Mountains in the northwestern portion of the

basin confirm Oviatt's (1997) U2 oscillation and documents two additional oscillations, termed the Upper Hogup (UHO) and Lower Hogup (LHO) Oscillations, respectively (Nelson and Jewell 2015). The LHO corresponds roughly to the 1479 m shoreline and U2 corresponds to the 1493 m shoreline of this study (Fig. 11); the UHO is not seen among the erosional shorelines identified here.

5.3 Future work

The next step in applying LiDAR to Lake Bonneville features might be examination of the large inventory of depositional features between the Bonneville and Provo shorelines, starting with the well-documented depositional embankments of Gilbert (1890, p. 135-137). As mentioned previously, the source material for these depositional shorelines may have been varied and complicated. Research by the author has documented significant modern mass wasting in alluvial watersheds feeding fans that formerly provided material for the Stockton bar in central Utah. In other words, many depositional Lake Bonneville features maybe related to relatively rapid delivery of sediment to the lake rather than a prolonged lake stillstand.

A second, more challenging step will be quantitatively identifying and describing shorelines between the Stansbury and Provo shorelines (Fig. 1). These have been called "sub-Provo" shorelines and could have formed either during the transgressive or regressive phases of the lake; if the former, their ages are close to the limit of radiocarbon methods (Sack, 1999) and will thus be even

more challenging to place within a paleoclimate context. Nevertheless, the procedures and results outlined here provide hope for wider understanding of both the very earliest stages and latest stages of this important paleoclimate archive.

6 Conclusions

- 1) Application of the Savitsky-Golay filter and the methodology of Hare et al. (2001) is successful in quantitatively identifying both the well-known Bonneville and Provo shorelines of Lake Bonneville and the intermediate shorelines between the two.
- 2) For the first time, five erosional, transgressive intermediate shorelines have been correlated across the Lake Bonneville basin.
- 3) One of the newly recognized shorelines roughly corresponds to the U2 lake oscillation of Oviatt (1997) and another to the Lower Hogup oscillation of Nelson and Jewell (2015).

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518 Table 1. Summary Bonneville and Provo shoreline elevations determined using
519 the Savitsky-Golay method described in this paper (locations shown on Figure 8).
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Profile	Bonneville (m asl)	Upper Provo (m asl)	Lower Provo (m asl)	Bonneville – Upper Provo difference (m)
Central Promontory b	1596.0	1483.4	1482.0	112.5
Central Promontory c	1594.4	1483.3	1481.3	111.0
Central Promontory d	1594.1	1481.5	1479.1	113.3
Central Promontory e	1596.1	1481.8	1480.2	114.3
Central Promontory f	1595.5	1482.0	1481.0	113.5
Ave +/- Std. Dev	1595.2 +/- 0.9	1482.8 +/- 0.8	1480.7 +/- 1.1	112.9 +/- 1.2
SE Cent Promontory a	1596.2	1485.3	1483.1	110.8
SE Cent Promontory b	1599.7	1489.9	1488.9	109.8
SE Cent Promontory c	1596.2	1484.2	1483.9	112.0
SE Cent Promontory d	1598.1	1483.8	1481.9	114.3
SE Cent Promontory e	1597.4	1484.2	1483.3	113.2
Ave +/- Std. Dev	1597.5 +/- 0.8	1485.5 +/- 2.4	1483.1 +/- 2.6	112.0 +/- 1.8
SE Promontory a	1598.1	1483.8	1482.1	114.2
SE Promontory b	1598.3	1486.7	1485.4	111.5
SE Promontory c	1600.4	1487.3	1486.6	113.2
SE Promontory d	1596.3	1487.0	1484.8	109.3
Ave +/- Std. Dev	1598.2 +/- 1.8	1486.2 +/- 1.5	1484.8 +/- 1.7	112.0 +/- 2.1
Antelope a	1590.3	1478.7	1477.0	111.6
Antelope b	1588.1	1478.0	1474.8	110.1
Antelope c	1588.7	1477.9	1475.3	110.8
Antelope d	1585.0	1477.4	1475.5	110.3
Antelope e	1587.8	1478.3	1475.9	110.6
Antelope f	1590.9	1480.9	1477.3	110.0
Ave +/- Std. Dev	1589 +/- 1.2	1478.6 +/- 1.2	1476.0 +/- 1.0	110.6 +/- 0.6
Little Mountain a	1579.3	1472.8	1471.2	106.5
Little Mountain b	1578.7	1471.7	1469.9	107.0
Little Mountain c	1577.3	1470.9	1469.5	106.4
Little Mountain d	1579.4	1472.8	1470.7	106.6
Little Mountain e	1576.2	1468.7	1467.3	107.5
Ave +/- Std. Dev	1578.2 +/- 1.3	1471.4 +/- 1.6	1469.7 +/- 5.5	106.6 +/- 0.5
Bear River a	1566.1	1461.3	1459.5	104.8
Bear River b	1568.8	1457.7	1456.2	111.1
Ave +/- Std. Dev	1567.5 +/- 1.6	1459.5 +/- 2.0	1457.9 +/- 1.9	108.0 +/- 4.4
Table Mountain a	1584.7	1473.3	1470.9	109.6
Table Mountain b	1583.8	1475.1	1470.9	110.5
Table Mountain c	1583.8	1475.2	1471.8	108.6
Ave +/- Std. Dev	1584.1 +/- 0.5	1473.9 +/- 2.5	1471.9 +/- 2.5	109.6 +/- 1.0
Clarkson c	1559.7	1452.8	1450.6	107.0
Clarkson d	1559.2	1453.4	1452.7	108.8
Clarkson e	1564.8	1454.0	1452.8	110.9

