GEOLOGY OF THE INTERMOUNTAIN WEST
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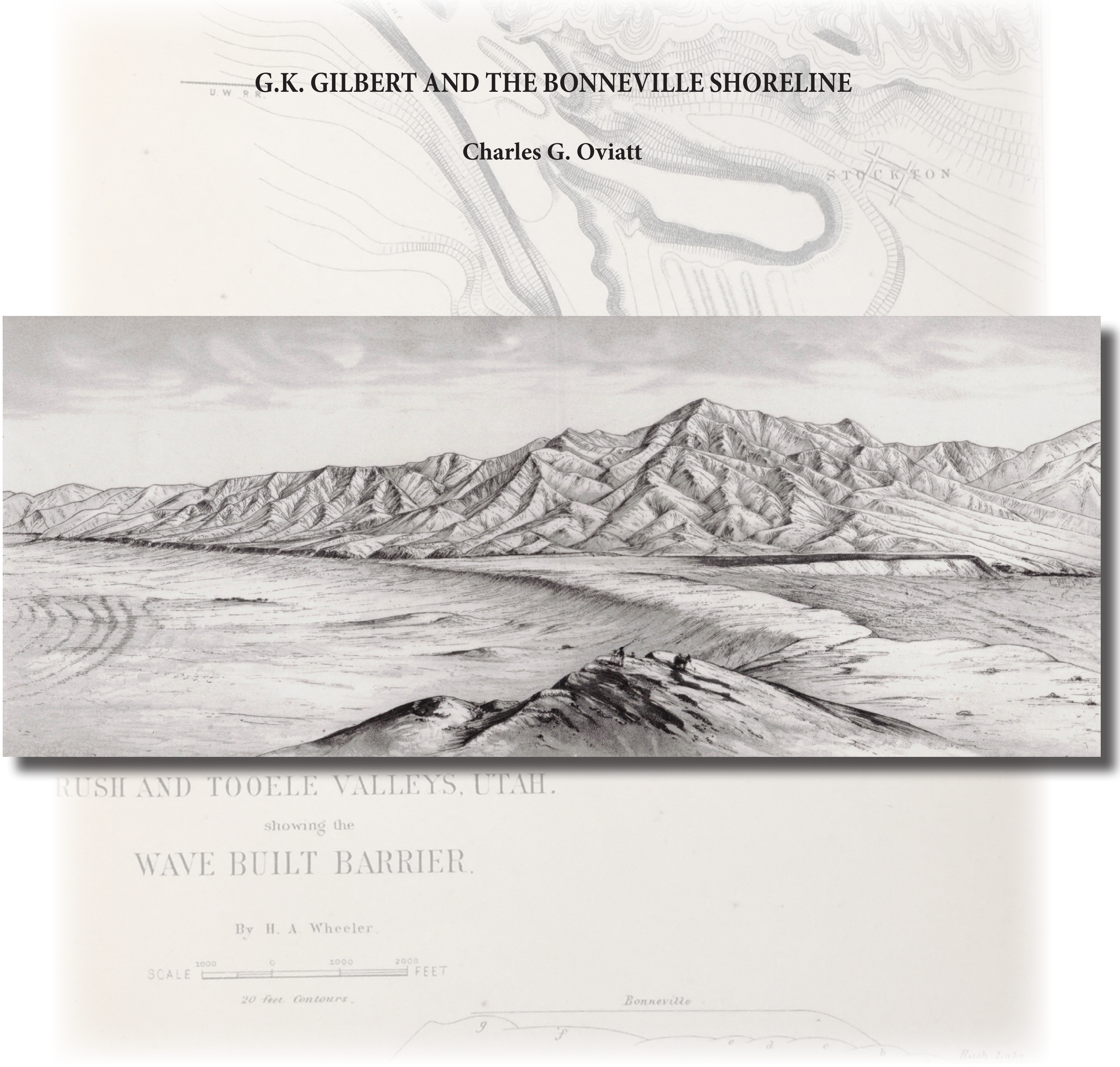
# G.K. GILBERT AND THE BONNEVILLE SHORELINE

Charles G. Oviatt



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*G.K. Gilbert's lithograph of the "Great Bar at Stockton" (Gilbert, 1890, plate IX). View looking east along the west side of the Oquirrh Mountains between the towns of Tooele and Stockton, near 40.47° N. latitude, 112.36° W. longitude. An erosional segment of the Bonneville shoreline, where it is cut into the alluvial fans on the north, aligns with the huge Stockton Bar depositional complex to the south (gravel from the fans was transported toward the south by longshore currents to the bars and spits). (For more information see Chan and others, 2003; Chan and Godsey, 2016). Background image is Gilbert's (1890; plate XX) map of the Stockton Bar. See figure 6 for more description.*

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# G.K. Gilbert and the Bonneville Shoreline

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## ABSTRACT

The Bonneville shoreline, the highest, and second-most prominent shoreline of Pleistocene Lake Bonneville in Utah, Nevada, and Idaho, has been thought for many years to have formed during a period of prolonged overflow (500 to 1000+ years) and lake-level stability prior to the Bonneville flood. That traditional idea was initially promoted by G.K. Gilbert during the 1870s before he spent over a decade on field work related to Lake Bonneville. During Gilbert's field work, his observations led him to a different interpretation of how the Bonneville shoreline developed, and by the time his final report on Lake Bonneville was published in 1890, he was no longer promoting the idea of prolonged overflow. Instead he thought of the Bonneville shoreline as a geomorphic record of the highest level attained by the transgressing lake in the closed basin; the shoreline marks the boundary between lacustrine-dominated landforms below and fluvial-dominated landforms above. For over 120 years after Gilbert's (1890) monograph was published, researchers ignored his interpretation, and assumed (but did not present supporting evidence), that Lake Bonneville had overflowed for a prolonged period prior to the Bonneville flood while the Bonneville shoreline developed. Re-examination of the geomorphology of the Bonneville shoreline, the stratigraphy of Lake Bonneville deposits, the geomorphology of the overflow area, and the history of Lake Bonneville, shows that Gilbert's 1890 interpretation is consistent with observations. Considering this, to accurately interpret the history of Lake Bonneville the Bonneville shoreline should be viewed as the level the lake had reached in the closed basin when its transgression ceased and it began to spill into the Snake River drainage basin.

## INTRODUCTION

The Bonneville shoreline, the highest, and second-most prominent shoreline of Pleistocene Lake Bonneville in Utah, Nevada, and Idaho (figures 1 and 2), for many years has been interpreted as having formed during a period of prolonged overflow prior to the Bonneville flood. The period of overflow was thought to be hundreds of years to 1000+ years in duration (see Scott and others, 1983, p. 277). In this interpretation lake-level stability for this prolonged period of overflow allowed the Bonneville shoreline to become strongly developed. This idea was first presented in print by G.K. Gilbert in the 1870s (Gilbert, 1875; it is possible Gilbert published something regarding this prior to 1875, but this is the earliest publication I have found) as he was beginning his field studies in the Bonneville basin as a member of the Wheeler Survey. Apparently the idea gained momentum when W.M. Davis published his interpretation of the Bonneville shoreline, probably influenced by Gilbert because Davis, himself, did

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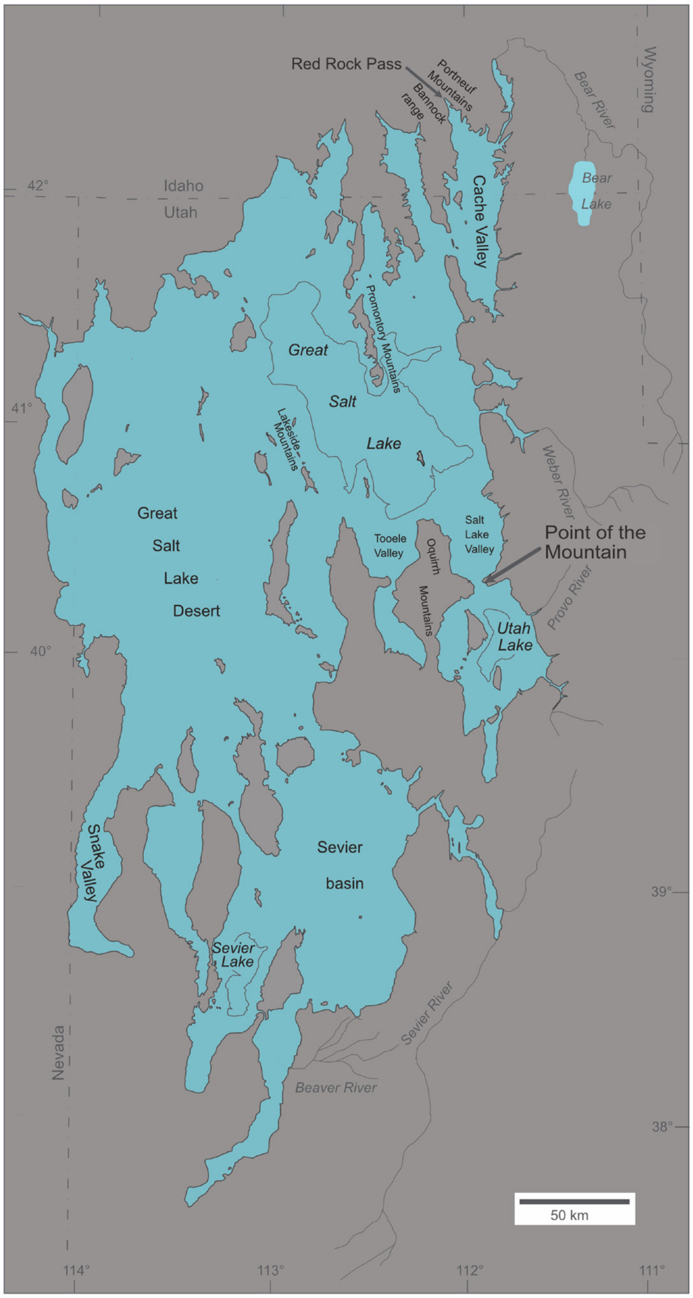

Figure 1. Map showing Lake Bonneville at its maximum level, the outline of which is the Bonneville shoreline. Based on the mapping of Currey (1982).

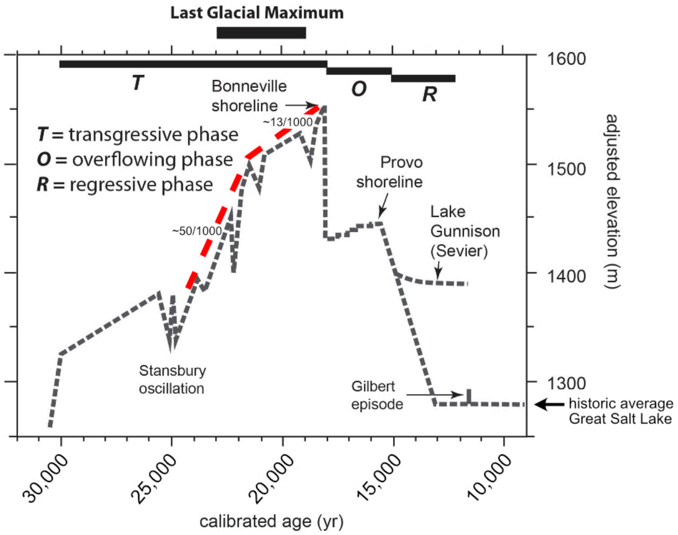

Figure 2. Hydrograph of Lake Bonneville (generalized from data in Oviatt, 2015). Elevations are adjusted for differential isostatic rebound in the basin (Currey and Oviatt, 1985; Oviatt, 2015). The red dashed line and the estimated long-term rates of transgression (about 13 m/1000 years, and about 50 m/1000 years) are based on approximate ages and elevations read from the diagram.

not work in the field in the Bonneville basin: “the highest or Bonneville terrace . . . marks a stand at the level of overflow northward to Snake River” (Davis, 1883, p. 570). Apparently Davis (1892) persisted with the interpretation of prolonged overflow and lake-level stability after Gilbert (1890) had published a different interpretation. The idea of prolonged overflow and lake-level stability was stated over and over by all researchers who studied the lake after Gilbert, through the 20th century into the early 21st century, as if it were simply a fact that everyone knew. But no evidence was ever presented to support it.

