Revisiting the deformed high shoreline of Lake Bonneville

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Abstract

Since G. K. Gilbert's foundational work in the eastern Great Basin during the late 1800s, the late Pleistocene Lake Bonneville (30–10 ka) has been recognized as a natural laboratory for various Quaternary studies, including lithospheric deformation due to surface loading and climate-forced water balance changes since the Last Glacial Maximum (~21 ka). Such studies rely on knowledge of the elevations of Lake Bonneville's paleoshoreline features and depositional landforms, which record a complex history of lake level variations induced by deglacial climate change. In this paper, we present (1) a new compilation of 178 elevation measurements of shoreline features marking Lake Bonneville's greatest areal extent measured using high-precision differential GPS (dGPS), and (2) a reconstructed outline of the highest shoreline based on dGPS measurements, submeter-resolution aerial imagery, topographic digital elevation models (DEMs), and field observations. We also (3) devise a simplified classification scheme and method for standardizing shoreline elevation measurement for different shoreline morphologies that includes constraints on the position of the still water level (SWL) relative to each feature type. The deformation pattern described by these shoreline features can help resolve the relative effects of local hydro-isostasy due to the lake load and regional solid earth deflection due to the Laurentide ice sheet, with potential implications for Earth rheology, glacial isostatic adjustment, and eustatic sea level change.

Keywords: Lake Bonneville, Great Basin, paleoshorelines, shorelines, still water level,

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27 **1. Introduction**

28 More than a century of study has shown that the ancient pluvial lakes of the western
29 U.S. host some of the world’s best-exposed archives of past climate change. Previous work
30 has estimated that such closed-basin lakes in the Great Basin were up to a factor of 10 times
31 greater in surface area than mean historical values during the last Pleistocene glaciation ~30
32 to 10 kyr ago (Mifflin and Wheat, 1979; Benson et al., 1990; Benson and Thompson, 1987).
33 The largest and best-known of these paleolakes is Lake Bonneville (30 to 10 ka; Oviatt et al.,
34 1992, 2015), predecessor to the Great Salt Lake. At its greatest extent, the lake reached
35 depths in excess of 300 m, attained a surface area roughly equal to that of modern day Lake
36 Michigan (~50,000 km²), and enclosed many islands that are now the mountain ranges of
37 western Utah. Due in large part to the semi-arid Holocene climate, relicts formed by Lake
38 Bonneville’s past high water levels have resisted erosion, and manifest in well-preserved
39 paleoshorelines and constructional landforms such as terraces, beach barriers, tombolos,
40 and spits. Together, these features record a complex history of climate-forced water balance
41 changes.

42 Spanish explorers Dominguez and Escalante were some of the very first to record the
43 presence of these prehistoric shorelines while on their expedition through the Great Basin in
44 1776 (Sack, 1989; Gilbert, 1890). Recognized as evidence of deeper lake successions that had
45 once occupied the basin of the Great Salt Lake, these paleoshorelines were briefly investigated
46 by Captain John C. Frémont and Howard Stansbury in the 1840s and 1850s (Sack, 1989).
47 However, it was G. K. Gilbert (1890) who revealed the paleoclimatic, geodynamic, and
48 geomorphic significance of the deposits and paleoshorelines of Lake Bonneville, jumpstarting
49 a century’s worth of careful research on the stratigraphy, sedimentology, geochronology,
50 paleohydrology, and anthropology in the area. Although much information has accumulated
51 since his work was first published, many of the hypotheses he developed have endured
52 scientific evaluation (Currey et al., 1984; Machette and Scott, 1988; Sack, 1989).

For simplicity and consistency, hereafter we drop the use of the *paleo-* prefix when discussing shorelines associated with Lake Bonneville, since the lake is prehistoric by definition. A *shoreline* is the line representing the physical boundary between the water surface and exposed land (Komar, 1998) and is constructed by connecting *shoreline features* like beach gravel barriers and wave-cut notches. We use the term *Bonneville shoreline* to refer to the shoreline marking the highest elevation Lake Bonneville attained.

1.1. Previous work on Bonneville shorelines

Riding on horseback throughout the basin using an altimeter, Gilbert (1890) was the first to observe the domed pattern of the deformed shorelines, measuring 33 elevation points on shoreline features marking Lake Bonneville’s greatest areal extent. After initially considering several hypotheses such as crustal expansion from warming and geoidal deformation, he deduced the present-day leading explanation for this phenomenon: a lithospheric response to the loading and unloading (filling and emptying) of lake water. He noticed that the shoreline deformation pattern approximately coincided with his estimates for maximum water depth, where areas with a greater water load exhibited greater amounts of deflection. Although he did not use the term “lithosphere,” Gilbert also estimated that some ~50 km-thick near-surface rock layer with significant elastic strength must be influencing the pattern of shoreline deformation, for it was smoother than actual water depth variations (Bills et al., 2002). Too little was known about Earth’s interior during his time to have made quantitative estimates of expected shoreline deformation. Nevertheless, Gilbert (1890) still had the insight to suggest that further study on the deformation of Lake Bonneville’s basin would yield more information on the composition and structure of Earth’s interior.

As Gilbert predicted, the deformed shorelines of Lake Bonneville have become one of the best records of Earth’s solid earth response to surface loading at relatively short wavelengths and timescales. Such studies have provided constraints on lithospheric thickness as well as upper mantle viscosity (e.g., Iwasaki and Matsu’ura, 1982; Nakiboglu and Lambeck, 1982, 1983; Bills and May, 1987; May et al., 1991; Bills et al., 1994, 2002), and have prompted many to improve and add to the dataset of shoreline feature elevation measurements. Crit-

tenden (1963a, 1963b) measured the elevations of 90 Bonneville shoreline features and detected a maximum difference of 71 m between the center and margins of the lake; Passey (1981) took 24 elevation measurements on Bonneville shoreline features and found 69 m of deflection. The most recent collection of elevational measurements of shoreline features is from Currey (1982). As an extremely skilled reader of stereoscopic aerial photographs and topographic maps (Oviatt, pers. comm.), Currey (1982) determined the elevations of 181 shoreline features on the Bonneville shoreline, covering a range of modern-day elevations between 1552 and 1628 m. Currey’s (1982) dataset laid the foundation for most studies of basin deformation thereafter, and has served as the primary source of shoreline feature elevation data for virtually all work on Lake Bonneville within the past thirty years.

Given that it has been over 30 years since Currey (1982) assembled his dataset, we thought it timely to revisit Lake Bonneville’s shorelines. It is essential to consider the limits of Currey’s (1982) compilation, as others have (Currey 1982; Nelson, 2012):

- (1) The data were collected before GPS became fully operational and available for civilian use. The coordinates and elevations of each point were either (1) determined via photo-mapping and stereoscopic interpretation of the best available aerial photos and topographic maps at the time (at scales of 1:24,000 and 1:62,500; 122 out of 181 points), (2) field checked with “rough-and-ready” closed hand-level surveys relative to sites of known-elevation benchmarks (41 out of 188 points), and/or (3) field checked with a telescopic alidade (18 out of 188 points). Thus, data accuracy depends on the method used.
- (2) The latitude and longitude coordinates of each measurement are only reported to the nearest hundredth of a degree, leaving a radius of ~ 1 km of uncertainty on the exact location of each data point. Thus, Currey’s (1982) data must be treated as references to small areas rather than point locations.
- (3) 67% of Currey’s (1982) elevations were extracted from contour maps and aerial imagery, with reported confidence intervals often as small as ± 1 m (the largest reported error being ± 5 m). These error estimates were based on the magnitude of contour

intervals used by the topographic map containing the feature of interest. The best topographic maps available for use at the time were of 1:24,000 scale (7.5-minute quadrangle maps), in which every inch on the map represents 2000 feet (~610 m) on the ground. The topographic maps available were from the 1960s–70s and were generated by photogrammetric methods from aerial photographs (Evans and Frye, 2009). Recent advances in computing and automation have reduced the need for manual operation of stereoscopic plotting instruments and tracing, which are possible sources of error.

- (4) Ideally, measurement of a shoreline feature elevation marks the mean location of the ancient shoreline. The elevation of the mean formative water surface, averaging the effects of wind-driven waves, is called the still water level (SWL). Unfortunately, the relationship between the SWL to shoreline features is not always consistent, even on modern shorelines. Shoreline features can be super-elevated or sub-elevated relative to the SWL. For example, the crests of constructional landforms such as beach barriers generally overestimate the SWL and more likely represent the maximum extent of storm deposits (Gilbert, 1890; Currey, 1982; Carter and Orford, 1984; Orford et al., 1991; Orford et al., 1995; Lorang, 2002). The majority of shoreline features measured by Currey (1982) are depositional, however Currey (1982) did not apply any geomorphic adjustments to account for super- or sub-elevation. There are unknown uncertainties associated with initial non-horizontality of shoreline features, and thus how each elevational measurement of shoreline features relates, in both a vertical and horizontal sense, to the true SWL.

In this paper, we improve upon Currey’s (1982) work, addressing these issues with technology now available to us. We present 178 new measurements of shoreline feature elevations from the Bonneville shoreline using dGPS, revisiting 85 shoreline features in Currey’s (1982) dataset for comparison. All measurements in the new compilation were measured in the field. Figure 1 illustrates these improvements by comparing the results of this study to that of Currey (1982) on Antelope Island, Utah. We use Currey’s (1982) dataset only as an aid in

identifying sites for remeasurement and comparison; thus, the data presented in this study are independent of previous efforts.

