Supplemental Materials


Datasets and supplementary materials associated with this publication can be found on our online open-source data repository hosted on Mendeley Data:


S1. Differential GPS measurements of Bonneville shoreline features

A GPS receiver (rover) calculates distance using the travel time and velocity of radio signals from orbiting satellites. These radio signals may be delayed by atmospheric disturbances in the troposphere such as cloud cover or charged particles in the ionosphere. Discrepancies between satellite and receiver clocks, varying levels of satellite connectivity, and inaccurate monitoring of satellite positions also can lead to errors. We use dGPS to correct for these errors by relying on the coordination of two receivers: a stationary base station and a roving receiver making dGPS measurements. The coordinates of the known locations of base stations set up around Utah, Nevada, and Idaho serve as solid local points of reference, which then are used for differential correction of rover data in post-processing. The base stations run around the clock collecting data on their location, quantifying drift by comparing their current measured GPS location with its single known location. In post-processing, the proprietary Trimble Pathfinder Office software differentially corrects rover data according to this calculated amount of drift at the time of measurement by comparing time stamps between rover and base station data.

To collect rover data, the GeoXH handheld was positioned on the location of the shoreline indicator for 5 to 30 seconds; thus, each individual dGPS measurement consists of 5 to 30 measurements of a single location, which are then averaged to yield one coordinate in x, y, and z space. With time and geomorphic preservation permitting, multiple equally-spaced
dGPS measurements were made along the length of the shoreline indicator for each shoreline feature in order to assess its altitudinal variability. The final elevation attributed to each shoreline feature is an arithmetic mean of all such dGPS elevation measurements (where each individual dGPS measurement is weighed equally), and the associated standard deviation ($\sigma$) is calculated by adding each individual dGPS measurement’s estimated vertical precision in quadrature.

For each individual dGPS measurement, we selected the base station closest in proximity for the post-processing differential correction. Stationary base stations were either Continuously Operating Reference Stations (CORS) maintained by the National Geodetic Survey (NGS) or stations maintained by UNAVCO (a non-profit consortium facilitating geoscience and geodesy research). Generally, a base station could be found within 50 km of each site of measurement. All dGPS measurements were made in the CORS 96 realization of the North American Datum of 1983 (NAD 83), with elevations reported as orthometric heights in the North American Vertical Datum of 1988 (NAVD 88) relative to mean sea level (MSL) as defined by the GEOID09 (Conus) geoid.

**S2. Surveying Lake Bonneville terraces with unmanned aircraft**

**S2.1. Methods**

301 RAW RGB aerial photographs were collected over the course of two flights by a single Ebee Sensefly unmanned aerial vehicle (UAV). The Sensefly is a 0.96 kg, hand-launched, programmable UAV equipped with a modified 12MP Canon S110 RGB camera. The images were geotagged using an onboard single-frequency GPS receiver and converted to 12-bit TIFFs in eMotion2, a proprietary flight planning and processing software package. The resulting geotagged TIFFs were processed through a workflow in Postflight Terra 3D.

A sparse point cloud of positional data was produced by detecting and matching features present in overlapping geotagged images. Next, control points, consisting of the corners of three orange tarps that were spread out along an access road, were marked in the point cloud in order to improve the absolute positioning of the data. The control points were
surveyed in the field using a handheld Trimble GeoXH6000 rover with an external Tornado antenna. The Trimble data were collected using the WGS84 datum and ellipsoid. These Trimble GPS data were differentially corrected using the GPS Pathfinder Office software package and data from the UNAVCO base station located in Riverton, Utah (coordinates: 40°26’02.47200” N, 112°00’51.17400” W). Horizontal accuracy of the corrected GPS data ranged from 0.10 to 0.20 meters with a mean of 0.10 meters and a standard deviation of 0.02 meters. Vertical accuracy ranged from 0.10 to 0.40 meters with a mean of 0.15 meters and a standard deviation of 0.06 meters. Following the positioning correction using Trimble-surveyed control points, Postflight Terra 3D produced, in succession, a densified point cloud, a digital surface model (DSM), and an orthophoto, all of which have a ground resolution of 4.83 centimeters per pixel.

Using Pix4D, GeoTIFF DSM data were output in WGS84 UTM horizontal coordinates using the EGM96 geoid for vertical coordinates. This dataset then was converted to the ArcRaster format using the Geospatial Data Abstraction Library (GDAL). The ArcRaster file was loaded into VDatum, where it was converted into NAD83 UTM horizontal coordinates and the NAVD88 vertical datum utilizing Geoid09. Once again, GDAL was used to convert the ArcRaster into a GeoTIFF file for use in ArcGIS and MATLAB.

When DSM pixels were compared to differentially-corrected Trimble elevations (Fig. S9), a mean vertical shift of approximately -0.5 m is observed. The vertical shift is due to the fact that the control points were located in the extreme southwest of the UAV scene, while the shoreline surveys were conducted in the center and northeast of the scene. In the future, control points should be distributed across the entire scene. For the purposes of the analyses in this section, we apply additional shifts to the DSM to improve the fit to dGPS data based on the offsets observed in Fig. S9.

S2.2. Results

We use the 4.83 cm/pixel UAV-derived DSM to evaluate the accuracy of shoreline locations defined by a combination of human interpretation of satellite imagery and field GPS surveys. In Figures S10, S11, S12, S13, S14, S15, S16, S17, S18 & S19, we find the following
general results:

- Trimble dGPS transects generally match DSM pixel transects to within 80 cm, conservatively (Fig. S9). If we apply a uniform vertical shift to each set of dGPS transect points associated with each shoreline feature (-30 cm for #22; -73 cm for #177, and -71 cm for #178; see Fig. S9B), the dGPS transect points batch DSM elevations to within 20 cm (Fig. S17D).

