Research Article

Lake Bonneville and the Wasatch Fault – new theories and new paradigms yield insights into present-day hazards in other regions of the world

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Three new theories challenge the assumptions underlying 150 years of research regarding Lake Bonneville and extend and redefine the history of this late-Pleistocene/early-Holocene lake. These new theories have relevance to current-day hazards in many areas of the globe and are important to our understanding of the climate of the western United States. The lake's level history and shorelines have presented a confusing array of conflicting data, which has universally and incorrectly been attributed to abrupt and temporary climate oscillations. The Earthquake-induced Surging Theory explains misunderstood lake features, extends the lake level data back to 40kya, and explains the Bonneville Flood, confirming a 17.4kya (cal) date for that event. The Isostatic Rebound Pop Seiche Theory explains the "Intermediate Shorelines" first identified by G.K. Gilbert with a shocking twist regarding timing. This theory teaches us something of importance regarding glacial lakes forming today. The Bear River Exclusion Theory explains the anomalously rapid fall from the Provo Level and resolves the early/late Provo Level controversy. This last theory is going to be important for addressing the future of the Great Salt Lake.

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Key Points:

- Three new theories redefine the history and timeline of Pleistocene Lake Bonneville and its relationship with the Wasatch Fault.
- The Earthquake-induced Surging Theory explains misunderstood lake features, extends the lake-level data back to 40kya, and explains the Bonneville Flood.
- The Isostatic Rebound Pop Seiche Theory explains how G.K. Gilbert's "Intermediate Shorelines" were formed and presents a surprising twist regarding timing.

- The Bear River Exclusion Theory explains the anomalously rapid fall from the Provo Level and resolves the early/late Provo Level controversy.
- The Bear River Exclusion Theory has direct relevance to current discussions concerning the survival of the Great Salt Lake.
- The new theories presented foreshadow current-day hazards in the fields of tsunami, isostatic rebound, and climate.
- Answers are provided to questions first posed by G. K. Gilbert, 130 years ago.

Keywords: Lake Bonneville, Wasatch Fault, Isostatic Rebound, Tsunami, Great Basin, Heinrich Event.

1. Introduction

Lake Bonneville was a large, late-Pleistocene lake with the eastern edge bordering the Wasatch Fault in the Great Basin of the western United States. (Figure 1)

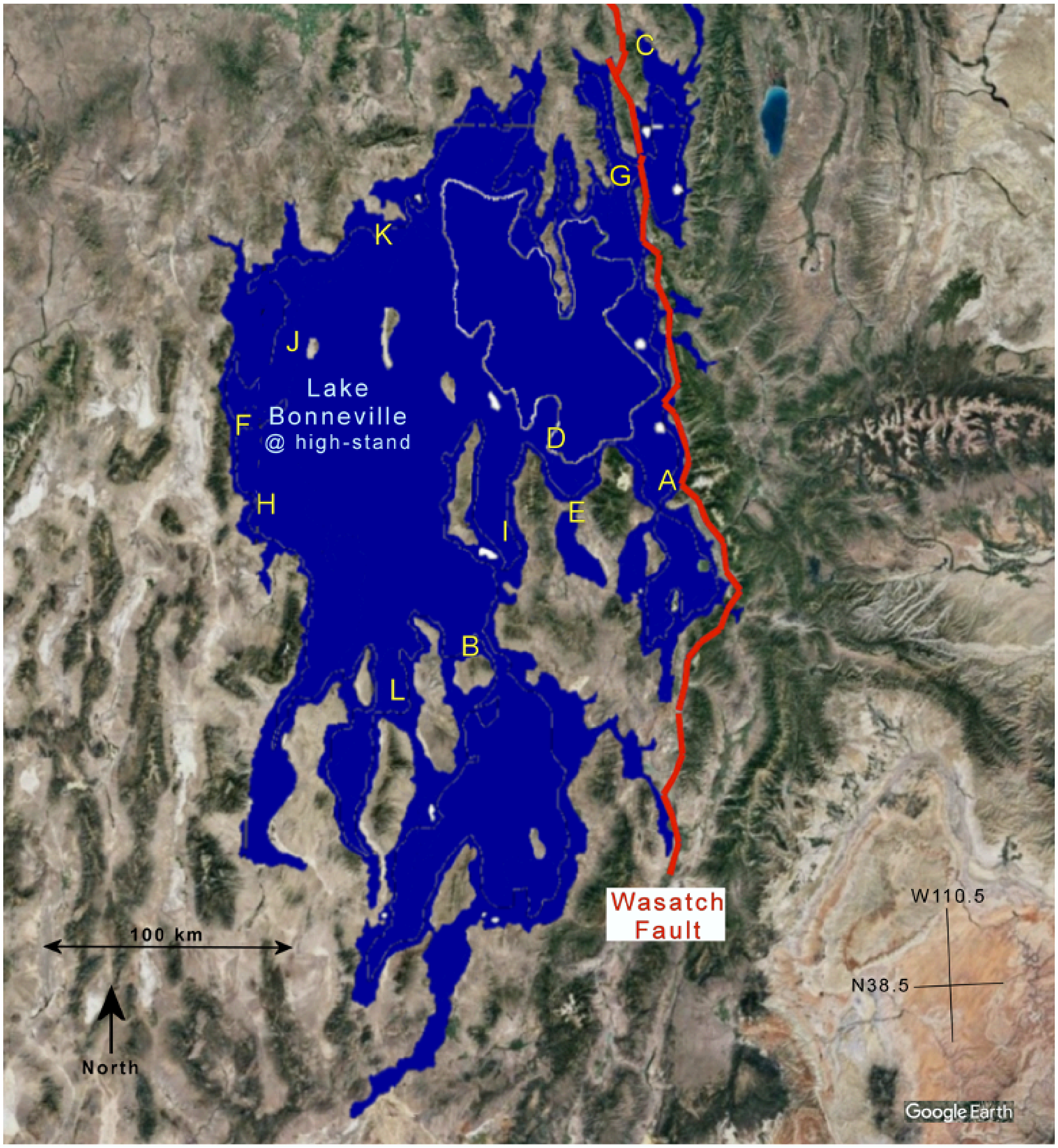

Figure 1. Lake Bonneville and the Wasatch Fault.

Legend:

A: Little Cottonwood Canyon, Wasatch Mountains

B: Keg Mountain

C: Lake Bonneville outflow. Marsh Creek alluvial fan. Zenda, Idaho

D: Stansbury Island

E: Stockton Bar and Spit

F: Ola Railroad Cut

G: Cutler Narrows

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H: Blue Lake, Benson coreI: Skull Valley

J: Pilot Valley

K: Matlin Basin

L: disrupted seiche bars

The Lake Bonneville shorelines and sediments have been the subject of detailed studies for 150 years. G. K. Gilbert started this effort with the Wheeler Survey in 1871. His work was published in 1890 as Lake Bonneville, USGS Nomograph 1 (Gilbert, 1890). Gilbert recognized that two major shorelines, Bonneville and Provo, corresponded with outflow levels of the lake, but the Stansbury shoreline did not. This presented the question of why this level should have an established shoreline. In a 1957 article, Armand Eardley referred to this as the "Stansbury problem" and he was the first to suggest that this might be the result of a climate fluctuation (Eardley, et al.).

A widely referenced timeline of Lake Bonneville was produced by Dr. Charles Oviatt (Oviatt, Currey, Miller, 1990). His timeline modified earlier efforts by others and has been the basis for numerous versions since. (Figure 2) Key features of this timeline are the history of dramatic, short-term fluctuations in the lake level during the lake's rise towards highstand. He and others attribute these oscillations to climate events and the effort to reconcile these oscillations with global climate factors has been a theme of numerous peer-reviewed papers related to the Bonneville basin climate.

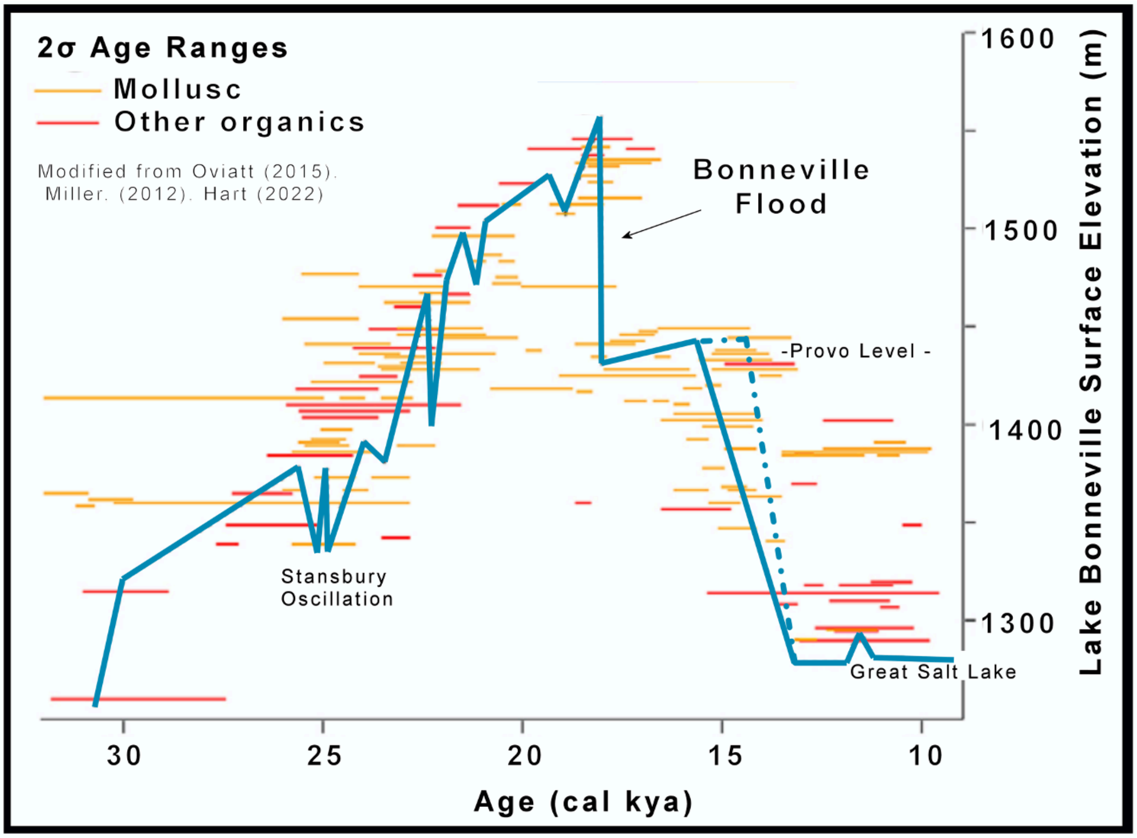

Figure 2. Example of a Lake Bonneville Hydrograph based on the well-accepted climate-oscillation theory. From Hart (2022) with the time axis flipped, modified from Oviatt (2015), Miller (2012). This timeline shows a rapid rise at around 31kya. It features the assumed climate-based, double dip of the Stansbury Oscillation, as well as the oscillations assumed to have formed the "intermediate shorelines" first identified by G.K. Gilbert. This timeline is based on the theory that Lake Bonneville overtopped and immediately failed the Zenda threshold causing the Bonneville Flood. The Provo level is shown as rising during that period and two possible interpretations of the data are indicated, followed by a precipitous fall from that level to a very stable Great Salt Lake level, with the exception of the Gilbert episode. The ^{14}C dating of organic materials provides a confusing picture.

An issue common to all Lake Bonneville sediment dating studies which has consistently perplexed researchers has been the distribution of the results (Hart, et al., 2022). Researchers have been frequently faced with 'date reversals' in the sediment chronology. Layered on this are the error ranges in the samples and the perennial struggle with the possibility of radiocarbon reservoir effects.

A heavily cited paper, by Benson, et al. (2011), studied sediment cores from the Blue Lake marsh region at the western edge of the Bonneville Basin. To compare Lake Bonneville records with global climate records, the team used patterns of inclination and declination variability to synchronize the timescales. With that, they were able to overlay Dansgaard-Oeschger and Heinrich events on timelines of the GISP2 $\delta^{18}O$ record and the

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Bonneville core Calcite, TIC, and $\delta^{18}O$ records. They reported a “possible correlation” between DO events in the Greenland ice core data (GISP2 $\delta^{18}O$) and the Bonneville record; however, when the curves from the two locations are superimposed, the correlation is not apparent, and no statistical correlation was offered. The identified Heinrich events do tend to consistently overlap some of the spikes in total inorganic carbon (TIC) in the sediments. TIC is commonly used as a lake-level proxy in closed systems. The theory is that a high level of evaporation from a climate shift results in a dropping lake level and an increase in the concentration of TIC in the water. The sample size of four Heinrich events is arguably small, and the timing of the TIC spikes in relation to the corresponding Heinrich event is inconsistent, but there is sufficient overlap over the 45,000-year record to warrant consideration of a link.

The Benson study of sediment cores states that the Heinrich events resulted in dry spells in the Bonneville basin which dropped the level of the lake:

> “Relatively dry periods in the BL04-4 records are associated with Heinrich events H1-H4, suggesting that either the warming that closely followed a Heinrich event increased the evaporation rate in the Bonneville Basin and (or) that the core of the polar jet stream (PJS) shifted north of the Bonneville Basin in response to massive losses of ice from the Laurentide Ice Sheet (LIS) during the Heinrich event.” (Benson, 2011, p. 3)

However, a study by McGee et al. (2018) of western lake expansions during Heinrich stadials found the opposite. They studied the level records of nine late Pleistocene lakes in the Great Basin. What they found was that the Heinrich events resulted in wetter climate conditions in the Great Basin and that the lakes in the region expanded during those periods. Their focus was climatology, and they went on to provide a detailed analysis of why and how the weather pattern shifted. The McGee study contradicts the prevailing view that the Heinrich events caused drought and dramatic level drops in Lake Bonneville.

Rhode (2016) studied the flora and fauna in the sediment record. He was able to correlate changes in the region’s biology with the fall from the Provo level and with the Gilbert episode. The study mentions the well-accepted theories of the Stansbury Oscillation and the existence of other oscillations leading to the last glacial maximum and the Bonneville Flood period but does not provide evidence of changes in flora and fauna that might support the idea that these were dramatic climate events.

The spits and bars in Lake Bonneville were first studied by G.K. Gilbert (1890). Dr. Paul Jewell (2007) studied the spit elevations, angles, and magnitudes to gain insights into climate variations. He found a strong correlation between the angles, the magnitudes, and the fetch (the length of open water in which waves can build). However, the largest spits did not follow the prevailing wind patterns and thus were interpreted as being the

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result of catabatic winds off the Canadian ice sheets during the 'climate fluctuations' identified by others. There have been several papers published based on these assumptions.

Felton, Jewell, Chan, and Currey (2006) did a survey of tufa deposits from Lake Bonneville. The tufa deposits vary in nature and chemistry. In studying the tufa deposits, they found that "tufas are prevalent on headlands and windward sides of islands that were exposed to high wave energy" and that "tufa commonly occurs at basin thresholds, where water is moving between a restricted subbasin and the main body of the lake." (Ibid, p. 338) As would be expected, they found that local chemistry was an important element; calcium had to achieve a high concentration for significant deposits to form. Others have also studied the tufa deposits, and a common theme is acceptance of the Stansbury Oscillation as representing an extremely dry period with extensive evaporation in the lake which raised the concentration of calcium and other minerals in the water (Nelson, et. al., 2005).

Climate, the size of the lake in the Bonneville basin, and snow in the Wasatch are inexorably linked. The last glacial maximum in the Wasatch was the Pinedale glaciation which coincided with the maximum of the Laurentide and Scandinavian ice sheets. At the glacial maximum, icebergs were being calved into Lake Bonneville at the mouth of Little Cottonwood Canyon in the Salt Lake Valley. The glacial till deposited in that area provides a valuable geological record since it forms a blank canvas upon which were etched events from the Wasatch Fault and Lake Bonneville over the last 22ky.

Janecke and Oaks (2011) of Utah State University have done extensive research on the Bonneville and Provo level thresholds of Lake Bonneville at the north end of Cache Valley. In a 2011 paper, they included a section titled "Did an earthquake, overland flow, or sapping, trigger the Bonneville Flood?" They hypothesized that "An earthquake on the Riverdale fault (or on some other Cache Valley fault) could have produced seiche waves that overtopped the Zenda sill with high-velocity waters of sufficient energy to destabilize that dam, to breach part of the Zenda sill, to rapidly incise the length of the dam, or to cause other damage." (Ibid, p. 1387) In a fascinating series of thought experiments, they also allow that a rapidly rising lake level might have triggered seismic activity that caused the flood, or that the flood might have caused seismic activity. They indicate that seismic activity might result in failure of the deltaic deposits of the Zenda threshold due to landslides or due to failure of sediments in the delta weakened by sapping.

Janecke and Oaks put forth an argument that there was "at least episodic overland flow from the Bonneville level", opening the door for the extended highstand argument. Reasoning that "To argue otherwise would require the unlikely coincidence of Lake Bonneville rising and falling repeatedly to within a few meters of an overflow and stabilizing there as a closed basin for a protracted period of time." (Ibid, p. 1384)

They also provide an analysis of the deposits of the Marsh Creek delta at the Zenda outflow and explain why the structure of those deposits might be able to support an extended period of Lake Bonneville outflow at highstand without substantial erosion of the channel.

In a 2020 paper, Oviatt gives an extensive argument for the case of the Zenda threshold failing quickly after being overtopped by the rising Lake Bonneville. The central point to his argument is that the prominent depositional shoreline benches of Lake Bonneville could be built up over time and did not represent an extended highstand.

In a 2020 GSA Connects presentation, I introduced a theory that the well-accepted "graben" at the mouth of Little Cottonwood Canyon in the Salt Lake Valley, Utah was instead a fissure, formed when earthquake-induced surging in Lake Bonneville shifted over 15km^2 of glacial till deposits in the area. The stable glacial till deposits shifted as large blocks sliding on the underlying lake-transgression sand layer which underwent liquefaction in the event. The point of failure was the intersection of the liquified transgression lakebed and the Wasatch Fault slip plane. The blocks shifted like puzzle pieces and the paper presented how those pieces could be resolved back into a cohesive initial state. The theory predicted fissures at multiple locations between different shifting glacial till masses and field examination proved those predictions correct. A written summary of that work was included in a post-meeting addendum provided to the GSA and that material is available on the acadamia.edu website. That work has not been peer-reviewed.

The 2020 presentation proposed that earthquake-induced, basin-wide surging caused the Bonneville Flood. In a presentation two years later at the 2022 GSA Connects conference, I expanded upon that work. This current paper adds both background and detail to what was presented at the 2022 conference and then expands on that with new findings and theories regarding Lake Bonneville.

2. The Earthquake-induced Surging-type Tsunami Theory, the Bonneville Flood, and the Stansbury Oscillation

Long-held and well-accepted theories tend to achieve axiom status. To challenge one requires compelling evidence. Accordingly, the case will be built using a broad range of features, geographically dispersed, and supported by a range of scientific disciplines. A plurality of seemingly unrelated features builds towards the singular conclusion that the major, sharp level dips were not due to climate oscillations, but instead due to seismic events. This is not to say that climate did not play the dominant role in the history of Lake Bonneville; it did. The Bonneville record is an important resource in climate studies, but some of the underlying assumptions need to evolve since scurrilous data does more harm than good.

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2.1. The Little Cottonwood Moraine Boulder Field

On the southern lateral moraine in Little Cottonwood Canyon in the Salt Lake Valley is a boulder field. (Figure 3) The base of this boulder field is about 18m above the Lake Bonneville highstand and the highest point is about 50m above the highstand. (Figure 4) The boulder field comprises rounded glacial moraine boulders inset into the moraine, and the field has undergone a gravity-separation with the smallest boulders at the top. The eastern sections of the field were harvested by builders for landscape boulders, leaving a scooped-out impression in the slope. This section shows that there was a clear boundary at a depth where the high density of boulders stopped and the moraine till started. The first impression is that it looks like a placer mining jet was used to blast into the moraine and then it was filled with boulders.

This field is not a scree slope; there is no source outcropping above. It is not a rock fall transported down the canyon by the glacier; the boulders all show evidence of being rolled by a glacier, the slope would not be as gravity separated as it is and the distribution along the face of the moraine would not have the upwards spikes. This is not an erosion feature; the shape of the scooped-out areas is wrong, but more importantly, the mass balance does not work, there are too many boulders in the scooped-out volume. Finally, this is not a collection of surface boulders rolling down to a lower point on the slope; the moraine slope is constant yet integrates the boulders into areas that are scooped out. Good examples of all the things this boulder field is not are available in the adjacent Bell(s) Canyon.