The organization of this paper is as follows: After briefly summarizing the relevant regional geologic history of Lake Bonneville in Section 2, we describe our methods for selecting, classifying, and measuring the elevations of Bonneville shoreline features in Section 3. In Section 4, we describe the results of our dataset of shoreline feature elevation measurements and the reconstructed Bonneville shoreline outline. We then discuss our best estimates on

Figure 1: A comparison of dGPS measurements of shoreline features and the shoreline outline presented in this study with Currey's (1982) shoreline feature elevation data. Panel A shows aerial imagery of the Bonneville shoreline on Antelope Island, Utah. Red and green lines represent traced gravel barriers and depositional terraces, respectively, from the reconstructed shoreline outline. Yellow circles mark the location of dGPS measurements, which were taken on two gravel barriers and one depositional terrace. The white diamond marks the coordinates of Currey's (1982) shoreline feature area for a "SE-facing beach ridge" (Currey ID #29). The shaded red circle with a dashed outline in Panel B shows the radius of lateral uncertainty associated with Currey's (1982) measurements due to the precision of the reported latitude and longitude coordinates (~ 1 km). Numbers in colored circles are the shoreline feature IDs of the shoreline features measured (Figure 7 and Table A1). Curry's (1982) reported elevation for the SE-facing beach ridge, which we interpret to correspond to ID 22, is 1599 ± 2 m (in the NGVD 29 vertical datum; Section S3). Our reported elevation for ID 22 is 1597.8 ± 0.3 m (1596.9 m in the NGVD 29 vertical datum).

the location of the SWL relative to our measured shoreline feature elevations in Section 5.

2. Regional setting

Closed-basin freshwater and saline lakes of various sizes have existed in the Great Basin since its establishment as a catchment during early Basin and Range strike-slip and extensional faulting 32 to 12 Ma (Stewart, 1978; Aguirre-Díaz and McDowell, 1993; Aranda-Gómez et al., 2000). Since then, the region generally has remained hydrologically closed, and during the Quaternary, lakes expanded and contracted in the basin many times (Oviatt and Currey, 1987; Oviatt et al., 1999). Lake Bonneville and Lake Lahontan (located in Nevada and California; Figure 2), the two largest pluvial lakes, occupied the eastern and western sides of the Great Basin, respectively, and were sourced by perennial rivers fed by snowmelt.

Figure 2 summarizes the well-established general chronology of the lake stages of the Bonneville cycle. We refer the reader to Reheis et al. (2014) and Oviatt (2015) for a more complete description of the transgressions and regressions of Lake Bonneville.

Many paleoclimatic studies linking lake-size and lake-level variations in the Bonneville basin to regional climate change rely on knowing the elevation of certain samples at the time of their formation (e.g., lacustrine carbonate deposits). When samples or features in question are geographically spread across a large region, it is more than likely that they possess differing isostatic histories. Thus, determining the magnitude and spatial variability of isostatic rebound in the basin is crucial to the adjustment of present-day shoreline elevations into paleoelevations for cross-correlation across long distances. The current lake-level history curve shown in Figure 2 was constructed via a simple linear equation under the assumptions that (1) the shorelines at the outer margins of the lake basin are approximately free of the impacts of isostatic rebound (“rebound-free”) and (2) the rebound in the basin is linearly proportional to the paleowater depth throughout the basin (Oviatt and Currey, 1985; Oviatt et al., 1992). In actuality, the load of Lake Bonneville was likely sufficient in size to induce far-field deflection outside of its boundaries (May et al., 1991). Although an oversimplification of a complex, non-linear geophysical phenomenon, Currey’s equation

Figure 2: Lake-level history of the Lake Bonneville lake cycle. Panel **A**: Map illustrating the maximum extent of the four major lake stages of Lake Bonneville from 30 ka to present. Lake stages are represented by different colors indicated by the swatches in the top right. Except for the Bonneville shoreline, shoreline outlines were drawn using modern contours of elevation recommended by [Benson et al. \(1990, 1992\)](#) and others: Stansbury (1372 m), Bonneville (1551 m), Provo (1445 m), Gilbert (1295 m), and the Great Salt Lake (1284 m). The outline for Lake Bonneville's greatest areal extent is that which is presented in this paper. Bottom-right inset in this panel features the extent of Lake Bonneville in relation to other pluvial lakes in the Great Basin (outlines from [Reheis, 1999](#)). Contours were generated from a 30 m DEM from the National Elevation Dataset (NED), maintained by the U.S. Geological Survey ([Gesch, 2007](#); [Gesch et al., 2002](#)). Panel **B**: Lake hydrograph of Lake Bonneville from 30 ka to the present based on previous work ([Oviatt et al., 1992](#); [Godsey et al., 2005, 2011](#); [Miller et al., 2013](#); figure courtesy of [Oviatt, 2015](#)). Elevations are adjusted based on a method by Currey ([Currey and Oviatt, 1985](#); [Oviatt et al., 1992](#)). Horizontal bars represent two-sigma calibrated radiocarbon ages. Bold black bars at the top of the panel mark the transgressive (**T**), overflowing (**O**), and regressive (**R**) phrases of the lake. Average elevation and approximate timing of the four main shorelines associated with Lake Bonneville are as follows: the Stansbury shoreline at ~25 cal ka ([Oviatt et al., 1990](#)) and ~1372 m; Bonneville at 18 cal ka ([Oviatt, 1991](#)) and ~1551 m; and the Provo from 18–15 cal ka ([Oviatt et al., 1992](#); [Godsey et al., 2011](#)) at ~1445 m. See [Oviatt \(2015\)](#) for further details.

(Oviatt and Currey, 1985; Oviatt et al., 1992) was considered accurate for the purposes of paleoclimatic interpretations (which require accuracy of elevations to within ± 10 m).

3. Methods

3.1. Selection of shoreline features for measurement

Along a single isochronous shoreline around a basin, the shoreline height relative to the SWL varies due to differences in local sediment supply, wave environment, shoreline geometry, and the depositional or erosional nature of the shoreline-forming process (Adams and Wesnousky, 1998; Atwood, 2006; Atwood et al., 2016). Lateral variations in relative height also can result from differential erosion or aggradation after lake regression. In order for the signal of solid earth deformation to be preserved, differences in the elevations of shoreline features caused by deformation must be larger than the inherent elevational variability of the shoreline features themselves (Tackman et al., 1998). Because a large signal-to-noise ratio is sought, previous shoreline surveys of paleolakes have primarily focused on measuring the elevations of depositional gravel barriers due to the high quality of their preservation and lack of post-formational modification relative to erosional shorelines (Currey, 1982; Tackman et al., 1998; Adams and Wesnousky, 1998, 1999; Adams et al., 1999).

While our new elevational dataset is also mostly composed of measurements on well-preserved gravel barriers, we also incorporate data from other shoreline morphologies for three main reasons:

- (1) The spatial distribution and relative proportion of different shoreline morphologies throughout the lake basin is unbalanced. If we consider the entire Bonneville shoreline, the vast majority ($\sim 95\%$) of the shoreline length takes the form of shoreline features such as terraces and incised alluvial fans (Section 4.2). Only a very small percentage of the shoreline is comprised of gravel barriers. Due to the steepness and resistant bedrock of the Wasatch Range flanking the eastern boundary of Lake Bonneville, depositional shoreline features are less common in the northeast and eastern parts of the lake basin. A spatial disproportionality between different erosional shoreline morphologies

also exists due to the greater presence of alluvial fans in the southern and western parts of the lake basin, which may have provided an abundant sediment supply for gravel barrier development. To only consider data from one shoreline morphology may leave large regions of the basin over- and under-represented.

(2) For any type of shoreline feature, there are a variety of ways to interpret the relative position of the SWL, and a quantitative understanding of how each shoreline morphology relates to the SWL is not well-constrained. By studying adjacent, isochronous shoreline features of different morphological types, which were all created by the same water body over the same interval of time, we can address the relationship between shoreline morphology and the SWL.

(3) Although uncertainties on the elevation of erosional features likely are larger than those for depositional gravel barriers, estimates with large uncertainties are still useful in Bayesian inverse problems (e.g., [Kopp et al., 2009](#)).

We took care to optimize the geographical distribution of remeasured shoreline features throughout the basin. Fortunately, Bonneville shoreline features are readily discernible and easy to correlate basin-wide due to the lack of coastal features at higher elevations in the surrounding area ([Gilbert, 1890](#)). We generated contour lines between 1550 and 1630 m in elevation from the 1 arc second National Elevation Dataset (NED; [Gesch et al., 2002](#)) to act as guides in identifying other Bonneville shoreline features not considered by [Currey \(1982\)](#).

3.2. Classification of shoreline features

Bonneville shoreline features can be grouped into three major classes based on their formation and morphology:

(1) **Gravel barriers:** Strong surface winds on the lake induce waves that act as agents of erosion, transportation, and deposition of sediments. If the transportation of sediment along and to the shore is greater than the amount of sediment washing offshore in the undertow, over time, the result is a raised, narrow convex-up mound of disk-shaped

Figure 3: Block diagrams depicting the location of the shoreline indicator (thick dashed line) for each shoreline feature type: (A) gravel barriers, (B) depositional terraces, and (C) incised alluvial fans. We also illustrate how the profiles of the depositional terrace and incised alluvial fan have changed since their initial formation.

cobbles, sand, and gravel (Figure 3A). Examples of different types of gravel barriers include baymouth barriers, pocket barriers (Figure 4), tombolos (ridges connecting two islands or a former island to the mainland), and cusped barriers and forelands (King, 1972; Duffy et al., 1989; Adams and Wesnousky, 1998; Currey and Sack, 2009). Gravel barriers and incised alluvial fans are easily visible in aerial imagery.