The purposes of this paper are to describe the Bonneville shoreline, including its geomorphology and geochronology, and its history of development, and to describe a process of shoreline development that is consistent with Gilbert’s (1890) interpretation. Field observations are consistent with the interpretation that prolonged overflow did not occur.

## GEOMORPHOLOGY AND STRATIGRAPHY OF THE BONNEVILLE SHORELINE

The Bonneville shoreline (figure 3) is prominent in many places in the basin (figure 4), but in some areas it is poorly developed and difficult to identify (figure 5). A typical location where no shoreline is developed

Figure 3. Oblique aerial view, looking toward the southwest, of the Bonneville shoreline on Steep Mountain, at the south end of Salt Lake Valley on the Traverse Mountains (permission to reproduce this photograph was obtained from University of Washington Libraries, Special Collections, John Shelton Collection, KC3275). The large spit and barrier complex is called "Point of the Mountain" (figure 1). For many years the prominent snow-covered bench visible in the photograph was considered one of the best-developed erosional platforms at the Bonneville shoreline in the lake basin. However, careful investigations of the geomorphology at the Steep Mountain site indicate that the bench is a constructional platform, not an erosional platform — it was produced by deposition of sand and gravel rather than by erosion of the underlying material (Oviatt and Jewell, 2016).

may have near-vertical exposures of resistant bedrock, and in such a situation incoming waves bounced off the bedrock and accomplished no geomorphic work. The character of the shoreline changes along its length, ranging from being constructional or depositional in some places (expressed as barrier beaches, spits, and bars; figure 6), to erosional in other places (expressed as scarps, "sea" cliffs in bedrock, or "sea" bluffs in unconsolidated alluvium; Gilbert, 1885; 1890; Currey, 1982; Chen and Maloof, 2017). In some places it is possible to trace the shoreline from an erosional reach into a depositional reach (figure 7).

In areas where waves eroded directly into unconsolidated alluvium or easily eroded bedrock, erosional shorelines are well formed (figures 3 and 8). Where abundant sediment was available and the geomorphology was conducive to producing constructional landforms (figure 6), tremendous constructional landforms were produced.

The elevation of the Bonneville shoreline (and of the Provo shoreline) varies from place to place in the basin because of the effects of isostasy. As recognized by Gilbert (1886; 1890), the weight of the water in Lake Bonneville caused Earth's crust to be bowed downward, and when the water evaporated from the basin the crust bowed back up or rebounded (Gilbert, 1890; Crittenden, 1963; Currey, 1982; Bills and others, 2002). Shorelines that had formed on horizontal planes while the basin was isostatically depressed became warped as they rebounded. As a result the Bonneville shoreline is now 74 m higher in the Lakeside Mountains, just west of Great Salt Lake (figure 1), where the water load was greatest, than it is at Red Rock Pass, at the edge of the lake far from the center of load. The isostatic gradient is very low (about 0.0005), so that from one viewpoint within the basin the shoreline appears to be horizontal, but at a basinwide scale the deformation is readily apparent (see maps in Gilbert, 1890; Bills and others, 2002).

A particular kind of barrier that Gilbert (1890) called a "V-bar" is commonly found at the Bonneville shoreline and at lower levels in the Bonneville basin. V-bars are barriers that have a V shape in map view (figures 9 and 10), so they appear distinctly different than barriers that are linear in form. The exact mechanism of formation of V-bars has not been discussed in the literature, but Gilbert's description (1890, p. 57–59) is excellent:

> "They are triangular in ground plan, and would claim the title of delta were it not appropriated, for they simulate the Greek letter more strikingly than do the river-mouth structures. They are built against coasts of even outline, and usually, but not always, upon slight salients, and they occur most frequently in the long, narrow arms of old lakes."

Gilbert further stated:

> "The V-bar, while a conspicuous feature of the Bonneville shores, is not believed to be a normal feature of lakes maintaining a constant level."

V-bars resemble "cuspate forelands" in plan form

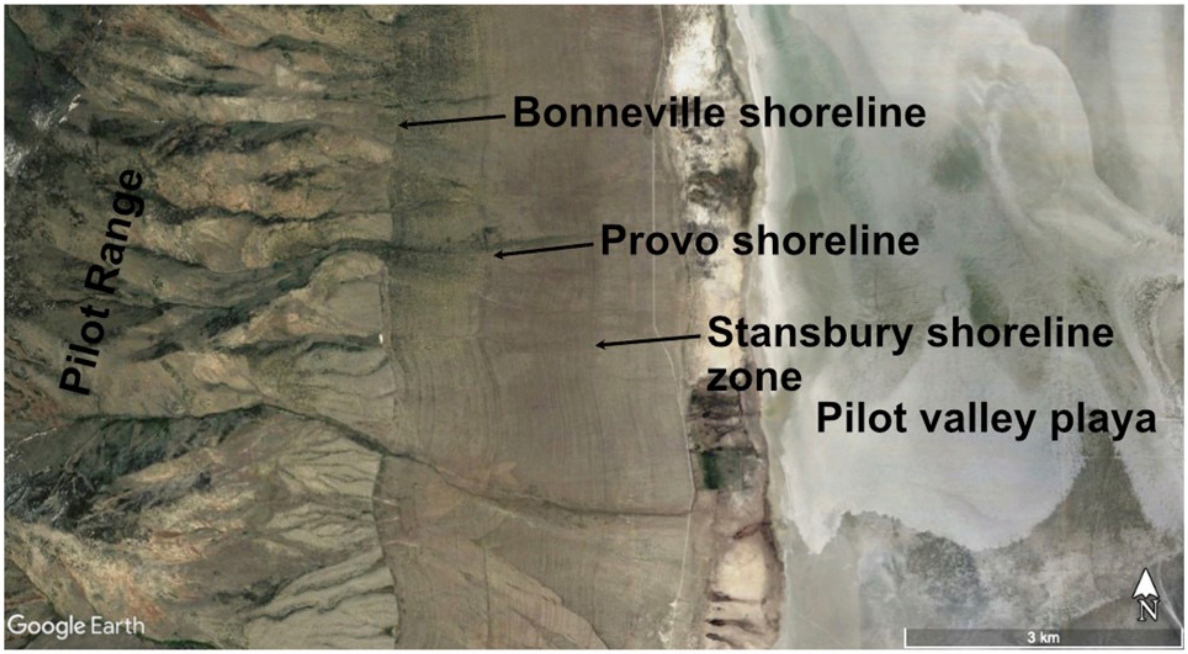

Figure 4. Google Earth image of part of the eastern piedmont of the Pilot Range, far western Utah and eastern Nevada (41.1° N. latitude, 114.0° W. longitude). In this area the Bonneville shoreline has an elevation of about 1590 m; the elevation of Pilot valley playa is about 1296 m. Note how the Bonneville shoreline is very conspicuous in this area, primarily because it marks the boundary between the lacustrine landforms below and the fluvial-dominated landforms above. Map data ©2020 Google.

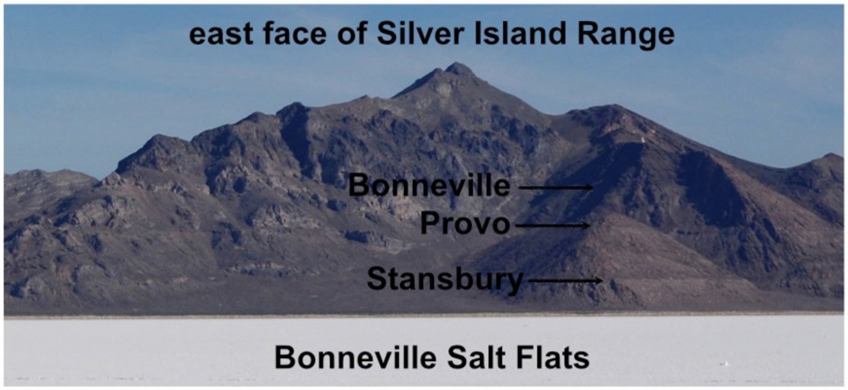

Figure 5. Photo of the east face of the Silver Island Range, northeast of Wendover, Utah, near 40.8° N. latitude, 113.9° W. longitude), showing the Stansbury, Provo, and Bonneville shorelines. Note that the Stansbury and Provo shorelines are obvious from a distance, primarily because of the accumulations of shoreline tufa, but that the Bonneville shoreline is not well defined on the steep bedrock exposures where tufa is uncommon. Photograph credit: Ken Krahulec.

(e.g., Semeniuk and others, 1988), but the genetic relationship between V-bars and cuspate forelands has not been thoroughly investigated. Field observations (unpublished) suggest that V-bars, which may be 10s of meters high, were built by vertical accretion in a generally rising lake, in contrast to cuspate forelands, which were built by lateral accretion of sediment (Semeniuk and others, 1988).

It is common in the Bonneville basin to find places where “stacks” of V-bars rise from the basin floor (most commonly at elevations above the Provo shoreline) up to the Bonneville shoreline (figure 9). At such places the V-bar at the top of the stack, the one at the Bonneville shoreline, is pristine – that is, except for any post-Bonneville erosion and alluvial or eolian deposition that might be present on the V-bar, the lacustrine character is well preserved and easily visible. However, the surface expressions of the lower V-bars in the same stack are subdued, as would be expected if the lake had continued to rise to higher levels after each V-bar was formed at the lake margin during the transgressive phase (figure 9).

