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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. 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.

1. Introduction

More than a century of study has shown that the ancient pluvial lakes of the western U.S. host some of the world's best-exposed archives of past climate change. Previous work has estimated that such closed-basin lakes in the Great Basin were up to a factor of 10 times greater in surface area than mean historical values during the last Pleistocene glaciation ~30 to 10 kyr ago (Mifflin and Wheat, 1979; Benson et al., 1990; Benson and Thompson, 1987). The largest and best-known of these paleolakes is Lake Bonneville (30–10 ka; Oviatt et al., 1992; Oviatt, 2015), predecessor to the Great Salt Lake. At its greatest extent, the lake reached depths in excess of 300 m, attained a surface area roughly equal to that of modern day Lake Michigan (~50,000 km^2), and enclosed many islands that are now the mountain ranges of western Utah. Due in large part to the semi-arid Holocene climate, relicts formed by Lake Bonneville's past high water levels have resisted erosion, and manifest in well-preserved paleoshorelines and constructional landforms such as terraces, beach barriers, tombolos, and spits. Together, these features record a complex history of climate-forced water balance changes.

Spanish explorers Atanasio Domínguez and Silvestre Vélez de Escalante were some of the very first to record the presence of these prehistoric shorelines while on their expedition through the Great Basin in 1776 (Sack, 1989; Gilbert, 1890). Recognized as evidence of deeper lake successions that had once occupied the basin of the Great Salt Lake, these paleoshorelines were briefly investigated by Captain John C. Frémont and Howard Stansbury in the 1840s and 1850s (Sack, 1989). However, it was G. K. Gilbert (1890) who revealed the paleoclimatic, geodynamic, and geomorphic significance of the deposits and paleoshorelines of Lake Bonneville, jumpstarting a century's worth of careful research on the stratigraphy, sedimentology, geochronology, paleohydrology, and anthropology in the area. Although much information has

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accumulated since his work was first published, many of the hypotheses he developed have endured 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 maximum 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 the 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. Crittenden (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 (1982)'s 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 over the last few decades.

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 (1982)'s 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 (1982)'s data must be treated as references to small areas rather than point locations.

(3) 67% of Currey (1982)'s 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-min quadrangle maps), in which every inch on the map represents 2000 feet (~610 m) on the ground. These maps were generated in the 1960s–70s 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 gravel 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, 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. Thus, there are unknown uncertainties associated with initial non-horizontality of shoreline features, and, by extension, uncertainty in 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 (1982)'s 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 (1982)'s dataset for comparison. All measurements in the new compilation were measured in the field. Fig. 1 illustrates these improvements by comparing the results of this study to that of Currey (1982) on Antelope Island, Utah. We use Currey (1982)'s 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