- In general, gravel barriers (Figs. S13 & S15) are easier to locate accurately on satellite images and are easier to find on elevation profiles. Therefore, gravel barriers can be located to within 5 m horizontally and 0.3 m vertically, or about 2–3x better than depositional terraces (Fig. S17).

- According to the automated detection of shoreline indicator location on the DSM, the elevation of the inflection point of depositional terraces may vary by several (∼10 m) meters within short (<1 km) distances (Fig. S19). A more detailed field dGPS survey of the shoreline is necessary to test this result.

- The shoreline outline defined by human interpretation of satellite images match automated detection of shoreline indicators from DSM elevation profiles to within <10 m in the horizontal, and to within 5 m in the vertical (Figs. S17).

- When we compare the elevations of the DSM-derived shoreline indicator location between depositional terraces and gravel barriers, we observe that the gravel barrier crest is systematically offset above the inflection point of the depositional terrace profile (Fig. S18).

S3. Comparison with Currey (1982): Converting between vertical datums

Currey (1982) reported his elevations in the National Geodetic Vertical Datum of 1929 (NGVD 29), a legacy datum no longer in use that was superseded by the North American Vertical Datum of 1988 (NAVD 88). The data presented in this study are in the NAVD 88.
vertical datum. Because Currey (1982) did not report precise coordinates for his paleoshoreline measurements, his points cannot be readily converted to NAVD 88 without accruing additional uncertainty. Thus, we convert our high-precision dGPS elevation data to the NGVD 29 datum using VERTCON 2.0, the North American Vertical Datum Conversion program maintained by the NGS. For a given location specified by latitude and longitude, VERTCON computes the modeled distance in orthometric height between the two datums for the lower 48 contiguous United States. The VERTCON model is considered accurate at the 2 cm (1-σ) level, thus the results of the conversion from NAVD 88 to NGVD 29 are suitable for comparison. Comparisons to data by Currey (1982) were made only if we were confident that the measurements were made on the exact same feature. The average datum shift from NAVD 88 to NGVD 29 for all dGPS measurements associated with these 85 paleoshorelines was 1.09 ± 0.04 m (N = 589).

S4. Statistics on the dGPS elevation measurements of shoreline features

Regarding the total number of dGPS measurements comprising each reported shoreline elevation (N), ∼41% consist of 4 or more measurements; however, ∼82% of those shoreline features with ≥ 4 measurements are gravel barriers. In contrast, ∼25% of the compilation consists of a single dGPS measurement; ∼82% of these singular dGPS measurements are for depositional terraces and incised alluvial fans. We attribute these differences in N to differences in the ease of measurement of the shoreline indicator for different shoreline features types. As discussed previously in Section S8, locating the crest of gravel barriers is more straightforward than finding the inflection point of terrace profiles and the base of an incised fan scarp. Furthermore, because the effects of post-lacustrine processes of hillslope diffusion and aggradation are more laterally variable for depositional terraces and alluvial fans, we were more limited in the number of measurements we could make for those shoreline features than we were for gravels barriers.

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S5. Comparison of dGPS elevation measurements and digital elevation maps

We considered three different DEMs for use in reconstruction the Bonneville shoreline: (1) a 10 m (1/3 arc-second) DEM from the National Elevation Dataset (NED), a seamless raster dataset of the conterminous United States produced and maintained by the U.S. Geological Society (Gesch, 2007; Gesch et al., 2002), (2) a 30 m (1 arc-second) NED DEM, and (2) a 90 m (3 arc-second) DEM derived from Shuttle Radar Topography Mission (SRTM) radar data collected by the Space Shuttle Endeavor in early 2000. Each of the raw datasets are in conformance with the NAD 83 and NAVD 88 datums. The primary difference between the two DEM sources is that the NED provides bare ground elevation (no objects, like plants and buildings), whereas SRTM, being radar based, provides surface elevation (includes objects). We do not believe that that the radar-based SRTM data is dramatically affected by vegetation in our area of interest because the eastern Great Basin is generally devoid of such large vegetation (i.e., trees). For the Great Basin area, the source information of the NED is 7.5-minute digital contours from USGS topographic maps of the 1970s and 1980s. DEMs were created from these contours via a contour-to-grid interpolating software called LT4X (Osborn et al., 2001). It is possible that the NED DEM is derived from the very same topographic maps that were used by Currey (1982). The reported overall absolute vertical accuracy of the DEMs is 2.44 m for the NED and ~10 m for SRTM (root mean square error; Gesch, 2007; Gesch et al., 2002).

To evaluate the relative accuracy of these DEMs compared to our dGPS measurements, we extracted the elevation given by each DEM at each x-y coordinate of our dGPS data (N = 872), and compared the extracted elevation to our differentially-corrected elevations. When considering all dGPS data as a whole, the 90 m SRTM DEM appears to match the dGPS elevations best; on average, the 90 m SRTM DEM was 0.1 ± 3.3 m lower than dGPS measurements, compared to 0.4 ± 3.0 m and 0.4 ± 2.8 m higher for 30 m and 10 m NED DEMs, respectively.