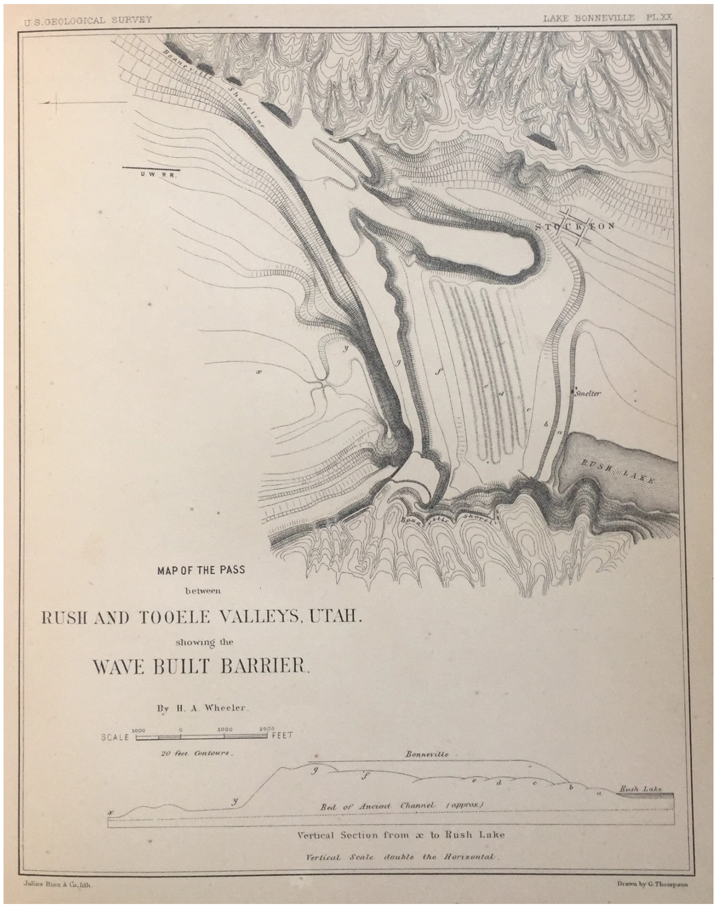

Figure 6. Plate XX from Gilbert (1890). This is Gilbert's map of the Stockton Bar, a depositional complex that includes the Bonneville shoreline at the top of the sequence. North is to the left on the map. The Stockton Bar is one of the places in the basin where the Bonneville shoreline is depositional or constructional. The coarse gravel in the Stockton Bar was transported by longshore currents from erosional sites in alluvium and bedrock to the northeast; the southwestern-most erosional sites are shown on the map, and more of the eroded alluvial fan complex is visible in the cover image. The rate of longshore transport of gravel that was deposited in the Stockton Bar was between 9600 and 16,000 $m^3$/yr (volume estimates by Oviatt [unpublished] and D.T. Nelson [Utah Valley University], personal communication, 2013; these estimates are for gravel accumulated at Stockton Bar in about 2000 years). Published estimated rates of longshore transport in modern systems range between about 6000 and 3,800,000 $m^3$/yr (Johnson, 1956; Galvin, 1973; Schoones, 2000), with a mean near 300,000 $m^3$/yr. The estimate of longshore transport rate for Stockton Bar is near the low end of that range. In other words, although the Stockton Bar is an impressive feature, it is not nearly as big as it might have been if the longshore transport rate were close to average. A period of prolonged overflow and stillstand at the Bonneville shoreline (which has been proposed by Burr and Currey, 1988) is not required for gravel to accumulate in Stockton Bar.

Lake Bonneville was dammed by an alluvial fan at the north end of Cache Valley in southeastern Idaho (figure 1; Gilbert, 1890; O'Connor, 1993; O'Connor, 2016; Shroder and others, 2016). The alluvial fan was built by Marsh Creek, which flowed out of the Portneuf Mountains into the pass between the Portneuf Mountains on the east and the northern end of Oxford Mountain (commonly referred to as the Bannock Range) on the west (Gilbert, 1890; Janecke and Oaks, 2011; Shroder and others, 2016). As the lake rose during its transgressive phase and reached an elevation where it intersected the fan alluvium, water began to leak through the permeable fan deposits and to discharge in springs on the north flank of the alluvial fan (O'Connor, 1993; O'Connor, 2016; Shroder and others, 2016). At an elevation about 50 m below the Bonneville shoreline (1550 m), at about 22,000 years B.P. (before present), the long-term rate of transgression of the lake slowed from about 50 m/1000 years to about 13 m/1000 years (figure 2), and this may mark the elevation and time when significant groundwater discharge from the lake slowed the transgression (a thorough investigation of the possible causes of the change in the long-term transgressive rate has not been conducted; one possible cause of the change in rate [change in the rate of groundwater outflow] is mentioned here; another possible cause — a possible change in the shape of the basin, that is, a flattening of the hypsometric curve at an elevation of about 1550 m—is not supported by evidence… the hypsometric curve in this elevation range is straight and does not flatten [Currey, 1990; Wambeam, 2001]).

Traditionally it has been thought that Lake Bonneville overflowed at the low point on the Marsh Creek alluvial fan (many references could be cited here, but some important ones are Gilbert [1890], O'Connor [1993], and Shroder and others [2016]). An exception to that interpretation was by Malde (1968), who thought that Lake Bonneville first rose higher than the Marsh Creek

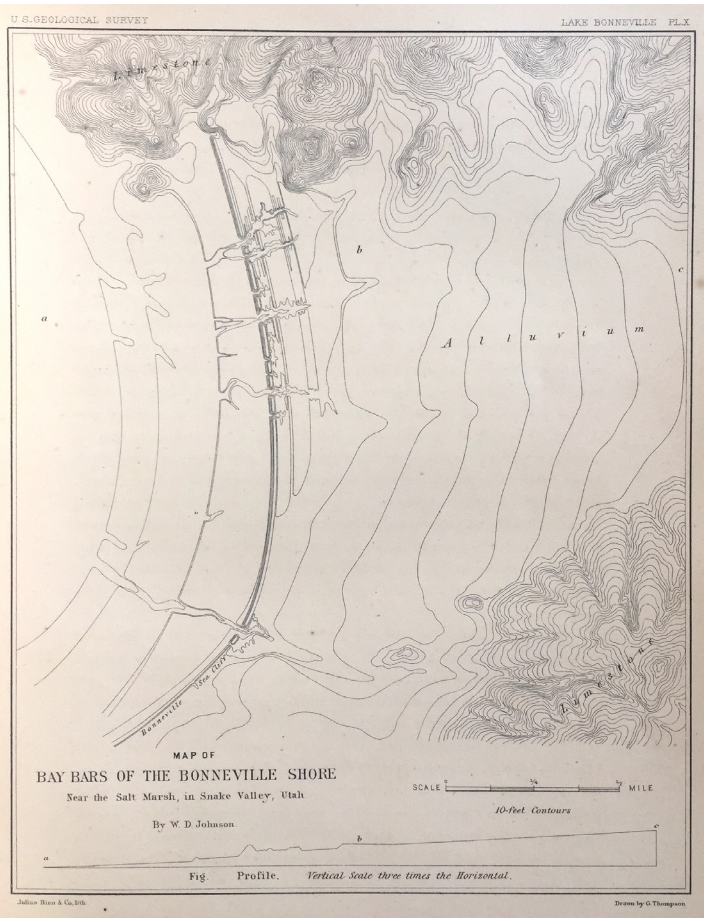

Figure 7. Plate X from Gilbert (1890) showing the Bonneville shoreline at a locality on the east side of Snake Valley in western Utah (near 39.46° N. latitude, 113.86° W. longitude). North is toward the right. Note that the topographic feature labeled "Bonneville sea cliff" in the lower part of the map area is an erosional shoreline that grades into a depositional complex in the Bonneville shoreline zone in the central and upper parts of the map area.

fan to a level he did not identify, then dropped during the Bonneville flood to the level of the Bonneville shoreline, which in his interpretation was determined by overflow across a bedrock threshold (this interpretation has not been reproduced by subsequent researchers). The interpretation that Lake Bonneville overflowed at the low point on the alluvial fan cannot be directly supported by evidence because the low point of the fan was eroded away during the Bonneville flood. The geomorphology and stratigraphy of the fan have not been studied in detail, but no evidence or arguments have been presented that conflict with the interpretation that the lake overflowed across the low point of the alluvial fan, and that interpretation is used here.

Groundwater seepage would have caused sapping and the formation of rounded first- and second-order valleys on the fan slope away from the lake (i.e., the north flank of the fan; O'Connor, 1993; Shroder and others, 2016). Those first- and second-order valleys would have migrated headwardly upslope toward the fan crest as long as seepage continued, in a direction generally opposite that of the groundwater flow direction. In this interpretation, as lake level continued to rise, the difference in hydraulic head between Lake Bonneville in Cache Valley and the water table on the north flank of the fan would have increased, thus leading to a greater rate of groundwater discharge and sapping. In this scenario, by the time the lake had transgressed to the elevation of the low point on the fan crest, sapping would have facilitated the rapid erosion of the fan deposits by weakening the fan dam, and the Bonneville flood was initiated as soon as the lake began to overflow. The alluvial-fan dam would have collapsed just as modern earthen dams collapse when they are subjected to similar processes of sapping and overflow (Shroder and others, 2016).

Gilbert (1890) may or may not have been aware of groundwater sapping as a geomorphic process. However, he did recognize fluvial erosion of unconsolidated fan materials as being important: "uncemented alluvium is easily and rapidly torn up and removed, and as soon as a current began to flow across the divide, it must have commenced the excavation of a channel"(Gilbert, 1890, p. 175).

Most gravel in barriers at the Bonneville shoreline is horizontally bedded. Ground-penetrating radar (GPR) results (Smith and others, 2003; Schide and others, 2018) and observations in gravel pits (unpublished observations by C.G. Oviatt) are consistent with this conclusion. For barrier gravel to be dominated by a thick sequence of horizontal beds rather than dipping foresets, the gravel must have been deposited in a vertically accreting sequence in a rising lake rather than in a constant-level lake, where lateral accretion and foreset bedding would dominate (figure 11). Dipping beds of gravel will be present even in features dominated by vertical accretion, because dipping beds of gravel would have