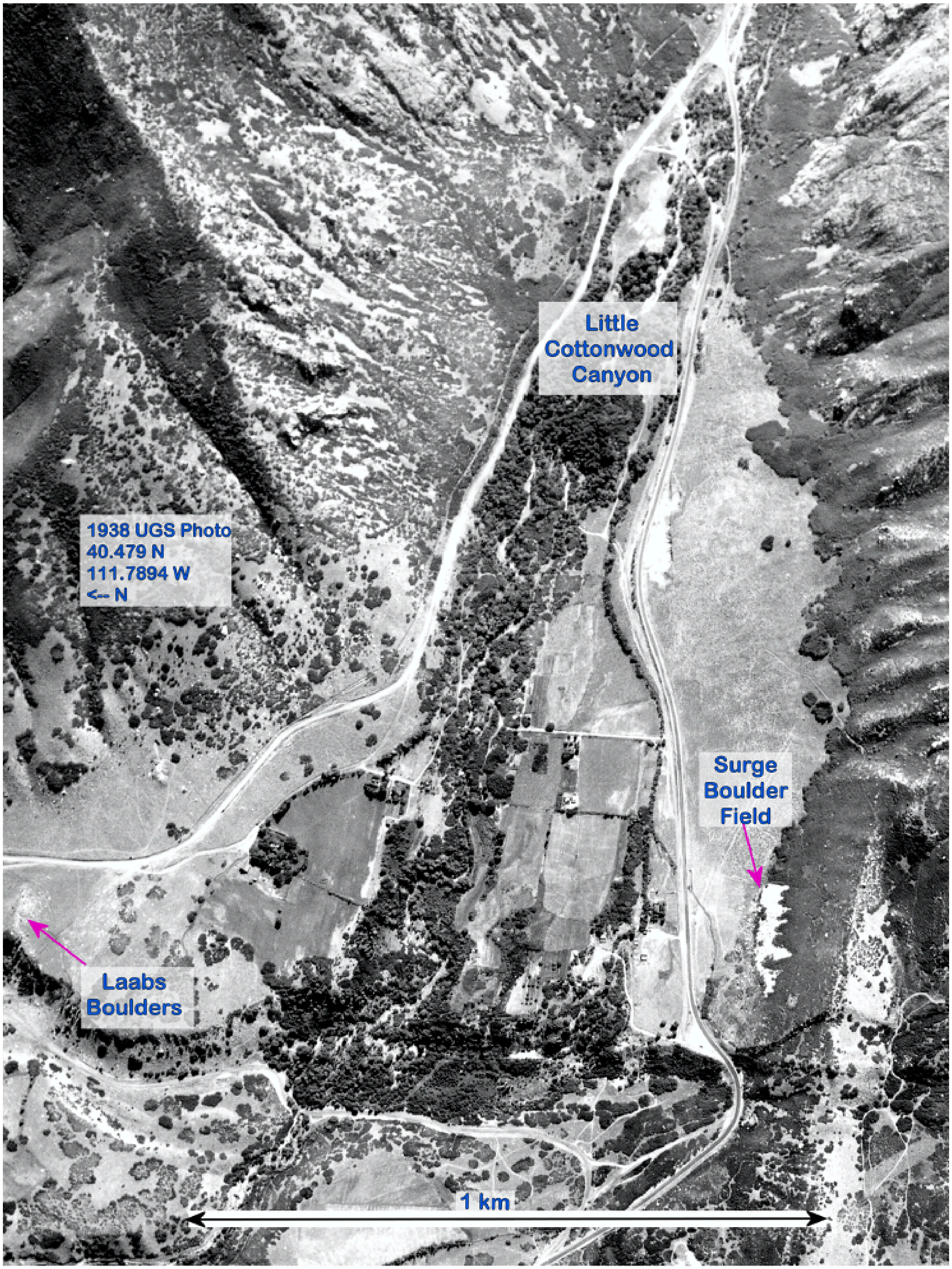

Figure 3. The mouth of Little Cottonwood Canyon in the Wasatch Mountains of Utah in a pre-development 1938 aerial photo. The scarp of the Wasatch Fault is visible running across the mount of the canyon. The southern lateral moraine is on the lower right with the tsunami deposit of boulders from the earthquake-induced surging embedded

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in the lower slopes. The boulders of the northern lateral moraine which were dated by Laabs et al. are strewn across a field in the lower left.

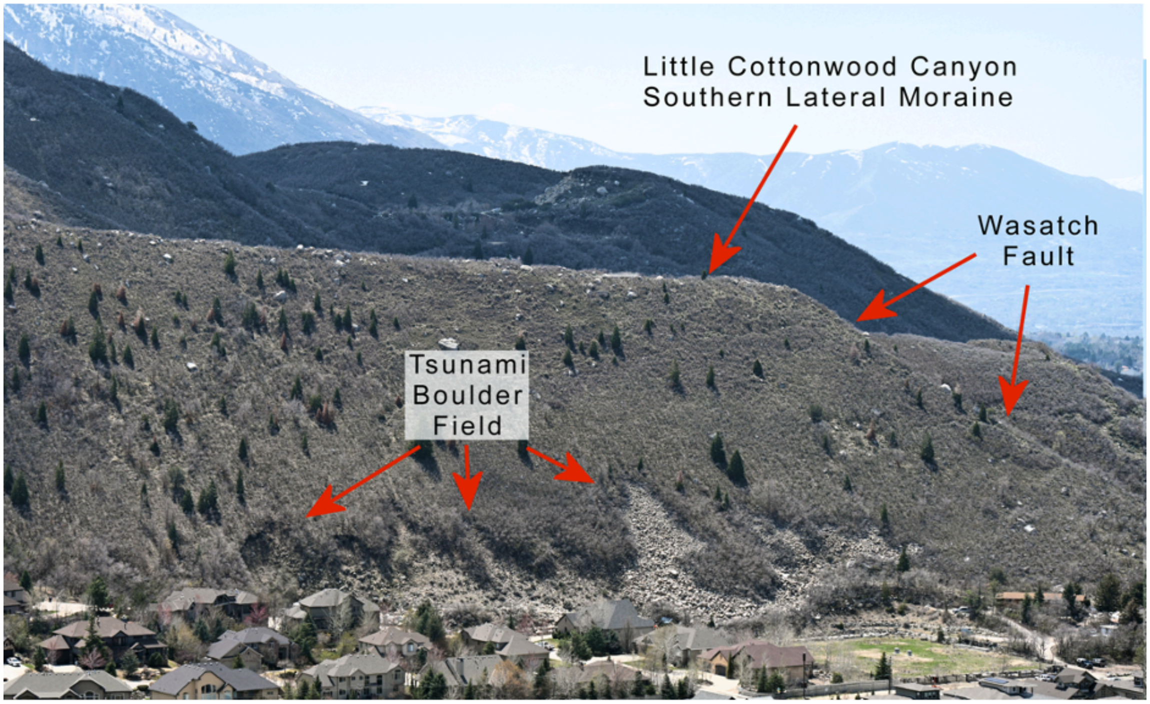

Figure 4. Looking south at the tsunami boulder deposit in the Little Cottonwood Canyon southern lateral moraine. Boulders in the eastern, up-canyon portion of the field have been removed by builders for construction and landscaping. The top of the field is 50m above the Lake Bonneville highstand. (40°34′17.52″N, 111°47′37.59″W)

The Little Cottonwood Canyon moraine boulder field is an upslope debris field from a tsunami. These types of deposits have been identified along ocean coastlines in other parts of the world. (Scheffers, 2008, 2021, Dewey, et al. 2021) G.K. Gilbert identified a series of indistinct terminal moraines at the mouth of Little Cottonwood Canyon down-canyon from this point, however, there are no boulder-wall-type terminal moraine bands remaining as might be expected. At the 2022 GSA Connects, I presented that when the Bonneville Flood event earthquake-induced surge occurred, it swept up the bands of terminal moraine boulders. The surge would have come from the open reach (also, fetch) to the northwest. Looking at the pattern of the boulder field, the most likely scenario is that at the time of the surge, the Little Cottonwood glacier had receded well off its maximum depth at the canyon mouth. (Quirk, et al., 2020) A glacial tongue would still have extended down to or close to the shore of Lake Bonneville, but the bottom section of the glacier was a crumbled field of ice. (Figure 5) When the surge hit, it lifted the lower 0.25km or more of the glacier and drove in underneath it, creating a high-pressure hydraulic blast into the moraine and carrying the terminal moraine boulders into that area. Where the

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lifted glacier cracked, streams of liquid and rocks were blasted higher into the moraine slope creating vertical spikes of deposits. The point running up the canyon where the glacier was too solid to yield is presented as a very sharp termination line of the boulder field area on the moraine face.

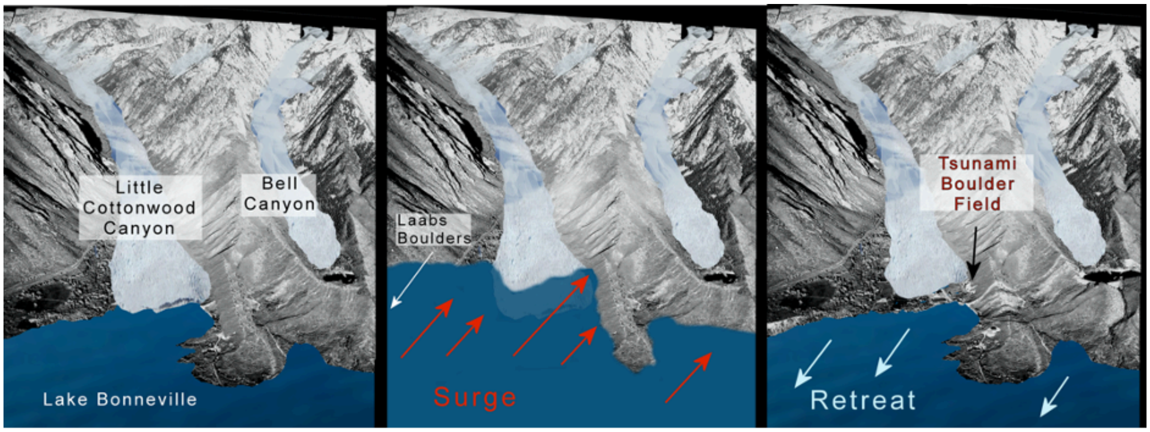

Figure 5. Rendering of the Bonneville highstand surging sequence at the mouth of Little Cottonwood Canyon based on the evidence. The glacier in the canyon had receded off its highstand but was probably still to the water's edge. The surge came from the open fetch to the northwest and the main body of the lake. The surge lifted the broken base of the glacier and drove in underneath transporting terminal moraine boulders and depositing them into the soft bank of the southern lateral moraine creating the boulder field of Figure 4.

This boulder field gives us an approximate height of the surge at this point on the Wasatch front: about 50m. The purpose of leading with the boulder field is to convey that this was a massive event; the 2011 tsunami in Japan was estimated at 40m. There is evidence on the Bell Canyon moraine, just south of the Little Cottonwood moraine, that the surface waves may have run about 100m up that slope (Location: 40.56659N, 111.79876W).

2.2. The Laabs Boulders

The southern lateral moraine at the mouth of Little Cottonwood Canyon is a very distinctive and high moraine, whereas the northern moraine is quite dispersed. On the north side, the canyon spreads out. Curiously, there are no distinct lines of moraine boulders in this area as one might expect from a glacier advancing and retreating. Instead, the moraine boulders are strewn across the hillside, labeled as the Laabs Boulders in Figure 3.

Dr. Benjamin Laabs and associates have done extensive dating of boulders in the Wasatch to track the glacial advances (Laabs, 2011, 2020, Quirk, et al., 2020). Their work is based on measuring the accumulation of terrestrial cosmogenic nuclides (TCNs) on exposed rocks. Through the years, that technology has advanced, and the assumptions refined. Two papers appeared in 2020, one by Laabs et al. and one by Quirk et al. which included Laabs as a co-author. The Quirk paper was focused just on the Wasatch, whereas the Laabs paper was

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looking at the dating throughout the western United States. The following discussion will present the Quirk paper data followed by the Laabs paper data in parenthesis. The differences are not significant since the error margins overlap. The Quirk data will be used in the figures and detailed discussions.

Of particular interest is their dating of the glacial moraine boulders on the north and south sides of the mouth of Little Cottonwood Canyon in the Salt Lake Valley. On the very tall and well-defined southern lateral moraine, the boulders were dated at 20.8kya +/-2.2 ka (20.8kya +/- 4.5 ka). That puts it in the timeframe of the Laurentide maximum. The error range on this data is over twice the typical error range from other areas they studied suggesting that multiple factors are in play at this location.

The dispersed boulders of the north side, however, were found to be deposited three thousand years later: 17.4kya +/-0.3 ka (17.3kya +/- 0.7 ka). Note the much tighter error margin on the north side data, suggesting that the deposit was the result of a single, well-defined event, in spite of the fact that these boulders are strewn across the hillside. Quirk et al. attributed this more recent date to a glacial resurgence; however, a major resurgence that could deposit boulders this high up, on the other side of a knoll and around the corner from the low point of the canyon mouth and on the sunny southern exposure side of the canyon would have left evidence high on the other side of the canyon also, which it did not.

Reinterpreting the data using the earthquake-induced surging model of this paper, what Laabs and his team identified was the date of the Bonneville Flood. The northern lateral moraine boulders the team tested are about 15-20m above the Bonneville highstand shore and would have been swept up in the maelstrom of the surge (see Figure 5). That surge would have rolled and sandblasted the glacial boulders in the area, essentially resetting the isotope timestamp on the surfaces.

The 17.4kya (17.3kya) dating of those boulders puts the surge in the same time frame as the Bonneville Flood dating by others of 17.4kya based on features in Idaho and using earlier calibrations of TCN (Janecke and Oaks, 2011). Godsey reported the end of the Bonneville highstand at 17.5kya based on a calendar equivalent of ^{14}C dating (Godsey, et al., 2005). In his work on Lake Bonneville sediments, Benson determined that the Bonneville Flood occurred before 17.0kya (Benson, et al., 2011).

There is a 'catch-22' in all of this. Cosmogenic nuclide dating requires calibration against a standard time reference of a well-documented event, and the Bonneville Flood has been used as just such a reference standard in this region. In this paper, the 17.4kya (TCN) date will be assumed the most accurate date for the Bonneville Flood, with the understanding that as the science advances, dating estimates will continue to be refined. Cause and effect relationships are more important in establishing relative dates. In this paper, TCN and ^{14}C data will be used as supporting data or placeholders with the realization that they are approximations.

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2.3. The Keg Mountain Oscillation

A very distinctive level oscillation during the Lake Bonneville highstand has been documented by several researchers (Currey and Burr, 1988, Milligan and Chan, 1998). Their work was based on the radiocarbon dating of sediments and on shoreline evidence at Keg Mountain in the southwestern region of the lake basin (see Figure 1). While the researchers agree that there was an oscillation when Lake Bonneville was at or near its highstand, the duration of the Bonneville highstand is a matter of debate.

Currey and Burr (1998) presented one scenario: when Lake Bonneville was at or near its highstand (the early Zenda threshold), the outflow inexplicably dropped by 20m to the 'late Zenda threshold', this dropped was immediately followed by a climate oscillation where over a 200 year period the level of this massive lake dropped by an additional 30m below the late Zenda threshold, only to immediately rise again over the next 200 year period back to the late Zenda threshold, where it remained for 50 years at a stable outflow before the new threshold catastrophically failed, causing the Bonneville Flood.

In my 2020 GSA presentation, I suggested that lake-wide, earthquake-induced surging caused the Bonneville Flood and that it could have been misinterpreted as a climate oscillation. In such an event, the valleys along the Wasatch Fault on the east side of the lake would drop in the fault slip. The full depth of the lake would surge eastward to equalize. Once in motion, momentum would cause the surge to overshoot the highstand on the eastern side of the basin. This overshoot would be exacerbated by the basin topology, analogous to ocean swells approaching a shore where, as the water gets shallower, the energy gets concentrated into a smaller column of water. As with an ocean tsunami, the result is short frequency waves superimposed on a very long wavelength, high amplitude surge. The surge is what creates a long-term impact on the landscape.

On the western side of the basin, the surging or sloshing would draw the lake down from the highstand shoreline by the same amount that the surge on the eastern side moves up. At Keg Mountain in the western deserts, this is evidenced by shallow water sediments being drawn down into the lake and covering deeper water sediments, basically mimicking a climate-oscillation lake level drop. As the basin sloshed back a very pronounced shoreline band or bar would be formed at the original shoreline elevation. This bar would have the same features as one formed by a massive storm or a tsunami. The bar would top out above the normal waterline and the sediments would slope shoreward. If the return surging wave was rushing up a feature such as an alluvial fan, that shoreline band would take the form of an even-sided V-bar; in contrast, a typical a cuspid-foreland V-bar would have more of a cursive shape due to prevailing winds in the area.

On the eastern side, the surge up above the highstand shoreline would capture land-based flora and fauna and then draw it back down into deeper lake sediments. This again would confuse the interpretation of the

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sediments and the use of carbon dating to establish lake levels. Date reversals in the sediments would be a common problem.

The surging in the lake would also have stirred up deep water sediments. As the lake returned to a quiescent state, these suspended solids would have settled out forming a sediment band that would mimic the passage of time. An event that took a day or less might appear as 50 years of deposits in the sediment record, such as with Currey and Burr's interpretation where they assumed the life of the Late Zenda Threshold to be about 50 years.

Significantly, the total lake level drop identified by Currey and Burr at Keg Mountain on the western side of the basin from the Bonneville highstand to the nadir of the 'climate oscillation' was 50m, which is what I found as the surge height on the eastern side of the basin at the Little Cottonwood Canyon boulder field.

The last piece of this puzzle is the transition from the early to late Zenda thresholds at the lake outlet up near Red Rock Pass. Currey and Burr assumed the transition occurred leading into the Keg Mountain Oscillation. However, if we examine the same data with the earthquake-induced surging model, a very different picture emerges as the last puzzle piece neatly fits.

The early Zenda threshold, which formed the dam holding Lake Bonneville at its highstand, was an alluvial fan formed by Marsh Creek northwest of present-day Red Rock Pass. For Lake Bonneville to be stable at its highstand and form the very distinctive benches and eroded cliffs, the material of the alluvial fan would have to be of a nature to withstand erosion from the relatively low velocity of the outflow from the lake for a period of several hundred to a thousand years (judging from the shoreline features in other areas). Janecke and Oaks, in a 2011 analysis of the Lake Bonneville outflows, provided just such an argument for how the Marsh Creek delta sediments might have provided a stable outflow and resisted erosion for an extended period of time (Janecki and Oaks, 2011).

When the earthquake occurred and the surge flowed into and up the Cache Valley, the topology of the valley (narrower and shallower as you move north) would have concentrated the surge. Because of constrictions leading into Cache Valley (Cutler Narrows) and the pinch point at Red Rock Pass, the surge may have peaked at something less than the 50m evident in other areas of the lake. But even a surge half that height would result in deep water (high hydraulic pressure at depth), rapid flow over the surface of the Marsh Creek Alluvial fan (the Zenda threshold), and result in rapid erosion. The erosion would start at the downstream (highest velocity) end of the path over the alluvial fan and eat back towards the high point (like the formation of the Niagara Gorge, but at an incredibly rapid rate through the soft deposits).

The erosion cut back through the alluvial fan to where it encountered the bedrock of the Marsh Creek Canyon ridge. At this point, the dam of the alluvial fan had been dropped by 27m (late Zenda threshold).

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In a surge event such as this, which is essentially sloshing in a basin, at some point, the water in the basin will slosh back to equilibrium near the original highstand level. Once the sloshing in the basin subsided, the solids stirred up in the surging settled out before the lake level had time to fall from the effects of the Bonneville Flood. The result was a band of lake bottom sediments that mimics evidence of a 50-year passage of time.

At the Zenda threshold, though, the damage was done; the new Zenda Threshold was now 27m below the lake level and the Bonneville Flood ensued.

2.4. The Zenda Threshold and The Bonneville Flood

Knowing the approximate surge height entering the Cache Valley, an onsite search was conducted for evidence of the Bonneville Flood surge on slopes of the Marsh Creek alluvial fan above the Bonneville highstand level at the Zenda threshold.

There is a 1km long, 6m high, horizontal step running across the face of the alluvial fan. The terrain above is smooth, and the terrain below is undulating, exactly as you would expect from a flood-disrupted landscape. (Figure 6)

Figure 6. The Marsh Creek alluvial fan in Zenda, Idaho, looking north towards the Marsh Creek Canyon. This is evidence that the earthquake-induced surging that caused the Bonneville Flood ran 30m above the Bonneville highstand in this area. The farmhouse is the reference point. Upper image: the land above the surge-affected zone indicates that prior to the flood the alluvial fan was a smooth plain. Lower image: The initial surge of the flood scoured down the surface by five meters, leaving an undulating flood landscape below a level 30m above Bonneville highstand. (42°23′6.85″N, 112° 2′33.32″W)

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The Idaho Geological Survey has identified this anomaly as the only visible section of a suspected normal fault in the area (DeVecchio, 2002). (Figure 7) However, if this were a fault, it might be expected to parallel the ridgeline above, which it does not. Instead, it runs perpendicular to the slope of the alluvial fan, a surface feature. This line is an artifact of the surge overtopping the natural dam of the alluvial fan.

From this data point, the main surge ran 30m above the Lake Bonneville highstand and was about 3km across. The initial surge very quickly focused into a 2km wide erosion channel in the alluvial fan, part of which is still visible today. After the surge receded, the flood proceeded in earnest in the erosion channel.