Ave +/- Std. Dev	1562.2 +/- 0.5	1453.3 +/- 0.5	1452.0 +/- 1.1	108.9 +/-2.0
West Mountain b	1556.4	1451.6	1450.2	104.9
West Mountain c	1555.0	1451.4	1450.1	103.6
West Mountain d	1557.3	1450.0		107.3
West Mountain e	1558.0	1451.0	1449.1	107.0
West Mountain f	1556.3	1451.8		104.5
West Mountain g	1559.5	1455.3	1454.0	104.2
West Mountain h	1558.9	1452.2	1450.5	106.7
West Mountain i	1558.4	1452.6	1450.2	105.8
West Mountain j	1556.8	1450.5	1450.5	104.7
West Mountain k	1558.0	1453.3	1453.3	102.2
Ave +/- Std. Dev	1557.4 +/- 1.3	1452.4 +/- 1.8	1451.0 +/- 1.7	105.1 +/- 1.6
Lake Mountain a	1556.0	1450.4		109.5
Lake Mountain b	1561.4	1453.1		108.4
Lake Mountain c	1562.2	1454.5	1453.2	107.8
Lake Mountain d	1560.3	1454.3	1452.3	106.0
Lake Mountain e	1561.7	1455.0	1452.8	106.8
Ave +/- Std. Dev	1561.1 +/- 0.9	1453.4 +/- 1.7	1452.4 +/- 0.4	107.7 +/- 1.4

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Table 2. Comparison of Bonneville and upper Provo elevations determined in this study with previously published values (Currey = Currey, 1982; Miller = Miller et al., 2013, Table 2). Exact UTM coordinates can be found in these references. ORB = Old River Bed

Shoreline	Name	Published locality designation (feature type)	Horizontal distance between published locality and closest profile of this study (km)	Published depositional elevation (m)	Erosional elevation of this study (m)	Elevation difference (m)
Bonneville	West Mountain	Currey-18 (beach ridge)	0.7	1562	1558	4
Bonneville	Antelope Island	Currey-29 (beach ridge)	0.6	1593	1588	5
Bonneville	Table Mountain	Currey-57 (beach ridge)	0.9	1593	1584	9
Bonneville	East Promontory	Currey-166 (beach ridge)	0.9	1606	1596	10
Bonneville	Clarkston	Currey-178 (spit)	13.7	1570	1565	5
Bonneville	Antelope Island	Miller-81 (beach)	1.2	1601	1588	13
Bonneville	Promontory Point	Miller-82 (beach)	7.1	1613	1598	15
Bonneville	Table Mt./ ORB	Miller-64 (v-bar spit)	15.1	1591	1584	7
Bonneville	Table Mt./ ORB	Miller-66 (v-bar spit)	10.7	1587	1584	3
Bonneville	Table Mt./ ORB	Miller-67 (beach)	6.7	1591	1565	5
Provo	Table Mountain	Currey-55 (beach ridge)	1.6	1477	1474	3
Provo	Antelope Island	Miller-81 (beach)	1.2	1484	1479	5
Provo	Promontory Point	Miller-82 (beach)	7.1	1489	1479	10
Provo	Table Mt./ ORB	Miller-64 (v-bar spit)	15.1	1468	1474	-6
Provo	Table Mt./ ORB	Miller-66 (v-bar spit)	10.7	1472	1474	-2
Provo	Table Mt./ ORB	Miller-67 (beach)	6.7	1473	1474	-1

534 Table 3. Summary of intermediate shorelines and their relation to standard
 535 Bonneville and upper Provo elevations.