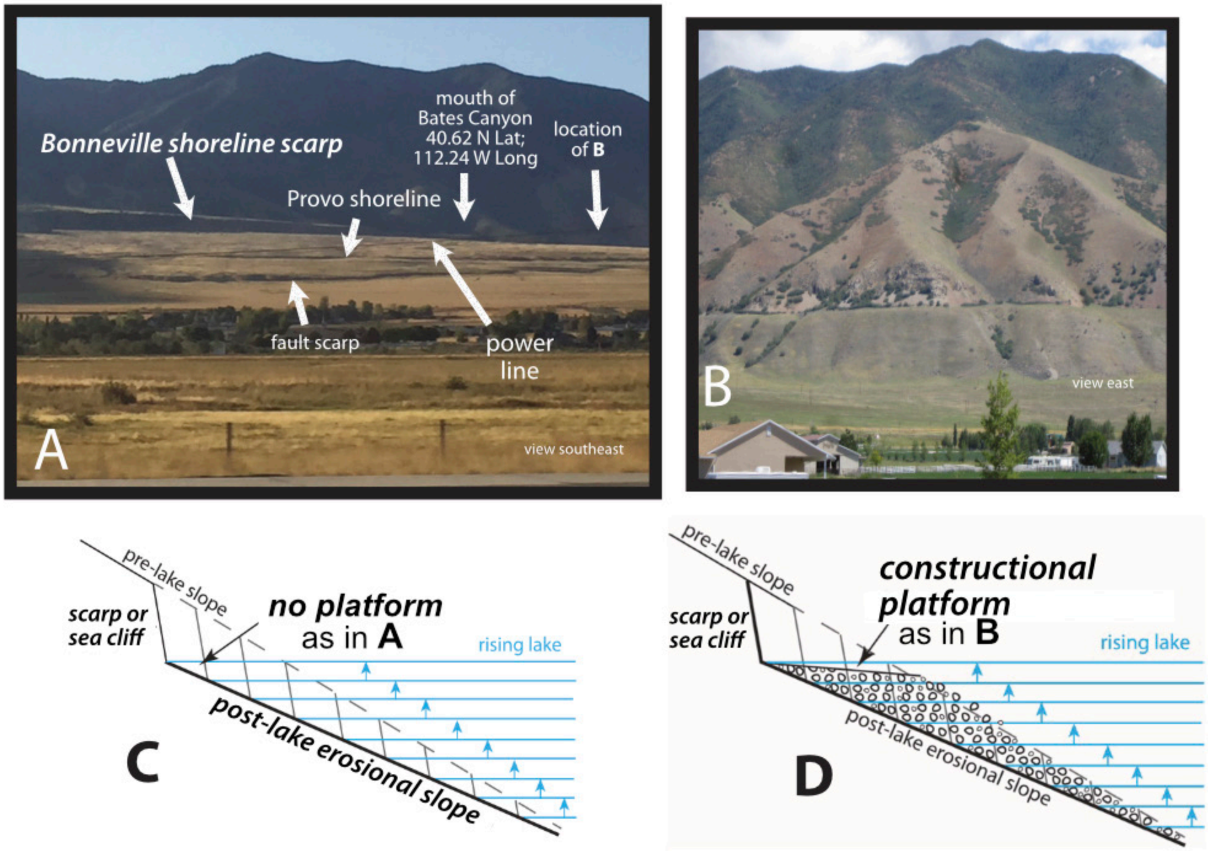

Figure 8. The Bonneville shoreline in Tooele Valley, on the west side of the Oquirrh Mountains, west of Salt Lake Valley. The photographs show two expressions of the Bonneville shoreline at locations adjacent to each other. (A) Photograph taken from Interstate Highway 80 toward the southeast of the high scarp at the Bonneville shoreline at the upper end of a long erosional slope formed on pre-Bonneville alluvium. (B) Prominent Bonneville shoreline where it has been cut into sandstone and limestone bedrock of the Pennsylvanian-Permian Oquirrh Group, view looking east. (C) Schematic cross section of the relationships shown in photograph A; note that no platform is present at A and that the scarp (or "sea" bluff) indicates a tremendous amount of wave erosion during the transgressive phase; the Bonneville shoreline at this locality is erosional. (D) Schematic cross section of the relationships shown in photograph B; note that a prominent constructional platform marks the upper limit of wave erosion, deposition of coarse-grained gravel eroded from the bedrock, and the Bonneville shoreline.

been deposited on the flanks and fronts of barriers and spits, or any place where depositional surfaces were not level. In addition, foreset bedding would have been associated with progradation during each of the frequent fluctuations and oscillations that occurred during the transgressive phase.

Bedding observed in barriers and spits at the Bonneville shoreline is similar to that in transgressive-phase barriers throughout the basin (Schide and others, 2018). Gilbert (1890) called many of the large barriers "intermediate" because they are found at elevations between those of the Bonneville and Provo shorelines (numerous transgressive-phase barriers are also found at elevations lower than the Provo shoreline). The intermediate barriers were formed during the transgressive phase, which was the approximate 12,000-year period during which the long-term trend was for Lake Bonneville to rise to its highest level from levels near those of modern Great Salt Lake. Short-term fluctuations and oscillations during the transgressive phase were frequent, and some are documented based on stratigraphic relationships (Oviatt, 1997; Nelson and Jewell, 2015). The causal relationships between intermediate barriers and short-term oscillations and fluctuations of lake level, in addition

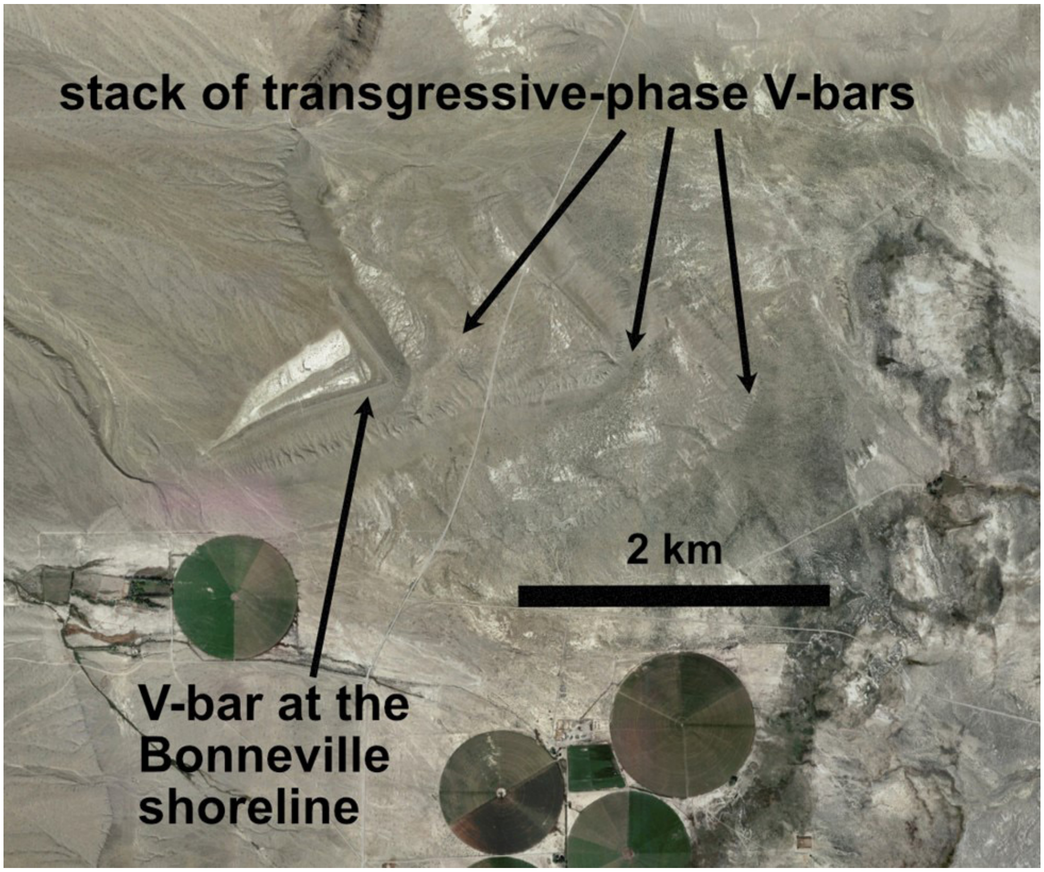

Figure 9. Stack of transgressive-phase V-bars in Snake Valley (39.47° N. latitude, 114.00° W. longitude)—the general slope of the land surface is upward from right to left. The highest, best-preserved V-bar is at the Bonneville shoreline; the lower V-bars, which are not as well preserved, were deposited earlier during the transgressive phase. Map data ©2020 Google.

to other potential factors in the development of transgressive-phase barriers, is an ongoing, but in-complete, field of investigation. Study of those causes began with Gilbert (1890, p. 135–153), who proposed the hypothesis that the intermediate shorelines formed as lake level generally rose but was punctuated by oscillations.

## GEOCHRONOLOGY OF LAKE BONNEVILLE

The general history of Lake Bonneville is well known (see Gilbert, 1890; Oviatt, 2015; and Oviatt and Shroder, 2016; and numerous references cited therein), but details of the chronology are still under investigation (Laabs and others, 2019). The Bonneville lake cycle consisted of three main phases: the transgressive phase, the overflowing phase, and the regressive phase (figure 2). The transgressive phase lasted about 12,000 years from 30,000 years B.P. until 18,000 to 17,500 years B.P., during which the lake rose by over 270 m in a hydrographically closed basin with no river outflow. The Stansbury shoreline, one of three regionally mappable shorelines in the Bonneville basin (Bonneville and Provo are the other two), formed during at least two of the many oscillations of lake level that occurred during the transgressive phase (Gilbert, 1890; Oviatt and others, 1990; Nelson and Jewell, 2015; Oviatt, 2015). At the end of the transgressive phase the Bonneville flood (O'Connor, 1993; 2016) dropped lake level by over 100 m (Miller and others, 2013) in less than a year, an event that marked the beginning of the overflowing phase of Provo shoreline development in the hydrographically open basin. The overflowing phase lasted until about 15,000 years B.P. (figure 2), or possibly until about 16,500 years B.P. (Laabs and others, 2019). The regressive phase in the once-again closed basin lasted until about 13,000 years B.P. (figure 2) when the lake dropped to elevations similar to those of modern Great Salt Lake. Of primary interest for this paper is the chronology at the end of the transgressive phase.

The Bonneville flood occurred at the end of the transgressive phase. The age of the flood is not known with high precision (figures 12 and 13), but some ages

Figure 10. V-bars in closed Pleistocene lake basins in Nevada. (A) Stack of V-bars in Railroad Valley (38.52° N. latitude, 115.54° W. longitude). (B) Stack of V-bars near Walker Lake, Lake Lahontan basin (38.67° N. latitude, 118.65° W. longitude). Map data ©2020 Google.

help to narrow the possibilities. The age is limited by three radiocarbon dates for samples collected from basal stratigraphic positions at elevations close to the Bonneville shoreline (figure 13). Two of the samples consist of charcoal from a soil buried by Bonneville gravel 7 m below the Bonneville shoreline (Oviatt, 1991, 2015), and one sample consists of wood in lagoon deposits near the base of Bonneville gravel 15 m below the Bonneville shoreline (Scott, 1988; Oviatt, 2015). The wood and charcoal ages are limiting ages — the Bonneville flood cannot be older than those ages.

If simple assumptions about a steady rise of lake level are used (figure 13), the three ages suggest that the lake had reached the elevation of the Bonneville shoreline by approximately 18,000 years B.P. (Oviatt, 2015), although the actual time of the initiation of overflow and of the Bonneville flood could have been as young as about 17,000 cal yr B.P. (calibrated years before present) (figure 13). Amidon and Farley (2011) used an age of 17,500 cal yr B.P. for the Bonneville flood for calibrating cosmogenic $^3$He production rates in western North America. Until more information becomes available the

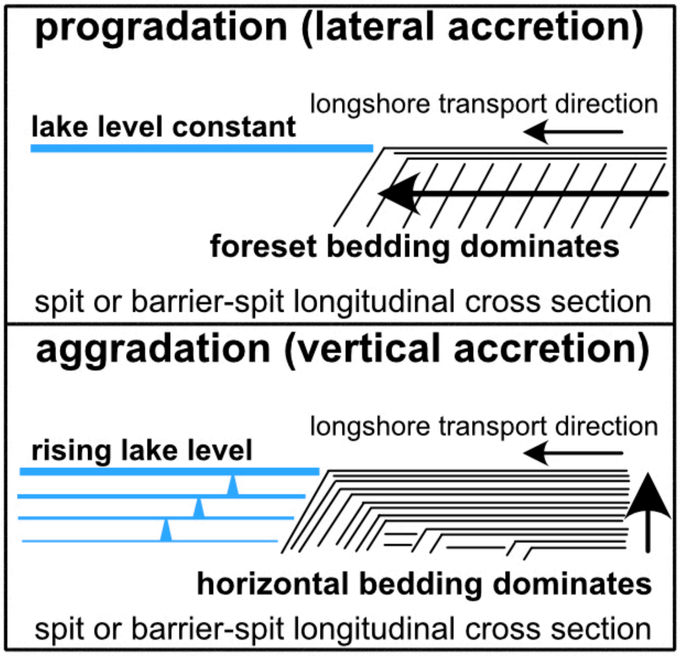

Figure 11. Schematic diagrams showing the expected differences in bedding between lateral and vertical accretion.