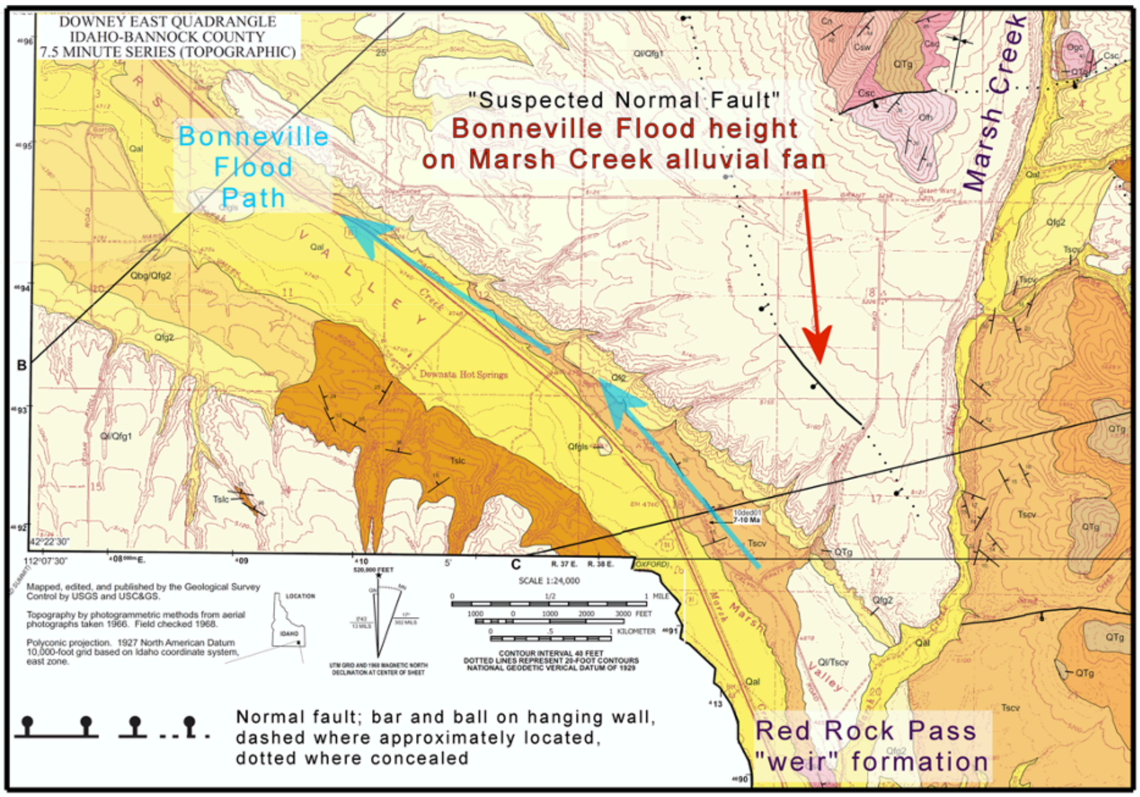

Figure 7. Section of USGS map covering the Zenda threshold area of Lake Bonneville. The Bonneville Flood scour disturbance on the Marsh Creek alluvial fan is identified as the only visible section of a "suspected normal fault" in the area. This line actually delineates the smooth plain of an alluvial fan above and the undulating flood-scoured landscape below.

The Bonneville Flood can be thought of as occurring in three, weir-controlled phases:

Phase 1 – initial surge. If we ignore the time for ramp up to the surge high point and the velocity of the surge, and we assume a profile for the undisturbed Marsh Creek alluvial fan and a pre-flood slope of the Red Rock Pass gap just to the southeast, a simple weir calculation yields a flow in the range of 0.3-0.5 million m^3/sec for the

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initial overtopping. There are two higher saddles to the east of Red Rock Pass that top out around 45m above the Bonneville highstand. There are surface features that suggest that the surge or waves from the surge may have briefly overtopped these higher saddles, but there is insufficient data to make a definitive statement on that at this time.

Phase 2 – Late Zenda Threshold tsunami-surge state. Once the 30m deep surge had overtopped the Marsh Creek Alluvial fan, this high velocity, deep flow started a catastrophic dam break scenario.

The surge was a long wavelength sloshing in the basin. So, the peak surge of 30m at the alluvial fan was transitory, but its effective time at or near the highstand might have been up to several hours long. The peak flow rate in the Bonneville Flood would most likely have been at a time that balanced the surge falling off its peak and the increasing erosion of the channel underneath permitting more flow. Ultimately, the limiting factor would have been the Red Rock Pass "weir". This is the gap between the two ridgelines leading down into Red Rock Pass. These ridges would be more difficult to erode.

J. O'Connor (2016) analyzed the flood and came up with a peak flow rate of the Bonneville Flood of 1 million m^3/s based on evidence at several locations in the flood plain and the Portneuf Valley connecting Red Rock Pass and the Snake River plain. He used multiple geographic points to verify his calculations, which greatly diminishes the chances that an assumption in one area has an overbearing impact on the result.

In my research, I did weir calculations on the various phases of the flood under various surge and erosion scenarios, I kept coming up with numbers in the same order of magnitude. However, O'Connor's calculations at Red Rock Pass are based on a Bonneville highstand level driving the flood, and mine are based on a surge of up to 30m higher. The results are similar because during the initial surge, it was overtopping an uneroded Marsh Creek obstruction, and by the time the erosion channel had fully developed the surge had subsided.

Bonneville highstand shoreline features in a cove between the Marsh Creek alluvial fan and Red Rock Pass provide evidence that the lake extended through Red Rock Pass. Pre-highstand erosion gulley features in this cove indicate that in the years just prior to the highstand, Marsh Creek was flowing south down the eastern side of the alluvial fan and through Red Rock Pass and into the Bonneville basin. With this, the slope of the Marsh Creek Alluvial fan through Red Rock Pass as well as the adjacent ridgelines can be reconstructed to form a well-shaped, pre-flood pass consistent with other landforms in the area. The Red Rock Pass weir was the limiting factor once the Marsh Creek alluvial fan failed. The initial surge wore the pass down to the Late Zenda Threshold and the peak flow occurred at that point. Even as the surge fell, the ridgeline slopes continued to be undercut and a series of landslides occurred both during and after the flood, widening the pass (Eardley, et al., 1957).

Phase 3 – Post-surge flood. With the pass 27m below the Bonneville highstand, the flood was able to proceed in earnest even after the basin sloshing from the earthquake-induced surge settled out. The basin sloshing would have settled very rapidly due to the number of dashpots in the system such as the Cache and Provo Valleys and the very dispersed western extremes of the system.

2.5. The Stansbury Oscillation

Researchers have identified another abrupt 'climate oscillation' during the Lake Bonneville transgression sometime around 25,000 years ago called the Stansbury oscillation and shoreline (Eardley, et al., 1957, Oviatt, Currey, and Miller, 1990). (See Figure 2) The widely accepted theory is that in the middle of a steady rise in lake level during the 10,000-year colder and wetter period which saw the Laurentide and other ice sheets grow, there was a brief period where the lake not only stopped rising but actually evaporated at an incredible rate, dropping 47 meters. The climate then immediately shifted to a wetter period and rose back to its previous level before immediately dropping again in another dry spike to almost the same low shoreline, whereupon the climate turned wet again and returned the lake to the pre-oscillation level, at which point Lake Bonneville continued its steady transgression rate of rise that it had before the oscillation.

The theory also presents that at the two low points, the suspended calcium in this very large freshwater lake had achieved a high enough concentration such that very distinctive tufa shoreline deposits on Stansbury Island, a mid-lake mountain range. (Figure 8)

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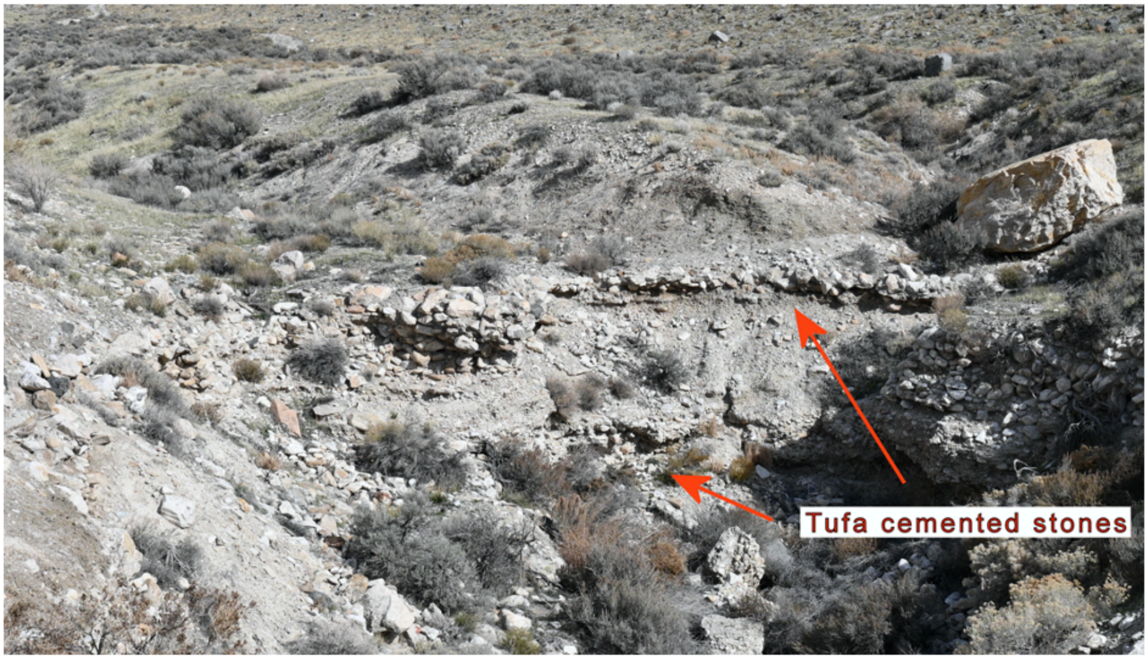

Figure 8. Stansbury event tufa deposit layers in Stansbury Island gulley. Two large bands of deposits with a degree of size sorting evident. While some stones show evidence of beach-cobble-type wear, most are run-of-the-mill hillside stones. (40°47′30.28″N, 112°31′1.07″W)

When this oscillation is revisited under the earthquake-induced surging model, previously unexplained details come into focus and a consistent picture emerges.

In the earthquake-induced basin surging (or colloquially, sloshing) event where one side of the basin drops, water would surge from one side of the basin to the other. The middle of the basin would be a node typified by high-velocity flow with minimal elevation change. The fault (east) side of the basin would see a runup and overshoot in level change due to the momentum of the slosh, such as what was evidenced in Red Rock Pass and the Little Cottonwood boulder field during the Bonneville Flood event. The other side of the basin would see a corresponding drop in level consistent with sloshing in a basin. This was also seen in the Bonneville Flood event with the Keg Mountain oscillation.

The Stansbury shoreline has been an enigma in Bonneville research, in part because in certain areas of the lake, the shorelines are very pronounced and in others, they are difficult or impossible to find. What is apparent in traveling the basin is that the shoreline is most pronounced where the surging would have created strong currents resulting in either rapid erosion or the accumulation of deposits.

In a study focused on the Stansbury ‘climate oscillation’, Oviatt, Currey and Miller (1990) included a table giving the observed Stansbury levels at various points around the lake. They found that the level changes during the

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Stansbury oscillation were different at different locations. Plotting their data on a satellite image of the region with a depiction of Lake Bonneville at the Stansbury level superimposed shows exactly what the earthquake-induced basin surging model predicts: Stansbury Island near the center of the lake is a node with minimal elevation change during the oscillation, whereas, in the western arms of the lake, the elevation variation is approximately proportional to the distance to the center. (Figure 9) The data these researchers presented is difficult to reconcile with a climate oscillation scenario but does support the theory of earthquake-induced-surging in Lake Bonneville.

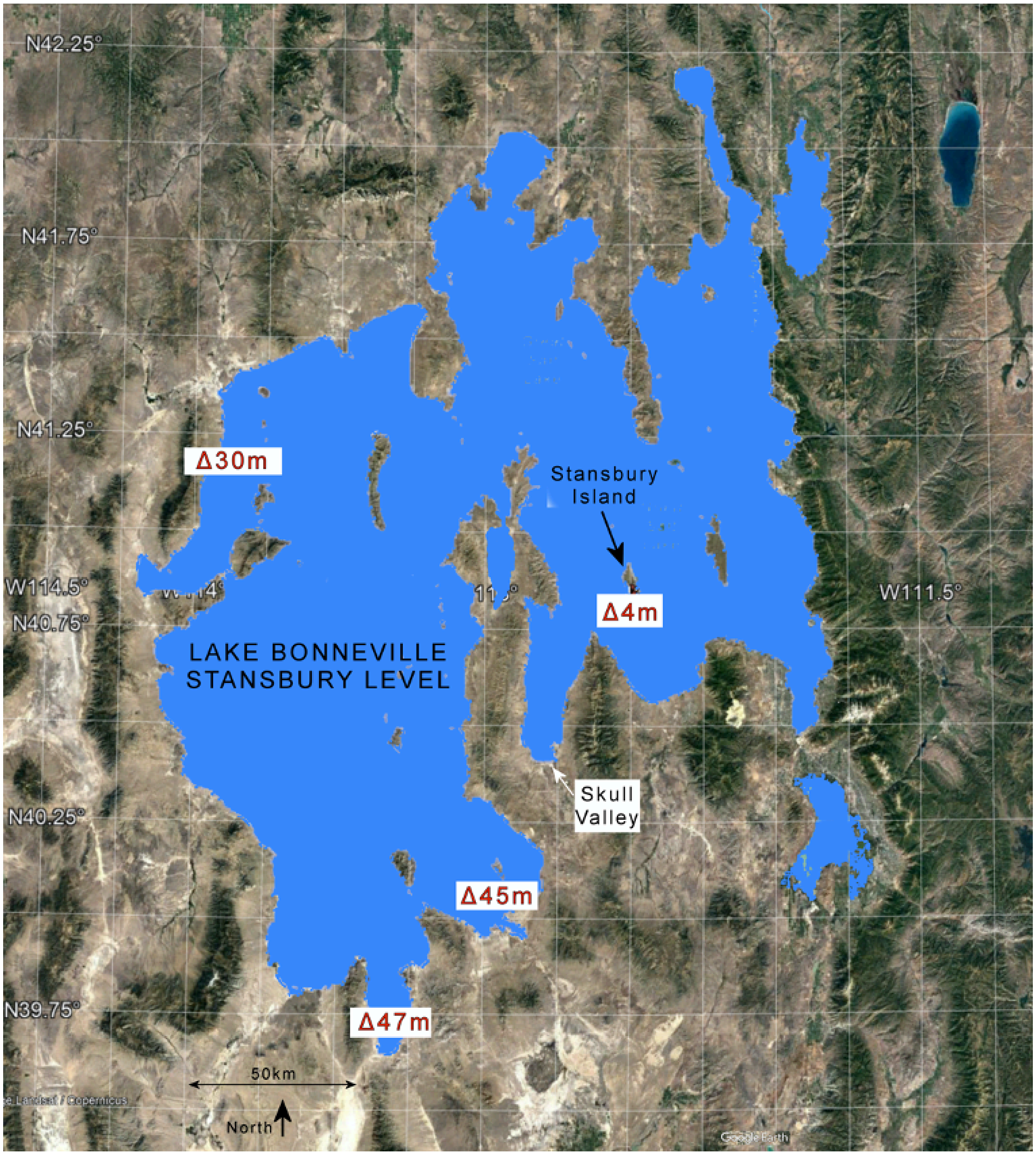

Figure 9. Stansbury oscillation shoreline variations in different parts of Lake Bonneville from Oviatt, Currey, and Miller (1990) plotted on a Google Earth™ view with Lake Bonneville at the Stansbury level superimposed. The variations in the shorelines from the Stansbury oscillation are roughly proportional from the distance to the center of the north-south axis of the lake, supporting the contention that these are from surging or sloshing in the basin with the center as a node in the oscillation rather than evidence of a lake standstill shoreline.

The Stansbury Oscillation was an earthquake-induced surging event. In the 2022 GSA presentation, I made the point that an earthquake-induced surging-type tsunami is different from an earthquake-induced shock-type

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tsunami. The first is a displacement phenomenon, which can travel at up to 80kph, the second is a shock wave that travels at 800kph. The 47-meter swing of the Stanbury event is very close to the 50-meter swing of the later Bonneville Flood/Keg Mountain event. If this were a shock-type tsunami, the depth of the water would be more of a factor, and the two events would be quite different from what occurred. The fact that the oscillation amplitudes are similar also suggests that the fault displacements in the two events were similar.

2.6. The Tufa shoreline deposits.

On Stansbury Island, in the middle of the Bonneville basin, is one of the distinctive features of the Stansbury Oscillations: thick bands of tufaglomerates (cemented beach rock deposits) separated by bands of deep lakebed sediments (see Figure 8).

These bands led researchers to believe the lake had either evaporated to a higher concentration of dissolved minerals where shoreline waves resulted in CO2 degassing and calcium compound precipitation, or that algae contributed to the calcium coming out of solution in the shore zones (Oviatt, 1987). The issue with the first of these theories is that the lake was a very large freshwater lake, so it would take a lot of evaporation to meaningfully concentrate the ions. Also, the lake supported a healthy diversity of freshwater flora and fauna before and after the Stansbury Oscillation, where a dramatic shift in chemistry would be expected to be accompanied by a die-off. Two climate oscillations spanning hundreds of years each would be a significant shock, however in a review of the available literature, no references to appropriate biodiversity shocks were found. The issue with the second theory is that algae-based tufa formation should be prevalent at many levels in the lake if it was a significant contributor and the evidence of that is missing.

High concentrations of calcium in lakebed sediments occur in areas of the lake where calcium has leached from above-lake deposits in the surrounding terrain. This is prevalent in the middle and western portions of the basin, away from the major dilution flows from the Bear, Weber, and Provo rivers and the snowmelt streams of the Wasatch. During the Stansbury level earthquake-induced-surging event, lakebed sediment would have been stirred up by the high velocity flows. At points where high-velocity flows encountered landform obstructions, turbulence would occur, and the surface of the water would become heavily aerated. The introduction of oxygen would result in carbon dioxide degassing and the rapid precipitation of calcium and other minerals, a tufa layer.

The two bands of tufa on Stansbury Island from this period are interesting. The deposit is in a gulley on the western flank of the range. At other locations where the shoreline is visible, the band appears as a single tufa shoreline. At the peak velocity of the surge in the lake center, large hillside stones caught in the surge would have been deposited into a thick bed in the gulley to be cemented together by the precipitated calcium.

A surge flow would do a natural size selection. As the surge built towards peak velocity, large stones would be carried into the gulley and deposited, but the smaller stones, gravel, and sand would be carried on, except for what might reside in interstitial spaces. As the surge slowed, the deposits would quickly change to smaller-sized materials. This size distribution is quite evident in the Stansbury gulley deposits. In the layers adjacent to the large stone layers are thinner layers of tufa gravel, suggesting that small secondary surges followed the main surges.

Tufa shoreline deposits are a distinctive feature of the lake and define a number of the shorelines at very specific locations. There have been several studies of the tufa deposits (Felton, et al., 2006, Nelson, et al., 2005, Nelson, et al. 2005b). In the 2006 Felton study, they found that the thick tufa deposits tend to be in two types of areas:

a. zones where a long fetch distance in the western reaches of the lake would result in high wave energy and
b. at subbasin thresholds.

Felton stated that tufa formation at subbasin thresholds was "because reductions of water flow when the lake level dropped may have isolated the waters of subbasins" (Ibid, p. 385), this assumes the result was an increased calcium concentration as the subbasin dried up or influx of fresh water was reduced. However, both long-reach obstructions and pinch-points between subbasins are where there would be highly turbulent and aerated flows during an earthquake-induced surging event, which would explain tufa deposits at those locations.

The Felton team also found the thick tufa deposits correlated with three primary lake levels: Stansbury, Bonneville, and Provo. The Bonneville and Provo levels were extended occupations, but the Stansbury level was not. What the three levels have in common is that they coincided with major earthquake-induced oscillations (the Provo level will be discussed later).

While tufa can be formed by several different processes, an indication of potential earthquake-induced surging is a tufa deposit layer in a sediment sequence where tufa deposits are not the norm.

2.7. The Stockton Bar and Spit

Evidence of the Bonneville Flood event surging is prevalent in shoreline features throughout the Bonneville basin.

Gilbert and others have discussed at length the bars and spits in the Bonneville record, attributing these to prevailing winds and monster storms. (Gilbert, 1890, Jewell, 2007) This needs to be re-examined. Large spits which follow potential surge flow and eddy patterns and deviate from prevailing wind patterns are probably from earthquake-induced surges.

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The Stockton bar and spit formations were first discussed by G. K. Gilbert (Figure 10). They are being discussed here because not only are they well-known and extensively studied features, but they also stand as an excellent example of the type of analysis I am proposing as lake features are reconsidered in light of the earthquake-induced surging theory.

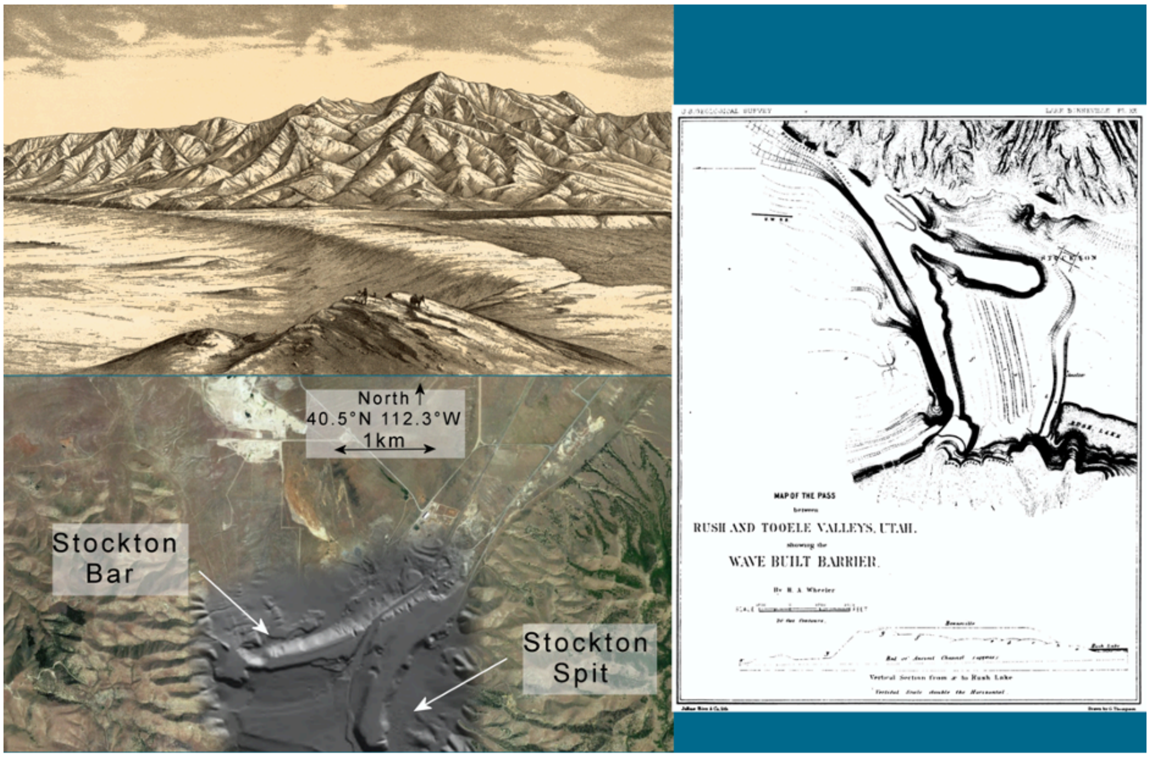

Figure 10. The Stockton Bar and Spit. Illustrations from USGS Nomograph 1. The lower image is a Lidar image embedded in a Google Earth™ view. The Stockton Bar is a lake transgression feature built up over time, while the Stockton Spit was formed in two main surges in the S17.4-Bonneville-1551 earthquake-induced surging event. (40°27′54.90″N, 112°21′46.42″W)

This paper does not dispute that the Stockton bar is a long-term lake feature built over time with obvious sediments and a top about 20m below the highstand. When the Bonneville Flood event occurred, the surging stirred up the mineral-rich sediments in the lakebed and the turbulent flow over the obstruction of the bar across the Tooele Valley aerated the mixture, creating an anomalous thick tufa layer on the top of the bar, but well below the sustained highstand level. There are a few very thin tufa layers in the lower sediments of the bar, which may be from storm events during transgression.