However, when the dGPS data are broken down by shoreline type and compared (Figure S7), the 90 m SRTM DEM only matches dGPS measurements of gravel barriers best, by a
small margin of \( \sim 0.2-0.3 \) m. In contrast, both NED DEMs outperform the SRTM DEM for depositional terraces and incised alluvial fans by margins of \( \sim 1.2-1.7 \) m. In comparing the NED DEMs with one another, we find that although the 10 m NED DEM matches dGPS measurements better than the 30 m NED DEM by \( \sim 0.2-0.3 \) m, the contour lines of elevation generated by the 10 m NED DEM capture detail that would misrepresent the accuracy to which we know the true location of the Bonneville shoreline. As a result, we used the 30 m DEM to generate contours of elevation at 1-m intervals between 1550 and 1640 m elevation for use as guides in our shoreline mapping.

**S6. Reconstructing the Bonneville shoreline outline**

Mapping was done exclusively in ESRI’s ArcMap software using high-resolution Bing Maps aerial imagery accessed from June 2012 to November 2013, and was carried out in the NAD 83 (CORS 96) and NAVD 88 datums, coinciding with those used for the dGPS elevation data.

Since the perimeter of the lake is \( \sim 9000 \) km (including islands), it would have been nigh impossible to trace the entire shoreline via dGPS within reasonable time constraints. As such, there are many gaps in the spatial coverage of our dGPS data, which was a problem when mapping areas with little to no shoreline evidence (e.g., where the lake was likely very shallow, \(< 5 \) m in depth) or when the shoreline was difficult to recognize from sheer aerial imagery (e.g., depositional terraces). Thus, we used the 30-m DEM from the National Elevation Dataset (NED) to further aid shoreline reconstruction, using contour lines of elevation generated from the DEM to represent segments of the Bonneville shoreline for which we have few other constraints (Section S5). For each of these segments, we chose the elevation for these contour lines based on the elevation recorded by the nearest dGPS shoreline feature measurements. For gravel barriers, the difference between our dGPS elevation measurements and the elevation given by the DEM was \( 1.0 \pm 2.1 \) m; for depositional terraces, the difference was \(-0.5 \pm 5.4 \) m; and for incised alluvial fans, the difference was \(-3.2 \pm 2.3 \) m (Figure S7).

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Generally, we are able to trace continuous shoreline segments of at least \( \sim 500 \) m in length in the manner described above. In our subsequent visits the following years (2013 and 2014), we went to previously unvisited sites where we had made manual visual interpretations of the shoreline indicator location using only aerial imagery and DEM-derived elevation contours. As before, we used dGPS to record our field interpretation of the location of the shoreline indicator. As a result, we are able to quantify the agreement between our pre-field photo-interpretation and in-field dGPS measurements of the shoreline indicator in order to assess the uncertainty of the shoreline outline in places we did not visit.

Given that our dGPS points do not cover the entire extent of the lake perimeter, the vast majority of shoreline segments (\( \sim 98\% \) when segments are weighted by length) were drawn via photo-interpretation without guide from on-site field measurements or observations. Nevertheless, our knowledge on the nature of different shoreline type’s representations in aerial imagery compared to their in-field physical manifestations enabled us to construct a shoreline outline that we believe is the most precise to date. Furthermore, because construction of the entire shoreline outline was done manually by a single operator (Chen), paleoshoreline interpretation of aerial imagery is highly consistent (Section S6.1).

**S6.1. Tracing the Bonneville shoreline on aerial imagery**

Each segment of the shoreline outline has the following baseline attributes: shoreline type (i.e., gravel barrier, depositional terrace, incised alluvial fan), length, field visitation (Y/N), and data sources used for photo-interpretation (e.g., aerial imagery, DEM-derived contours). A new segment was created when any of the following occurred: (1) the shoreline type changed; (2) the elevation of the shoreline changed by more than \( \pm 4 \) m, as suggested by contours of elevation from the 30 m DEM; (3) the shoreline was discontinuous/the quality of shoreline preservation changed; or (4) the data source(s) used for photo-interpretation changed (e.g., switching from solely using evidence from aerial imagery to receiving guidance from elevation contours).

For the visited shoreline features, we simply connected the dots between dGPS points along the length of the feature. We mainly examined the aerial imagery at scales of 1:10,000
(1 inch on the map = 10,000 inches, or 1 cm = 100 m), using ArcMap software to zoom in and out when necessary. For unvisited segments of the Bonneville shoreline without any dGPS measurements, we used many aspects of the aerial imagery to our advantage to locate the shoreline indicator. For instance, because the apex of gravel barriers often makes an even platform amenable for flat roads in otherwise variable topography, crests frequently were delineated by a dirt road in aerial imagery. In these locations, segments traced the road. For incised alluvial fans, sharp contrasts in albedo due to abrupt transitions in landscape fabric (i.e., from a channelized debris-flow to a smoother plain) and/or vegetation type and spatial density put an upper limit on the location of the base of the incised alluvial fan scarp. For example, a distinct transition from desert sage brush to grassland along an alluvial fan often marks the top of the scarp, thereby placing an upper bound on the shoreline indicator (Figure 6). Oftentimes, a dirt road near the base of the scarp provides a lower bound. For these locations, we consistently traced segments on the side of the road closer to the scarp. Even without dirt roads, we find that we are able to readily detect the shoreline indicator in the aerial imagery of well-preserved and easily recognizable gravel barriers and incised alluvial fans.