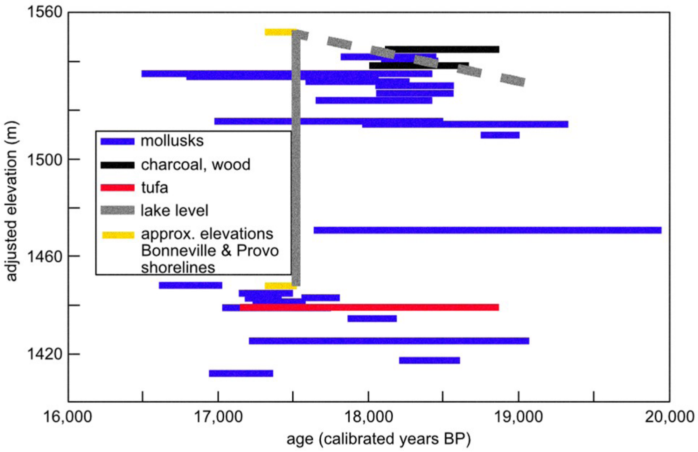

Figure 12. Geochronology of the latter part of the transgressive phase at elevations higher than the Provo shoreline. The approximate long-term trend of the transgressive phase for this part of the chronology (about 13 m/1000 yr; figure 2) is shown by the dashed gray line, and the Bonneville flood is shown by the vertical gray line. The approximate elevations of the Bonneville and Provo shorelines, adjusted for the effects of isostatic rebound, are shown with the yellow lines (data from Currey, 1982, and Oviatt, 2015). The calibrated, two-sigma age ranges for radiocarbon ages of samples of three different categories of material, plotted relative to their isostatically adjusted collection elevations, are shown with the blue, black, and red lines. Note that the age of the Bonneville flood is not precisely constrained by the available calibrated radiocarbon ages; a likely age is 17,500 ± 500 years B.P., although it could easily be younger than that (figure 13) if the rate of transgression were less than the estimated value of about 13 m/1000 yr (figure 2).

precise age of the end of the transgressive phase and of the Bonneville flood cannot be determined, but 17,500 ± 500 years B.P. is an acceptable estimate.

At Tabernacle Hill in the southern Sevier basin (figure 1), a basalt flow and tuff ring were erupted into Lake Bonneville after the Bonneville flood had dropped the lake to the level of the Provo shoreline (Gilbert, 1890; Oviatt and Nash, 1989; Oviatt, 1991). Eight radiocarbon ages for tufa (Lifton and others, 2015) cemented to the outer edges of the basalt flow provide age estimates for the lake at that level. The maximum range of all the calibrated tufa ages from Tabernacle Hill is about 1500 yr, and that range overlaps by about 630 yr with the limiting age range for the wood and charcoal ages from just below the Bonneville shoreline.

A proposed age for the beginning of the Provo overflowing phase (18,300 years B.P.; Lifton and others, 2015) is based on the assumption that there was no radiocarbon reservoir at Tabernacle Hill at that time, an assumption that may not be correct considering the local hydrogeology and the history of the lake. The area near Tabernacle Hill is characterized by a high modern water table and flowing wells (Holmes and Thiros, 1990). A gigantic hot-springs tufa mound was deposited nearby in late Quaternary time (Meadow Hot Springs tufa mound; Nelson and Fuchs, 1987; Oviatt, 1991), and hot springs are still active at the tufa mound (https://utah.com/meadow-hot-springs; website accessed on October 5, 2020). These observations suggest that modern groundwater is actively discharging in the Tabernacle Hill area. It is reasonable to think that groundwater discharge was enhanced in that area in late Pleistocene times when the climate was cooler and wetter than today (Ibarra and others, 2018).

Groundwater discharge would have abruptly increased in many places within the lake at the Provo level, including near Tabernacle Hill, after the Bonne-

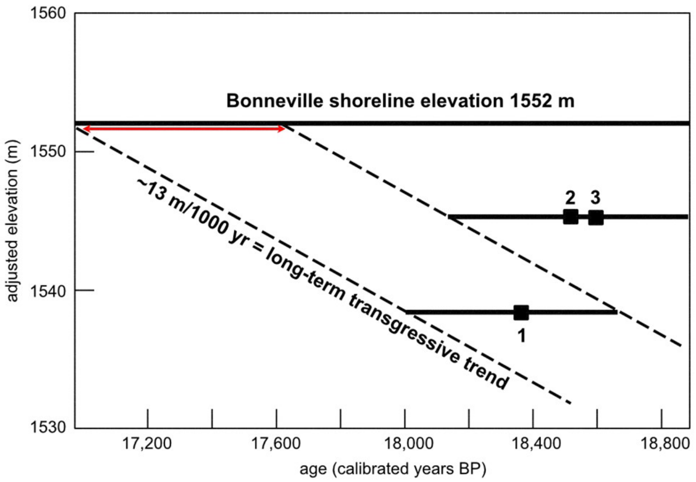

Figure 13. An enlargement of the chronology of the end of the transgressive phase, as determined by the limits placed on the transgression by radiocarbon ages (calibrated) of two charcoal samples from a buried soil 7 m below the Bonneville shoreline near Kanosh, Utah (dates 2 and 3 and thick black line representing 2-sigma age range), and a sample of wood from basal lagoon deposits 15 m below the Bonneville shoreline (date 1 and thick black line) (data from Scott, 1988; Oviatt, 1991, 2015), compared to the approximate long-term average rate of transgression (about 13 m/1000 yr; figures 2 and 12), which is shown by the two black dashed lines, one that intersects the young end of the 2-sigma range for date # 1, and one that intersects the old end of the 2-sigma range for data # 1. The age of the Bonneville flood (the end of the transgressive phase) falls between those two lines, marked by the red, double-pointed line. Based on this analysis, an age between about 17,600 and 17,000 years B.P. is reasonable.

ville flood had increased the difference in hydraulic head by over 100 m from recharge areas to discharge areas (with the drop in lake level from Bonneville to Provo). Groundwater that discharges in springs or in diffuse discharge areas has been travelling through the groundwater system for some amount of time since it was recharged to the groundwater system (Freeze and Cherry, 1979). Therefore, groundwater is usually older than the surface water (i.e., precipitation or runoff) in the same area. Lerback and others (2019) have shown that modern groundwater in the Great Salt Lake Desert (figure 1), in the western Bonneville basin, has ages that range from 0 (zero) to over 21,000 years B.P Although the possibility of a radiocarbon reservoir in Lake Bonneville in the area of Tabernacle Hill when the lake was at the Provo shoreline has not been tested, it is a reasonable expectation and could be an important factor in accounting for the overlap in tufa ages from the Provo shoreline with the wood and charcoal ages near the Bonneville shoreline.

Radiocarbon ages for gastropod shells from Provo-aged deposits (Miller and others, 2013) have potential for helping with the chronology of the Provo shoreline, but are difficult to interpret because they are older than expected. The age ranges overlap with the tufa age ranges from Tabernacle Hill. Some "old" gastropod ages reported by Miller and others (2013) are for samples collected from gravel that forms the two prominent barrier beaches at the Provo shoreline, which formed relatively late in the overflowing phase (Miller, 2016). More work is needed to be certain, but it is reasonable to conclude that the gastropod ages have been influenced by radiocarbon reservoirs in the lake water (possibly different magnitudes of the reservoirs at different locations in the basin) — this would be consistent with the input of groundwater into the Provo lake.

Previously I and most authors have assumed that Lake Bonneville overflowed during a prolonged period of 500 to 1000 $^{14}$C years, or more, at its highest level prior to the Bonneville flood (Oviatt and Jewell, 2016). For this to have happened, however, several events would have occurred during the apparent about 630 year period of overlap between the wood and charcoal ages near the Bonneville shoreline and the tufa ages at the Provo level — these events are: the completion of the transgressive phase in its uppermost 7 to 15 m, the proposed prolonged period of overflow, the Bonneville flood, the eruption and cooling of the basalt flow and tuff ring at Tabernacle Hill, and the precipitation of tufa on the basalt at Tabernacle Hill. It is likely that Provo-shoreline tufa (including the tufa at Tabernacle Hill) was precipitated during the latter part of the overflowing phase rather than at the beginning of that phase. Considering the uncertainty of the numerical ages and their collective age ranges (individual ages are not points in time, but rather are age ranges), and the limited availability of appropriate ages for the Bonneville and Provo shorelines, it may be possible, if prolonged overflow did actually occur, to add in a period of prolonged overflow into the Lake Bonneville chronology. But if that were to be done, independent observations should be available to clearly support the conclusion of prolonged overflow. It turns out that no such evidence has been described and apparently does not exist (Oviatt and Jewell, 2016).

Following the publication of Gilbert's monograph on Lake Bonneville in 1890, all publications on the history of the lake that were published during the 20th century include statements or assumptions that Lake Bonneville had reached its highest level and overflowed for a prolonged period so that the prominent Bonneville shoreline could develop at a stabilized lake level. Importantly, this presumed overflow was presented as not causing rapid downcutting of the Marsh Creek alluvial fan (the speculation was that it took time for the overflowing river to cut headwardly up the north flank of the alluvial fan to the overflow point [i.e., Scott and others, 1983, p. 276–277]).

## GILBERT'S INITIAL IDEAS

Gilbert expressed in print in 1875 (p. 90–91) the idea of prolonged overflow at the elevation of the Bonneville shoreline.

> "The level of Great Salt Lake, like that of other lakes without overflow, is notoriously inconstant, for the obvious reason that it depends on the ratio between precipitation and evaporation over a limited area — factors which diverge, and change their conditions of equilibrium, with every fluctuation of annual mean temperature or humidity. It is difficult to imagine that so unstable a climatal equilibrium was maintained for the time that was consumed in the production of either the Bonneville or the Provo beach, and, before we accept such explanation of their origin, we are led to inquire whether at these levels the stage of water was not regulated by an overflow. The coincidence of one of the constant levels with the highest water stage of all, renders the presumption of an outflow at that stage especially strong."

In 1875, Gilbert had not thoroughly studied the geomorphology of Red Rock Pass or the Bonneville shoreline. It is important to realize that Gilbert recognized that lakes in closed basins do not maintain a constant level for a prolonged period — if evidence were to be found that a lake had maintained a constant level for a extended period, some causal mechanism would be required, and such a mechanism is likely to be surface-water overflow. Even in a hydrographically open-basin lake, the level does vary to some extent, depending on the geometry of the overflow channel and changes in the rates of inflow and outflow. But that variation is likely to be limited to a narrow vertical range, measured in meters or tens of meters in extreme cases (Street-Perrott and Harrison, 1985). Lake Bonneville, on the other hand occupied a hydrographically closed basin for most of its history, in which the total range of lake-level variation was hundreds of meters. The largest oscillations of lake level during the transgressive phase, which are likely to have been caused by millennial-scale changes in climate, were probably on the order of 40 to 50 m in amplitude (Oviatt, 1997; Nelson and Jewell, 2015).