The 2km long Stockton spit, however, is a surge feature formed during the Keg Mountain / Bonneville Flood earthquake-induced surging event when Bonneville shoreline deposits were stripped from the west slope of the

Oquirrh Mountains and carried south over the bar.

The angle of projection of the spit off the point of land to the north is consistent with a high-velocity eddy flow stream projecting well off of the point of land in the area.

The 2km Stockton spit has a distribution of large stones along its entire length. Some near the southern tip weigh about 50 kilograms and are on the windward side, a couple of kilometers from potential sources. (Figure 11) The common explanation for such anomalies is that they have been transported by ice rafting. Ice would explain anomalies, but not the consistent pattern of deposition seen here.

Figure 11. Boulder estimated at 50kg, located on the west side of the Stockton Bar. Example of an earthquake-induced surging transported boulder. USGS geological map for reference. (40°27′25.22″N, 112°21′56.26″W)

Unlike the Stockton Bar, the Stockton Spit has no indications of sedimentation other than leeward-side Holocene aeolian deposits, suggesting single-event deposition.

Finally, the 2km Stockton spit lacks a tufa cap. Material transport was dominant during its formation and there was no aeration event afterward. The Stockton bar, however, was an existing landform and obstruction, so it ended up with a tufa cap.

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In 2003, Smith et al. used ground penetrating radar to study the Stockton spit. The data from that paper supports the concepts presented here. (Smith, et al., 2003) The Stockton bar was a pre-existing feature at the time of the surging. There were then three principal surges in the event, forming three progressive layers in the Stockton Spit complex. The second was the largest and buried the first in its core. The third was a small, high spit closer to shore formed as the surging was ramping down with smaller turbulence waves. That third spit has now been quarried out of existence, but a conversation with the quarry manager confirms that, unlike the main spit, it contained highly striated deposits typical of multiple wave deposition.

Spits and bars are common features in the Bonneville Basin. Some of the smaller ones may be storm event shorelines, however, a lot will be found to provide a record of seismic activity along the Wasatch Fault. Dr. Jewell discussed the presence of large stones at the far reaches of some spits in Lake Bonneville and suggested that these could be used as an indicator of large storm events. Identifying those stones as an anomaly was very astute, here it is just suggested that they indicate something else.

3. A 45,000-year history of multi-segment earthquakes on the Wasatch Fault and new insights into the climate record of the Great Basin and The Bear River Exclusion Theory

The study of individual earthquakes on the Wasatch Fault has been generally limited to the last 17.4ky, the post-Bonneville-Flood period. The fault scarps from prior to that are obscured by Lake Bonneville sediment (Swan, et al., 1980, McCalpin, 2002). In a 2009 paper, Mayo did some novel work in examining cave sediments east of the fault to understand varying slip rates over the last 750kya, but this type of analysis does not provide information on the timing of specific events (Mayo, et al., 2009). In a 2016 article, DuRoss explored the possibility of multi-segment earthquakes on the Wasatch Fault (DuRoss, et al., 2016). While they found no Holocene record of events spanning multiple segments, they also did not find a reason to exclude that possibility and suggested further study.

3.1. The Lake Bonneville sediment record

In a 2016 study by Rey, Bonneville sediment cores from the Pilot Valley on the Utah/Nevada border were studied (Rey, et al. 2016). In that study, an abrupt and anomalous sand layer showed up in most of the cores. It is best covered by directly quoting the study:

> "The cause of the deposition of the sandy layer in Unit III at 167 cm is not well understood. It could have been the result of a major storm event that washed coarse-grained material into the

> lake. The thickness of the sand bed generally decreases away from the Silver Island Mountains and the Pilot Range, and the layer is missing in some interior playa cores. Further work is required to better understand the origin, and potential cause, of the sandy layer." (Ibid, p. 208)

Anomalous sand layers show up at just a very few levels in most stratigraphic studies of Lake Bonneville. If these were storm events, there would be examples of similar layers of varying thickness showing up on a more regular basis. A 100-year storm is a common occurrence in a 45,000-year timeline.

The earthquake-induced-surging theory predicts the existence of these types of abrupt transitions in sediments that show reworking. In the course of the current study, this type of transition was treated as a necessary but not sufficient condition. In trying to identify an earthquake-induced surging event, it is important to look for corroborating evidence across locations and different evidence types.

Deposits need to be considered in the context of how location might affect them. In the Pilot Valley example above, results were dependent on proximity to the shore. Both the swash zone of a beach and earthquake-induced surge strata in deeper water can present similar evidence:

a. laminated sand layers,
b. reworked shells,
c. a higher concentration of stones,
d. tufa-coated solids,
e. shoreline organic carbon materials at depth.

A deeper lake would tend to reduce the amount of disruption of the lake bottom sediments but would not be immune to the larger surge events. A very shallow lake might see almost continuous disruption from not only earthquake-induced surging but also storms.

In an earthquake-induced-surging event, previously deposited sediment layers are swept back up into suspension, basically disrupting the record of the timeline by removing material, mixing the age strata, and then redistributing it. The total thickness of deposited material may not change significantly, but the time sequence within the disrupted zone has changed. Additionally, lightweight organic carbon materials such as shells and wood could be transported in from other levels in the lake and buried in the chronologically wrong sediment.

In an earthquake-induced surging event, as lake-bottom sediment gets resuspended, the chemistry of the lake changes. Turbulence can result in aeration and precipitation of solids. Rapid settling of these compounds can result in spikes in total inorganic carbon (TIC) in the resulting sediment. Researchers use TIC as a lake-level proxy for trying to understand historic variations in level on the premise that in a closed lake system with no other external factors, TIC increases as the level drops.

Calcium carbonate is a component of TIC. In a surging event, aeration near the shoreline results in degassing of CO_2 and $CaCO_3$ (tufa) precipitation. This type of precipitation is accelerated by nucleate precipitation, with the result being a tufa coating of pebbles and shells. Large storms might cause this type of effect, but it would tend to be limited to zones very close to the shore, and as stated earlier, if storms were the cause, it would be expected to be a common occurrence in the sediment record, and it is not. Anomalous spikes in TIC in the deep-water sediments are an indicator of potential earthquake-induced surging.

With the Stansbury Oscillation and the Bonneville Flood events as models, a search was conducted for evidence of other earthquake-surging events in the Lake Bonneville record. The Benson stratigraphic study from the Blue Lake Marsh provides just such an opportunity (Benson, et al., 2011). Blue Lake is a spring-fed feature in the very western extreme of the Bonneville basin. Working with the Benson lake-level-proxy graphs and stratigraphic sections permits a search for matching patterns.

Figure 12 is the Benson data for TIC (black line). Note that the y-axis represents decreasing concentration, since as a lake level proxy that would correlate with increasing lake levels. Approximate Heinrich Event periods are indicated. The other markings are relevant to the interpretation of the data in the context of the present earthquake-induced surging theory and do not reflect the content of the Benson paper.

Figure 13 is the sediment core depiction from the Benson et al. paper. This has been included as a visual reference; the Benson legend has not been included so as not to suggest that any synopsis here is a substitute for reading the Benson paper. The Benson image has been annotated to reflect my analysis of how the sediments would correlate to the lake events identified herein. Only the pre-Younger-Dryas layers of the core are shown because that is the limit of what will be addressed here.

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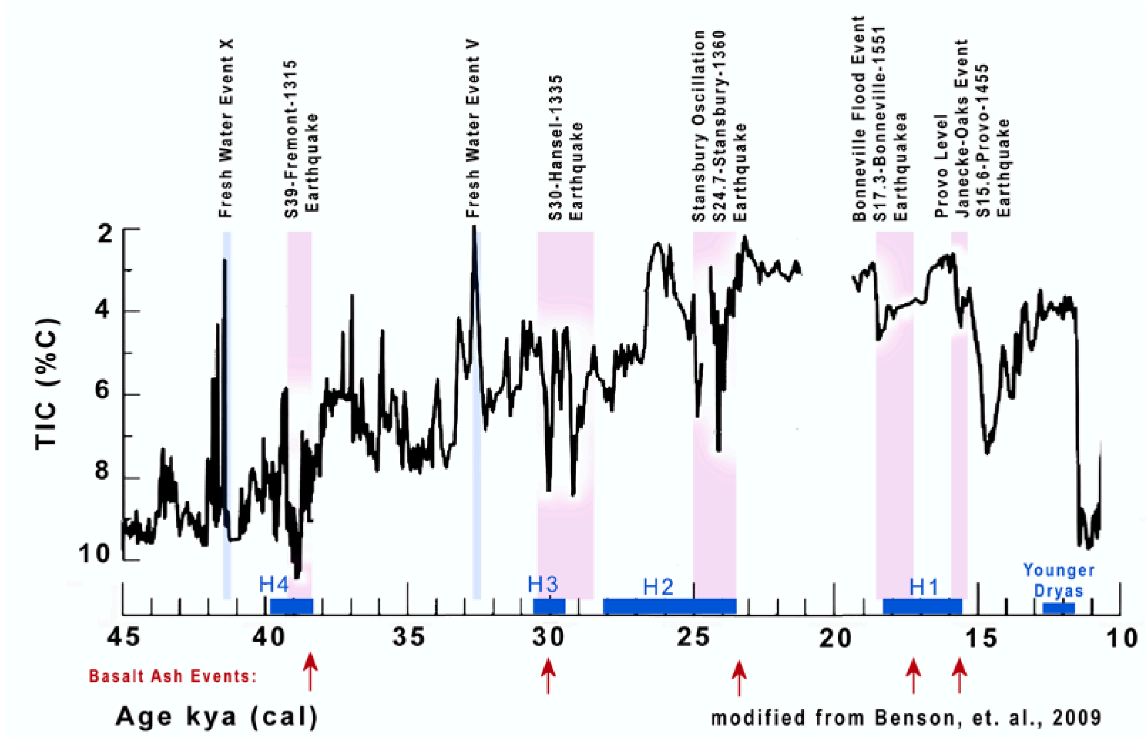

Figure 12. The Total Inorganic Carbon (%C) over Time (cal kya) plot of the Benson et al. (2009) core at Blue Lake in the Bonneville Basin. Superimposed on the Benson data are the named events of this paper and the Basalt Ash Events from various sources.

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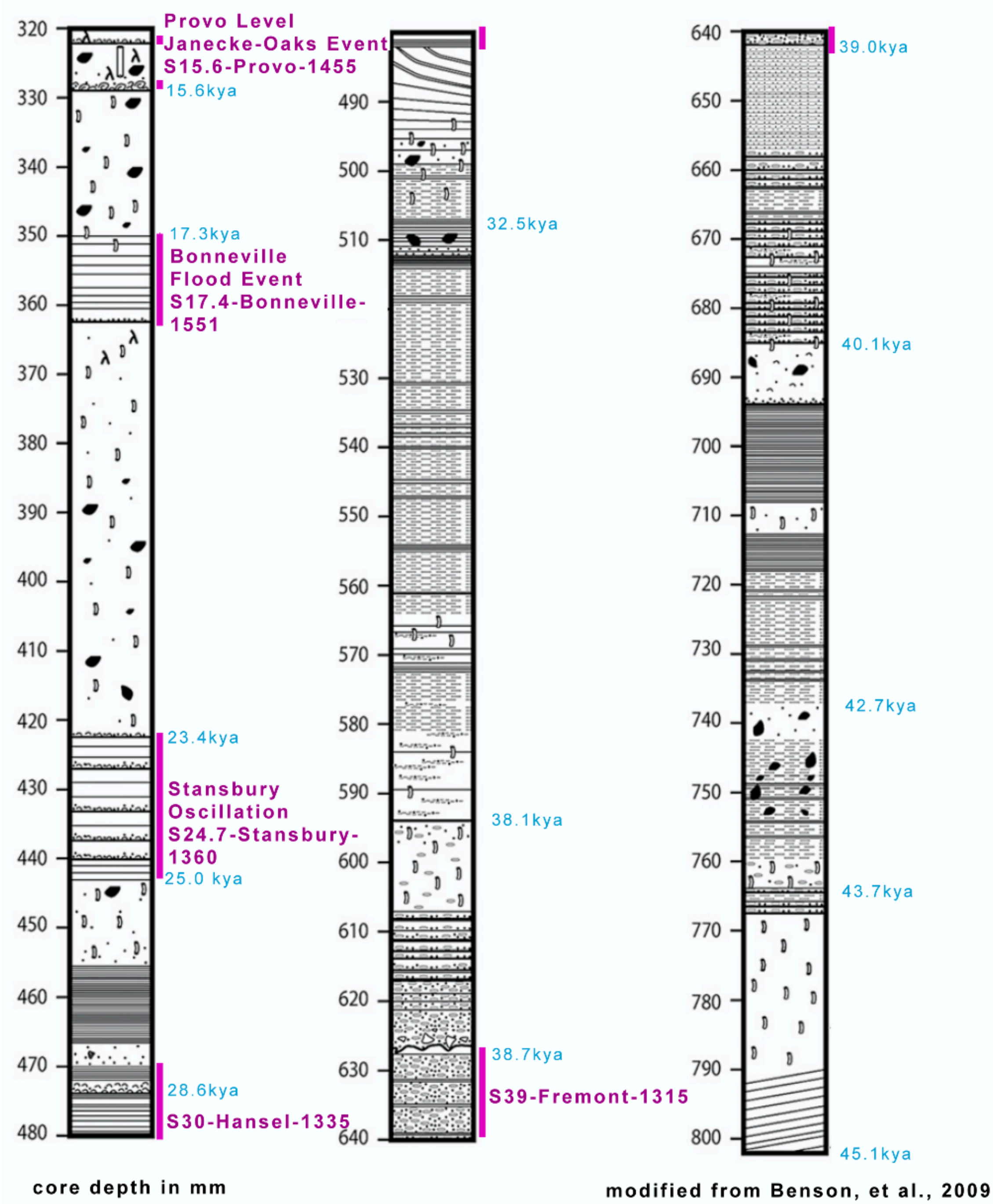

Figure 13. Stratigraphy of the Benson et al. (2009) core at Blue Lake in the Bonneville Basin. Superimposed on the Benson data are the named events of this paper and calendar dates at key points based on the Benson data. Refer to the Benson paper for legends and descriptions of their interpretations.

In studying the Benson cores, the Stansbury Oscillation was used as a reference feature. The Stansbury Oscillation resulted in two very dramatic TIC concentration spikes about 1ky apart in the Benson timeline

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starting at 25kya. If these two TIC spikes are assumed to be level proxies, that would appear to support the climate-based level drop theory. However, a closer examination of the details of the research opens the door to a completely different interpretation.

The Benson study compared the natural remanent magnetization directional changes (inclination and declination) against the records of other North American lakes and ocean sediments to develop a depth/age model and they checked that against carbon dating where possible. The dates in Figure 13 are interpreted using the Benson correlation curve. Using this correlation for the Stansbury Oscillation timing, we see striated sand layers starting at the appropriate 25kya time, though the Benson stratigraphic depiction shows five independent layers with abundant shells, the last of which is about 1.6kya later. This 20 cm section of the core stands in contrast to the deep lake sediments on either side. This forms our standard model or fingerprint for earthquake-induced surging, though the double spike in TIC would have been expected to be a special case.

What jumps off the page in Figure 12 is that 5ky before the Stansbury Oscillation there was an almost identical double spike TIC event, with two dramatic spikes about 1ky apart. The core sample in this timeframe showed a stratified organic laminate and at the top of the zone a layer that Benson described as “created by wave reworking of older, higher-elevation deposits”. (Benson, et al., 2011, p. 65) Using the Stansbury model, this spike in TIC and the wave reworking of deep-water sediments flag this as another earthquake-induced surging event.

Going back another 9ky to about 39kya, there is another spike deviation in TIC concentration. In the sediment record, this corresponds with a 15cm thick bed of “wave-reworked, pelleted aragonite”, otherwise known as tufa. This yields a third candidate for an earthquake-induced surging event. The TIC timeline is inconclusive on whether this exhibits a double spike, but the apparent duration of the disturbance is about the same as the latter two. The lake was quite shallow in this area at that time and that could have affected the surging and settling in a number of ways.

Evidence of the Bonneville Flood event is also apparent in the lakebed core. The Bonneville Flood event has a tight timeline fix at 17.4kya. Looking at the core sample first, there is a very distinct laminated calcite zone from 18.6kya to 17.0kya in Benson’s timeline, though equating timelines between different studies is always a bit problematic. On the TIC graph, there is a sharp drop at the start of this period and then a recovery at the end. This is during the Bonneville highstand and a deep lake, so the lakebed may not see as much disturbance in an event and any TIC would be diluted into higher volumes so the TIC concentration may not spike as much.

Based on an analysis of the Benson sediment core data, five principal candidates for earthquake-induced surging events were identified. These events will be referred to as:

- S15.6-Provo-1455
- S17.4-Bonneville-1551

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- S24.7-Stansbury-1360
- S30-Hansel-1335
- S39-Fremont-1315

Dating techniques and level determinations will continue to be refined in the future and the designations will need to evolve. But for now, this should suffice in keeping the reader oriented to when, what others might have put in the titles of their papers regarding a similar level, and a typical rebound level where evidence might be found. Of course, those levels will vary in different parts of the lake, but the objective is to just keep the reader oriented. Each of these levels and the supporting evidence will be discussed later.

Others have identified a shoreline at the 1305m level and referred to it as the Pilot shoreline or level (Miller and Phelps, 2016). That level is complex and presents evidence as a transgression level and as a regression level, depending on the location in the basin. I think this "level" is just a coincidence of factors. The transgression bar may be from a low point of a surge from higher events, and the regression bar may be a product of a Holocene event which will be discussed later. In either case, I found no evidence to suggest that 1305m was a sustained shoreline level.

3.2. The Basalt Ash Deposits

The Bonneville basin has evidence of periodic basalt flows, some as recently as 600 years ago (Utah Geological Survey, 2023, Stahl, 2019). Basalt ash deposits have been found in the Lake Bonneville sediments and used by researchers as timeline markers to correlate between sites (Oviatt and Nash, 1989).

Researchers have identified five principal events in the Lake Bonneville sediments: Hansel Valley, Pony Express, Pahvant Butte, Tabernacle Hill, and the Lower Basaltic Ash, the first four named after the source locations, the last for where it showed up in the core sample (Oviatt and Nash, 2014, Godsey, et al., 2011, Miller, et al., 2012, Miller, et al., 2008, Oviatt and Nash, 1989, Thompson, et al., 2016). In the course of the present work, it became apparent that there was a timing correspondence between these events and the earthquake-induced surging events.

In the sediment record, the Tabernacle Hill eruption is in the timeframe of the Provo oscillation (S15.6-Provo-1455), the Pahvant Butte ash is in the window after the Keg Mountain oscillation, and possibly during or just after the Bonneville Flood (S17.4-Bonneville-1551), and the Pony Express basalt ash shows up just after the Stansbury Oscillation (S24.7-Stansbury-1360).

The Hansel Valley eruption in the northern reaches occurred during the initial rise of Lake Bonneville. In a 2007 paper, Miller recounted a 1997 trip with Oviatt where they "traced the ash bed upslope from deepwater lake to shore zone facies, establishing that the ash fell into Lake Bonneville when the lake level was approximated at

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1335m altitude.” (Oviatt and Miller, 1997, Miller, Oviatt, and Nash, 2008, p. 239) They dated the deposit as “~28 cal ka” based on the carbon dating of marl in the vicinity. Allowing for carbon dating variances, the timing and elevation match what would be expected for the S30-Hansel-1315 event.

The Lower Basaltic Ash was identified by Thompson, et al. in their study on flora in Bonneville sediment cores. In the lowest strata of their sample, they found what they tagged as the ‘lower basaltic ash’ (Thompson, et al., 2016). It is always problematic trying to compare the dating of materials between studies, even between labs, particularly when looking at samples this old. They came up with a ^{14}C age of 33.38kya, but then they deducted 1.8kya to try to account for what they assumed were reservoir carbon interferences. They ended up with a calibrated date of 35.5kya. The dates used in Figure 12 are based on Benson’s work. Benson did not apply a reservoir carbon factor, but he did use the same CAMS lab as Thompson for the analysis of samples in this same time period. Benson had a sample dated 34.56kya ^{14}C which equated to 39.55kya cal and one at 30.3kya ^{14}C which equated to 34.84kya cal. Extrapolating on the Benson data would yield a date for the lower basaltic ash event at 38.25kya cal on the Benson scale. That would place it close enough to be the missing sixth ash event (S39-Fremont-1315). A basalt ash eruption might take some time to manifest itself, the sediment timeline might be off because surging disrupted and redistributed prior layers, or there may be inconsistencies between the different dating efforts.