(2) **Depositional terraces:** These bench-like landforms formed on the steep slopes of mountainous areas are perhaps the most recognizable shoreline features to a casual observer. Oviatt and Jewell (2016) describe these features as gently-sloping depositional platforms of coarse debris formed nearshore on top of an eroded bedrock slope created by a rising lake (Figure 5). These features differ from the “cut-and-built” terraces described by Russell (1885) and Adams and Wesnousky (1998) in that the platform does not consist entirely of abraded bedrock. On the Bonneville shoreline, very few (or any) abrasional platforms exist, although much of the Provo shoreline consists of abrasional platforms (Oviatt and Jewell, 2016). Unlike gravel barriers, depositional terraces have undergone a non-negligible amount of landform diffusion since their formation (Figure 3B, post-lacustrine colluvial wedge). Of the three shoreline types, depositional terraces are the most visible from the ground, but the least recognizable in aerial imagery.

(3) **Incised alluvial fans:** In contrast to the other two shoreline feature types, these features form strictly via erosional processes. Coalescing alluvial fans pre-dating the Bonneville lake cycle were incised by waves to form scarps ranging from ~ 0.5 to > 20 m in height (Pelletier et al., 2006), providing an abundance of coarse clastic material from which the aforementioned gravel barriers were made. In aerial imagery, these alluvial fans appear truncated at the elevation of the Bonneville shoreline (Figure 6) and bear some physical resemblance to fault scarps; however, unlike fault scarps, these truncations often follow contour lines for long distances and often exhibit striking lunate (scalloped) geometry. Depending on the depth of incision, fan-incised shorelines are the most recognizable features in aerial imagery, largely due to (1) the abrupt

change in surface texture from the channelized, braided-stream fabric of debris flows above the scarp to a smoother plain below the scarp, and (2) changes in vegetation type and density on the slopes of escarpments. Like depositional terraces, the scarp profiles of incised alluvial fans have also undergone post-lacustrine alteration (compare the freshly incised alluvial fan scarp profile to the present-day profile in Figure 3C). Of the three shoreline types, incised alluvial fans are the most recognizable in aerial imagery.

In some localities, the products of depositional and erosional processes are found in close proximity to one another, imparting some shoreline features with traits from multiple categories (e.g., gravel barriers around inselbergs and abutting the scarps of incised alluvial fans).

3.3. Detection of shoreline indicators

Given these three distinct shoreline feature morphologies and differences in how the features have changed following lake-level fall, the challenge is to devise a rigorous and repeatable technique for consistent measurement of shoreline feature elevations. With our measurements, we aim to best capture the height of the SWL at the time of the Bonneville shoreline’s active formation. For pragmatic purposes, we choose to measure the elevation of a specific, visually discernible physical feature common to each respective shoreline feature type—a *shoreline indicator*—to serve as a proxy for the SWL, following the strategy of numerous studies mapping shorelines of modern coasts (e.g., Rose, 1981; Boak and Turner, 2005, and the sources therein).

Figure 3 illustrates the location of each shoreline feature type’s respective shoreline indicator. For gravel barriers, we chose to measure the *crest of the ridge*. For depositional terraces, we chose to measure the *inflection point of the terrace profile*. For incised alluvial fans, we measured the *base of the fan scarp*, the intersection between the scarp face and the gentle basal plane into the desert basin below it (i.e., the “fault line” if these were fault scarps), carefully avoiding measurement near the outlets of stream cuts (Figure S1).

Figure 4: Aerial imagery, photographs, and characterization of gravel barriers of the Bonneville shoreline. The top half of panels (A, B, and C) corresponds to shoreline feature ID 159; the bottom half (D, E, F, and G) corresponds to ID 76. White insets in the bottom right corner detail relevant information on each shoreline feature: the number of dGPS measurements along the length of the shoreline feature (N), the mean elevation (μ) and standard deviation (σ), and confidence (scale of 1–4, with 4 representing the greatest confidence; Section S8). Yellow points mark the locations of dGPS elevation measurements. Panels A and D show the areal extent of the visited shoreline features relative to the paleowater level and surrounding shoreline, with black rectangles indicating the areal extent of the aerial imagery shown in panels B and E, respectively. Colors of the shoreline outline represent different shoreline feature types (red = gravel barriers; green = depositional terraces; blue = incised alluvial fans). White diamonds represent the coordinates given by Currey (1982) for each shoreline feature area. Panels B and E are aerial images of the gravel barriers in closer detail. Camera icons show the approximate location from which the photographs shown in panels C and F were taken. Cardinal directions given in the photographs indicate the camera-facing direction. Christine Chen and field assistant Ballard Metcalfe are pictured standing on the shoreline indicator of the shoreline feature in panel F. Elevational measurements were made on the crests of the barriers. Panel G is a photo of beach pebbles found at the crest. Numbers in colored circles correspond to IDs indexed in Table A1 and shown in Figures 7 and S5. Aerial imagery from Bing Maps accessed in April 2013.

Figure 5: Aerial imagery, photographs, and characterization of depositional terraces of the Bonneville shoreline. The top row of panels (A, B, and C) corresponds to shoreline feature ID 33; the middle row (D, E, and F) to ID 23; and the bottom row (G, H, and I) to ID 1. White insets in the bottom right corner detail relevant information on each shoreline feature: the number of dGPS measurements along the length of the shoreline feature (N), the mean elevation (μ) and standard deviation (σ), and confidence (scale of 1–4, with 4 representing the greatest confidence; Section S8). Yellow points mark the locations of dGPS elevation measurements. Note that only one yellow point is used to mark the location of the shoreline feature in the photographs, even if more measurements exist, so as not to obscure the photograph. Panels A, D, and G show the location of the visited shoreline features relative to the paleowater level and surrounding shoreline, with black rectangles indicating the areal extent of the aerial imagery shown in panels B, E, and H, respectively. Colors of the shoreline outline represent different shoreline feature types (red = gravel barriers; green = depositional terraces; blue = incised alluvial fans). Camera icons represent the approximate location from which the photographs shown in panels C, F, and I were taken. Cardinal directions given in panels C, F, and I indicate the camera-facing direction. Numbers in colored circles correspond to IDs indexed in Table A1 and shown in Figures 7 and S5. Aerial imagery from Bing Maps accessed in April 2013.

Figure 6: Aerial imagery, photographs, and characterization of incised alluvial fans of the Bonneville shoreline. The top row of panels (A, B, and C) corresponds to shoreline feature ID 98; the middle row (D, E, and F) to ID 56; and the bottom row (G, H, and I) to ID 113. White insets in the bottom right corner detail relevant information on each shoreline: the number of dGPS measurements along the length of the shoreline feature (N), the mean elevation (μ) and standard deviation (σ), and confidence (scale of 1–4, with 4 representing the greatest confidence; Section S8). Yellow points mark the locations of dGPS measurements. Note that not all points measured on a particular shoreline feature are necessarily shown in order not to obscure the photograph. Panels A, D, and G show the location of the visited shoreline features relative to the paleowater level and surrounding shoreline, with black rectangles indicating the areal extent of aerial imagery shown in panels B, E, and H, respectively. Colors of the shoreline outline represent different shoreline feature types (red = gravel barriers; green = depositional terraces; blue = incised alluvial fans). Camera icons represent the approximate location from which the photographs shown in panels C, F, and I were taken. Cardinal directions given in panels C, F, and I indicate the camera-facing direction. Numbers in colored circles in the top right corner correspond to IDs indexed in Table A1 and shown in Figures 7 and S5. Aerial imagery from Bing Maps accessed in April 2013.

Each of these shoreline indicators represents different vertical positions relative to the SWL due to differences in the processes forming their corresponding shoreline types, as well as differences in the way each landform has been altered since they were formed (e.g., hillslope diffusion of scarp profiles). We discuss these issues and evaluate each shoreline indicator’s ability to serve as a proxy of the SWL in Section 5.2. Nevertheless, we contend that each of these chosen shoreline indicators is the physical feature that is the most discernible for consistent measurement of each shoreline feature type.

Prior to measurement, the location of each shoreline indicator was first judged from a short distance. After locating the shoreline indicator, we used a Trimble GeoExplorer 6000 GeoXH handheld device, a high-accuracy dual-frequency Global Navigation Satellite System (GNSS) receiver, to collect the elevation data. After post-processing with proprietary software, we are able to achieve horizontal and vertical measurements accurate to within ± 30 cm ($2\text{-}\sigma$ error) by correcting for errors in GPS measurements (Section S1).

In order to assess the reproducibility of our in-field interpretation of the shoreline indicator location, we revisited previously measured shoreline features in subsequent field seasons and approached the measurement as if it were a novel location, using no guides aside from our field observations while collecting dGPS data. We also assessed the accuracy of our in-field interpretations of the shoreline indicator location with an ebee Sensefly drone-derived 5 cm pixel digital surface model (DSM) of a 0.75 km^2 portion of Antelope Island, Utah (Section S2). Using the DSM, we objectively located the true location of gravel barrier crests (IDs 22 and 178) and the inflection point of a depositional terrace profile (ID 177), and compared the results to our dGPS elevation data.