The idea of prolonged overflow at the Bonneville shoreline was probably part of Gilbert's interpretations of the Bonneville shoreline prior to 1875, but it is hard to know exactly when the idea originally arose. In 1874, in a brief description of the lake for the report of the Wheeler Survey (Gilbert, 1874), he said nothing about the length of time the lake might have lingered at either the Bonneville or Provo shorelines. Perhaps the idea of prolonged overflow and lake-level stability while the Bonneville shoreline formed was just a natural conclusion that anyone might have arrived at after first seeing the shorelines.

Gilbert's field notes from the period from about July 1876 to November 1880 as transcribed by Hunt (1982), give hints that during that period when he was investigating the geology of the Bonneville basin on the ground, he was thinking that both the Bonneville and Provo shorelines had formed during periods of prolonged overflow and stable lake levels. However, during that period his ideas may have begun to shift. A drawing from Gilbert's field notes for September 24, 1877 (figure 14A), shows a description and interpretation of the shoreline that is consistent with his 1890 statement. The accompanying drawing (figure 14B) and comments in Gilbert's field notes from the same day are more am-

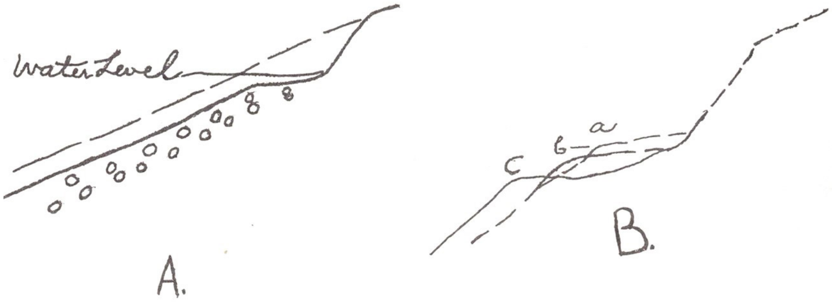

Figure 14. Drawing from Gilbert's field notes (Hunt, 1982, figure 8.2). (A) Gilbert showed relationships similar to those in figure 5D of this paper—assuming lake level was rising, in Gilbert's drawing the constructional platform grew in height as the waves cut into the underlying materials (alluvium or bedrock); the abrupt angle between the platform and the scarp or cliff is the shoreline. Gilbert said in his field notes, as related to this drawing: "As the water rose on a salient point its waves carried a cliff before them and at any time of the progressive advance the profile might be a continuous advance leaving a somewhat continuous surface behind it." (B) Gilbert showed field relationships of depositional features near the Bonneville shoreline. Apparently at this point Gilbert thought the beginning of the regression from the Bonneville shoreline was slow and he had not realized at that time that lake level dropped very rapidly from the Bonneville shoreline during the Bonneville flood. That realization would come later after he had spent more time at Red Rock Pass and assembled all the pieces of the puzzle.

biguous. Perhaps at that point he was not aware of the rapid regression from the Bonneville shoreline caused by the Bonneville flood.

## GILBERT'S IDEAS IN 1890

During the 1880s, Gilbert published a few papers related to his work on Lake Bonneville (e.g., Gilbert, 1885; 1886), but he said little about the formation of the Bonneville shoreline in those publications. Much of the material from the 1880s was revised and republished as part of Monograph 1 in 1890. The following quote from Gilbert's 1890 monograph on Lake Bonneville summarizes his thinking at that time (Gilbert, 1890, p. 171).

> "Thirteen years ago I had the temerity to predict, first, that the position of the Bonneville shore-line would eventually be shown to have been determined by an overflow of the lake, and second, that the Provo shore-line would be found to have been similarly determined. The first of these predictions has been verified in its letter, but not in its spirit; the second has proved to have full warrant. My anticipation was based on the following consideration: A lake without overflow has its extent determined by the ratio of precipitation to evaporation within its basin; and since this ratio is inconstant, fluctuating from year to year and from decade to decade, it is highly improbable that the water level will remain constant long enough to permit its waves to carve a deep record. I failed to take account of the fact that the highest shore-mark of the series is conspicuous by reason of the contrast there exhibited between land sculpture and littoral sculpture. We now know that the height of the Bonneville shore-line was determined in a certain sense by overflow, since a discharge limited the rise of the water; but the carving of the shore was essentially completed before the discharge; and as soon as that began, the water level fell. At the Provo horizon, on the contrary, a constant or nearly constant water-level was maintained by discharge for a very long time."

It is not exactly clear what he meant by "13 years ago." He said in Monograph 1 (Gilbert, 1890, p. 17) that, "The field work that afforded this information [that is, the information published in Monograph 1] was performed chiefly in the years 1867–70, but publication was delayed until 1877–78." Presumably, "1877–78" referred to reports of the Wheeler and Powell Surveys of the American West, in which he was employed. Thirteen years prior to 1890 is 1877. The publication of Monograph 1 took many years to complete (Hunt, 1980; Pyne, 1980), but regardless of the precise year, "13 years ago" would have been sometime during the decade of the 1870s.

In the 1890, p. 171, quote, Gilbert eloquently described his interpretation of how the Bonneville shoreline developed. As is discussed below, however, I have found no case in the published literature (or in unpublished sources) where anyone paid attention to his 1890 interpretation. I include myself in this.

## POST-GILBERT INTERPRETATIONS

During the last decade of the 1800s, and for all of the 20th century into the early 21st century, everyone assumed that the Bonneville shoreline had formed during a period of stable lake level caused by prolonged overflow (Oviatt and Jewell, 2016). The assumption was made with apparent certainty.

My own experience is not different from that of others. When I first began learning about Lake Bonneville in the field in the late 1970s, the assumption of prolonged overflow was part of the "lore" of Lake Bonneville — no one thought to question the idea and it was part of the well-known history of the lake that everyone accepted. For decades as I continued to learn about the lake and to publish papers, I inserted, without the slightest hesitation, a period of prolonged overflow into diagrams and summaries of lake history. I never heard anyone question the idea of prolonged overflow, and authoritative statements, such as "the 10- to 20-m-wide wave-cut benches that were locally cut in bedrock at the Bonneville shoreline require a stand of some duration at the highest level" (Scott and others, 1983, p. 277), left no doubt that prolonged overflow was real.

This spell was broken for me, however, sometime early in the decade of 2011–2020, when I realized that I didn't know what the evidence was for prolonged overflow or for its duration. For all those years I had been blindly repeating the word of others without checking for myself. I have been unable to find any published or unpublished interpretations of the Bonneville shoreline that are consistent with or that cite Gilbert's (1890) interpretations. In the literature I discovered that no evidence for prolonged overflow has ever been presented, and that the presumed period of overflow has never been dated (Scott and others, 1983, did not give the locations of "the 10- to 20-m-wide wave-cut benches that were locally cut in bedrock at the Bonneville shoreline"— all benches I have seen at the Bonneville shoreline are constructional [depositional]).

Since Gilbert (1890), depictions of the end of the transgressive phase and the initiation of the Bonneville flood have varied. Here are a few published accounts from the literature (see Oviatt and Jewell, 2016, for additional examples): "The Bonneville shore line . . . was formed while the lake stood at the level of overflow . . ." (Boutwell, 1933, p. 36). "Here [at the Bonneville shoreline] it [Lake Bonneville] came to a halt and remained stationary for a very long time, long enough, indeed, to construct a terrace much larger than it had done at any of the lower levels" (Pack, 1939, p. 31). "The well-developed shore features throughout the Bonneville Basin at the highest level of the lake seem to require that the highest lake was maintained at constant level by outflow" (Williams, 1952). ". . . a level later controlled by the height of resistant bedrock in Red Rock Pass . . . The true height of overflow is not determinable, but it could have been 100 feet above the Bonneville shoreline . . ." (Malde, 1968, p. 11). "The lake briefly overflowed (probably less than 500 yr) near Red Rock Pass, ID, as the Bonneville shoreline formed . . ." (Oviatt and Miller, 1997, p. 349).

## PROCESSES OF FORMATION

At the CRONUS-Earth Project site (Cosmic-Ray Produced Nuclide Systematics on Earth) in the Promontory Mountains (figure 1; Lifton and others, 2015), a tremendous amount of quartzite bedrock was eroded during the late transgressive phase of Lake Bonneville. Many sites in the basin have similar geomorphology, but I discuss this one here because it has been well described in the literature (figure 15; Lifton and others, 2015). At this site the ground surface below the "sea" cliff, along line A-A' but not necessarily in the adjacent valleys, is a wave-cut erosional surface on quartzite bedrock. An abrasion platform with a very low lake-ward gradient, which would have been produced by wave erosion if the lake had remained at a nearly constant level for a prolonged period, is not present. The erosional surface was produced by waves eroding the quartzite as the lake