Figure 5 demonstrates how depositional terraces are the least recognizable from aerial imagery. In 5C, we observe that the dGPS points marking the shoreline feature do not correspond to any distinctive feature in the aerial image in 5B. Likewise, for some incised alluvial fans, the scarp appears as a diffuse cut into the alluvium in aerial imagery, possibly due to a lack of vegetation change or from a more gentle scarp-face slope. In these situations, we use contours of elevation to guide us towards areas where the shoreline would more likely manifest. Oftentimes, the contour lines fall along a faint but continuous feature that may represent some preservation of relict land-water interaction. If the contour lines are unable to identify a possible continuous feature of land-water interaction in the aerial imagery, a contour line was used to represent the shoreline outline in that area.
S6.2. Accuracy of the reconstructed Bonneville shoreline outline

Regarding the accuracy of our shoreline outline in unvisited locations, we compared our pre-field photo-interpretation of shoreline indicators in aerial imagery to our in-field interpretations for 46 unique shorelines features, and found that the mean and median of the average horizontal (in x-y space) discrepancy in interpretation was 8.5 and 6.0 m, respectively. Figure S8 shows the distribution of photo- versus field interpretation with a stacked histogram, which is heavily skewed and not normally distributed. Approximately 25% of the examined shoreline features were photo-interpreted to within ~5 m of the field measurements.

Our drone-derived DSM shows that our reconstructed shoreline outline matches the true horizontal location of shoreline indicators to within ± 10 m in the horizontal and ± 5 m in the vertical (Section S2, Figures S10, S13, S14, S15, & S16). Gravel barriers are easier to locate on satellite images and can be located to within ± 5 m horizontally, and ± 2 m vertically.

S7. Ballpark estimate of volume of the lake represented by the Bonneville shoreline

For our lake volume estimate, we primarily relied on ESRI’s ArcMap 10.2.2 geostatistical and spatial analyst tools. First, we projected our data into the USA Contiguous Albers Equal Area Conic projection in order to minimize the distortion of area measurements across standard parallels. We converted the shoreline outline into evenly spaced points separated by 50 m and extracted the value of the 10 m NED DEM for each point. We then used ArcMap’s built-in kriging tool to interpolate a surface through these points in order to reconstruct the paleowater surface represented by the Bonneville shoreline. We did not statistically analyze our dataset to determine which type of kriging method or semivariogram is most appropriate for our dataset, so we used the default kriging parameters (ordinary kriging with a spherical semivariogram). Assuming that the present-day topography has not significantly changed since the time of the Bonneville shoreline, we simply subtract the
elevation of the basal topography from the reconstructed paleowater surface to create the
map of paleowater depth. We arrive at the lake volume estimate by summing all the values
of water depth and multiplying this sum by the grid cell size represented by each pixel.

S8. Levels of confidence

The ease of identifying each of the three shoreline indicators in the field varied greatly
based on the quality of shoreline preservation and shoreline feature type. We account for
and quantify possible sources of error in the in situ detection of each shoreline indicator
by ascribing each measurement an attribute representing our confidence in locating the
shoreline indicator. The confidence levels are based purely on uncertainties surrounding the
detection of the shoreline indicator as observed in the field and from aerial imagery; they do
not take into account the total number of dGPS elevation measurements made on a given
feature ($N$), or the standard deviation ($\sigma$) of such elevation measurements.

Levels of confidence were assigned on a scale of 1 to 4, in which 4 represents the greatest
relative amount of confidence. The criteria for each level of confidence are described as
follows:

4. A confidence level of 4 indicates that the location of the shoreline indicator is
   unambiguous both in the field and in aerial imagery, and we are reasonably certain,
   to within $\pm 1 \text{ m}$ that the dGPS measurement falls on both (a) the vertical plane
   and (b) the horizontal plane of the shoreline indicator. In other words, satisfying
   (a) means that the dGPS measurements record the $z$ (elevation) coordinate of the
   shoreline indicator, and satisfying (b) means that the dGPS measurements record
   the $x$-$y$ (longitude and latitude) position of the shoreline indicator.

3. A confidence level of 3 indicates that the shoreline indicator is unambiguous in
   aerial imagery, but in the field, we only are certain of its location in (a) to within
   $\pm 1 \text{ m}$ and (b) to within $\pm 2 \text{ m}$.

2. A confidence level of 2 indicates that the location of the shoreline indicator is
detectable in aerial imagery, but we are less certain of both (a) and (b) in the
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field. Here, we are reasonably confident that the measurement is within $\pm 2\text{ m}$ in all planes of the shoreline indicator.

1. A confidence level of 1 indicates that the position of the shoreline indicator is ambiguous in the field, and its representation in aerial imagery is also obscure. Here, we estimate that we measured the $x$, $y$ and $z$ position of the shoreline indicator to within $\pm 2.5\text{ m}$ in all planes.

Most measurements on the crests of gravel barriers were assigned a confidence level of 4 because the highest point on these features was easily ascertained (Figures 3A, 4). If the apex of the ridge was relatively diffuse (meaning that post-lacustrine erosion or diffusion has relaxed the profile) or wide, we assigned a confidence level of 3. If there was clear evidence of heavy disturbance by human development (e.g., farmland plowing), we assigned a confidence level of 2.

Confidence levels for incised alluvial fans ranged from 3 to 1. Figures 6C and 6F show the approximate placement of the inflection point for two incised alluvial fans assigned a confidence level of 3. In some locations, the topography at the base of fan scarps undulates as much as $\pm 1\text{ m}$ in conjunction with the location of stream outlets (Figure 3C). We avoided stream outlets and measured the inflection points along scarps associated with the lowest of these oscillations, believing these locations to be the least affected by post-Bonneville aggradation. Figure 6I is a field photograph of an incised alluvial fan affected by deposits near stream outlets and/or slumping of the slope. Such localities are assigned confidence levels of 2. Incised alluvial fans assigned confidence levels of 1 either experienced heavy human disturbance and/or consisted of a more shallow, gentle scarp face, thus making detection of the transition between the scarp and the basal plane difficult.