The five well-documented basalt ash events in Lake Bonneville have a one-to-one correspondence with the five identified multi-segment-earthquake-induced surging events.

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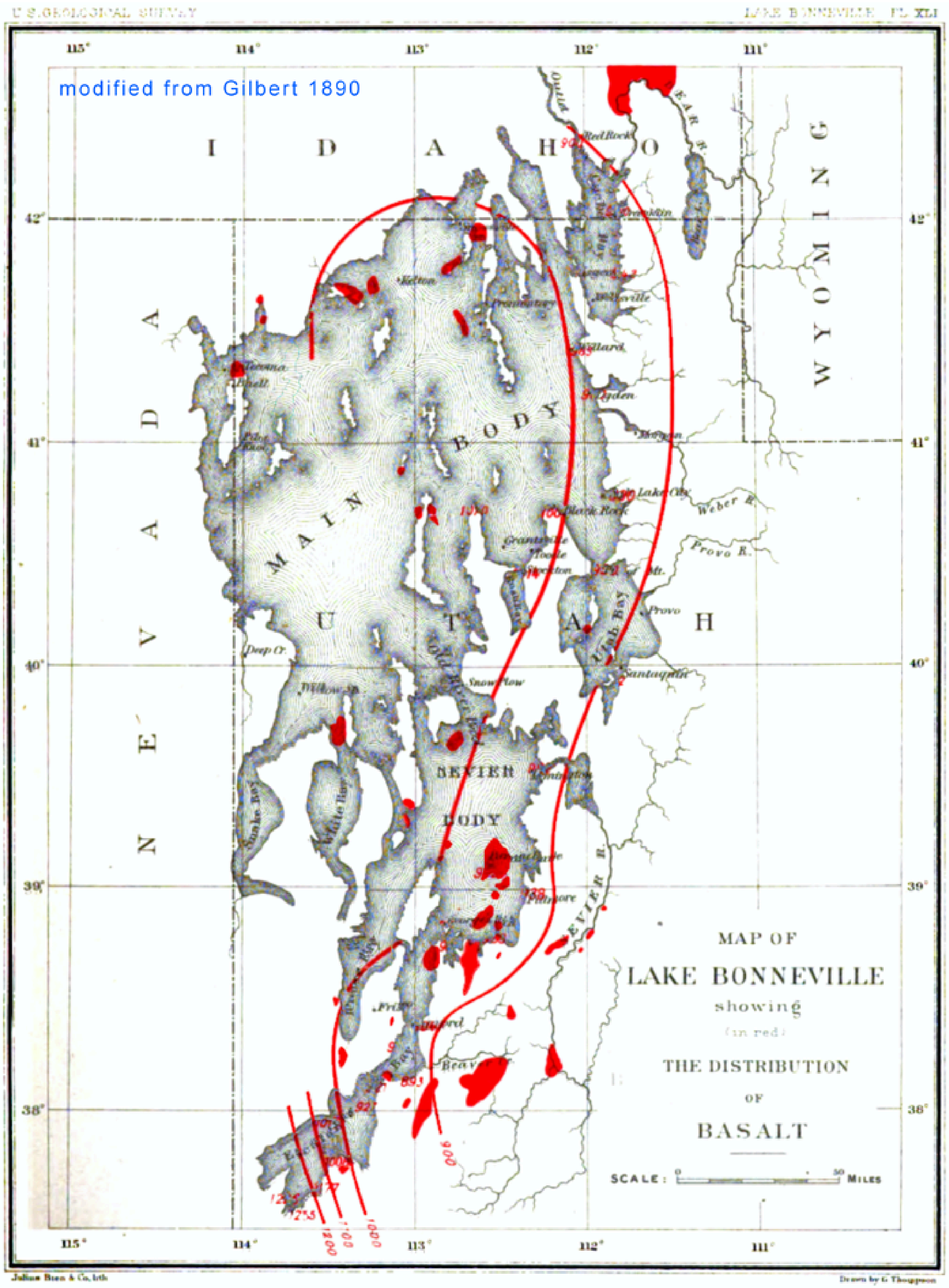

Figure 14. USGS Nomograph No. 1 Plate XLVI of the “Deformation of the Bonneville Shoreline” superimposed on his Plate XLI of the basalt flows in the region. G. K. Gilbert used the same background map for both plates. Red was used in the original 1890 publication to present the data in both plates.

G. K. Gilbert mapped out "The Distribution of Basalt" in the Bonneville basin in USGS Nomograph No. 1 (Gilbert, 1890). Figure 14 is his Plate XLVI of the "Deformation of the Bonneville Shoreline" superimposed on his Plate XLI of the basalt flows in the region. Basalt flows would be the natural complement to block fault activity and the flows in this region started before Lake Bonneville and continued after. The interesting thing here is the distribution of the flows in this area. Many of the flows are clustered in areas where there would be the maximum stress in the crust from the isostatic deformation caused by a deep lake in the basin. There are outliers to this pattern in the south and the extreme north near the ends of the Wasatch Fault displacements and that certainly is a topic for a different discussion.

The Bonneville basin is a very old lake basin and has had a long history of resident lakes, so isostatic deformation in this area has been going on for a long time.

The salient point is that the five known major ash events during the Bonneville period correspond to the five identified multi-segment surging events during that period. A one-to-one correspondence. With both a coincidence of timing and appropriate locations, a correlation between the multi-segment earthquake events, isostatic deformation, and the basalt ash eruptions rises to the 'most likely scenario' status.

3.3. Lake Bonneville Isostatic Depression, aseismic intervals, and multi-segment earthquakes

The Lake Bonneville time period is a confusing array of controlling factors and level evidence. This paper assumes the reader is familiar with research concerning the structure of the Basin and Range province and the anomalously thin section of stretching crust in this region, along with the body of work surrounding the isostatic deformation of the Bonneville basin by lakes and glaciers (Hetzel and Hampel, 2005, Adams and Bills, 2016, Mayo, et al., 2009). Also pertinent to the current discussion is the variation in the slip rate of the Wasatch Fault. In a 2009 paper, Mayo found indications that the slip rate during the late Pleistocene was about half the rate that it is today. (Ibid, 2009) The stresses in the crust and on the Wasatch Fault were a combination of both tectonic factors and isostatic factors, and the isostatic factors were dependent on long-term climate. In this section, the previously unidentified earthquake events in the Bonneville timeline will be discussed along with the supporting evidence.

As mentioned earlier, the spits in the western areas of the basin have long been thought to be the result of prevailing winds and large storms. The V-bars have been interpreted as cuspid forelands due to longshore currents driven by prevailing winds. The numerous bars in the lake have been treated as the products of established lake levels. While there certainly are exceptions, for the most part, none of that is correct. These features were instead each formed in a relatively short period of time by massive wave and current actions created by shocks from events in the crust. These features appear in other lake basins in the Great Basin and those need to be addressed on a case-by-case basis. The majority of the features studied in the Bonneville basin exhibit characteristics of crustal shock origin.

3.3.1. The S24.7-Stansbury-1360 Event

The Stansbury event is a good place to start since it is isolated in time from the other events and the shoreline records associated with it are still discernable.

Skull Valley was a mid-lake arm of Lake Bonneville southwest of Stansbury Island (Figure 9). The valley floor gradually rises to the south. The Stansbury event surged into this valley, running up the long rise of the valley floor until the energy of the surge was exhausted. From the low point in the cycle to the high point, the initial surge spread out linearly over 3.25km of distance. The deposits left on the valley floor provide a very unique record of this surging event.

This type of sloshing in the Bonneville basin would start with a large amplitude surge and then the oscillation would be dampened with each cycle. The type of evidence at the top end of the cycle would depend on the local slope. A steep slope would leave little enduring evidence aside from a slight increase in erosion. A moderate slope would permit a bar to form if the surge was moving soft sediment. A low-angle incline such as in Skull Valley would spread the entrained material in the surge over a band. At the bottom end of the cycle, the result would be a bar. This is because as the cycle bottoms out, all the entrained material suddenly hits a low-velocity wall of the existing lake and settles out immediately. That bar would then get spread out a bit by subsequent cycles, but as the cycles moved shallower, the bar would quickly be at a depth where the cycles occurring above no longer affect it, preserving it as evidence of the event.

The material stirred up in these cycles includes the calcium which had previously collected in the lake bottom sediments. In places like Skull Valley, the waves running up the shore in the initial cycles distribute the calcium compounds over a very wide band, painting images of the surges on the valley floor.

Things changed as the cycle pattern dissolved into noise. What was left were small waves of calcium-rich water smashing against a small band on the shore, still degassing and precipitating calcium carbonate. In Skull Valley, the calcium carbonate resulted in a bathtub ring of white calcium deposits. In many places, lacustrine wave action washed away the bathtub ring. But in other locations, such as Skull Valley, this bathtub ring can be used as an indicator of lake level.

Figure 15 is a Google Earth™ image of the deposits in Skull Valley. The upper-end smear deposits, lower-end bars, and bathtub ring final deposits are all visible. Things get interesting when the levels are plotted (Figure 16). The result is a very well-mannered, damped sine curve, defined by nine data points, supporting a high level of confidence in these findings and the concept that these cycles occurred at a frequency measured in hours, not decades or centuries.

At first glance, there is an apparent first law of thermodynamics violation. The system starts at equilibrium and then surges away towards the earthquake slip depression in the east. However, when the wave returns, it runs higher than the equilibrium level. There are a couple of things in play here that contribute to this, and it comes down to the position of Skull Valley in the Bonneville basin and the topology of the valley. The valley is at a pinch point between east and west, so on the return flow it gets a concentration of energy beyond its contribution, and the valley has the Bay of Fundy effect of being shallower and narrower as you go up the valley.

Eventually, the surging cycle dissolves to noise, random large waves crashing on the shore and forming a thick band of tufa. In some places in the lake basin such as on steeper slopes, this appears as a band. In other places, only the bottom edge sticks out from under later deposits. Once the noise of the event settles out, the lake still has an elevated calcium concentration and the normal waves on the shore sometimes form a second tufa band, usually about four meters above the first. This is not as frequently visible because it is dependent on more factors and is a more subtle feature.

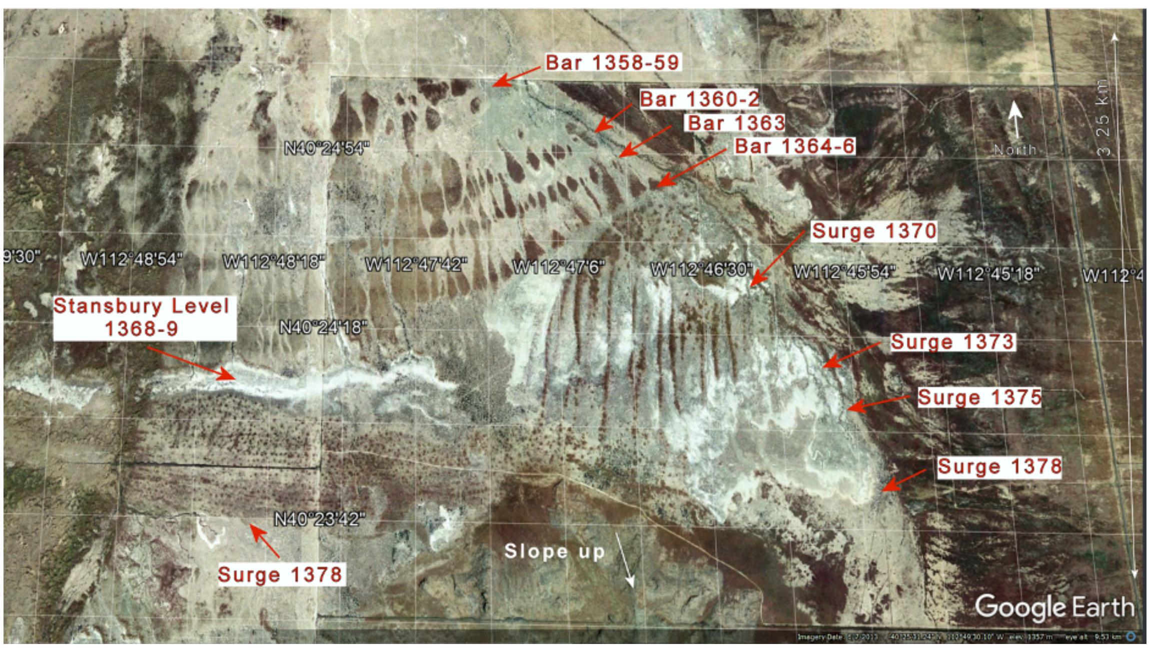

Figure 15. Google Earth™ view of S24.7-Stansbury-1360 Event surge features on the floor Skull Valley. Elevations are in meters. Bar formations are at the bottom ends of a surge cycle and surge formations are from the wave breaking at the top of a surge cycle. (40°24′18″N, 112°47′6″W)

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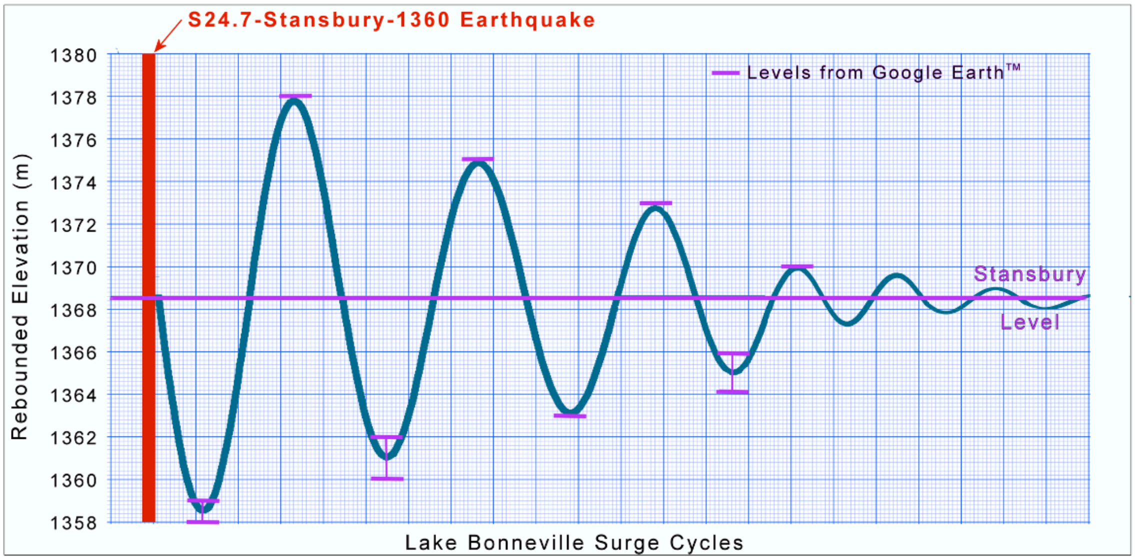

Figure 16. Plot of the elevations of the S24.7-Stansbury-1360 Event surge features identified in Figure 15 against a non-dimensioned time progression. Three of the bar levels are given as ranges due to uncertainty on the most probable centerline. The sine curve indicated is for visualization purposes only. The dampened harmonic of a vibrating bar was used as a model for the general shape.

Calcium carbonate is a cement. When deposited in concentration it forms an erosion-resistant layer. On steep slopes, this can appear as a band. When it forms on a depositional bench, it creates a shelf. In some areas of the lake, the bench erodes out from underneath and the tufa shelf drapes over the edge.

The Stansbury surging event is what flooded Puddle Valley (40°55N, 112°57W) in the middle of the Bonneville basin rather than the gradual overtopping of the barrier as previously thought (Miller and Phelps, 2016). The Puddle Valley was isolated from Lake Bonneville up until the Stansbury Event when the barrier at the north end failed catastrophically. The barrier was above the 1364m level, possibly as much as 10m. Puddle Valley would have eventually flooded at some point in the Bonneville transgression, however, a massive overtopping of the barrier by surging explains the extensive debris tongue carried into the valley at the point of barrier failure, which was in the form of a front not a delta.

3.3.2. The S30-Hansel-1335 Event

The evidence for each successive event back in time becomes more muted. Deposits, erosion, and subsequent surging all take their toll on the evidence. The shoreline for the S30-Hansel-1335 event shows up as a calcium bathtub ring in some places and a shoreline platform in others. The subsequent Stansbury oscillation was close enough in level to erase much of the surging evidence with at least one exception.

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In the Pilot Valley at the base of Pilot Peak in the western extreme of the Bonneville basin are a unique series of double horizontal stripes on the slopes of the eastern side of the valley, seen in the Google Earth™ view of Figure 17. The lowest stripe is around the 1305m level, which corresponds to bar evidence in other parts of the lake and is known as the Pilot Level in research papers on the lake (Miller and Phelps, 2016). Moving up the slope, the stripes diminish in intensity, yet the separation between lower and upper stripes in each set stays consistently at about 2m. The series tops out at the base of a cliff above where a calcium band is evident in the 1335-1338m range.

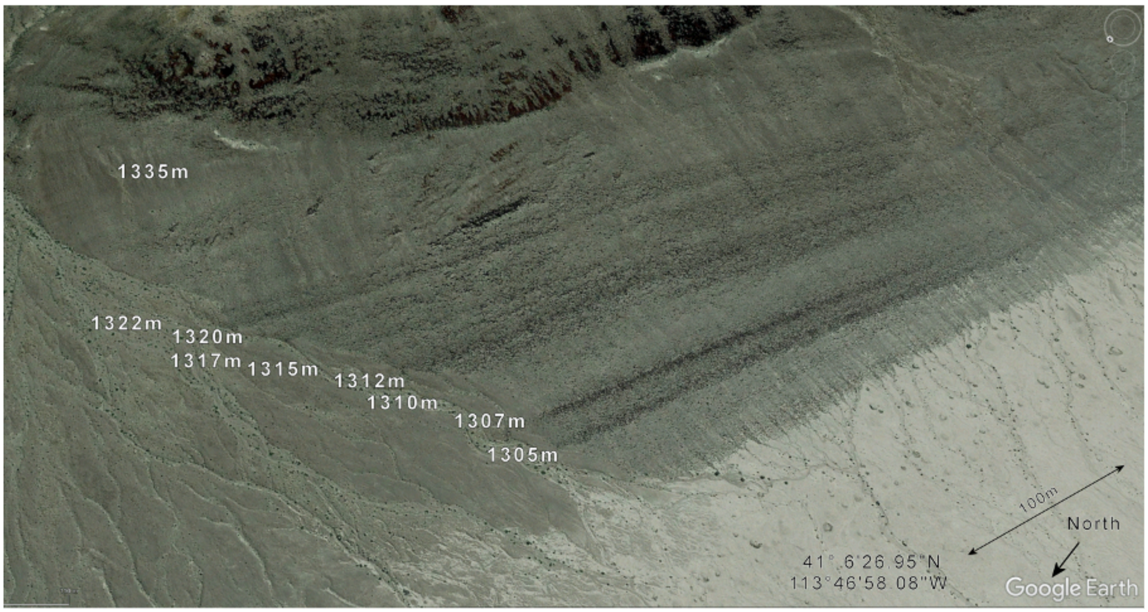

Figure 17. Google Earth™ view of cross-shore current surge deposits in the Pilot Valley attributed to the S30-Hansel-1335 Event surge. The calcium deposits at the top of the slope are from waves crashing on the shore at the end of the event when there was a high concentration of stirred up calcium in the lake. The ascending double bands are from waves and secondary surges in each cycle of the event. (41°6′27″N, 113°46′58″W)

Each of the eroded bands is defined by small black rocks trapped in the pockets of the rough surface of the slope. These rocks are dolomite stripped from the Guilmette Formation outcrop 1-1.5km north along the shoreline from this point.

In the surging event, the surge back into the area was a turbulent event. The lead wave resembled the front of a flash flood transporting stones and other materials in a tumbling, aerated front of debris. The S30-Hansel-1335 Event started with a 30m draw down in Pilot valley. When the surge rushed back into the valley, it transported dolomite sand up the valley leaving a 1305m level band. Apparently, the surge back into Pilot Valley during each cycle was broken into two waves, one riding on top of and just after the other. This may have been due to the

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pinch point in the center of Lake Bonneville, but I think it is more likely due to the fact that the path back into the Pilot Valley is not a straight shot from the east, the surge had to negotiate a couple of sharp curves. The result was that the surge broke into a main wave and a 2m higher reflected wave.

Each successive surge was not as deep as the preceding and not as forceful, but the reflected wave was always 2m higher than the initial wave of the surge.

The event settled down at the 1335m lake level and the residual noise waves left a pronounced calcium bathtub ring at that level.

At other locations in the basin, where the current was perpendicular to the mouth of a bay with soft sediment, the initial drawdown left a distinct bar at about the 1305m level. There would be successively higher bars, but they would be less distinct.

In his 2015 paper on the chronology of Lake Bonneville, Oviatt (2015) indicated in one figure that, at about the time of the Hansel Valley ash event, mollusk shells were deposited at an elevation of 1355-1360m. This would be inconsistent with previous level assumptions for that time but would be well within the potential upward bounds of the S30-Hansel-1335 event surge: 1335m with surging +/-30m.

3.3.3. The S39-Fremont-1315 Event

The Benson core TIC data suggests an earthquake-induced surging event occurred 9ky before the Hansel event. While the sediment record of this event has been securely stored under the depths of Lake Bonneville, the record at the surface has been subjected to 39ky of erosion and surging events, consequently, much of the shoreline evidence has been obscured or destroyed. However, there still is evidence of a significant event in the 1312-1318m in many parts of the basin.