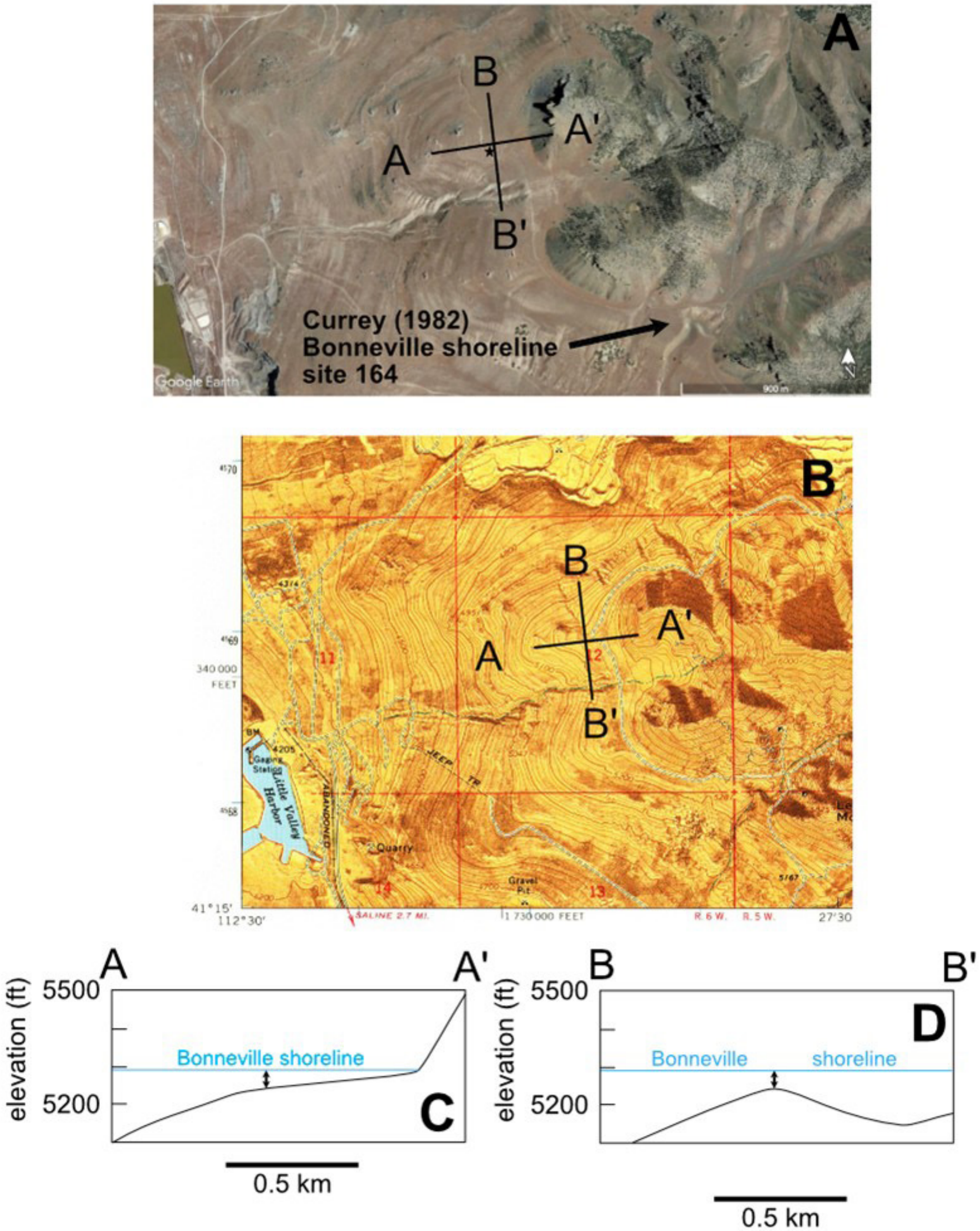

Figure 15. Information about the CRONUS site in the Promontory Mountains (near 41.264° N. latitude, 112.473° W. longitude), where a tremendous volume of quartzite bedrock (Cambrian Tintic Quartzite) was eroded during the late transgressive phase of Lake Bonneville (Lifton and others, 2015). (A) Google Earth image of the site area (map data ©2020 Google). The elevation of the barrier at Currey (1982) site 164 is 1614 m (5295 ft). (B) Same area shown on U.S.G.S. 7.5-minute Pokes Point topographic map (for scale, the red lines mark U.S. Land-Survey sections of 1 mi$^2$; contour interval = 20 ft). (C) Topographic profile along line A-A', drawn using contours in map B. (D) Topographic profile along line B-B', drawn using contours in map B. The two profiles cross at the location marked by the arrows. At that location water depth would have been about 17 m at the time the lake occupied the Bonneville shoreline. The eroded surface along profile A-A' appears, from an appropriate vantage point, to be a wave-cut platform, but its slope is too great to have formed while the lake maintained a constant level during a prolonged period of overflow.

generally rose over time to multiple contiguous levels.

Topographic profiles at the CRONUS site (figure 15, A-A', B-B') intersect on the erosional surface at an elevation of about 1597 m (about 5240 ft). The Bonneville shoreline has an elevation of about 1614 m near the CRONUS site (Currey, 1982, site number 164; Lifton and others, 2015) (this elevation estimate ignores the difference between still-water level and the level of the geomorphic expression of that level; the geomorphic ["paleo-shoreline"] evidence could be 2 to 3 m higher than the still-water level, but that difference is rarely obvious or measurable in late-Pleistocene cases [Atwood and others, 2016]). So, the water depth on the erosional surface where the two profile lines intersect was about 17 m, which is too great for significant (if any) wave-caused abrasion of the quartzite bedrock. It took approximately 1300 years for Lake Bonneville to transgress the last 17 m to its highest level — this estimate is based on a long-term transgressive rate of 13 m/1000 years (figure 2), but if the transgressive rate slowed during this time interval the amount of time it took the lake to transgress the last 17 m would have been longer than about 1300 years.

The observations at the Promontory CRONUS site, plus other observations of the geomorphology of the Bonneville and transgressive-phase shorelines, indicate that Lake Bonneville did not maintain a near-constant level for a prolonged period of time during the formation of any shoreline (except for the Provo shoreline, which is not discussed in this paper). Instead, all field observations are consistent with the interpretation that the Bonneville shoreline formed as part of an evolutionary sequence (i.e., as part of a sequence of incremental changes over a long period) — the Bonneville shoreline marks the highest level attained by the transgressing lake (figures 2, 12, and 16). If the overflow threshold, which was the low point on the basin divide (i.e., the low point on the crest of the Marsh Creek alluvial fan), had been higher, the Bonneville shoreline would have been higher. If the threshold had been lower, the Bonneville shoreline would have been lower. As Gilbert stated in 1890 (p. 171):

> ". . . the height of the Bonneville shore-line was determined in a certain sense by overflow, since a discharge limited the rise of the water; but the carving of the shore was essentially completed before the discharge; and as soon as that began, the water level fell."

Observations described above are consistent with the interpretation that the Bonneville shoreline represents the highest level attained by Lake Bonneville, and that the shoreline is conspicuous because it marks the boundary between lacustrine-dominated landforms below and fluvial-dominated landforms above (as noted by Gilbert in 1890). Some important observations that are consistent with the idea that the lake continued to transgress while the Bonneville shoreline formed are the dominance of horizontal bedding in barriers and the presence of depositional platforms that from a distance look like erosional platforms. The interpretation that Lake Bonneville overflowed for a prolonged period prior to the Bonneville flood apparently originated with Gilbert himself as an unsupported assumption and then persisted for over 120 years. However, observations are consistent with the interpretation that the Bonneville shoreline represents only a moment in time at the end of the transgressive phase of the Bonneville lake cycle, consistent with Gilbert's 1890 interpretation.

I have not found a publication of Gilbert's in which he defended his 1890 view. He passed away in 1918 and published many insightful papers and books on geology in the 28 years after the monograph on Lake Bonneville was released (Yochelson, 1980). If Gilbert did publish something related to his understanding of how the Bonneville shoreline developed, other than the 1890 monograph, it has not been recognized by the researchers who came after him.

## CONCLUSIONS

G.K. Gilbert was an amazing observer and scientist. Although he made a few mistakes in his career as a geologist, his 1890 interpretation of the history of the Bonneville shoreline was not one of them. We should recognize that Gilbert's (1890) interpretation of the Bonneville shoreline was correct and abandon the idea of prolonged overflow prior to the Bonneville flood.

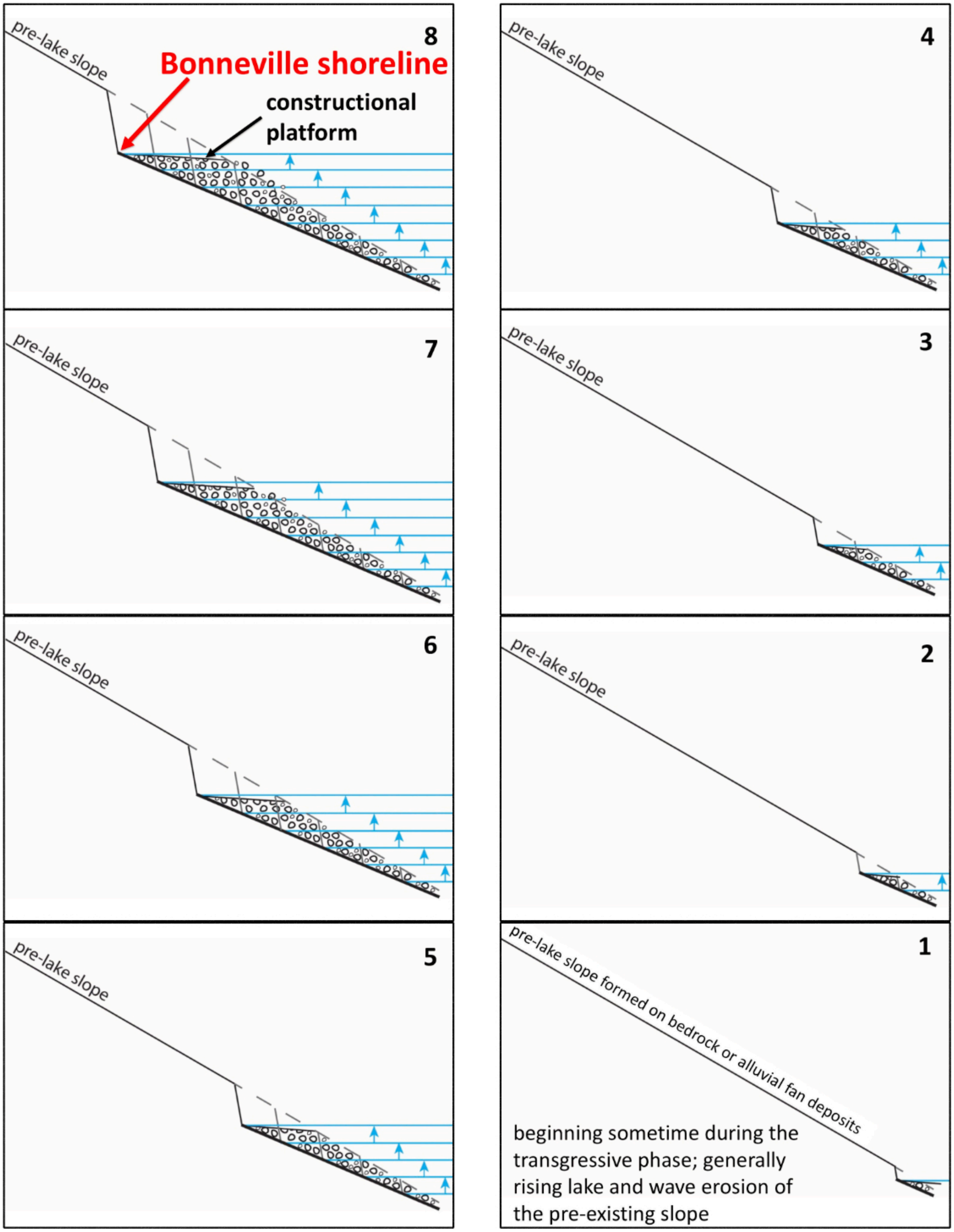

Figure 16. Schematic diagrams showing the evolution of the highest shoreline of Lake Bonneville, from time 1 through time 8. Blue arrows and blue lines show the long-term rise of the lake during the transgressive phase (probable multiple fluctuations and oscillations of lake level in the hydrographically closed basin are not shown).

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## REFERENCES

Amidon, W.H., and Farley, K.A., 2011, Cosmogenic $^3$He production rates in apatite, zircon and pyroxene inferred from Bonneville flood erosional surfaces: Quaternary Geochronology, v. 6, p. 10–21.

Atwood, G., Wambeam, T.J., and Anderson, N.J., 2016, The present as key to the past—paleoshoreline correlation insights from Great Salt Lake, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20, Elsevier, p. 1–27.

Bills, B.G., Wambeam, T.J., and Currey, D.R., 2002, Geodynamics of Lake Bonneville, *in* Gwynn, J.W, editor, Great Salt Lake—an overview of change: Utah Geological Survey, Utah Department of Natural Resources Special Publication, p. 7–32.

Boutwell, J.M., 1933, Excursion 1 — Wasatch Front, *in* Boutwell, J.M., editor, The Salt Lake region: International Geological Congress, XVI session United States, Guidebook 17—Excursion C-1, Government Printing Office, Washington, D.C., p. 32–45.

Burr, T.N., and Currey, D.R., 1988, The Stockton Bar, *in* Machette, M.N. editor, In the Footsteps of G.K. Gilbert – Lake Bonneville and Neotectonics of the eastern Basin and Range Province: Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 66–73.

Chan, M.A., Currey, D.R., Dion, A., and Godsey, H.S., 2003, Geoantiquities in the urban landscape—Earth history records in the cities, *in* Heiken, G., Fakundyiny, R., and Sutter, J., editors, Earth science in the cities—a reader: American Geophysical Union (AGU) Monograph, p. 21–42.