The confidence levels for depositional terraces ranged from 2 to 1 (except for one exception, where we combined our dGPS data with an ebee Sensefly drone-derived 5 cm pixel DSM and determined that our measurement of the inflection point was within $\pm 0.15\text{ m}$ of the true inflection point, thus giving it a confidence level of 4; Section S2 for details). Although these shoreline features are best viewed from the ground, they are both hard to
measure in the field and difficult to discern in aerial imagery. As with the incised alluvial fans, places that experienced human disturbance and/or consisted of a more gentle profile across the terrace were assigned confidence levels of 1.

Table S2 summarizes the uncertainties associated with each level of confidence, and the confidence levels typically assigned to each shoreline type.

S9. Best estimate of the SWL elevation from shoreline feature elevations

The following MATLAB function shorelin2SWL.m illustrates how we propagate the uncertainty from confidence levels and relative vertical offsets to arrive at an estimate for the SWL elevation:

```matlab
% DESCRIPTION
3 % Estimates the elevation and vertical uncertainty of the SWL for each shoreline elevation measurement. Calculations are based on confidence level and the vertical relationships between different shoreline types.
4 % INPUT VARIABLES
5 % dGPS elev Differential GPS data of all 178 shoreline elevation measurements in dataset
6 % conf Confidence levels
7 % shoreline_type Shoreline type, where a value of 1 = gravel barrier,
8 % 2 = depositional terrace, and 3 = fan incision
9 % LOCAL VARIABLES
10 % vert_uncert_sig Vertical uncertainty in elevation of shoreline indicator based on the value of the conf level.
11 % vert_offset Vertical offset of shoreline measurement relative to the SWL, based on the shoreline type.
12 % vert_offset_sig Uncertainty of the vertical offset, based on shoreline type.
13 % OUTPUT VARIABLES
14 % SWL elev Elevation of the SWL
15 % SWL vert_uncert Vertical uncertainty of SWL.
16 % AUTHOR: Christine Y Chen [CYC]
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function [SWL_elev, SWL_vert_uncert] = shoreline2SWL(dGPS_elev, conf, shoreline_type)

for i = 1:length(dGPS_elev)
    switch conf(i)
    case 1 % Lowest confidence = shoreline indicator within 2.5 m of dGPS measurement
        vert_uncert_sig = 2.5;
    case 2
        vert_uncert_sig = 2;
    case 3
        vert_uncert_sig = 1;
    case 4 % Highest confidence = shoreline indicator within 0.5 m of dGPS measurement
        vert_uncert_sig = 0.5;
    end

    switch shoreline_type(i)
    case 1 % Gravel barriers
        vert_offset = 0.9;
        vert_offset_sig = 0.4;
    case 2 % Depositional terraces
        vert_offset = -6.0; % Offset from gravel barriers
        vert_offset_sig = 3.3;
    case 3 % Alluvial fan incisions
        vert_offset = -1.4; % Offset from gravel barriers
        vert_offset_sig = 1.5;
    end

    % Assume normal distribution of uncertainties; add random and systematic errors in quadrature
    SWL_elev(i) = dGPS_elev(i) - vert_offset;
    SWL_vert_uncert(i) = sqrt(vert_uncert_sig^2 + vert_offset_sig^2);
end
Table S1: Statistics on the number of dGPS measurements (N) associated with each shoreline feature in the compilation. Numbers in parentheses indicate percentages relative to the total counts in the rightmost column, such that totals add up to 100% along the rows, not columns.

<table>
<thead>
<tr>
<th>Shoreline Type</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>≥ 4</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel barrier</td>
<td>8 (7.9%)</td>
<td>21 (20.8%)</td>
<td>12 (11.9%)</td>
<td>60 (59.4%)</td>
<td>101 (56.7%)</td>
</tr>
<tr>
<td>depositional terrace</td>
<td>23 (59.0%)</td>
<td>6 (15.4%)</td>
<td>4 (10.3%)</td>
<td>6 (15.4%)</td>
<td>39 (21.9%)</td>
</tr>
<tr>
<td>incised alluvial fan</td>
<td>13 (34.2%)</td>
<td>10 (26.3%)</td>
<td>8 (21.1%)</td>
<td>7 (18.4%)</td>
<td>38 (21.3%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>44 (24.7%)</td>
<td>37 (20.8%)</td>
<td>24 (13.5%)</td>
<td>73 (41.0%)</td>
<td>178 (100%)</td>
</tr>
</tbody>
</table>

Table S2: Summary of confidence levels and their associated horizontal (x-y) and vertical (z) uncertainties, as well as which levels of confidence are possible for each shoreline type, indicated by an asterisk. Note that there is one exception to this table, in which ID 177, a depositional terrace, was given a confidence level of 4 (Section S2).

<table>
<thead>
<tr>
<th>Uncertainty</th>
<th>vertical</th>
<th>horizontal</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>± 1 m</td>
<td>± 1 m</td>
<td>± 2 m</td>
<td>± 2 m</td>
<td>± 2.5 m</td>
<td>± 2.5 m</td>
</tr>
<tr>
<td>Shoreline Type</td>
<td>gravel barrier</td>
<td>depositional terrace</td>
<td>incised alluvial fan</td>
<td>*</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>*</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table S3: Statistics on levels of confidence for different shoreline feature types measured by dGPS. Numbers in parentheses indicate percentages relative to the total counts in the rightmost column, such that totals add up to 100% along the rows, not columns.

<table>
<thead>
<tr>
<th>Shoreline Type</th>
<th>4</th>
<th>3</th>
<th>2</th>
<th>1</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>gravel barrier</td>
<td>86 (85.1%)</td>
<td>13 (12.9%)</td>
<td>2 (2.0%)</td>
<td>–</td>
<td>101 (56.7%)</td>
</tr>
<tr>
<td>depositional terrace</td>
<td>1 (2.6%)</td>
<td>–</td>
<td>25 (64.1%)</td>
<td>13 (33.3%)</td>
<td>39 (21.9%)</td>
</tr>
<tr>
<td>incised alluvial fan</td>
<td>–</td>
<td>17 (44.7%)</td>
<td>15 (39.5%)</td>
<td>6 (15.8%)</td>
<td>38 (21.3%)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>87 (48.9%)</td>
<td>30 (16.9%)</td>
<td>42 (23.6%)</td>
<td>19 (10.7%)</td>
<td>178 (100%)</td>
</tr>
<tr>
<td>Shoreline Feature Type</td>
<td>gravel barriers</td>
<td>depositional terraces</td>
<td>incised alluvial fans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>------------------------</td>