The north end of Stansbury Island in the middle of the basin is a location prone to tufa deposits during surging events. Consequently, it provides a record of events identified in this paper. Shelf formations can be formed by a variety of lacustrine occurrences, but the ones identified are very distinctive and at elevations commensurate with other evidence in the basin. (Figure 18) The Stansbury and Provo levels are very prominent in this area. The S30-Hansel-1335 event is not as prominent at this location, but this may be due in part to the location on the steep slope just below the dominant S24.7-Stansbury-1360 event shelf. The S39-Fremont-1315 level is quite distinctive here. Also, there appears to be another shelf between the Hansel and Stansbury levels, fainter still, though this corresponds to the elevation of the adjacent ridge, so it may just be an artifact of lacustrine long-shore currents.

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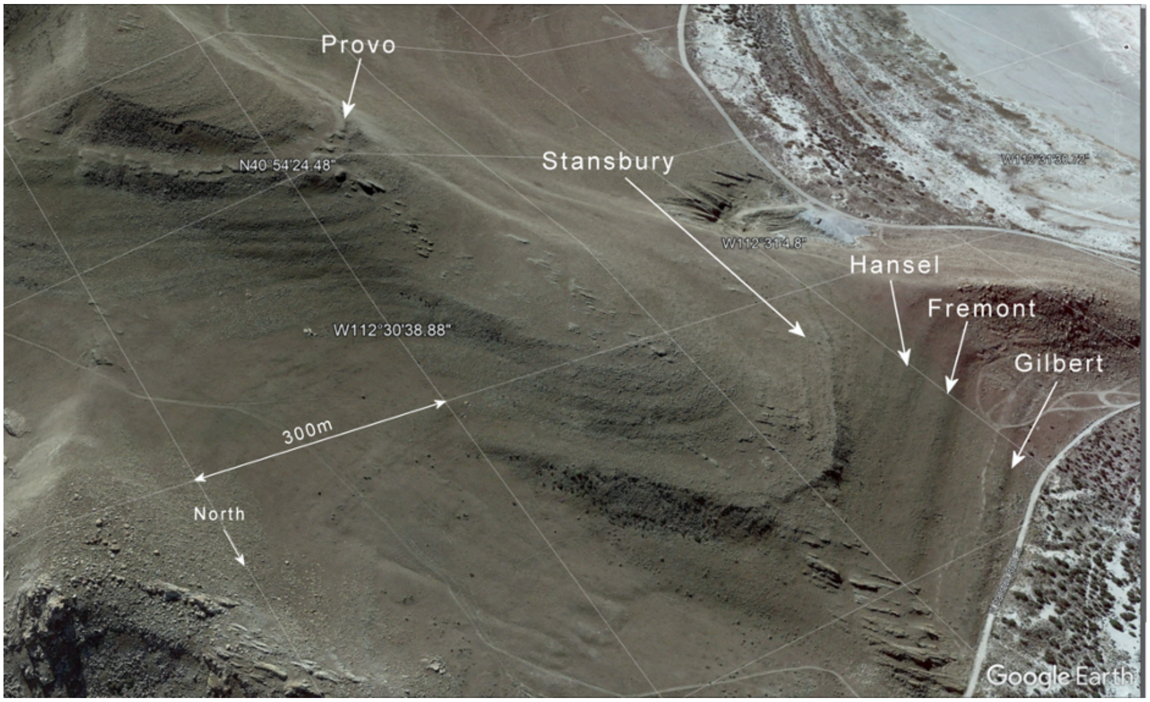

Figure 18. Google Earth™ view of the north end of Stansbury Island showing the benches associated with the S39-Fremont-1315 event in relation to the other known surging events. (40°54'46.74″N, 112°30′59.77″W)

3.3.4. The S11.6-Gilbert-1300 Event

In a 2022 study, Pigati and Springer reported that the Younger Dryas (12.9-11.7kya) manifested in two stages in western North America. (Pigati and Springer, 2022) The first stage ran until about 12.2kya and was consistently a cool wet period, typified by high water tables in the Death Valley region west of the Great Basin. The second stage, which ran until 11.7kya was unsettled with varying water-table levels but overall was a dryer than normal period.

The Gilbert Level episode in Lake Bonneville corresponds with the Younger Dryas. In a paper on the Gilbert Level by Oviatt (2014), he analyzed prior work and reported new information regarding this level. He found that the lake achieved a maximum elevation of 1295-1297m at 11.6kya. Others have studied lake levels in the Great Basin from the late Pleistocene through the Younger Dryas (Reheis, et al., 2014, Adams, et al., 2008). In the various Great Basin lakes, the Younger Dryas highstands can vary by thousands of years between lakes for unknown reasons, but in all cases, there is a bump up in level at a time during or just after the Younger Dryas. This is interesting because of Pigati and Springer's finding of a two-stage Younger Dryas with a wetter-than-normal first half and a dryer-than-normal second half. In the Lake Bonneville basin, a resurgence of glaciers in the Wasatch and Uinta Mountains during the first half of the Younger Dryas would have stored water for a continued rise leading into the second half. This same pattern occurred eight thousand years earlier when Lake Bonneville continued to rise after the last glacial maximum in the Wasatch.

The Benson core at Blue Lake in Lake Bonneville is of limited use at this level for resolving this issue since that area was a marsh or shallow lake at the time.

Since the Gilbert Level was never threshold controlled, there is no reason other than chance for there to be a sustained Gilbert Level.

The suggestion that there was a seismic event during the occupation of the Gilbert level was introduced by Hyland in a 2012 trench study on the eastern shores of the Great Salt Lake (Hyland, et al. 2012). That trench work also revealed a tufa layer resting on an unconformity above Lake Bonneville deposits; this is consistent with the model of surging presented in this current study.

Oviatt further supported the concept of a Gilbert-level earthquake in his 2014 work. In his analysis of a sediment core, he states: "The inclination of these laminations is interpreted to represent wave agitation or earthquake disruption of the Great Salt Lake bottom during the Gilbert episode." (Oviatt, 2014, p. 11)

The Hylland and Oviatt data of an earthquake at 11.6kya is accepted as a base assumption in this current work.

For such a recent period, identifying a 'Gilbert Level' has been a problem for researchers. Above and below the level range that Oviatt settled upon are a complex array of level artifacts. This is compounded by the fact that this is the same elevation range of the transition from the basin playa to the rise of the mountains. Identifying the lake level at the time of this earthquake event is of value because it gives a hard date and level fix for the otherwise transient Gilbert episode.

Currey did the initial mapping of the Gilbert shoreline in 1982 and the features he studied ranged from 1293 to 1311m in elevation (Currey, 1982). In his 2014 paper, Oviatt debated the level-evidence, before settling on the 1295-1297m range as the most likely. However, in his conclusions, he limited the level statement to "An assumption that the lake reached altitudes higher than about 1297 during the Gilbert episode may not be valid." (Oviatt, 2014, p. 18)

Without a sustained level, any evidence of a Gilbert highstand would have been washed away by the surging of a Gilbert-level event. Not only would a Gilbert surging event create multiple bars and erosion features, but anything up to around 1300m would also see surges from any later Great Salt Lake level events.

The ^{14}C dating samples reported by Oviatt in developing his Bonneville hydrograph (Figure 2) show multiple potential levels in this time frame running up to almost 1320m. Surging would explain that.

In the previously referenced Miller et al. paper on Provo shoreline deposits, they depicted in their Figure 5, a pair of shorelines stacked one on top of the other, one two meters above the other (Miller, et al., 2012, p. 347). In the 2014 paper by Oviatt on the Gilbert level he depicted in his Figure 3, two bars at the Magna spit stacked one on top of the other, one two meters above the other (Oviatt, 2014, p. 7). The top bar was found to be at about 1295m, two meters below the 1297m level assigned by Oviatt to the Gilbert level.

The shoreline shelf in Figure 18 supports a Gilbert event level of 1300-1301m. Calcium bathtub rings in the western reaches also support a 1300m elevation (41°24′3.85″N 113°42′9.98″W. The difference between this and Oviatt's Magna spit elevations might be due to Wasatch Fault displacement. Crittenden discusses the tilting of the block just west of Stansbury Island to the Wasatch Fault in the east (Crittenden, 1963, p.E28). The Magma spit is mid-point between the two. 11.6ky of fault displacement would explain a difference. Picking and choosing reference points in the basin could support levels anywhere within the 1295-1302m range. The 1300m level is being used in this paper to be consistent with some of the more prominent features and is being used as the level of the Gilbert earthquake event, not the Gilbert highstand. The Gilbert highstand was probably quite transitory.

What the Gilbert level event is missing is a known basalt ash event in the relevant time frame. At the Gilbert level, isostasy was far less pronounced, supporting speculation that the ash eruptions during the Bonneville period were a byproduct of the isostatic depression of the crust in the basin, so ash eruptions would not be expected at the Great Salt Lake/Gilbert levels.

3.4. The Provo level Shorelines and the Provo Oscillation

In 2011, Godsey et al stated "The Provo shoreline is actually a complex of several coalescing coastal landforms…". (Godsey, et al., 2011, p. 443) That may rank as an understatement. It is difficult to find consensus among researchers. From a distance, the distinctive shoreline on the mountains makes this level look quite straightforward but interpreting it has been complicated. Researchers have cited issues with isostatic rebound, landslides that repeatedly blocked the outflow and raised the level, earthquakes shifting and dropping the outflow, storms, and an uncertain duration due to a plethora of dating issues. The one thing that is absolutely certain is that at the end of the Provo level was the most significant climate-based level drop in the lake's history, which ended as abruptly as it started.

Janecke and Oaks have done extensive studies of the Red Rock Pass outflow. (Janecke and Oaks, 2011) They identified a climate (level) oscillation towards the end of the Provo level, with a drop in the outflow level immediately following. This level oscillation is based on ^{14}C dating anomalies in the lake sediments, and it appears to also be supported by the $\delta^{18}O$ level proxy data. The signature of this mid-Provo level oscillation event mimics what was seen with the Keg Mountain oscillation and the Bonneville Flood: a level oscillation immediately followed by what is interpreted as a drop in the outflow elevation. They determined the drop in outflow elevation based on their surveys of shorelines and features at the outflow in northern Cache Valley.

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Their analysis shows that the initial outlet level was controlled by the Swan Lake sill and the later outlet by the Clifton sill, about 9m lower. In their 2011 paper, Janecke and Oaks noted "The pair of Provo shorelines that we identify in Cache Valley are quite different from another doublet of Provo shorelines in the Bonneville basin that typically lie a few meters apart and are variants of our upper Provo shoreline (Gilbert, 1880, 1890 called this "the underscore"; J. Oviatt, 2008, written communication)." (Ibid, p. 1381) They went on to suggest a possible correlation with some other more widely spaced, ~13m, shorelines in the central Bonneville basin.

Miller disputes the Janecke and Oaks finding of upper and lower Provo levels in both a 2013 journal article, coauthored with Oviatt and McGeehin, and a 2016 book chapter. (Miller, 2016, Miller, Oviatt, McGeehin, 2012) He based this on what he reports as a lack of corresponding evidence of a "mid-Provo drawdown" in shoreline features in other parts of the lake, and on the 2011 work by Godsey, Oviatt, Miller, and Chan. He states this later work on gastropods in nearshore sediment "also found little support for the mid-Provo drawdown". (Miller, 2012, p. 345). Miller coauthored the Godsey paper, so the assumption has to be that this is an accurate paraphrasing of the conclusions of the earlier paper, though the exact phrase in the Godsey paper was "We found no conclusive evidence from the stratigraphic record that a climate-induced drawdown of the lake, and subsequent return to threshold control occurred during mid-Provo time." (Godsey, Oviatt, Miller and Chan, 2011, p. 450) "Little support" and "no conclusive evidence" have different connotations, but the consensus in the literature seems to be that the change in Provo level outflow levels between the Swan Lake sill and the Clifton sill did not translate to the overall Lake Bonneville level.

The Godsey team, which included Oviatt and Miller, did report on an anomalous sand layer near the top of the Provo level marl appearing in several cores (Godsey, 2011, p. 445). This layer has reworked shells and small tufa heads. They suggested that this layer was due to "winnowing" during a storm event. Dating of shells in this layer put some of them just before and some just after their date of the fall from the Provo level of 12.6kya ^{14}C, but with error margins that overlapped the alternate fall date in the 15kya cal range. The Godsey, et al. descriptions are consistent with what would be expected in the earthquake-induced surging event being presented here. Many aspects of the mid-Provo level oscillation described by Janecke and Oaks also fit the pattern of an earthquake-induced surging event.

Miller et. al. surveyed the Provo shoreline at 83 points around the lake basin (Miller, Oviatt, and McGeehin, 2012). They did a very detailed analysis and considered many factors, including isostasy. One of the sites they studied was at a railroad cut west of Wendover, Utah (the Ola railroad cut) which runs through the Provo level deposits and the Bonneville Flood sediment (18.1kya in their dating timeframe, where 17.4kya is assumed here). (Figure 19)

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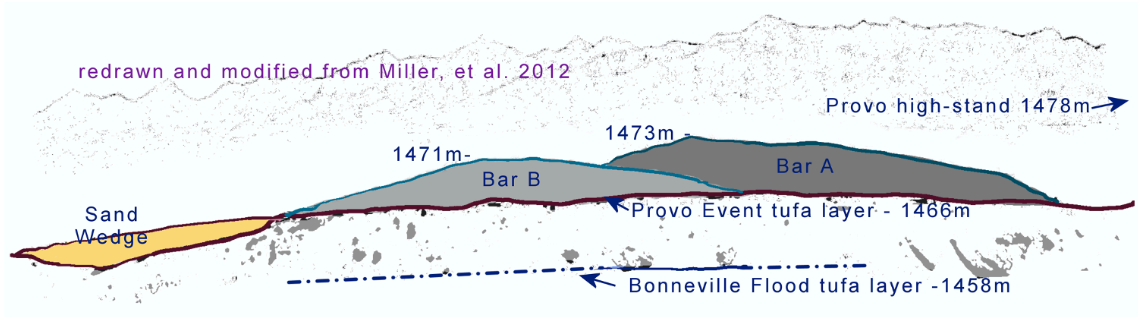

Figure 19. Provo level bars at the Ola Railroad Cut. These bars were formed at the end of the S15.6-Provo-1455 event surging that created the tufa layer below them. Redrawn from Miller, Oviatt, McGeehin (2012). (40°45′37.20″N, 114° 8′19.82″W)

In these deposits they found three "subhorizontal resistant beds... that are poorly sorted, matrix-rich and typically tufa cemented" (Ibid, p. 349). Though later in the text they report that the tufa is only present in the top and bottom layers and not the middle layer. The description of those top and bottom layers tufa layers matches the proposed indicators of earthquake-induced surging in the sediment record. The bottommost of these tufa beds was just below the Bonneville Flood sediment, making it consistent with the theory of earthquake-induced surging causing the Bonneville Flood. Their dating of that tufa layer was 18.1kya (cal) or an offset of 0.7ky from this paper's 17.4kya dating of that event.

The topmost tufa bed is 1-1.5m thick and comprises "flat-bedded, fine pebble gravel with a poorly sorted sand matrix... this bed is resistant owing to cementation by tufa coats on casts" (Ibid, p. 349). There is some evidence of "aquatic plants mats" at the base, which are known to promote tufa formation. However, it would be unusual for aquatic plants to grow for such a brief period in a location and at no other time in the thousand-plus-year timespan of the Provo level. The top bed is in the right location to be evidence of a Provo-level earthquake-induced disturbance.

At the Ola railroad cut, directly above the upper tufa layer are two shoreline bars identified by the Miller team, the newer bar at a higher elevation on the slope than the older, suggesting a rising lake level. These two bars are a consistent feature of the Provo level at locations throughout the Bonneville basin, generally at the top ends of valleys and coves where loose sediment was present, though the elevation differences between the two bars are different in different locations. (Figure 20)

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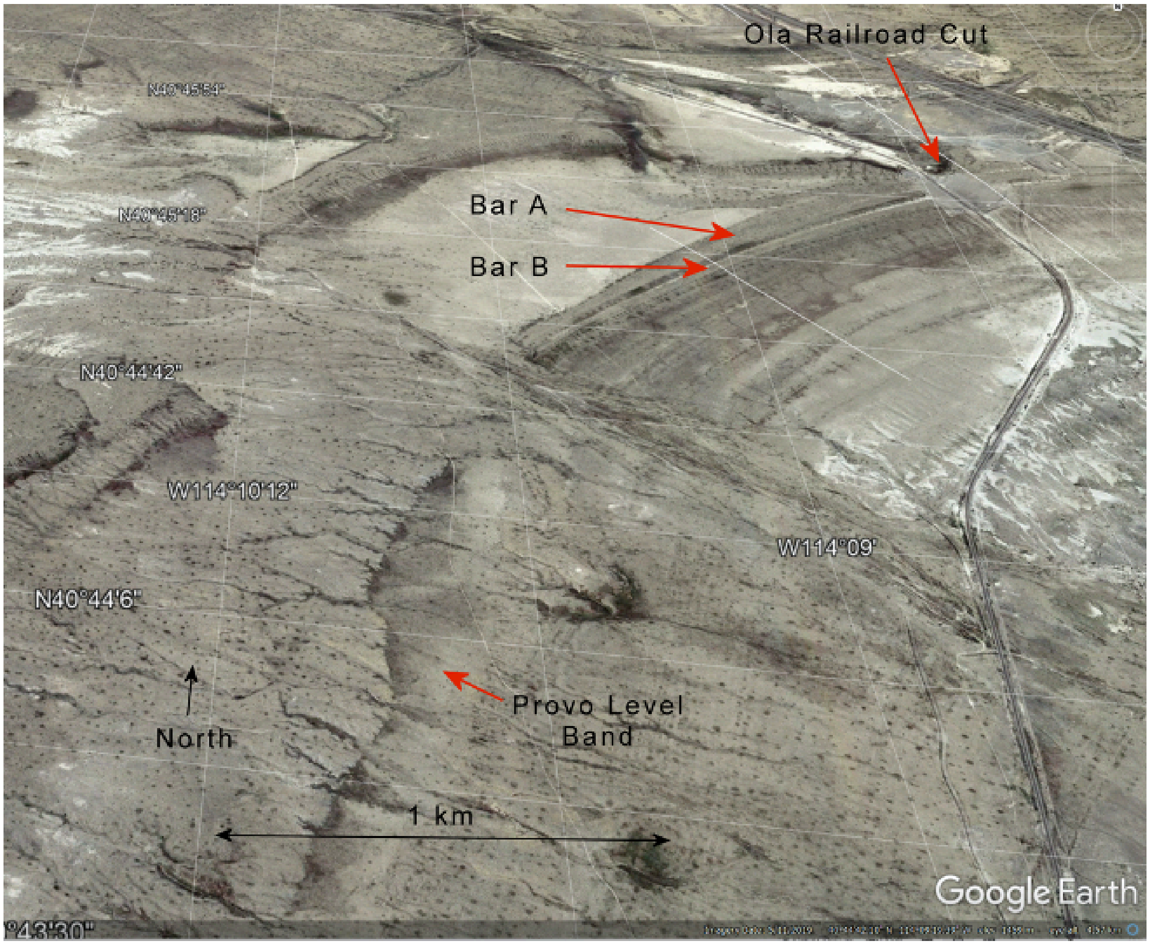

Figure 20. Google Earth™ view of Provo shorelines in the area of the Ola Railroad Cut. Shorelines manifest differently based on orientation and available loose material. (40°45′37.20″N, 114° 8′19.82″W)

The interesting thing about these two bars is how they fit into the broader context of the situation, or more specifically what is missing in the Ola railroad cut cross-section. Between the Bonneville Flood tufa layer and the Provo oscillation tufa layer is 9m of lake-bottom sediment with no evidence of bar formation, so the Provo level went through an extended period with no bar formation in this area. (Miller, et al, p. 350, Fig. 7) Above the Provo oscillation tufa layer are two bars, each about 4-5m thick, with no evidence of static lakebed sediment accumulation. Remember the earlier point that bars are quickly destroyed by normal shoreline wave action unless the level change is quick enough to preserve the bars. The physical evidence points to an extended Provo shoreline after the Bonneville Flood event, then a tufa forming level oscillation, basically an earthquake-induced surging event, followed by the formation of two shoreline bars by extraordinary wave action, followed by an immediate drop in lake level.

The Miller team did ^{14}C dating of gastropods recovered from three of the locations they studied, including the Ola railroad cut. The perennial problem of comparing dates between studies surfaces again, but fortunately, they dated a Bonneville Flood sediment in their work. Their 18.1kya cal date for the Flood corresponds to the 17.4kya date used in this paper, so all the following dates will be converted and referenced in the form: 17.4 (18.1) kya +/-0.4ky.

They dated the underlying tufa layer at the railroad cut at 16.6 (17.3) kya +/- 0.3ky, placing an approximated date on the Provo level earthquake-induced disturbance, about 800 years after the Bonneville Flood. Benson, et al. (2011) put the Bonneville Flood at 17.0kya and my interpretation of their core data and using their dating puts the Provo oscillation at 15.6kya. Janecke and Oaks (2011) put the Bonneville Flood at 17.4kya, the Provo oscillation at 15.9kya and the abandonment of the Provo level around 15.2kya, placing the occupation of the higher Provo level at 1.5ky and the lower Provo level at 0.7ky. Janecke and Oaks reference Benson for the 15.9kya date of the Provo oscillation. Benson uses the 15.9kya date at several points in his text, but his description of the sediment core places the date at 15.6kya, which is used in this paper.