Chan, M.A., and Godsey, H.S., 2016, Lake Bonneville geosites in the urban landscape—potential loss of geological heritage, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20: Amsterdam, Netherland, Elsevier, p. 617-633.

Chen, C.Y., and Maloof, A.C., 2017, Revisiting the deformed high shoreline of Lake Bonneville: Quaternary Science Reviews, v. 159, p. 169–189.

Crittenden, M.D., 1963, New data on the isostatic deformation of Lake Bonneville: U.S. Geological Survey Professional Paper 454-E, p. E1–E31.

Currey, D.R., 1982, Lake Bonneville—selected features of relevance to neotectonic analysis: U.S. Geological Survey Open-File Report 82-1070, 31 p.

Currey, D.R., and Oviatt, C.G., 1985, Durations, average rates, and probable causes of Lake Bonneville expansions, stillstands, and contractions during the last deep lake cycle, 32 to 10,000 years ago, *in* Kay, P.A., and Diaz, H.F., editors, Problems of and prospects for predicting Great Salt Lake levels: Salt Lake City, University of Utah Center for Public Affairs and Administration, p. 9–24.

Davis, W.M., 1883, Lake Bonneville: Science, v. I, no. 20, p. 570.

Davis, W.M., 1892, The ancient shore-lines of Lake Bonneville: Goldthwaite's Geographical Magazine, v. 3, no. 1, p. 1–5.

Freeze, R.A., and Cherry, J.A., 1979, Groundwater: Englewood Cliffs, New Jersey, Prentice-Hall, Inc., 604 p.

Galvin, C.J., Jr., 1973, A gross longshore transport rate formula: Coastal Engineering 1972, p. 953–970.

Gilbert, G.K., 1874, Preliminary geological report, *in* Wheeler, G.M., Progress-report upon geographical and geological explorations and surveys west of the one hundredth meridian in 1872, appendix D: U.S. Government Printing Office, Washington, D.C., p. 48–50.

Gilbert, G.K., 1875, Glacial epoch, *in* Wheeler, G.M., Report upon geographical and geological explorations and surveys west of the one hundredth meridian, Volume III, Geology part I, Report on the geology of portions of Nevada, Utah, California, and Arizona, examined in the years 1871 and 1872: U.S. Government Printing Office, Washington, D.C., p. 86–104.

Gilbert, G.K., 1885, The topographic features of lake shores, *in* Powell, J.W., director, Fifth annual report of the United States Geological Survey to the Secretary of the Interior 1883-'84: Government Printing Office, Washington, D.C., p. 75–123.

Gilbert, G.K., 1886, The inculcation of scientific method by example, with an illustration drawn from the Quaternary geology of Utah: American Journal of Science, v. 31, no. 184, 284 p.

Gilbert, G.K., 1890, Lake Bonneville: U.S. Geological Survey Monograph 1, 438 p.

Holmes, W.F., and Thiros, S.A., 1990, Ground-water hydrology of Pahvant Valley and adjacent areas, Utah: State of Utah, Department of Natural Resources Technical Publication No. 98, 64 p.

Hunt, C.B., 1980, G.K. Gilbert's Lake Bonneville studies, *in* Yochelson, E.L., editor, The scientific ideas of G.K. Gilbert—an assessment on the occasion of the centennial of the United States Geological Survey (1879–1979): Geological Society of America Special Paper 183, p. 45–59.

Hunt, C.B., editor, 1982, Pleistocene Lake Bonneville, ancestral Great Salt Lake, as described in the notebooks of G.K. Gilbert, 1875–1880: Brigham Young University Geology Studies, v. 29, pt. 1, 225 p.

Ibarra, D.E., Oster, J.L., Winnick, M.J., Caves Rugenstein, J.K., Bryne, M.P., and Chamberlain, C.P., 2018, Warm and cold wet states in the western United States during the Pliocene-Pleistocene: Geology, v. 46, p. 355–358.

Janecke, S.U., and Oaks, R.Q., Jr., 2011, New insights into the outlet conditions of late Pleistocene Lake Bonneville, southeastern Idaho, USA: Geosphere, v. 7, no. 6, p. 1369–1391.

Johnson, J.W., 1956, Dynamics of nearshore sediment movement: American Association of Petroleum Geologists Bulletin, v. 40, p. 2211–2232.

Laabs, B.J., Oviatt, C.G., and Jewell, P.W., 2019, Cosmogenic $^{10}$Be exposure dating of erosional landforms of the Provo shoreline, Lake Bonneville basin [abs.]: Geological Society of America Abstracts with Programs, v. 51, no. 5, doi:10.1130/abs/2019AM-337212.

Lerback, J.C., Hynek, S.A., Bowen, B.B., Bradbury, C.D., Solomon, D.K., and Fernandez, D.P., 2019, Springwater provenance and flowpath evaluation in Blue Lake, Bonneville basin, Utah: Chemical Geology, v. 529 [https://doi.org/10.1016/j.chemgeo.2019.119280.

Lifton, N., Caffee, M., Finkel, R., Marrero, S., Nishiizumi, K., Phillips, F.M., Goehring, B., Gosse, J., Stone, J., Schaefer, J., Theriault, B., Jull, A.J., and Fifield, K., 2015, In situ cosmogenic nuclide production rate calibration for the CRONUS-Earth project from Lake Bonneville, Utah, shoreline features: Quaternary Geochronology, v. 26, p. 56–69.

Malde, H.E., 1968, The catastrophic late Pleistocene Bonneville flood in the Snake River Plain, Idaho: U.S. Geological Survey Professional Paper 596, 52 p.

Miller, D.M., 2016, Chapter 7, The Provo shoreline of Lake Bonneville, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20, Amsterdam, Netherlands, Elsevier, p. 127–144.

Miller, D.M., Oviatt, C.G., and McGeehin, J.P., 2013, Stratigraphy and chronology of Provo shoreline deposits and lake-level implications, late Pleistocene Lake Bonneville, eastern Great Basin, USA: Boreas, v. 42, p. 342–361.

Nelson, D.T., and Jewell, P.W., 2015, Transgressive stratigraphic record and possible oscillations of late Pleistocene Lake Bonneville, northern Hogup Mountains, Utah, U.S.A.: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 432, p. 58–76.

Nelson, M.E., and Fuchs, W.E., 1987, Geology of a Quaternary travertine deposit, central Utah, *in* Kopp, R.S., and Cohenour, R.E., editors, Cenozoic geology of western Utah—sites for precious metal and hydrocarbon accumulations: Utah Geological Association Publication 16, p. 351–365.

O'Connor, J., 1993, Hydrology, hydraulics, and geomorphology of the Bonneville flood: Geological Society of America Special Paper 274, 83 p.

O'Connor, J., 2016, Chapter 6, The Bonneville flood—a veritable débâcle, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20, Amsterdam, Netherlands, Elsevier, p. 105–126.

Oviatt, C.G., 1991, Quaternary geology of the Black Rock Desert, Millard County, Utah: Utah Geological and Mineral Survey Special Studies 73, 23 p.

Oviatt, C.G., 1997, Lake Bonneville fluctuations and global climate change: Geology, v. 25, p. 155–158.

Oviatt, C.G., 2015, Chronology of Lake Bonneville, 30,000 to 10,000 yr B.P.: Quaternary Science Reviews, v. 110, p. 166–171.

Oviatt, C.G., and Jewell, P.W., 2016, The Bonneville shoreline—reconsidering Gilbert's interpretation, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20: Amsterdam, Netherlands, Elsevier, p. 88–104.

Oviatt, C.G., Currey, D.R., and Miller, D.M., 1990, Age and paleoclimatic significance of the Stansbury shoreline of Lake Bonneville, northeastern Great Basin: Quaternary Research, v. 33, p. 291–305.

Oviatt, C.G., and Miller, D.M., 1997, New explorations along the northern shores of Lake Bonneville, *in* Link, P.K., and Kowallis, B.J., editors, Mesozoic to recent geology of Utah: Brigham Young Geology Studies, v. 42, pt. 2, p. 345–371.

Oviatt, C.G., and Nash, W.P., 1989, Basaltic volcanic ash and volcanic eruptions in the Bonneville basin, Utah: Geological Society of America Bulletin, v. 101, p. 292–303.

Oviatt, C.G., and Shroder, J.F., Jr., editors, 2016, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20, Amsterdam, Netherlands, Elsevier, 659 p.

Pack, F.J., 1939, Lake Bonneville—a popular treatise dealing with the history and physical aspects of Lake Bonneville: Bulletin of the University of Utah, v. 30, no. 4, 112 p.

Pyne, S.J., 1980, Grove Karl Gilbert—a great engine of research: Austin and London, University of Texas Press, 306 p.

Schide, K.H., Jewell, P.W., Oviatt, C.G., Jol, H.M., and Larsen, C.F., 2018, Transgressive-phase barriers as indicators of basin-wide lake-level changes in late Pleistocene Lake Bonneville, Utah, USA: Geomorphology, v. 318, p. 390–403.

Schoonees, J.S., 2000, Annual variation in the net longshore sediment transport rate: Coastal Engineering, v. 40, p. 141–160.

Scott, W.E., 1988, Transgressive and high-shore deposits of the Bonneville lake cycle near North Salt Lake, Utah: Utah Geological and Mineral Survey Miscellaneous Publication 88-1, p. 38–42.

Scott, W.E., McCoy, W.D., Shroba, R.R., and Rubin, M., 1983, Reinterpretation of the exposed record of the last two cycles of Lake Bonneville, western United States: Quaternary Research, v. 20, p. 261–285.

Semeniuk, V., Searle, D.J., and Woods, P.J., 1988, The sedimentology and stratigraphy of a cuspate foreland, southwestern Australia: Journal of Coastal Research, v. 4, no. 4, p. 551–564.

Shroder, J.F., Cornwell, K., Oviatt, C.G., and Lowndes, T.C., 2016, Landslides, alluvial fans, and dam failure at Red Rock Pass—the outlet of Lake Bonneville, *in* Oviatt, C.G., and Shroder, J.F., Jr., editors, Lake Bonneville—a scientific update: Developments in Earth Surface Processes 20, Amsterdam, Netherlands, Elsevier, p. 75–87.

Smith, D.G., Simpson, C.J., Jol, H.M., Meyers, R.A., and Currey, D.R., 2003, GPR stratigraphy used to infer transgressive deposition of spits and a barrier, Lake Bonneville, Stockton, Utah, USA, *in* Bristow, C.S., and Jol, H.M., editors, Ground penetrating radar in sediments: London, Geological Society Special Publication 211, p. 79–86.

Street-Perrott, E.A., and Harrison, S.P., 1985, Lake levels and climate reconstruction, *in* Hecht, A.D., editor, Paleoclimate analysis and modeling: New York, Wiley, p. 291–340.

Wambeam, T.J., 2001, Modeling Lake Bonneville basin morphometry using digital elevation models: Salt Lake City, University of Utah, M.S. thesis, 75 p.

Williams, J.S., 1952, Red Rock Pass, outlet of Lake Bonneville: Geological Society of America Bulletin, v. 63, no. 12, p. 1375.

Yochelson, E.L., editor, 1980, The scientific ideas of G.K. Gilbert—an assessment on the occasion of the centennial of the United States Geological Survey (1879–1979): Geological Society of America Special Paper 183, 148 p.