<td>-----------------</td>
<td>-----------------------</td>
<td>----------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Visibility of Feature</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Field</td>
<td>average</td>
<td>best</td>
<td>worst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerial Imag.</td>
<td>average</td>
<td>worst</td>
<td>best</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shoreline Indicator</td>
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<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Field</td>
<td>crest</td>
<td>inflection point of profile</td>
<td>base of scarp profile</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerial Imag.</td>
<td>best</td>
<td>worst</td>
<td>average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detectability of Indicator</td>
<td>Field</td>
<td>best</td>
<td>worst</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aerial Imag.</td>
<td>best</td>
<td>worst</td>
<td>average</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Range of Confidence</td>
<td>4–2</td>
<td>2–1</td>
<td>3–1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Elevational Variability of Indicator</td>
<td>as much as ± 1 m</td>
<td>?</td>
<td>?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vertical Offset from SWL</td>
<td>higher by 0.9 ± 0.4 m</td>
<td>equal to or lower than</td>
<td>equal to or slightly lower than</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal Offset from SWL</td>
<td>negligible</td>
<td>offshore</td>
<td>offshore</td>
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<tr>
<td>Horizontal Uncertainty of Shoreline Outline</td>
<td>± 5 m</td>
<td>± 25 m</td>
<td>± 10 m</td>
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<tr>
<td>Percentage Representation of Total Shoreline Outline*</td>
<td>5.0%</td>
<td>76.1%</td>
<td>18.9%</td>
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<tr>
<td>Quality of SWL Proxy</td>
<td>best</td>
<td>worst</td>
<td>average</td>
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Table S4: Summary of shoreline indicators used in this study to capture the SWL of the lake represented by the Bonneville shoreline. Visibility of the feature refers to the ease with which each shoreline feature type can simply be seen in the field and in aerial imagery. Detectability of the indicator refers to the ease in identifying and measuring the shoreline indicator of each shoreline feature in the field and in aerial imagery. Each shoreline type is given a ranking in terms of their visibility and detectability (‘best’, ‘average’, or ‘worst’). The range of confidence is between 1–4, in which 4 represents the greatest relative amount of confidence. The natural elevational variation of each shoreline indicator along a shoreline feature is listed if known (Section 5). The vertical offset of each shoreline indicator from the SWL is also included (Section 5.2). The horizontal uncertainty of the shoreline outline listed in this table only applies to segments traced without aid from dGPS measurements (Figure S17). Note that we have one measurement of a depositional terrace that has a confidence level of 4 due to constraints from a drone-derived DSM. All the factors listed in this table were considered when ranking the relative quality of these SWL proxies (Section 5.3).
Figure S1: A: Frontal view of an incised alluvial fan near Stockton, UT, which shows evidence of post-lacustrine deposition of debris flows due to stream erosion (40.495751°N, 112.330077°W). B: Super-imposed lines emphasizing the key geomorphic features pictured. Solid line outlines the fault scarp. Thin dashed lines mark the boundaries of the post-lacustrine stream deposits. The thick dashed line represents the location of the shoreline indicator, which is predominantly obscured by the stream deposits. When choosing where to take dGPS measurements, we aimed for spots that were the least obscured by post-lacustrine aggradation (blue). C: Aerial imagery of the incised alluvial fan. Camera icon shows the approximate location from which the photograph shown in panels A and B were taken (the camera-facing direction being southeast). No elevation measurement was taken in this location due to restricted land access.
Figure S2: Comparison of Currey’s (1982) shoreline feature elevation measurements with dGPS measurements from this study (N = 85). Panel A compares all shoreline measurements taken on the same feature. Bottom row of histograms compares elevations based on the method of measurement used by Currey (1982): Panel B (Method 1) Photo-mapped on the best available aerial photos and topographic maps at the time; Panel C (Method 2) Field checked with “rough-and-ready” closed hand level surveys relative to sites of known-elevation benchmarks; and Panel D (Method 3) Field checked with a telescopic alidade (Section 1.1). Black dashed line marks the location of the mean difference μ. Shaded gray area marks the 1-σ range of the difference. Our dGPS elevation measurements were converted from the NAVD 88 vertical datum to the NGVD 29 datum using VERTCON 2.0 (Section S3). See Table A1 for raw data used in this comparison.
Figure S3: Comparison of dGPS elevation measurements for two gravel barriers that were independently measured during two separate field seasons. Panels A-C correspond to shoreline feature ID 30; panels D-F to shoreline feature ID 37. Aerial imagery shown in panels B and E correspond to the black rectangular boxes in A and D, respectively. Red circles correspond to the location of dGPS measurements from the first visit (2012 or 2013); blue circles to measurements from the second visit (2014). White diamonds represent the coordinates given by Currey (1982) for each shoreline feature area. Insets in the bottom right corner of panels B and E list the number of dGPS measurements \(N\), the mean elevation \(\mu\) and standard deviation \(\sigma\), and confidence associated with each shoreline feature from the first (red text) and second (blue text) visits. Panels C and F compare the dGPS measurements of the first and second visits (see legend to see the specific year) along the length of the shoreline feature. Error bars for the dGPS measurements represent the reported vertical precision after post-processing. Red and blue lines mark the arithmetic mean of the dGPS elevation measurements for the first and second visits, respectively.