In order to compare our elevation measurements with those of Currey (1982), we first reconciled both datasets within the same vertical datum, since Currey’s (1982) elevation data are in a legacy datum no longer in use (Section S3 for details on the conversion between vertical datums). Comparisons to Currey’s (1982) data were done only if we were certain that both measurements were made on the exact same feature. Because Currey (1982) did not provide precise coordinates and explicit descriptions of the shoreline features he measured, we were only able to confidently compare elevation data for 85 shoreline features,

of which all but one are gravel barriers. We attribute this bias in our comparison to the fact that Currey’s (1982) dataset is comprised mostly of gravel barriers, allowing us to more easily identify the specific feature Currey (1982) measured. Where possible, the coordinates corresponding to Currey’s (1982) shoreline feature areas are represented by a white diamond in all figures.

3.4. *Reconstructing the Bonneville shoreline outline*

The development of geospatial information software and improved resolution of aerial imagery, topographic maps, and DEMs has enabled researchers to map at much finer scales and at greater accuracy than was possible at the time of Currey (1982). Upon return from the field, we used dGPS data, field observations, and over 1000 field photographs of shoreline features as aids and constraints in the construction of a new shoreline outline that accurately represents the pattern of the deformed Bonneville shoreline. Our shoreline outline is meant to capture the x - y location of the SWL at the time Lake Bonneville reached the highest elevation it ever attained. As with the dGPS measurements, we use the aforementioned shoreline indicators—the crest of gravel barriers, the inflection point of depositional platforms, and the base of incised alluvial fan scarps—as proxies for the SWL.

Using GIS software, we constructed the shoreline outline by tracing thousands of smaller segments, starting at Red Rock Pass in the northeast corner of the lake (Figure 2A) and continuing along the expected path of the Bonneville shoreline in a clockwise fashion. Each segment was categorized into one of the three shoreline feature types. In places where there is little to no remaining geomorphic evidence of past lake occupation due to extensive post-depositional alteration (e.g., burial by talus, fluvial erosion, human disturbance), we based our best guess of the original shoreline feature type on the nature of the surrounding substrate (Section S6).

We then used the outline to compute a first-order estimate of the water volume represented by the Bonneville shoreline and create a map of paleowater depth (Section S7).

4. Results

4.1. The compilation of dGPS elevation measurements of Bonneville shoreline features

We present a new compilation of 178 individual dGPS elevations of Bonneville shoreline features (Figure 7; Table A1). In line with the findings of Gilbert (1890) and Currey (1982), we observe a ~ 76 m elevational difference between shoreline features at the center of the basin and those at the margins (Figures 8, 9). The lowest elevation recorded is 1548.0 ± 0.1 m (ID 1), measured on a depositional terrace in the northeast corner of the lake. The highest elevation recorded is 1624.0 ± 0.1 m (ID 38), measured on a gravel barrier in the Grassy Mountains near the lake center. Overall, more than half of the dataset consists of measurements on gravel barriers (Table S1). Based on our independent measurement of two gravel barriers in different field seasons, our interpretations of the shoreline indicator location and dGPS measurements are reproducible to within 0.1–0.2 m (Figure S3). Section S4 contains further statistics on the compilation.

Our drone-derived digital surface model (DSM) and objective identification of shoreline indicators show that we are accurately placing the vertical location of gravel barrier crests to within ± 0.3 m and the inflection point of depositional terraces to within ± 1.0 m (Section S2).

In comparing our measurements to that of Currey (1982), we observe that Currey’s (1982) elevations for 85 shoreline features are, on average, 1.8 ± 1.4 m higher than those reported in this study (Figure S2A). If we separate Currey’s (1982) data by the method of collection, we see that data collected via in-field surveys better matches our dGPS measurements than data collected via photo-mapping alone (Figures S2B–D). Table A1 includes data from Currey (1982) for comparison to our dGPS elevation measurements.

4.2. The reconstructed Bonneville shoreline outline

The Bonneville shoreline outline (Figure 7) is composed of over 2000 individual segments, including those tracing the shoreline on former islands that resided in the interior of the lake (Section S6.2). The vast majority ($>95\%$) of the Bonneville shoreline is represented by depositional terraces and incised alluvial fans, with gravel barriers only comprising a small

Figure 7: Overview map showing the new compilation of 178 unique Bonneville shorelines features measured by dGPS (white and colored circles with numbers) and the new Bonneville shoreline outline (colored lines). Small white circles on the outline mark locations of measured shoreline features; numbers in the corresponding colored circles are the shoreline feature IDs of each shoreline feature, which are indexed in Table A1. Circle colors and colored segments of the Bonneville outline represent shoreline type and will be used consistently in other figures. White star marks location of Salt Lake City. Refer to Figure S5 for Panels A and B, which correspond to the shoreline feature IDs listed in the “other locations” inset. Black and white relief in the background was generated from the 30 m NED DEM.

Figure 8: Domed pattern of deformation illustrated by the dGPS elevations of Bonneville shorelines. Circle sizes indicate the level of confidence associated with each measurement (on a scale of 1–4, with 4 representing the greatest confidence; see ‘Confidence’ legend above). Black circles indicate locations of other visited sites in which measurements were either not taken or deemed inaccurate in post-processing. White star marks location of Salt Lake City.

Figure 9: Present-day shoreline feature dGPS elevations as a function of distance from the center of the lake basin (41.10 °N, 112.88 °W). Colors represent shoreline feature type and shapes represent levels of confidence (Section S8). We chose a location close to our highest points in the Lakeside Mountains to serve as the lake basin center, consistent with previous researchers (Gilbert 1890; Crittenden 1963b; Crittenden 1963a; Currey 1982; Bills and May 1987; Bills et al. 1994; and others).

fraction (Table S4). Based on this distribution, it is clear that our dataset over-represents gravel barriers and under-represents depositional terraces. This sampling bias is unsurprising given that the crest of gravel barriers is easy to detect and relatively better preserved.

The shoreline outline reveals a distinct lack of gravel barriers in the northeastern and eastern margins of the lake, which primarily are dominated by depositional terraces. This observation may be due to the fact that the deep eastern lake basin rises steeply into the resistant Wasatch Range, making it difficult to stimulate enough sediment accumulation for the generation of gravel barriers. In contrast, the prevalence of gravel barriers along the southwestern and western margins can be attributed to increased sediment supply from re-worked alluvium from incised alluvial fans and shallower slopes; indeed, these same regions are also host to a larger proportion of incised alluvial fans. In the northern, northwestern, and central parts of the lake, increased sediment supply couples with increased accommodation space from the steeply-sloped mountain ranges.

Our first-order estimates of the surface area and lake volume of the lake represented by the Bonneville shoreline are 51,200 km² and 10,300 km³, respectively. The resulting map of lake depth places the deepest part of the lake around 41.1 °N, 112.9 °W, close to the Grassy and Lakeside Mountains of Utah (Figure S6), which is consistent with our shoreline

elevation measurements (Figure 9).

5. Discussion

5.1. Estimating the SWL from elevation measurements of Bonneville shoreline features

If the Bonneville shoreline and elevation measurements are to be used for future modeling studies of deglacial climate change and mantle/lithospheric deformation from regional water and ice loads, we must first examine the physical relationship between our dGPS-anchored shoreline elevations and the SWL recorded by the Bonneville shoreline. First, in order to accurately estimate the location of the SWL, we must quantify the factors contributing to our uncertainty of the SWL:

- (1) The precision of the dGPS elevation measurements themselves;
- (2) The ability of the surveyor to accurately and consistently detect and measure the shoreline indicator on shoreline features in the field;
- (3) The natural variation in elevation of the shoreline indicator across the length of a shoreline feature; and
- (4) The appropriateness of the shoreline indicator as an approximation for the SWL.

With each factor, we focus primarily on the vertical uncertainty because the horizontal uncertainty will have negligible impact on calculations of water volume and lake depth (Section S7), whereas the total vertical deformation recorded by the shoreline is only on the order of tens of meters. For (1), the manufacturer’s reported vertical precision of the dGPS elevation measurements is ± 15 cm ($1-\sigma$), and the average standard deviation associated with the calculated arithmetic means of elevation for each measured shoreline feature is well within half a meter (Table A1). For (2), we assigned “confidence levels” to each of our elevational measurements to quantify the degree of certainty to which we have measured the shoreline indicator in the field, which is highly dependent on the quality of shoreline feature preservation and shoreline type (Section S8; Tables S2, S3). Of these two factors, the greatest

uncertainty is caused by the visual *in situ* determination of the shoreline indicator by the operator.

For (3), we can assess the natural elevational variation of shoreline indicators by examining measurements across the entire lengths of shoreline features. Figure S4 shows examples of the undulating pattern of elevations observed across the length of three individual gravel barriers of varied lengths (~ 300 , 700 , and 1300 m). The shortest of these gravel barriers exhibits a range in elevation of ~ 0.35 m (ID 66; Figure S4B), whereas the longest exhibits a range of ~ 1.6 m (ID 53; Figure S4F). These observations are not artifacts of time-varying dGPS solutions, but rather are true measurements of deviations in crest height along the length of a beach ridge.

Similarly, Adams and Wesnousky (1998) conducted Total Station surveys of 10 different constructional highstand gravel barriers within a ~ 20 km² embayment of Lake Lahontan and observed a ~ 2.6 m range in elevation between distinct constructional shoreline features (impacts of isostatic rebound are broadly uniform within this area). Atwood (1994) also observed that relatively modern constructional shorelines of the Great Salt Lake, formed during the winter between 1986–1987, also feature a natural variability in crest elevation of ~ 2 m. These observations reflect natural differences in the height of crest formation relative to the SWL between unique shoreline features due to differences in local slope, shoreline geometry, *et cetera* (Zenkovich, 1967, p. 292-3). Consequently, our results show that, in addition to these differences in crest height formation between individual gravel barriers, each feature also has its own natural alongshore internal variability (< 2 m) in crest height.