This analysis results in a 1ky discrepancy between the Miller tufa layer and the Benson sediment core data, but everything else points to the two being the same event. Later in the Miller paper, he presents "Fig. 14. Plot of culled radiocarbon ages for the Provo beach deposits and associated offshore deposits and tufa." (Miller et al. 2012, p. 358). This is a typical timeline plot of the Provo shoreline ^{14}C data in the literature and the same data shows up in many papers. The data ranges from 18kya to 14kya (cal) at the Provo highstand with over half a dozen of the mid-age points showing up as being 30m below the highstand. Miller addresses this by indicating two possible Provo level scenarios in the hydrograph, one with the drop from the Provo level at about 16kya and the other with the drop at about 15kya.

Based on the physical data and trying to extract the dating information that appears most consistent, the drop from the Provo level most likely started at about 15.6kya, at the time of Janecke and Oaks disputed "mid-level drop" from the Swan Lake sill to the Clifton sill.

3.5. The fall from the Provo level – The Bear River Exclusion Theory - more than just a cautionary tale

No one can agree upon when the fall from the Provo level started, or whether there was an early and a late Provo level based on the Swan Lake and Clifton sills. Strangely enough, on the question of whether there was one Provo level or two, everyone is right, it just depends on the reference point. The Bear River Exclusion Theory presented here not only embraces all the data, but also explains previously ignored features.

Researchers have noted a correlation between the highstands of the numerous Pleistocene lakes in the Great Basin with the Heinrich 1 stadial, though the timing of the highstands varied widely in the region. They also found that the lakes of the region all fell at some point during an extended period between the H1 stadial and the Younger Dryas, though the supporting data is sparse and at times contradictory. (Benson, et al., 1990, Benson and Thompson, 1986, Munroe and Laabs, 2013, Reheis, et al. 2014). Clearly, the Great Basin moved into an extended dry period and different drainage basins had different responses.

In a 2019 paper studying lake level fluctuations in the Northern Great Basin from the late Pleistocene on, Santi, et al. found that "In many cases, lake transgressions to their highstand levels (from moderate stillstand levels) happened in a relatively short period of time between 17 and 14 ka, while regressions tended to occur over a much longer period." (Santi, et al., 2019, p. 183) However, she and others have consistently remarked on the fact that the fall of Lake Bonneville was quite rapid. (Reheis, 2014, Oviatt, 2014)

The history of Lake Bonneville's transgression and regression is summarized as follows: Sometime around 55kya, lava flows in the Gem Valley of southwestern Wyoming blocked the Bear River's course to the Pacific Ocean via the Blackfoot River, the Snake River, and the Columbia River (Pederson, 2018). The Bear River was diverted into the Bonneville basin and the addition of this major Uinta Mountains drainage was sufficient to start a long, gradual rise of Lake Bonneville. During this period, the Bear River developed a well-established meander channel along the valleys at the foot of the Wasatch Mountains, running south for 35km from the Oneida Narrows to the marshes of the present-day Bear River Migratory Bird Refuge.

About 25kya, during the H2 Heinrich Stadial, the climate in the region turned colder and wetter and the increased precipitation and decreased evaporation greatly accelerated the rise of Lake Bonneville. The wetter, colder climate continued to around 22kya when a glacial maximum was achieved in the Wasatch and Uinta Mountains, but melting glaciers overcame any shortfalls in precipitation and Lake Bonneville continued to rise until it became outlet-bound by the outflow at the Zenda threshold of the Marsh Creek alluvial fan. At about that same time, the climate entered the H2 Heinrich Stadial with another boost to precipitation in the area. The Bonneville Flood event occurred in this time period, but while dramatic, that was a sideshow. Lake Bonneville was overflowing before the Bonneville Flood and it continued to overflow for possibly 1.4ky after the Bonneville Flood (Janecke and Oaks, 2011 [Geosphere])

About the time H1 ended, something extraordinary happened: after over 30ky of a net positive water balance in the region, Lake Bonneville started to dry up at an unprecedented rate. There is nothing anywhere else in the Bonneville records to compare with what occurred at the end of the Provo level. In a few hundred years, this massive lake dropped over 150m in level, total freefall, and then it stopped, … and here is the problem: aside from the Younger Dryas blip and smaller fluctuations, the level has remained essentially unchanged for almost 15ky. By all rights, the shallow puddle of the Great Salt Lake should have dried up several times over. Other lakes

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in the Great Basin fell in level over the same general period and then more or less stabilized, but the data for Lake Bonneville is discrete in nature, or colloquially, like someone closed a valve, shutting off the water one day and then much later just opened the valve again.

Stealing a line from the detective novel genre, ‘here is what happened’. Lake Bonneville and the Great Salt Lake had and have four principal rivers as sources: the Sevier, the Provo, the Weber, and the Bear. According to the Utah Geological Survey, today the Bear River supplies nearly 40% of the water input to the Great Salt Lake (UGS website). It represents the largest single source of water feeding the Great Salt Lake. That is why the 55kya diversion of the Bear River into the basin was so critical.

The rising Lake Bonneville created lacustrine features throughout the basin. In a 2020 paper, Oviatt suggested that the very prominent Bonneville level benches were depositional in nature and built up over time (Oviatt, 2020). These benches can be observed adjacent to where the Bear River enters the Great Salt Lake Basin at the Cutler Narrows coming out of Cache Valley, and at that point, the deposits extend down and cover the Wasatch Fault in the area. As the lake level rose, these benches would have extended across the narrow gap of the Narrows. Earthquake-induced surging events would have carried those bench sediments into the Cutler Narrows gap, filling it to within meters of the lake level in any given event. A single surge can carry an enormous amount of material, as evidenced by the Stockton Spit discussed earlier. The top of the Stockton Spit is about 6m below the Bonneville highstand in that area, so it is reasonable to assume that the Cutler Narrows was filled to the same level. There is evidence of a Bonneville-level shelf just inside the Cache Valley that may be the remnants of surge spit from the Bonneville basin projecting through the Cutler Narrows gap. That sediment deposit does not continue beyond the immediate area suggesting that this is a spit-type deposit.

During the S17.4-Bonneville-1551 surging event, and the initial stages of the Bonneville Flood, the flow would have overtopped not just the obstruction in the Cutler Narrows, but also over 5km of adjacent ridgeline. This wide front would have defeated the formation of any barrier bars between the main Bonneville basin and the Cache Valley. Basically, insufficient material to dam off that broad a front with that great a flow.

As the surging died out and the lake level dropped during the Bonneville Flood, the flow would have channeled down to where it was all flowing through a 0.75km wide sluice in the Cutler Narrows. The flow would have eroded away the top layers of the soft sediments previously deposited in the gap, but as the flow started to be limited by the Swan Lake sill, the velocity would have dropped until it was just the flow necessary to maintain the level between the main basin and the Cache Valley. This flow preserved the connection between the two bodies of water, though it was probably at best a shallow connection or at times even just a river from Cache Valley into the Great Salt Lake basin. The Bear River was a major component of the Lake Bonneville water balance, so the net flow would have been from Cache Valley to the main body of the Lake, with the excess flowing out to the Pacific Ocean through Red Rock Pass.

For over a millennium, the Provo level of Lake Bonneville was controlled by the Swan Lake sill near Red Rock Pass. Then something happened to cut the Swan Lake sill down by 9m to the Clifton sill (Janecke and Oaks, 2011). Janecke and Oaks postulated an earthquake in the Cache Valley, though this paper has presented evidence that the event was much larger: the S15.6-Provo-1447 earthquake and surging event. The initial surge carried up into the Cache Valley and caused the erosion of the Swan Lake sill outflow.

The surging would have also carried more bench sediment material into the Cutler Narrows gap. The S15.6-Provo-1447 episode formed two successively higher bars on shorelines throughout the Bonneville basin (Miller, et al., 2011) and there is no reason to believe that this barrier would not have also occurred across the Cutler Narrows gap.

With the new, lower outfall, the level of the lake in Cache Valley quickly dropped to a level below the obstruction in the Cutler Narrows. Suddenly, the Cache Valley was no longer hydraulically connected to the main body of Lake Bonneville. With this, the flow of the Bear River was short-circuited directly to the new Clifton sill and down the Portneuf, Snake, and Columbia Rivers to the Pacific Ocean. Overnight Lake Bonneville lost 40% of its inflow. The region was already well into the dryer cycle between Heinrich events, and the loss of this flow was catastrophic. Without sufficient inflow to maintain the level, Lake Bonneville dropped rapidly and at a very consistent rate dictated by evaporation.

During this same period, the newly isolated 'Lake Clifton' in the Cache Valley remained well-fed by the Bear River and level limited by the Clifton sill. Janecke and Oaks write about the "landforms of an ancient meandering river" in the area between the Clifton sill and Red Rock Pass to the north (Janecke and Oaks, 2011 field guide, p. 204). They further elaborate: "The channel and floodplain of this large river system formed below, and after, the higher Provo shoreline."

One other comment of note by Janecke and Oaks: "The average wavelength and width of the meander belt are many times larger than those of the modern Bear River (Fig. 2) but are similar in scale to incised meanders that were cut by the late Pleistocene Bear River..." (Janecke and Oaks 2011b, p. 1384). The reason Janecke and Oaks found that the river going over the Clifton sill was the size of the Bear River of the time, was because it was the Bear River. The other significant point is that the Bear River of that time was larger than the current Bear River, so depriving Lake Bonneville of it would have a significant impact.

This explains why massive Lake Bonneville, which for at least 30ky had a water balance excess, suddenly started to dry up. The other part of the puzzle is that after maybe another half a millennium something happened and both the outflow at the Clifton sill stopped, and the lake level stabilized and started to fluctuate around the Great Salt Lake level.

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Janecke and Oaks have theorized about earthquakes in the Cache Valley, and on the Riverdale fault in particular, and that those might have both produced a seiche and disrupted the outflow at the Clifton sill. (Janecke and Oaks, 2011). Consistently, their findings have proven to be sound resources for events in Cache Valley. An earthquake in the Cache Valley that resulted in surging or seiche would have sent waves over the soft-sediment dam in the Cutler Narrows. Once overtopped, the dam would have quickly failed under such an onslaught and a flood into the Great Salt Lake ensued. The evidence on the west side of the Cutler Narrows in the valley of the Great Salt Lake is clear and unmistakable as being from a major flood event.

The Great Salt Lake basin had a well-established meander channel from the Bear River before being flooded by Lake Bonneville. The channel was well-preserved under Lake Bonneville with probably a few meters of lake sediment covering it by the time of the S15.6-Provo-1455 event. As Lake Bonneville rose, the slope leading up to the Cutler Narrows was buried under thick Bonneville and upper Provo shoreline benches.

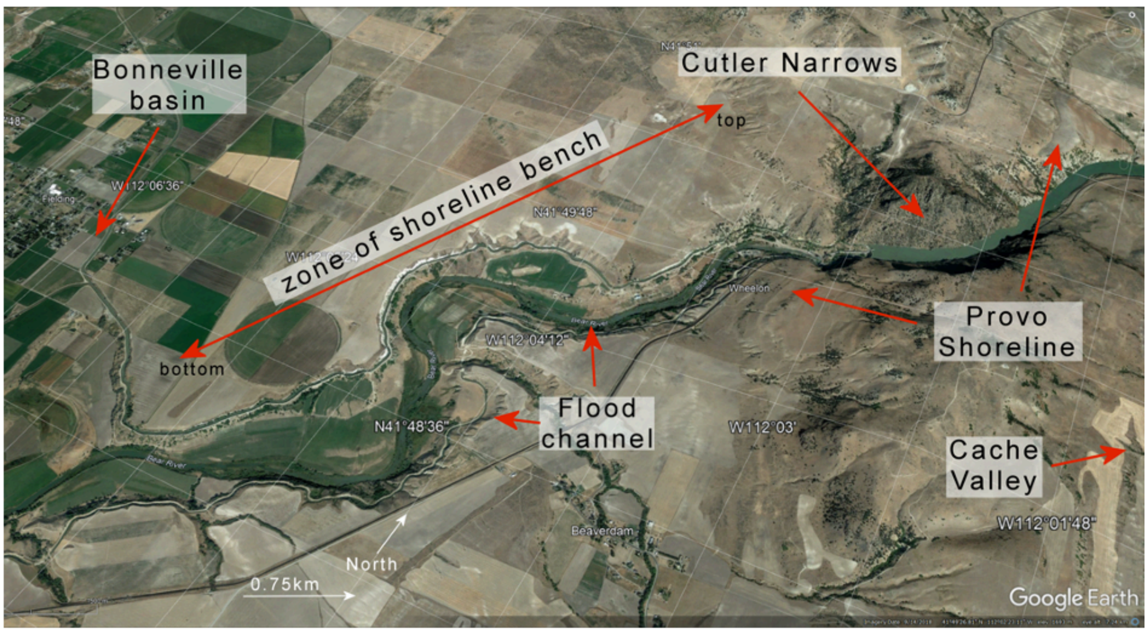

Figure 21. Google Earth™ view of the Cutler Narrows of the Bear River between the Cache Valley and the Great Salt Lake and Bonneville basin. The Provo level shoreline sediments formed a natural dam in the gap and isolated the Bear River from the western valleys during Lake Bonneville's fall from the Provo level. The dam failed catastrophically and created the flood feature leading down to the Great Salt Lake level, cutting through the transgression lake bench sediments. The flood flow spread out when it hit the valley floor before being captured by the ancient Bear River meander channel. (41°50′10″N, 112° 2′56″W)

When the Cutler Narrows dam broke and the flood into the Great Salt Lake ensued, it would have quickly cut a channel into the bench sediment on the lower slopes of the Wasatch Mountains at that point. That channel

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would have formed large sweeping turns as it cut the least-resistance path down to the valley floor. Once on the valley floor, it would have been captured by the historic Bear River meander channel. But the flow was too great and too fast to be constrained by the meanders and would have jumped the bends in the channel. All of this is readily visible today and the challenge to any alternate theory is to explain how these features could be consistent with any other scenario.

Figure 21 is a Google Earth™ view of the Cutler Narrows and the flood features cutting through the Bonneville benches. The cut is over 30m deep and the bends are sweeping. At the bottom of the bench, the flood hit the plain of the valley and spread out before being captured by the Bear River meander channel. Figures 22 and 23 are two of the meanders in the channel where the flood swept over the bend and filled the channel. Figure 22 shows the classic shapes of a burst flood path as is seen in the Missoula Flood landscapes. In Figure 23, the lines of the flood can be seen on the land between the current-day meanders. These flood features are prevalent in the meander channel and exceed what occurs with seasonal variations and 100-year storms. To put things into perspective, these features are over 35m above the current river level, and at Corrine, Utah in this same area, the largest flood in the last 20 years has been no more than 4m above river level.

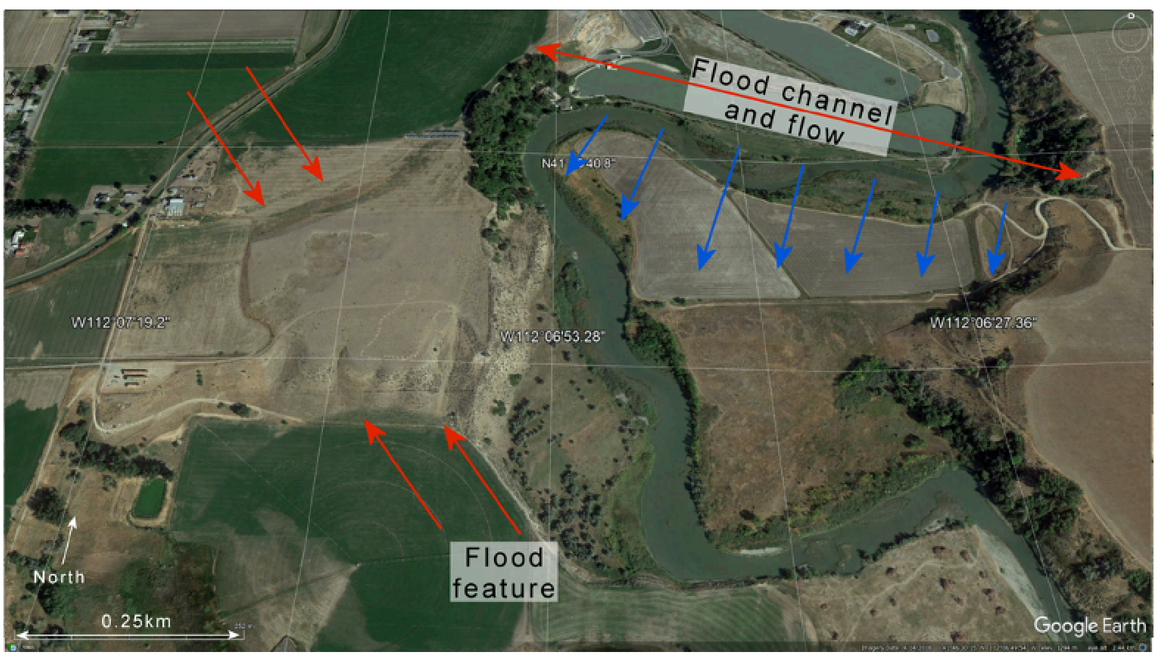

Figure 22. Google Earth™ view of a Cutler Narrows dam flood feature in the Bear River meander channel leading to the Great Salt Lake. Filling the channel, the flood swept over the banks and meander bends. On the left of the photo, it created a classic flood deposit with sides expanding out and a fluted base where it waterfalled into a previous meander in the channel. (41°46′28.03″N, 112° 7′4.19″W)

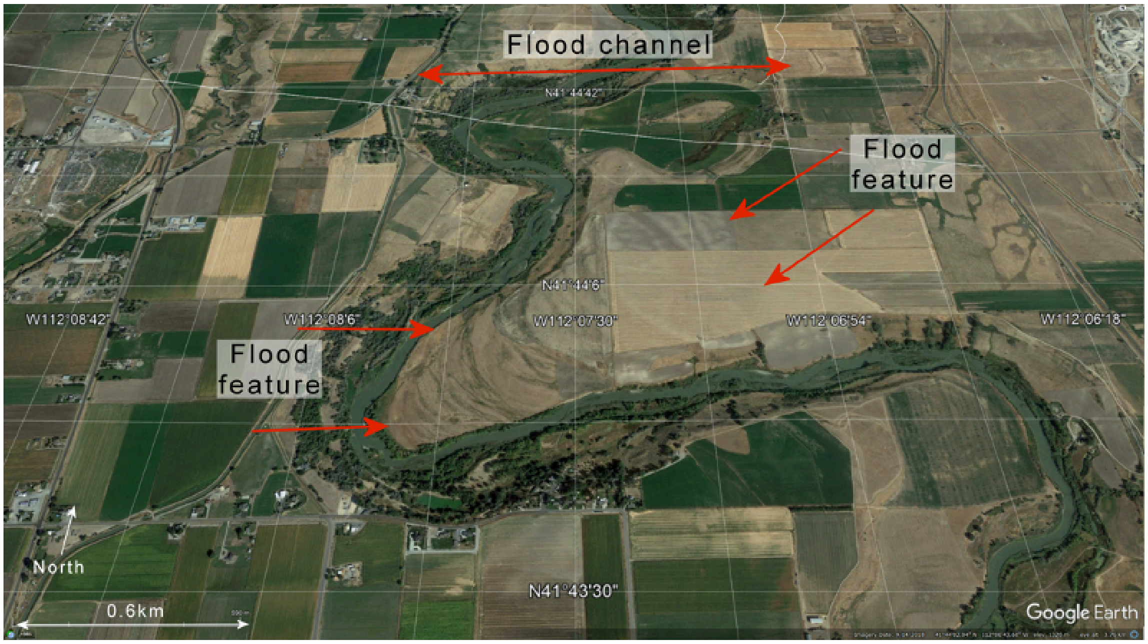

Figure 23. Google Earth™ view of a Cutler Narrows dam flood feature in the Bear River meander channel leading to the Great Salt Lake. The flood overwhelmed the meanders in the channel and repeatedly swept over the bends, leaving contours still visible in the plowed fields. The features in this meander bend are typical for the channel. (41°44′3.47″N, 112° 7′18.57″W)

Within the steep-walled Cutler Narrows gap, any evidence of the Bonneville-bench sediment dam has been erased by 14ky of erosion. Within the Cache Valley, evidence of either abrupt or gradual lowering of the lake level is missing, but it would have been obscured by subsequent farming in the area anyway.

The volume of water from draining Lake Clifton would have raised the level of the Great Salt Lake by 3-6m, though any evidence of that level bobble would have been lost in other lake fluctuations, such as the Gilbert episode.

The important consequence of the failure of the Cutler Narrows natural dam was that restoration of the Bear River flow to the basin immediately stabilized the level of the Great Salt Lake. This does open up a couple of interesting what-ifs. If the Cutler Narrows had remained open after the drop to the Clifton sill, and the Bear River had continued to supply Lake Bonneville, perhaps the lake would have continued as a freshwater lake at the Provo level. But that is just a 'what-if', the relevant question is what are the long-term consequences of diverting the equivalent of the flow of the Bear River away from supplying water to the Great Salt Lake today?

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3.6. *The Fresh Water Events*

Two other anomalous events stood out in the Benson study and these events do not fit the earthquake-induced surging model. There were two very dramatic low-concentration pulses in TIC (upward spikes on the graph, labeled Fresh Water Events X and V in Figure 12). Benson points to Dansgaard-Oeschger events 5 and 10 as possible causes for these types of spikes (Benson, 2011). I would like to offer another possible explanation for this and some of the other very abrupt and short-term drops in TIC concentration at this specific location. These spikes occur during the earlier and lower-level period of Lake Bonneville where a dilution stream into the Blue Lake area would be inordinately represented in the sediment record. This dilution could come from a flood flow into the lake from a storm or meltwater event, but such flows would most likely come from the mountains on the eastern side of the basin, though it is possible that events occurred in the western ranges. An alternate explanation might be a rapid release from a subterranean aquifer. The Blue Lake site is a spring-fed marsh today. A rapid release might be due to a seismic event local to that area, or it could be related to the rise of Lake Bonneville. The weight of the lake could have caused periodic collapses of the aquifer, releasing enough water to dilute the Blue Lake cove. In either case, barring additional evidence, these extreme-spike, low-concentration events are probably local and not basin-wide phenomena.