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Figure S4: (Caption on the following page.)
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Figure S4: Variation in dGPS elevation measurements along the length of the crests of three unique gravel barriers. The top row of panels (A, B, C, and D) corresponds to shoreline feature ID 66; the middle row (E, F, G, and H) to ID 53, and the bottom row (E, F, G, and H) to ID 38. Panels A, E, and I 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, F, and I, respectively. Colors of the shoreline outline represent different shoreline types (red = gravel barrier; green = depositional terrace; blue = incised alluvial fan). White diamonds represent the coordinates given by Currey (1982) for each shoreline feature area. Panels B, F, and I are aerial images of the beach ridges in closer detail, showing the location of each shoreline measurement as blue circles which are shaded according to their elevation (lighter = higher in elevation, darker = lower in elevation). Panels C, G, and K compare the shoreline elevation variation as recorded by the dGPS measurements (yellow circles) and the extracted elevation from the NED 10 m DEM (red circles). Error bars for the dGPS measurements represent the reported vertical precision after post-processing. Camera icons show the approximate location from which the photographs shown in panels D, H, and L were taken. Cardinal directions in photographs indicate the camera-facing direction. Field assistant Josh Zoellmer is pictured standing at the approximate location of the shoreline indicator in all three photographs. Only ID 38 is affected by a dirt road. Numbers in colored circles correspond to IDs indexed in Table A1 and shown in Figures 7 and S5. White insets in the bottom right corners detail relevant information on each shoreline: the number of dGPS measurements ($N$), the mean elevation ($\mu$) and standard deviation ($\sigma$), and confidence (scale of 1–4, with 4 representing the greatest confidence). Aerial imagery from Bing Maps accessed in April 2013.
Figure S5: Panels A (top) and B (bottom) from the overview map of Bonneville shoreline features (Figure 7) measured by dGPS. See legend in Figure 7 for symbology of colored circles and shoreline outline segments.
Figure S6: A first-pass estimate of the water depth distribution of Lake Bonneville at the time it attained its highest elevation (Section S7).
Figure S7: Histograms comparing dGPS elevation measurements to a 90 m (left column), 30 m (middle column), and 10 m DEM (right column). Each row of histograms corresponds to dGPS measurements of a particular shoreline type: gravel barrier (top, red bars); depositional terrace (middle, green bars); and incised alluvial fans (bottom, blue bars). 30- and 10 m DEMs are from the NED assembled by the USGS (Gesch, 2007; Gesch et al., 2002). 90 m DEM is SRTM data provided by the Consortium of Spatial Information (CGIAR-SCI). Black dashed line marks the location of the mean difference $\mu$. Shaded gray area marks the 1-$\sigma$ range of the difference. Solid gray line marks the location of zero (no difference). Relevant statistics, such as the number of dGPS measurements along the length of the shoreline ($N$), $\mu$, and $\sigma$, are provided in the white insets of each histogram. All raw data from the NED and SRTM are in conformance with the NAD 83 and NAVD 88 datums.
Figure S8: Comparison of photo-interpretation and field interpretation of the shoreline indicator location on \( N = 46 \) shoreline features. Photo-interpretation of aerial imagery occurred prior to field work and dGPS measurement for these 46 shoreline features. Stacked histogram shows the distribution of the average horizontal (in \( x-y \) space) discrepancy in interpretation. The mean (\( \mu \)) and median of these values is 8.5 and 6.0 m, respectively, represented by the black dashed line and solid gray line. Each color in the stack represents the shoreline featured type measured, following the scheme in which red corresponds to gravel barriers; green to depositional; and blue to incised alluvial fans. These average horizontal differences in interpretation were calculated by first finding the area bounded by the two lines of interpretation and then dividing this area by the length of the shoreline. The top right inset is one example illustrating the difference between the pre-field photo-interpretation (dashed black line) and field interpretation (solid red line) of the shoreline indicator for shoreline feature ID 175. Yellow dots mark locations of dGPS measurements.
Figure S9: A-C compare differentially-corrected Trimble GPS data collected in the field to the UAV-derived, control-point calibrated digital surface model (DSM). In panel (A), dGPS minus DSM elevations are depicted with respect to map location. dGPS control points show a small deviation with respect to the DSM consistent with the ∼10 cm measurement error associated with the Trimble dGPS collection. The difference between dGPS and DSM elevation increases with increasing distance from the control points, with the closest fit at shoreline #22 and the worst fit at shoreline #178. Panel (B) depicts the same pattern as (A) in a histogram. Panel (C) illustrates the deviation of DSM elevation from dGPS elevation compared to a 1:1 line.
Figure S10: Photo-interpretation and dGPS data overlain on UAV-generated orthophotomosaic
Figure S11: Photo-interpretation and dGPS data overlain on UAV-generated digital surface model (DSM).