We did not attempt to measure the natural elevational deviations of incised alluvial fans and depositional terraces because the inherent uncertainty of detecting and measuring the associated shoreline indicators in the field is likely on the same order of or larger than the magnitude of any true variability in elevation.

5.2. Spatial relationship between shoreline indicators and the SWL

Of the aforementioned factors contributing to our uncertainty of the location of the SWL, the main challenge is addressing (4), how each shoreline indicator spatially relates, in

a vertical and horizontal sense, to the physical boundary of the SWL. In an ideal world, our three different types of shoreline indicators would record the same physical location relative to the SWL. However, the processes controlling the development of each shoreline type are different. We first discuss how previous studies have weighed in on the relationship between the SWL and physical shoreline indicators.

The crests of gravel barriers are generally believed to represent the maximum extent of storm deposits rather than the SWL (Gilbert, 1890; Currey, 1982; Carter and Orford, 1984; Orford et al., 1991; Orford et al., 1995; Lorang, 2002), with swash-aligned gravel barriers tending to be more super-elevated than drift-aligned features (Davies, 1980). Atwood (2006) found that the constructional shorelines of the modern-day (1986–87) Great Salt Lake are, on average, 0.9 ± 0.4 m higher than the SWL due to differences in fetch, the slope of the shore face, and the strength, orientation, and duration of prevailing storm winds (measured crest elevations ranged from 0.2 m below to 3.7 m above the SWL, with a third of the measurements falling > 1 m above the SWL). Laboratory wave-tank studies have supported these observations, providing evidence that ridge heights are controlled by the wave run-up distance on the slope leading up to a shoreline, where the wave-run up distance is the maximum vertical extent of a wave swash on a beach (Bagnold, 1940; Sorenson, 1997; Komar, 1998). Adams and Wesnousky (1998) found that the barrier crests in their embayment of Lake Lahontan are elevated 1–1.5 m above paleolake levels, which were estimated by comparing the crest’s relative vertical position to the “hinge line” of the constructional feature, which they assert best marks the SWL. The “hinge line” is approximated as the point of inflection where horizontal topsets (formed by wave-washed sediment deposited over the crest of a barrier) steepen into backsets (formed by the same sediment cascading down a slip face into a lagoon). In Pyramid Lake, Nevada, Adams and Wesnousky (1998) observed that the water level in lagoons of modern highstand barriers is identical to the water level of the lake due to the high permeability of barrier sediments, and that the hinge line best approximates the lagoon water level.

For terrace landforms, the erosional notch (or knickpoint or ‘shoreline angle’) of a wave-cut terrace formed in resistant bedrock is generally thought to form at the SWL since

erosional effects of wave pounding from breaking waves on steep near-vertical cliffs are greatest at the water surface (Gilbert, 1890; Zenkovich, 1967; Trenhaile, 1987; Sunamura, 1991; Trenhaile, 2000). The depositional terraces of the Bonneville shoreline are not abrasion platforms, but it is possible that the intersection between the cliff face and the abutting depositional platform would be equivalent to the erosional notch of an erosional wave-cut terrace if cliff erosion and deposition on the platform kept pace with lake level rise (Oviatt and Jewell, 2016). However, if deposition on the platform slows for some reason, as the lake rises, this point can be left behind and appear lower than the SWL. Thus, the elevation of this feature would represent a minimum elevation for the SWL, meaning its elevation is equal to or lower than the SWL (Oviatt and Jewell, 2016). Wolinsky and Murray (2009) mathematically treat this case for larger length scales on marine shorelines in their model of shoreline transgression over decadal to millennial timescales, showing that as sea level rises on steep coasts, weathering of the cliff face produces sediment that is transported seaward and deposited on a nearshore platform.

For incised alluvial fans, although waves eroded into weakly consolidated alluvium rather than bedrock, the relationship between the erosional knickpoint and the SWL is the same. Thus, we would expect the base of the incised alluvial fan scarp to mark the SWL.

In summary: barrier crests tend to be super-elevated relative to the SWL by 1 m on average, and the amount of super-elevation varies between barriers; the notch-equivalent of depositional terraces is a limiting elevation, in which its elevation is equal to or lower than the SWL; and the base of the original incised alluvial fan scarp profile likely marks the SWL.

We now compare these aforementioned shoreline indicators with the shoreline indicators we chose and measured in this study. We have reliably measured the crest heights of gravel barriers, which are well-defined and have not suffered from significant time-dependent landform decay. Conversely, the true locations of the notch-equivalent of depositional terraces and the base of the original fan scarp profile are not visible, having been buried in colluvium (Figures 3B–C). For incised scarps, the original profile also has since relaxed due to hillslope diffusion processes such as flora and faunal bioturbation and creep (Pelletier et al., 2006). Although the post-lake colluvium burying the notch-equivalent of depositional ter-

races and the base of the original scarp profile could be several meters thick, the shoreline indicators we have chosen—the inflection point of the terrace profile and the base of the diffused incised fan scarp profile—minimize its impact on the vertical elevational difference between our shoreline indicators and the buried shoreline indicators with well-established relationships with the SWL. Theoretically, both the inflection point of the terrace profile and the base of the current fan scarp are locations where post-lake colluvium deposition is at a minimum (Figures 3B–C). Although this decision means that our shoreline indicators are horizontally offset from the notch-equivalent of the terrace and the original scarp base by several meters offshore, the amount of offset in the vertical should be considerably less. Alluvial fan incision elevations could be refined by measuring the height or slope of the incised alluvial fan scarps we measured; previous studies have shown that scarp height and gradient influence the rate of scarp diffusion, and thus the amount of colluvium covering the original scarp base (Roering et al., 1999; Pelletier et al., 2006).

Therefore, within our elevational dataset, we expect the barrier crests to overestimate the SWL by 0.9 ± 0.4 m, the inflection points of terrace profiles to represent an elevation equal to or lower than the SWL, and base of diffuse fan scarps to represent an elevation equal to or slightly lower than the SWL. Our compilation of Bonneville shoreline feature elevations is consistent with this interpretation. In Figure 10, we compare the elevations of pairs of (1) gravel barriers and depositional terraces and (2) gravel barriers and incised alluvial fans that are in close proximity to one another (within 2.0 km to avoid any differential effects due to isostatic rebound). When comparing seven barrier-terrace pairs, the inflection points of the terraces are consistently below the crests of gravel barriers (on average, the inflection point of depositional terraces are 6.0 ± 3.3 m lower than the crests of gravel barriers; maximum difference was 10.1 m lower, minimum was 1.0 m lower). These differences cannot be accounted for by the uncertainty associated with the detection of the shoreline indicators (i.e., levels of confidence). A similar observation can be made from Figure 9: depositional terraces are consistently the lowest in elevation relative to the other shoreline types. Adams and Wesnousky (1998) observed a similar result in Lake Lahontan, in which the elevation of the knick points (“shoreline angles”) of wave-cut terraces in their embayment were 1–3

Figure 10: Comparison of pairs of gravel barrier/depositional terrace (left; 7 pairs) and gravel barrier/incised alluvial fan (right; 8 pairs) that are within 2.0 km of each other so as to avoid any differential effects due to isostatic rebound. Each datapoint is labeled by a pair of shoreline feature IDs in parentheses that indicate which two shoreline features are being compared. The first number listed corresponds to the ID of the gravel barrier in the pair. The second number listed corresponds to the ID of the depositional terrace or incised alluvial fan. The size of the circle indicates the distance by which each pair is separated; smaller circles indicate close pairs whereas larger circles indicate distant pairs (see inset for legend). The solid line marks the one-to-one line.

m below the elevation of neighboring barrier crests. When comparing gravel barrier-incised alluvial fan pairs, the base of incised alluvial fan scarps are, on average, 1.4 ± 1.5 m lower than the crests of gravel barriers (maximum difference was 3.6 m lower, minimum was 1.0 m higher).

In addition, based on our drone-derived DSM, automated detection of the vertical location of inflection points of depositional terraces suggests that the elevation of this shoreline indicator may vary by several meters within short (<1 km) distances (Section S2, Figure S19).

5.3. Estimates of the SWL elevation from shoreline feature measurements

In our elevational dataset of Bonneville shoreline features, we have measured three different shoreline indicators corresponding to three different shoreline morphologies. Of these three shoreline indicators, we believe that the crest of a gravel barrier is the best proxy for the SWL due to the ease and consistency with which we can detect and measure the barrier crest

(i.e., high level of confidence), the well-characterized nature of alongshore variability in crest height, and the availability of estimates of the range of super-elevation observed in gravel barriers both modern and old. That the gravel barriers comprise the largest proportion of the three shoreline types in the dataset is an added bonus. The base of incised fan scarps is likely the second-best proxy of the SWL based on its close relationship to the SWL position but its low levels of confidence due to complications of post-lacustrine stream deposits and hillslope diffusion. Although the depositional terraces are the most visible and recognizable shoreline features in the field from afar, they frequently occur high on steep inaccessible slopes, and the inflection point of the profile underestimates the SWL by varying amounts throughout the basin. Thus, the inflection point of depositional terraces is the worst proxy for the SWL of the three shoreline indicators. Table S4 summarizes our interpretations on the relative vertical relationship between the different shoreline indicators and the SWL.