Intermediate shoreline (adjusted elevation)	Intermediate shoreline (relative to 1552 m Bonneville shoreline)	Intermediate shoreline (relative to 1444 m upper Provo shoreline)
1528 m	Bonneville minus 24 m	Provo plus 84 m
1515 m	Bonneville minus 37 m	Provo plus 71 m
1493 m	Bonneville minus 59 m	Provo plus 49 m
1479 m	Bonneville minus 73 m	Provo plus 35 m
1464 m	Bonneville minus 88 m	Provo plus 20 m

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538 Figures.

- 539 1. Lake Bonneville hydrograph in calibrated radiocarbon years (modified
540 from Oviatt, 2015). T = transgressive lake phase, O = flow through period
541 of the Provo stillstand, R = regressive lake phase, U1, U2, U3 = unnamed
542 transgressive oscillations (Oviatt, 1997).
- 543 2. A. Field example from the northern Promontory Mountains showing
544 Bonneville and Provo shorelines with numerous intermediate shorelines.
545 B. Erosional shorelines of Lake Bonneville from the central Promontory
546 Mountains of a hillshade of 1-m LiDAR-derived DEMs. B = Bonneville, I =
547 Intermediate, P = Provo, SP = sub-Provo, S = Stansbury. Both examples
548 from the Promontory Mountains (starred location).
- 549 3. Idealized shoreline profile showing RI (riser inflection), RC (riser crest), BT
550 (bench top), KP (shoreline knickpoint), and BW (bench window) (after
551 Hare et al., 2001). A) Raw, idealized elevation data. B) Residual
552 elevation data. C) 2nd derivative of the residual elevation data. D) 1st
553 derivate of the residual elevation data. Circles in C) and D) represent the
554 datum chosen for the analysis in this study
- 555 4. Idealized topography of a typical Lake Bonneville shoreline showing four
556 inflection points (*) approximated by a 5th order polynomial
- 557 5. Idealized wave cut slope in a shoreline.
- 558 6. Example topographic profile from the Promontory Mountains location. A.
559 Overall profile showing data (solid line) and 5th order polynomial (dashed

560 line). B. Detail of the residual first derivative of a Bonneville shoreline
 561 showing wave-cut slope (dashed line). C. Detail of wave-cut slope in an
 562 intermediate shoreline.

563 7. Example of transforming measured Bonneville (B), Intermediate (I), and
 564 Provo (P) altitudes to standard elevations (Bonneville = 1552 m, Provo =
 565 1445 m) for the purpose of correlating intermediate shorelines.

566 8. Outline of the maximum extent of Lake Bonneville based on the
 567 compilation of Currey et al. (1984). Localities of measured shoreline
 568 profiles. CL = Clarkson, BR = Bear River, LM = Little Mountain, PM =
 569 Promontory Mountains, AI = Antelope Island, WM = West Mountain, LA =
 570 Lake Mountains, TM = Table Mountain (Table 1).

571 9. Amount of isostatic rebound (meters) for A) Bonneville shoreline and B)
 572 upper Provo shoreline as calculated from the results of this study.

573 10. Scatterplot of Bonneville vs. upper Provo shoreline elevations as
 574 calculated in this study (Table 1). As suggested by Miller et al. (2013), the
 575 strong correlation between the two suggests that spatial variation across
 576 the basin is consistent for both shorelines.

577 11. Frequency plot of intermediate shorelines, evaluated at every 0.25 m with
 578 a 3-m moving window. A. Wave-cut slopes > 0.05. B. Wave-cut slopes
 579 > 0.10.

580 12. Elevation vs. wave cut slope for the major Intermediate shorelines
 581 identified in this study. Large symbols represent mean values and small
 582 symbols are one standard deviation.

583 13. Hillshade of LiDAR-derived DEMs showing prominent Bonneville, Provo,
584 and four of the five intermediate shorelines discussed in this paper with
585 additional minor shorelines. From the southern Antelope island sections.
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Figure 1

A. **B.**

Figure 2

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