Figure S12: The red/green line is the shoreline, as mapped by CYC, using the original satellite imagery available for Antelope Island. The blue lines are pixel transects extracted from the UAV-derived DSM (see Figs. S11, S13, S14, & S15). The green squares are shoreline locations determined in an automated fashion by searching the DSM for the position of slope=0 for gravel barriers (#22 and #178) or the inflection point near the steepest slope for depositional terraces (#177). The black dots are differentially-corrected Trimble GPS data collected in the field along transects perpendicular to shoreline features. The brown triangles represent the intersection between shoreline transects and the 1598 m contour derived from the DSM. The red diamonds represent the intersection between shoreline transects and field interpreted shoreline indicators surveyed with dGPS.
Figure S13: Elevation profiles across gravel barrier #22 (Fig. S10). The blue lines are elevation pixels sampled from the UAV-derived DSM. The black dots are Trimble GPS data with horizontal and vertical precision determined during the differential correction. Note that the DSM-derived transect has been shifted by -0.30 m due to the poor distribution of the dGPS control points that calibrate the DSM (see S9). The green square is the location of the gravel barrier, determined in an automated way as the position of slope=0 in the DSM, and usually the position of maximum elevation in the DSM transect. The blue circle is the location of the gravel barrier determined by CYC by visual inspection of available satellite imagery. The brown triangles illustrate intersections of the 1598 m DSM contour with the shoreline transect. The red diamonds represent the intersection between shoreline transects and field interpreted shoreline indicators surveyed with dGPS.
Figure S14: Elevation profiles across depositional terrace #177 (Fig. S10). The blue lines are elevation pixels extracted from the UAV-derived DSM. The black dots are Trimble GPS data with horizontal and vertical precision determined during the differential correction. Note that the DSM-derived transect has been shifted by -0.73 m due to the poor distribution of the dGPS control points that calibrate the DSM (see S9). The green square is the location of the depositional terrace, determined in an automated way as the position of the inflection point near the maximum slope of the DSM. The blue circle is the location of the gravel barrier determined by CYC by visual inspection of the satellite imagery. The brown triangles illustrate intersections of the 1598 m DSM contour with the shoreline transect. The red diamonds represent the intersection between shoreline transects and field interpreted shoreline indicators surveyed with dGPS.
Figure S15: Elevation profiles across gravel barrier #178 (Fig. S10). The blue lines are elevation pixels extracted from the UAV-derived DSM. The black dots are Trimble GPS data with horizontal and vertical precision determined during the differential correction. Note that the DSM-derived transect has been shifted by -0.71 m due to the poor distribution of the dGPS control points that calibrate the DSM (see S9). The green square is the location of the gravel barrier, determined in an automated way as the position of slope=0, and usually the position of maximum elevation in the transect. The blue circle is the location of the gravel barrier determined by CYC by visual inspection of the satellite imagery. The brown triangles illustrate intersections of the 1598 m DSM contour with the shoreline transect. The red diamonds represent the intersection between shoreline transects and field interpreted shoreline indicators surveyed with dGPS.
Figure S16: Elevation profiles across depositional terraces not surveyed in the field. The blue lines are elevation pixels extracted from the UAV-derived DSM. The green square is the location of the depositional terrace, determined in an automated way as the position of the inflection point near the maximum slope in the DSM. The blue circle is the location of the depositional terrace determined by CYC by visual inspection of the satellite imagery. The brown triangles illustrate intersections of the 1598 m DSM contour with the shoreline transect.
Figure S17: Histograms depicting the horizontal (first row) and vertical (second row) offsets between shoreline feature positions determined by an automated, unbiased method utilizing the UAV-derived DSM and (a) geomorphological shoreline indicators dGPS surveyed in the field (first column), (b) by visual inspection of satellite imagery by CYC prior to the UAV study (second and third columns).
Figure S18: Comparison of DSM-derived vertical positions of the shoreline indicators of gravel barriers (crests) and depositional terraces (inflection points) in the drone survey area. Solid green bars show the distribution of elevations of inflection points determined via the DSM transects (Fig. S14; red green bars show the distribution of elevations of crests (Figs. S13 & S15). Green and red circles show the distribution of DSM-derived elevations for the depositional terrace and gravel barriers as traced by the shoreline outline.
Figure S19: UAV-derived DSM elevation along the trace of the shoreline outline determined by CYC by visual inspection of available satellite imagery. With just one exception (at 200 m distance West to East), the shoreline indicator elevations calculated from analysis of DSM profiles (green squares; Figs. S13, S14, S15, & S16) are within ~1 m of the shoreline indicator outline (thick solid red and green line). For field surveyed shorelines #22, #177 and #178 (Fig S12), the agreement is even better, with shoreline elevations varying by 2 m and with discrepancies between methods usually less than 20 cm. The mean shoreline elevation derived from the shoreline outline is within 50 cm of the 1598 contour. Over the full 1.6 km of UAV-covered shoreline length, the shoreline trace appears to vary by 12 m in elevation, but this result cannot be adequately tested without a field dGPS survey of the shoreline.