Despite the shortcomings of the depositional terraces and incised alluvial fans as SWL proxies, we assert that the information captured by these landforms is still a valuable constraint on the SWL. We attempt to leverage this additional information and estimate the elevation of the SWL recorded by each shoreline feature measurement by applying a simple uncertainty propagation scheme (Section S9) that accounts for both (1) the uncertainty detecting the location of the shoreline indicator, represented by confidence intervals (Section S8), and (2) the systematic vertical offsets between different shoreline types (Section 5.2). For (2), we take advantage of the known relationship between the SWL and the crests of gravel barriers, as well as the paired comparison of the elevations of different shoreline feature types (Figure 10 & Section 5.2). Assuming a normal distribution of these uncertainties, we treat (1) as a “random” measurement error and (2) as a “systematic” error and add the errors in quadrature. Regardless of the true distribution of these uncertainties, we expect the distribution of the mean of the data to naturally tend towards a normal distribution as a consequence of the Central Limit Theorem. Table A1 contains these estimates on the elevation of the SWL.

5.4. Improvements to Bonneville shoreline feature elevations and shoreline outline

Following Section 1.1, the compilation of elevational measurements of Bonneville shoreline features presented in this study improve our understanding of Currey (1982) in the following ways:

- (1) Currey (1982) used 3 different methods to create his dataset (with only $\sim 33\%$ of the data being field-verified) and did not have access to the GPS tools that are available today. In this study, all shoreline feature elevation data were gathered using high-precision dGPS in the field.
- (2) After post-processing, our dGPS measurements are accurate to within ± 30 cm ($2\text{-}\sigma$ error) in both the horizontal and vertical domain, leaving little ambiguity with regards to the location of the feature measured. Thus, we improve the precision to which we know the location of Bonneville shoreline features by three orders of magnitude.
- (3) The reported uncertainties of the shoreline feature elevation measurements by Currey (1982) are optimistic based on (a) our comparison between his elevations and our dGPS-measured elevations, which reveal that his measurements are, on average, 1.8 ± 1.4 m higher than ours (Figure S2), as well as (b) our finding that individual gravel barriers have their own internal alongshore variability (as great as ± 1 m) in crest height. The method by which Currey (1982) assigned uncertainties was not always clear. In contrast, the uncertainties associated with our dataset are well-documented.
- (4) Although Currey (1982) acknowledged the possibility of super- or sub-elevated shoreline features relative to the SWL, he did not attempt to resolve the issue. Although we, too, have not completely resolved the issue, we address them by providing quantitative constraints on the vertical relationship between the shoreline indicators and the SWL.

Moreover, shoreline outlines produced by Currey (1982) were of coarser resolution and do not exist in any accessible digital format. Our dGPS elevation measurements and new shoreline outline are digitized and readily available for both research and education purposes.

We do not suggest that our dataset should be a complete replacement over that by Currey (1982). Rather, for future studies using the elevations of shoreline features of the Bonneville shoreline, we recommend that both our datasets be considered together. Since all of our measurements have been field-verified and measured with dGPS, our remeasurement of 85 out of the 181 shoreline features measured by Currey (1982) has greatly increased the precision of both the known location and elevation of these features. These remeasurements also give us a sense of how to consider the reported elevations of the other shoreline features by Currey (1982). Combining both our datasets yields a compilation of 274 elevations of unique Bonneville shoreline features that can constrain solid earth deformation models (93 new shoreline features from our study, 85 features measured by both studies, and 96 features measured by Currey (1982) that were not remeasured in this study).

Once higher resolution DEMs (e.g., LIDAR, drone-derived products) are available for the entire area encompassing the Bonneville shoreline, more quantitative and objective methods can be used to measure the elevations of shoreline features, (e.g., Hare et al., 2001; Jewell, 2016; Jewell et al., 2016; Section S2).

5.5. Applications to paleoshoreline studies in other lake basins

The results of our study convey a cautionary tale in estimating the SWL from shoreline features. When reporting any shoreline feature elevation measurement, researchers should report not only the feature type being measured, but also the shoreline indicator used. Care must also be taken to capture the amount of lateral elevational variation within an individual shoreline feature and between shoreline features in the same vicinity. If no gravel barriers or true wave-cut platforms are present, analyzing adjacent shoreline features of different types in a manner similar to that featured in Figure 10 can elucidate possible systematic offsets that may allow the use of other less conventional shoreline feature types. Reporting the geodetic reference systems (datum and geoid) used for shoreline measurements is also critical in order to facilitate multi-study comparisons (Section S1).

6. Conclusions

We determined precise elevations and horizontal positions of 178 Bonneville shoreline features. The shoreline features record an elevational range of ~ 76 m. The precision to which we know the horizontal location of Bonneville shoreline features is improved by 3 orders of magnitude compared to the dataset by [Currey \(1982\)](#). We quantified the uncertainties surrounding the position of the SWL relative to our measurements (Sections 5.2, S9; Table S4) and classified features by shoreline type and confidence level. We also present a detailed outline of the Bonneville shoreline that is based on our field observations, dGPS elevation data, and satellite imagery (Sections 3.4, S6).

Our classification scheme and techniques for standardized elevational measurement of shoreline features across different shoreline morphologies using shoreline indicators are applicable to other shoreline studies in the world. Due to their ease of detection and measurement, we find that the crests of gravel barriers are the best proxies for the SWL compared to the inflection points of depositional terraces and the base of incised alluvial fan scarps. However, depositional terraces and incised alluvial fans still bound the elevation of the SWL, and should be taken into account to avoid biases in the spatial representation of deformation in Lake Bonneville.

We hope that this new dataset will help re-stimulate research on solid earth deformation in the Great Basin (e.g., [Bills and May, 1987](#); [May et al., 1991](#); [Bills et al., 1994](#); [Bills et al., 2007](#)). The deformation pattern of Lake Bonneville's shorelines and shorelines of other paleolakes in the Great Basin (e.g., Lake Lahontan; see [Adams et al., 1999](#)) captures the effects of both local isostasy and regional tilting due to the loading of the contemporaneous Laurentide ice sheet. Previous studies that have used paleoshoreline evidence to test models of postglacial rebound in North America have mostly been confined to the near-field (e.g., [Tackman et al., 1998](#); [Lambert et al., 1998](#)). Therefore, after accounting for local isostasy, more accurately resolving the direction and magnitude of the far-field continental-scale tilt captured by shorelines of western U.S. paleolakes can add an important additional constraint on the ice loading and solid earth deformation history of North America. The western

U.S. paleolake shoreline data also may be able to uniquely constrain the rheology of the lithosphere and upper mantle. Thus, much like marine terraces (e.g., [Chappell et al., 1996](#); [Milne et al., 2002](#); [Peltier, 2004](#)), these ancient lacustrine shorelines have broad and far-reaching implications for Earth rheology, glacial isostatic adjustment, and eustatic sea level change.

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8. Author Contributions

Field work was conducted by CYC (9 weeks) and ACM (2 weeks), following initial project design and field season planning by CYC. CYC collected and analyzed the shoreline feature elevation data, wrote the manuscript, and drafted figures, all with input from ACM. CYC and ACM collected the drone data (2 days). ACM analyzed the drone data with input from CYC.

Table A1: Differential GPS elevation measurements of Bonneville shoreline features. Data listed in ascending order of shoreline **ID** (see location of each measurement in Figures 7 and S5). **N** is the number of measurements included in the mean elevation. **Type** refers to shoreline type, where 1 = gravel barrier, 2 = depositional terrace, and 3 = incised alluvial fan (Section 3.2). **Conf.** is the level of confidence assigned to each shoreline on a scale of 1–4, with 4 representing the greatest confidence (Section S8). **Elev.** is the dGPS elevation of each shoreline ID’s shoreline indicator (Section S1). **SWL Elev.** is the corresponding estimate of the elevation of the SWL (Sections 5.3, S9). Corresponding shoreline elevation data from Currey (1982) is included when available. **Match** indicates if the measurements were made on the exact same feature (yes) or on separate, but nearby features (no). All new data presented in this study are reported in the NAD 83 (CORS 96) datum, with elevations relative to mean sea level (MSL) in the NAVD 88 vertical datum (using the National Geodetic Survey’s GEOID09 geoid model). Note that Currey’s (1982) elevation data are listed here in the NGVD 29 vertical datum. In order to compare measurements, one must convert our data into the NGVD 29 datum (Section S3).

This study										Currey (1982)			
ID	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev. ± 1 σ	SWL Elev. ± 1 σ	ID	Meth.	Match	Elev. ± 1 σ		
1	42.2568921	-111.8357035	6	2	2	1548.0 0.1	1553.1 3.9						
2	42.1000990	-111.7926449	21	1	3	1554.1 0.1	1553.2 1.1	5	1	yes	1558 3		
3	41.6639785	-111.8032624	1	2	2	1568.9 0.1	1574.0 3.9	7	2	no	1571 3		
4	41.5837793	-111.8861124	7	1	4	1576.8 0.2	1575.9 0.6	8	2	yes	1577 3		
5	41.7210513	-112.0777764	1	2	2	1570.0 0.4	1575.1 3.9						
6	41.4949201	-111.9871387	2	2	2	1574.0 0.1	1579.1 3.9	9	2	no	1580 3		
7	41.0189131	-111.8932277	3	2	1	1580.6 0.3	1585.7 4.1						
8	40.4584788	-111.8984450	1	1	4	1571.0 1.3	1570.1 0.6	14	2	yes	1573 2		
9	40.3805817	-111.7226932	1	2	1	1564.9 0.1	1570.0 4.1						
10	40.1656837	-111.5744001	1	2	1	1559.3 0.2	1564.4 4.1						
11	40.0270765	-111.6591835	2	1	4	1552.8 0.2	1551.9 0.6	17	2	yes	1553 1		
12	40.0052822	-111.7320906	3	2	2	1556.9 0.3	1562.0 3.9						

Continued on next page

Table A1 – continued from previous page

This study										Currey (1982)			
ID	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev. ± 1 σ	SWL Elev. ± 1 σ	ID	Meth.	Match	Elev. ± 1 σ		
13	40.0303127	-111.8118153	2	1	4	1561.8 0.1	1560.9 0.6	18	2	yes	1562 1		
14	39.9781068	-112.0059135	3	3	3	1565.3 0.1	1565.8 1.9	21	1	yes	1565 2		
15	40.0707048	-112.1086687	1	3	2	1570.7 0.2	1571.2 2.6	22	2	no	1568 2		
16	40.2229453	-111.9814179	7	1	3	1569.5 0.1	1568.6 1.1	23	1	yes	1571 2		
17	40.2319606	-111.9796599	2	2	1	1565.2 0.4	1570.3 4.1	23	1	no	1571 2		
18	40.2809200	-111.8981347	2	3	2	1569.1 0.2	1569.6 2.6	24	1	no	1571 2		
19	40.3747202	-112.0437933	8	1	3	1574.0 0.1	1573.1 1.1	25	2	yes	1574 3		
20	40.5700771	-112.0640516	2	3	1	1581.9 0.1	1582.4 3.0	26	1	no	1580 2		
21	40.6305924	-112.0576957	1	2	1	1581.7 0.1	1586.8 4.1						
22	40.9262572	-112.1993850	8	1	4	1597.8 0.3	1596.9 0.6	29	1	yes	1599 2		
23	40.9803320	-112.2251442	3	2	2	1589.3 0.2	1594.4 3.9						
24	40.2224398	-112.4207093	1	3	1	1588.5 0.1	1589.0 3.0						
25	40.5290670	-112.5187688	1	3	3	1607.6 0.9	1608.1 1.9	35	1	no	1608 3		
26	40.6004610	-112.6698749	4	3	2	1609.3 0.2	1609.8 2.6	37	1	no	1613 3		
27	40.5953392	-112.6755433	7	1	4	1612.0 0.1	1611.1 0.6	37	1	yes	1613 3		
28	40.2299214	-112.6296788	2	3	3	1597.0 0.5	1597.5 1.9						
29	40.1961447	-112.6479088	8	1	4	1597.3 0.2	1596.4 0.6	39	1	yes	1598 2		
30	40.1091068	-112.6734621	13	1	4	1594.2 0.1	1593.3 0.6	40	2	yes	1595 1		
31	40.1713625	-112.7624257	25	1	4	1598.4 0.1	1597.5 0.6	41	1	yes	1600 2		
32	40.4812896	-113.0244495	10	1	4	1614.3 0.1	1613.4 0.6	43	2	yes	1615 2		
33	40.5168151	-113.0170470	13	2	2	1606.4 0.1	1611.5 3.9						
34	40.6102562	-113.0104172	8	1	4	1617.4 0.1	1616.5 0.6	44	1	yes	1617 2		

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This study										Currey (1982)				
ID	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev.	± 1 σ	SWL Elev.	± 1 σ	ID	Meth.	Match	Elev.	± 1 σ
35	40.7288349	-112.9457360	1	2	1	1607.3	0.1	1612.4	4.1					
36	40.7338114	-112.8711118	1	2	2	1614.0	0.2	1619.1	3.9					
37	40.9700759	-113.0475283	10	1	4	1623.3	0.1	1622.4	0.6	53	1	yes	1623	3
38	40.8970986	-113.0370757	25	1	4	1624.0	0.1	1623.1	0.6	54	1	yes	1623	3
39	40.8524945	-113.0168723	4	1	4	1622.8	0.1	1621.9	0.6	55	1	no	1623	2
40	40.0667211	-112.7368824	5	3	3	1592.5	0.3	1593.0	1.9					
41	39.9863300	-112.7909814	3	3	3	1594.8	0.3	1595.3	1.9					
42	39.9616296	-112.7954677	3	3	3	1592.5	0.1	1593.0	1.9					
43	39.9398311	-112.8844857	5	1	4	1592.7	0.1	1591.8	0.6	57	1	yes	1593	3
44	39.9100010	-112.7799867	1	1	4	1588.2	0.1	1587.3	0.6	58	1	yes	1593	3
45	39.8925728	-112.7673247	6	1	4	1589.6	0.1	1588.7	0.6					
46	39.8753388	-112.7177538	3	3	3	1584.0	0.1	1584.5	1.9					
47	39.8675186	-112.6612814	1	1	4	1585.5	0.1	1584.6	0.6	59	1	yes	1586	2
48	39.7890626	-112.5089605	3	1	4	1578.1	0.1	1577.2	0.6	60	2	yes	1580	2
49	39.4833776	-112.2453221	10	1	4	1564.1	0.1	1563.2	0.6	66	2	yes	1563	4
50	39.2390387	-112.3501748	8	1	4	1566.6	0.1	1565.7	0.6	67	3	yes	1568	1
51	39.1490656	-112.2727972	9	1	4	1562.2	0.1	1561.3	0.6	68	3	yes	1561	1
52	39.0487030	-112.3022301	11	1	4	1562.6	0.1	1561.7	0.6	70	2	no	1561	2
53	38.7609739	-112.6567939	44	1	4	1572.1	0.1	1571.2	0.6	72	1	yes	1574	2
54	38.7459906	-112.6905849	4	1	4	1570.3	0.1	1569.4	0.6					
55	38.7559659	-112.7272384	5	3	3	1568.6	0.1	1569.1	1.9					
56	38.7599191	-112.8525659	2	3	3	1567.6	0.4	1568.1	1.9					

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This study										Currey (1982)			
ID	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev. ± 1 σ	SWL Elev. ± 1 σ	ID	Meth.	Match	Elev. ± 1 σ		
57	38.7500324	-112.8885585	12	1	4	1566.8 0.1	1565.9 0.6	73	1	yes	1565 1		
58	38.5229918	-112.9222387	12	1	4	1558.3 0.1	1557.4 0.6	74	1	yes	1558 2		
59	38.1651457	-113.1208972	7	1	4	1554.3 0.2	1553.4 0.6	76	3	yes	1555 1		
60	38.0989106	-113.2618665	3	1	3	1553.9 0.2	1553.0 1.1	77	3	yes	1555 1		
61	38.2500612	-113.1451066	2	1	3	1554.8 0.1	1553.9 1.1	79	3	yes	1554 1		
62	38.4264117	-113.0309322	2	1	4	1556.8 0.3	1555.9 0.6	80	3	yes	1557 1		
63	38.5505503	-113.0848836	1	1	4	1560.4 0.1	1559.5 0.6	81	1	yes	1559 3		
64	38.8838680	-112.8585607	3	1	4	1571.3 0.4	1570.4 0.6	82	1	yes	1571 1		
65	39.0603185	-112.8527717	3	1	4	1573.7 0.1	1572.8 0.6	85	1	yes	1576 2		
66	38.8704733	-113.0571604	20	1	4	1568.2 0.1	1567.3 0.6	84	1	yes	1570 1		
67	38.6639006	-113.1896896	6	1	4	1562.0 0.1	1561.1 0.6	85	1	yes	1562 3		
68	38.5697640	-113.3265472	3	3	3	1558.0 0.3	1558.5 1.9	86	1	no	1559 3		
69	38.5657623	-113.3317910	12	1	4	1558.5 0.1	1557.6 0.6	86	1	yes	1559 3		
70	38.5299665	-113.3292032	3	3	3	1557.7 0.2	1558.2 1.9						
71	38.4300164	-113.4391380	2	1	3	1556.6 0.6	1555.7 1.1	87	1	yes	1555 3		
72	39.1443196	-113.2389148	2	1	4	1569.8 0.3	1568.9 0.6	88	1	yes	1571 1		
73	39.3001608	-113.1728862	2	1	3	1573.5 0.1	1572.6 1.1	90	1	yes	1576 1		
74	39.3893319	-113.0515996	5	1	3	1577.2 0.1	1576.3 1.1	91	1	yes	1579 2		
75	39.5972261	-112.9875446	4	1	3	1584.4 0.1	1583.5 1.1	92	1	yes	1583 2		
76	39.7096748	-113.0392397	7	1	4	1587.2 0.1	1586.3 0.6	93	1	yes	1588 3		
77	39.8106322	-112.9679297	4	1	4	1590.9 0.2	1590.0 0.6	94	1	yes	1592 2		
78	39.8576717	-113.1049917	9	1	4	1592.2 0.1	1591.3 0.6	95	1	yes	1591 3		

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ID	This study							Currey (1982)			
	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev. $\pm 1 \sigma$	SWL Elev. $\pm 1 \sigma$	ID	Meth.	Match	Elev. $\pm 1 \sigma$
79	39.5558744	-113.1841668	9	1	4	1581.1	1580.2	96	1	yes	1583
80	39.5839471	-113.3862909	5	1	4	1584.0	1583.1	97	1	yes	1583
81	39.2199090	-113.4421121	4	3	3	1567.2	1567.7				
82	39.1798746	-113.4548962	1	2	2	1563.0	1568.1				
83	39.0810917	-113.5310333	4	1	4	1566.2	1565.3	99	1	yes	1564
84	39.3391669	-113.6610442	1	3	1	1565.1	1565.6				
85	39.5668573	-113.6334779	3	1	4	1575.2	1574.3	101	1	yes	1576
86	39.6695215	-113.4845488	2	3	2	1582.8	1583.3	102	1	no	1583
87	39.6403141	-113.7360800	8	1	4	1577.4	1576.5	104	1	yes	1579
88	39.2658501	-113.8259733	5	1	4	1563.9	1563.0	105	1	yes	1564
89	39.1744599	-113.9062966	5	3	3	1559.8	1560.3				
90	39.1712531	-113.9154537	4	1	4	1560.4	1559.5				
91	39.0943986	-113.9231268	3	1	4	1558.7	1557.8	106	1	yes	1562
92	38.9892428	-113.8275138	2	1	2	1558.9	1558.0	107	2	yes	1560
93	39.1957723	-114.0170864	3	1	4	1558.7	1557.8	109	2	yes	1560
94	39.4220178	-114.0111599	2	1	4	1562.9	1562.0				
95	39.4350159	-114.0151509	2	1	4	1563.4	1562.5				
96	39.4417371	-114.0173273	1	3	1	1563.0	1563.5				
97	39.7313365	-113.8355490	2	1	4	1576.8	1575.9				
98	40.0284586	-113.7888254	3	3	3	1588.0	1588.5	113	1	no	1590
99	40.2119966	-113.9641283	3	1	4	1586.9	1586.0	115	1	yes	1590
100	40.1966431	-113.9787903	1	2	2	1576.9	1582.0				

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ID	Latitude [°]	Longitude [°]	N	This study				Currey (1982)			
				Type	Conf.	Elev. $\pm 1 \sigma$	SWL Elev. $\pm 1 \sigma$	ID	Meth.	Match	Elev. $\pm 1 \sigma$
101	40.1981342	-113.9779193	1	2	2	1577.3	1582.4				
102	40.1983420	-113.9812192	1	2	2	1578.2	1583.3				
103	40.3222883	-114.1325461	6	1	4	1583.0	1582.1	116	1	yes	1583
104	40.3360378	-114.1440978	4	3	2	1579.4	1579.9	116	1	no	1583
105	40.4786355	-114.1359931	3	1	4	1585.4	1584.5	117	1	yes	1588
106	40.7233574	-114.1949311	1	3	3	1582.3	1582.8				
107	40.7353993	-114.1854312	15	1	4	1584.4	1583.5				
108	40.7638448	-114.1932361	4	1	4	1583.6	1582.7	118	1	yes	1585
109	40.7726456	-114.1069134	1	1	4	1587.1	1586.2	119	1	yes	1589
110	40.9042862	-113.8448603	2	3	2	1592.1	1592.6				
111	40.9203194	-113.8405702	1	3	1	1593.6	1594.1	120	1	no	1600
112	40.9908869	-113.8263361	1	2	2	1589.8	1594.9				
113	40.7826324	-114.2096322	6	3	2	1581.2	1581.7				
114	40.8032452	-114.2304129	3	3	3	1581.3	1581.8				
115	40.8134028	-114.2347836	1	3	2	1580.3	1580.8				
116	40.8201708	-114.2396373	2	3	2	1579.5	1580.0				
117	40.8586866	-114.2535983	2	3	2	1577.6	1578.1				
118	40.8699882	-114.2550401	2	3	2	1578.0	1578.5				
119	40.8847161	-114.2603981	3	1	4	1580.2	1579.3				
120	40.9248401	-114.2552599	2	1	4	1579.5	1578.6	124	1	yes	1580
121	41.0862840	-114.1991671	1	3	1	1579.2	1579.7		1	no	1580
122	41.2745498	-114.2435024	7	1	4	1574.2	1573.3	127	1	yes	1574

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ID	Latitude [°]	Longitude [°]	N	This study				Currey (1982)			
				Type	Conf.	Elev. $\pm 1 \sigma$	SWL Elev. $\pm 1 \sigma$	ID	Meth.	Match	Elev. $\pm 1 \sigma$
123	41.3630643	-114.1641734	1	2	2	1570.7	1575.8				
124	41.1989780	-114.1184777	8	1	4	1581.2	1580.3	129	1	yes	1580
125	40.9902313	-114.1491897	3	1	4	1583.5	1582.6	130	1	yes	1584
126	41.0165329	-114.0100908	2	1	4	1590.2	1589.3	131	1	yes	1591
127	41.1270892	-113.9903770	2	3	2	1586.6	1587.1				
128	41.1852182	-113.9667363	1	3	2	1587.6	1588.1	132	1	no	1590
129	41.1889978	-113.9615226	2	1	4	1586.6	1585.7	132	1	yes	1590
130	41.4567293	-114.0050608	8	1	4	1579.1	1578.2	134	1	yes	1579
131	41.5897285	-113.8920362	14	1	4	1576.2	1575.3	135	1	yes	1577
132	41.4750122	-113.7935797	3	1	4	1586.8	1585.9	136	1	yes	1589
133	41.6086278	-113.6191808	1	3	2	1582.8	1583.3	138	1	no	1585
134	41.6754590	-113.5288150	16	1	4	1584.5	1583.6	139	1	yes	1585
135	41.6293727	-113.4320746	2	1	4	1591.3	1590.4	140	1	yes	1591
136	41.6159093	-113.3480020	4	1	4	1594.0	1593.1	141	1	yes	1598
137	41.5052640	-113.1604579	2	1	4	1604.8	1603.9	142	2	yes	1605
138	41.3827077	-113.2110113	3	2	2	1607.2	1612.3	143	1	no	1613
139	41.3860379	-113.1971476	1	1	4	1612.3	1611.4	143	1	yes	1613
140	41.3884413	-113.1346776	1	2	2	1604.4	1609.5				
141	41.4422170	-113.1251433	2	1	4	1610.6	1609.7				
142	41.4422139	-113.0842589	2	1	4	1610.6	1609.7	144	2	yes	1610
143	41.6904685	-113.2429711	2	1	4	1592.4	1591.5	146	1	yes	1592
144	41.7802862	-113.3140673	1	1	2	1583.2	1582.3	148	1	no	1587

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ID	Latitude [°]	Longitude [°]	N	This study				Currey (1982)			
				Type	Conf.	Elev. $\pm 1 \sigma$	SWL Elev. $\pm 1 \sigma$	ID	Meth.	Match	Elev. $\pm 1 \sigma$
145	41.8392507	-113.2041192	1	3	2	1574.1	1574.6				
146	41.8552278	-113.1884555	16	1	4	1582.8	1581.9	149	1	yes	1585
147	41.9382781	-113.1547035	1	3	3	1575.3	1575.8				
148	41.9669996	-113.1547577	16	1	4	1576.0	1575.1	150	1	yes	1577
149	41.9889075	-112.7699733	1	2	1	1570.3	1575.4	153	1	no	1580
150	42.0786468	-112.7623568	7	1	3	1573.2	1572.3	154	1	yes	1574
151	42.1530977	-112.7011953	10	1	4	1569.3	1568.4	155	1	yes	1571
152	42.2294630	-112.6137938	13	1	4	1564.6	1563.7	156	2	yes	1564
153	41.9843363	-112.6225898	1	2	1	1576.1	1581.2	158	1	no	1577
154	41.8166273	-112.6995015	2	2	1	1575.8	1580.9	159	1	no	1587
155	41.6976882	-112.5946355	2	1	4	1598.1	1597.2	162	2	yes	1600
156	41.5997206	-112.6025362	4	1	4	1604.3	1603.4	163	1	yes	1605
157	41.2713373	-112.4624050	1	2	2	1610.1	1615.2	164	2	no	1614
158	41.3195421	-112.4183540	1	2	2	1600.6	1605.7	165	1	no	1610
159	41.4513112	-112.4741936	8	1	4	1605.8	1604.9	166	1	yes	1606
160	41.4505185	-112.4692104	2	2	2	1598.4	1603.5				
161	41.5231936	-112.4941149	5	2	2	1602.9	1608.0				
162	41.9442345	-112.4401964	1	1	3	1575.2	1574.3	168	2	yes	1576
163	41.6679106	-112.3542210	2	1	4	1592.6	1591.7	169	1	yes	1593
164	41.6646354	-112.3448139	1	2	1	1582.5	1587.6				
165	41.5938196	-112.2514084	2	2	1	1580.8	1585.9	170	1	no	1591
166	41.6970138	-112.3300315	1	2	2	1581.4	1586.5				

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ID	This study							Currey (1982)			
	Latitude [°]	Longitude [°]	N	Type	Conf.	Elev. $\pm 1 \sigma$	SWL Elev. $\pm 1 \sigma$	ID	Meth.	Match	Elev. $\pm 1 \sigma$
167	41.7879720	-112.2594078	1	2	1	1578.9	1584.0	171	1	no	1582
168	41.8834063	-112.2569988	1	2	2	1571.7	1576.8				
169	41.8514189	-112.0558143	2	2	1	1567.6	1572.7	177	2	no	1575
170	41.9097686	-112.0642843	1	2	2	1565.0	1570.1	178	1	no	1570
171	41.1046547	-112.8822173	5	1	3	1623.2	1622.3	49	1	yes	1625
172	41.1086326	-112.8741361	6	2	2	1615.5	1620.6				
173	41.1455028	-112.8944966	10	1	3	1623.5	1622.6				
174	41.1455975	-112.8927062	5	2	2	1619.2	1624.3				
175	39.7277161	-113.5997668	18	1	4	1582.8	1581.9				
176	39.3212741	-113.6345259	24	1	4	1568.8	1567.9				
177	40.9274590	-112.1975887	4	2	4	1597.6	1602.7	29	1	no	1599
178	40.9287751	-112.1951588	17	1	4	1598.5	1597.6	29	1	no	1599

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