3.7. *A revised Bonneville Hydrograph*

The Lake Bonneville Hydrograph has gone through numerous iterations through the years. These timelines are based on ^{14}C dating of sediments combined with evidence from the traditional “shorelines” and judgment calls. The earthquake-induced surging theory puts some of those shorelines in question while introducing new time/level anchor points.

Figure 24 is a revised Bonneville timeline based on the findings in this paper. Bonneville timelines are by nature limited by the assumptions inherent in extrapolating between the available data. The rationale underlying this timeline is as follows:

45kya to S39-Fremont-1315 anchor point – The Benson core TIC and stratigraphic data indicate a rising lake level with numerous level fluctuations, as would be expected. There appears to be a wet period leading up to a Heinrich stadial of a couple of thousand years. There is insufficient data to indicate anything but an average-level trend during this period.

S39-Fremont-1315 to S30-Hansel-1335 – The TIC data suggests a fluctuating lake level, but the lack of stadials during this time period and the proximity in levels at the start and the end of this period suggest a stable climate.

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S30-Hansel-1335 to S24.7-Stansbury-1360 – This time period is dominated by the lengthy H2 stadial. The TIC data shows a transition to a wetter climate. However, the transition to a rapid level rise cannot have occurred until late in the period because of where the Stansbury event locks the level.

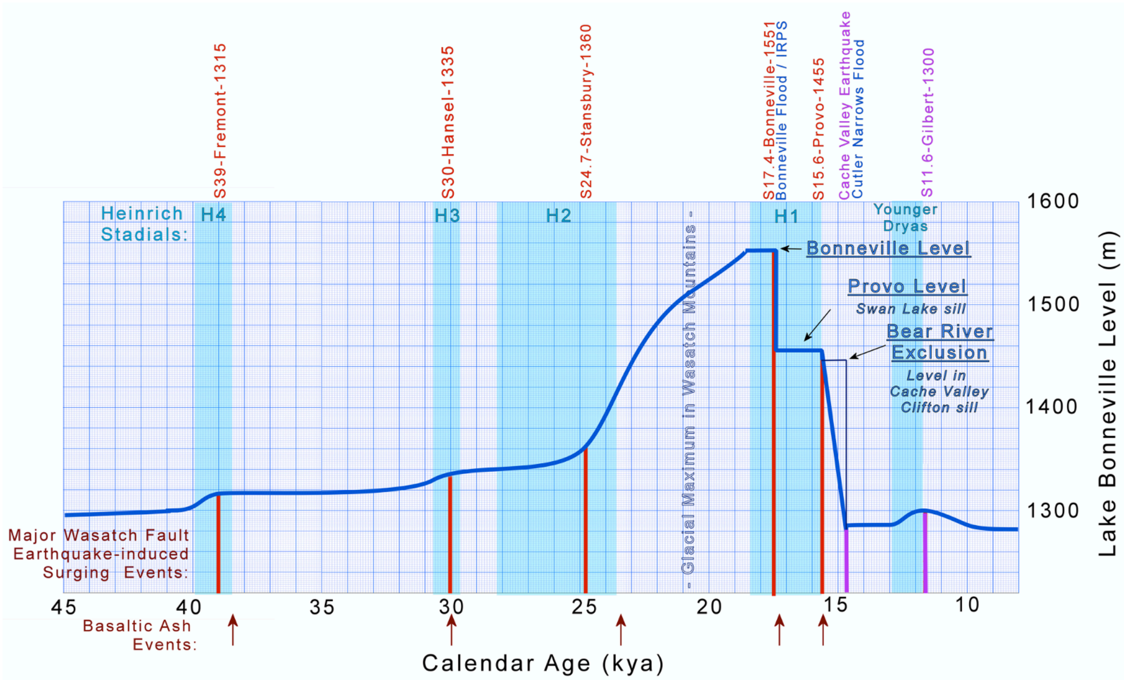

Figure 24. A 45ky hydrograph of Lake Bonneville based on the findings of this paper. The level anchor points are the earthquake events detailed in this paper. A slight bow is depicted between S24.7-Stansbury and S17.4 Bonneville to reflect the changing shape of the basin at higher elevations and attempt to account for the dispersed 14C data of other researchers. Over the 45ky period, there would have been constant fluctuations, but the details of those are beyond the resolution of this analysis. The thinner line level coming off of the fall from the Provo level indicates the level of the residual lake in the Cache Valley while all of the Bear River flow channeled directly to the Clifton sill outfall without contributing to the hydraulic balance of Lake Bonneville. S24.7-Stansbury-1360 to S17.4-Bonneville-1551 – This is the period of the dramatic rise of Lake Bonneville. ^{14}C dating data chronicles this rise, but it leaves a confusing pattern of date reversals. Diversion of the Bear River into the Bonneville basin would complement climate changes to explain such a rise, but candidate diversion locations for the Bear River or other feeder rivers have not been identified. The glacial maximum in the Wasatch and Uinta Mountains occurs around 20.7kya, suggesting a transition to a warmer climate. Glacial melting may have contributed to the continued rise of Lake Bonneville. The date that Lake Bonneville overtops the Marsh Creek alluvial fan near Zenda Idaho is a subject of debate.

The flooding of shallower arms of the lake as it rose suggests there would have been a change in the rate of level rise as the arms filled. Additionally, a decrease in inflow would be expected following the glacial maximum in the mountains feeding the basin. A change in rate is also suggested by the general trends in the diverse ^{14}C data in the literature. The drawing of the curve in this time range is subjective.

S17.4-Bonneville-1551 to S15.6-Provo-1455 – This period starts with the Bonneville Flood. While the lake level dropped by over 100m, the lake continued to overflow so the final transition to a dryer climate occurred after this. This period is neatly bracketed by the H1 Heinrich Stadial, suggesting that this colder and wetter period may have contributed to the continued overflow. Of note here is the comparatively short period of time between the Bonneville and Provo seismic events. This opens the question as to whether the offloading of the crust due to the Bonneville Flood resulted in 'unlocking' the Wasatch Fault and allowing more frequent earthquakes.

S15.6-Provo-1455 to S11.6-Gilbert-1300 – At the start of this period, the Provo level in the Cache Valley dropped from the Swan Lake sill to the Clifton sill, isolating the Cache Valley from the main body of Lake Bonneville and preventing the Bear River from contributing water to the main basin. Lake Bonneville then dropped to levels near the current Great Salt Lake level. How quickly the level dropped is difficult to determine because of the distribution of the ^{14}C data.

The failure of the natural dam in the Cutler Narrows spelled the end of the fall and caused Lake Bonneville to rise by the volume of water held in Cache Valley. According to Oviatt, after the fall from the Provo level, the lake was close to the average level for the Great Salt Lake (Oviatt, 2014). As to when this occurred, Oviatt only states that the lake fell to that level "before 13,000 calibrated" (Oviatt, 2014, p. 1). Two points that might help in determining that date would be identifying the date when the Clifton sill was abandoned, and then checking that against any evidence of a Cache Valley earthquake in the same time period.

3.8. Earthquakes and the Climate

The earthquake-induced surging events identified in this paper are supported by the lake sediment data and aspects of the shoreline deposits. The apparent one-to-one correspondence with ash eruptions in the area adds support to this argument and necessitates the consideration of other seemingly coincidental events.

Those still hanging on to the climate oscillation theory should have picked up on the fact that all the earthquake-induced surging events are within timeframes identified with Heinrich stadials (Figure 24). The exact timing of these stadials varies between researchers. (Hemming, 2004) But the spikes in TIC concentration occur during the Heinrich events and there are no Heinrich events in the time period without TIC spikes, putting the burden of proof on someone arguing against a climate link. I am left with either suggesting the correlation is a coincidence, which I do not believe, or I have to suggest there is a link between the weather and a multi-segment earthquake on the Wasatch Fault, which sounds absurd. I will risk going with that later because that is where the data leads.

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The theory of climate-based level oscillations in Lake Bonneville holds that the Heinrich events resulted in dramatic dry spells in the region which resulted in large evaporative water losses from Lake Bonneville. However, the 2018 work by McGee found that during the periods around a Heinrich event, the lake levels in the Great Basin rose at a faster rate (McGee, et al., 2018). This opens up a very intriguing possibility that enhances our understanding of isostatic response due to lake load, our understanding of the climate in the region, and our understanding of the Lake Bonneville levels during this period. If a Heinrich event results in an accelerated rise in the lake level, the result would be a rapid rise in stresses in the crust due to increased isostatic deformation. Isostatic effects are often transferred to adjacent faults (Wernicke and Axen, 1988). The isostatic stress induced in the Wasatch Fault would be additive to the normal block fault stresses. Consequently, there could be a correlation between Heinrich events and earthquakes on the Wasatch Fault, if a jump step in loading due to a rapid lake level change accelerates the occurrence of an already inevitable fault slip. A 2021 work by Egger et al. suggests just such a link can be demonstrated in lakes in the northwestern part of the Great Basin. (Egger, et al., 2021)

This leads to an interesting question: can relatively small step changes in lake level trigger otherwise overdue events on segments of the Wasatch Fault? The timing of events during the Lake Bonneville period certainly presents this as a possibility. In recent history, the Great Salt Lake rose a little over 6m between 1963 and 1987 with no corresponding events on the Wasatch Fault.

4. The Isostatic Rebound Pop Seiche (IRPS) Theory – detailed evidence of a climate-related hazard

Arthur Conan Doyle gave Sherlock Holmes a great line: “How often have I said to you that when you have eliminated the impossible, whatever remains, however improbable, must be the truth?” (Doyle, 1890)

That line consistently applies to Lake Bonneville. Unfortunately, a scientific paper is different from a mystery novel in that you have to lead with the startling revelation that the novel would leave for the last page, thus robbing the reader of the enjoyment of solving the mystery along with the researcher.

There are somewhere around 50 shorelines visible in some of the more protected coves in Lake Bonneville. A subset of those shorelines, which have received extensive study, are what Gilbert named ‘The Intermediate Shorelines’. This refers to the shorelines that appear on the mountainsides between the Provo and Bonneville levels. With these shorelines, a simple understanding of physics eliminates the impossible, as well as the current theories, and leaves the improbable truth of a good mystery novel.

4.1. The Intermediate Shorelines

When Gilbert first studied the intermediate shorelines, he recognized that, since the Bonneville Flood and the drop from the Bonneville level to the Provo level was such a decisive and short-term event, these intermediate shorelines had to be transgression events formed over the broad expanse of time. Oviatt, in his 1997 study correlating Lake Bonneville fluctuations and global climate change, identified three climate oscillations in this period: U1, U2, and U3 (Oviatt, 1997). These were based on the analysis of sediment cores along with shoreline deposits. Nelson expanded this to six intermediate shorelines in his doctoral dissertation (Nelson, 2012). The last of these was the double shoreline of the late Provo level, previously discussed. In a 2015 paper, Nelson and Jewell studied three shore-zone gravel wedges between finer-grained offshore sediments on an exposed slope of Hogup Mountain in the north-central part of the Bonneville basin (Nelson and Jewell, 2015). They interpreted the middle of the three as corresponding to Oviatt U2 and identified the other two as new climate oscillation events. A dating reversal appeared in their carbon dating of the middle event, but those types of reversals have been common in Bonneville carbon dating. The earlier presented figure of the Oviatt climate oscillation timeline (Figure 2) shows carbon dating results and the scatter of the data makes it difficult to decisively support any conclusion.

Gilbert identified a problem in these intermediate shorelines because he found little to no correspondence between the shorelines in one location to those in another other than what might be "referred to fortuitous coincidence" Gilbert, 1890, p.139).

In a later work, Jewell (2016) was able to correlate a few of the shorelines. Schide did an excellent analysis of these shorelines in a 2016 Master's thesis, available at the University of Utah website, and a subsequent peer-reviewed paper. (Schide, 2016, Schide, et al., 2018) Anyone interested in Lake Bonneville should read Schide's Master's thesis.

One of Schide's findings was that:

> "Lake Bonneville barriers display a wide range of morphologies determined by local sediment supply, wave energy, and other geomorphic conditions. The formation of these barriers cannot be described with one single theory since local factors have greater control on their elevations, shapes, and positions than basin scale water level changes." (Schide, 2016, p.38)

4.1.1. Definition of terms – Intermediate shoreline, bar, closed-spit, and spit. In this paper, the term "intermediate shoreline" refers to the distinctive bars in the elevations between the Bonneville and Provo shorelines, as opposed to the spits and long-shore erosion features in that zone. Spits and long-shore erosion features are often the result of different processes than shoreline bars, and as both Gilbert and Schide point out, in the Bonneville record there is frequently no correlation between the elevations of the shorelines and the bars between different areas of the lake.

In the western arms of Lake Bonneville, spits often take the form of wedding cake layers. This is prevalent in the levels just below the Bonneville highstand. (Thomas, 2014) If this were due to level standstills, you would expect corresponding level formations in other locations, which there are not. If these were storm events, that would require a surprising sequence of decreasing intensity of storms over a short period of time to create such a tiered formation. Earthquake-induced surging would create this type of tier sequence, in fact, it would be expected. The first surge would be the largest and occur at the deepest level and then each succeeding slosh would create a progressively higher and smaller (shorter) spit. The top of each tier would not only be a function of lake depth in the area but also of the local velocity of the surge, so there would be little correlation between tier elevations at different locations in the basin.

The basic physics of the formation of a spit is different from that of a bar unless the bar is formed by long-shore currents off a point of land (which would make it a closed spit). Spits are formed at eddy lines off of points of land. In this paper, I will restrict bars to what is formed when waves or surges perpendicular to shore draw sediment down into a transition zone to deeper and lower velocity water where the sediments immediately drop out.

4.1.2. The Intermediate Shoreline bars of Matlin Basin. Matlin Basin is in the western reaches of the Bonneville basin. (Figure 1) The First Transcontinental Railroad ran across the mouth of the basin. Both the Provo and Bonneville bars are evident here. This is a particularly useful location since it is sheltered from the east-west surge of the multi-segment events on the Wasatch Fault and yet it is exposed to the center of the lake. A cove such as this allows softer sediments to settle in and not get washed away in a storm or surging event, the result is a canvas upon which the events of the lake are recorded.

Below the Bonneville level bar and above the Provo-level bar in Matlin Basin are six readily identifiable additional bars, the ‘Intermediate Shorelines’. (Figure 25)

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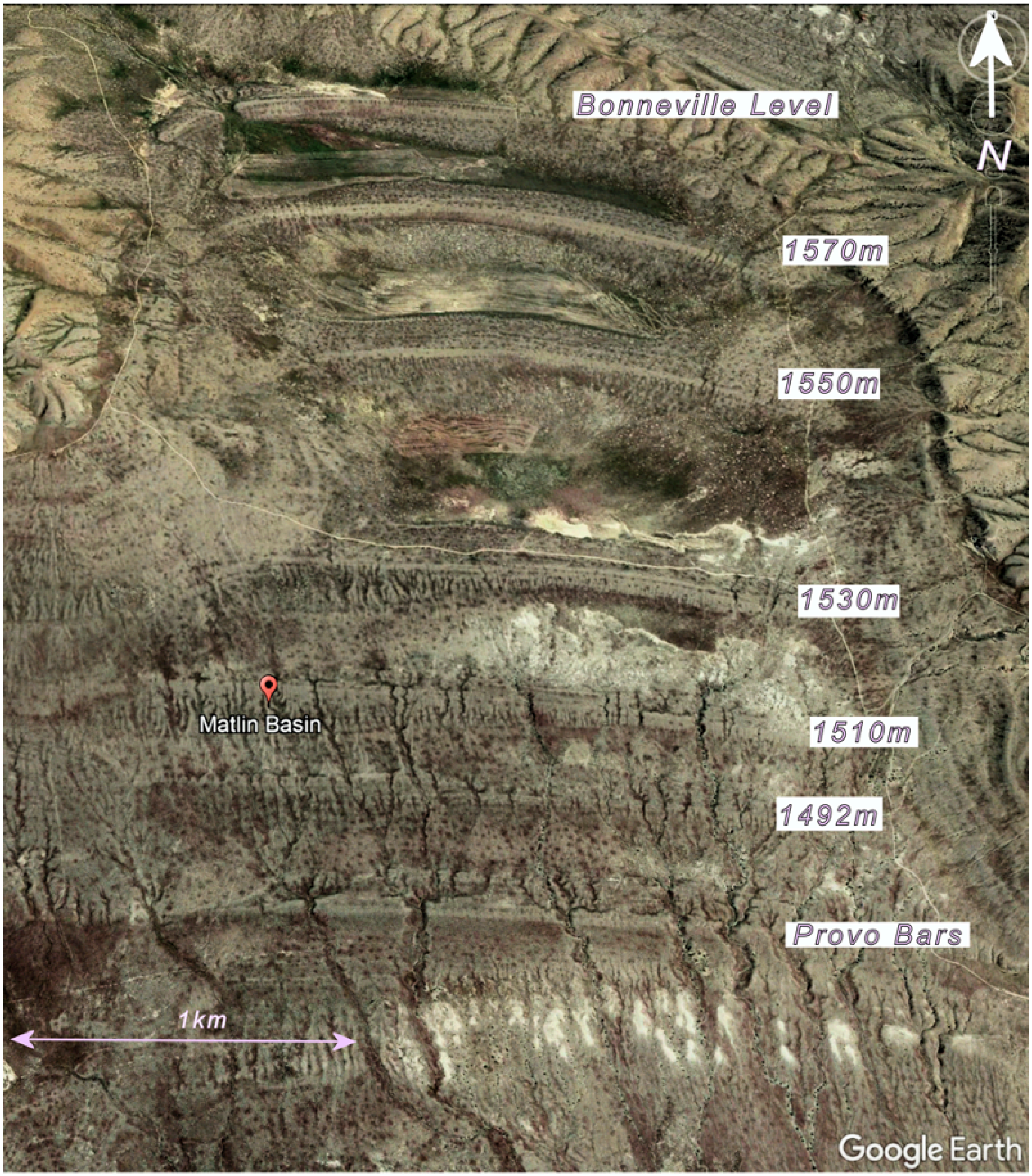

Figure 25. Google Earth™ view of the bar formations of G.K. Gilbert's 'Intermediate Shorelines' in Matlin Basin. (41°36′N, 113°20′W)

Under the widely-accepted climate oscillation theory, each of these Intermediate Bars formed during the lake's transgression and each at the peak of an extended dry period where the lake level dropped by over 20-50m followed by a wet period which exactly mirrored the dry period and raised the level back up. As previously noted, if these were climate events, variations in the flora and fauna records would be expected, but none have been identified. Such large climate-based oscillations might also be apparent in the sediment cores. In his 1997 paper, Oviatt did a chemical analysis of core samples and while there were fluctuations in the $CaCO_3$ and isotope concentrations throughout the transgression (Oviatt, 1997), it would be difficult to pick any potential climate-based fluctuations out from the noise in the data. The smaller, more frequent fluctuations in chemical composition are likely due to large storm events or short-term differences in annual rainfall.

Schide did a ground-penetrating radar examination of these intermediate shoreline bars in the Matlin Basin. What she found was that the Bonneville highstand bar was striated, and the deposits sloped towards the open water. The earthquake-induced surge would have formed this bar very quickly, similar to a storm surge. The smaller waves generated as the event died out would gradually diminish in size so this underwater bar would have layers that towards open water, which is consistent with what Schide found.

In contrast to the Bonneville level bar, Schide found that in all the Intermediate Bars, the strata sloped shoreward (upslope), indicating that the bars were built in an environment of rising water levels. This would support the well-accepted conclusion that these bars were formed during lake transgression. Schide discussed the normal bar formation and destruction process: bars normally form in the large waves associated with a storm, but after the storm passes the smaller, normal ocean waves start to erode away the bar. In a rising level situation, the level rise would have to occur very rapidly to avoid the bar being quickly eroded away in the over-topping process. From this, she derives the only logical conclusion and that is that after every one of these level drops or pauses, there was an exceptionally rapid level rise in this massive lake which preserved the bar. The problem with this necessary condition is that a single incident is a fortuitous coincidence, but a recurring pattern suggests that something else is in play.

Figure 26 is a Google Earth™ elevation profile of the Matlin Basin with each of the shorelines indicated with maximum elevations of each shoreline. It is apparent both visually and in the numbers that these intermediate shorelines occur at regular intervals. A consistent pattern such as this requires a harmonic system or a regulated system. To date, no one has proposed climate cycles that correspond to this frequency of bar formation.

When all you have in your toolbox is a hammer, everything looks like a nail. That applies to both the climate oscillation theory and the earthquake-induced surging theory. As with the climate oscillation theory, there are numerous and insurmountable problems with trying to tie the intermediate shorelines with the earthquake-induced surging theory. First, these shorelines don't exhibit the tufa deposits typical of surging. Second, there is no evidence of the large level swings in shorelines at the east and west extremes of the lake which would correspond to surging at the times these bars were formed. Third, these do not correspond with anomalous sand layer evidence in the deep-lake sediment record, anywhere. Fourth, the TIC records in the lakebed sediments do not support it. Fifth, where the earthquake-induced surging bars of the Bonneville and the double

Provo levels exhibit the outwardly sloping deposits of an initial surge followed by smaller waves, the intermediate shoreline bars are shoreward-sloped and were formed in rising water. Finally, there are no basalt ash eruptions that seem to support multi-segment earthquake events corresponding with the intermediate shorelines. These shorelines are not the result of earthquake-induced surging.

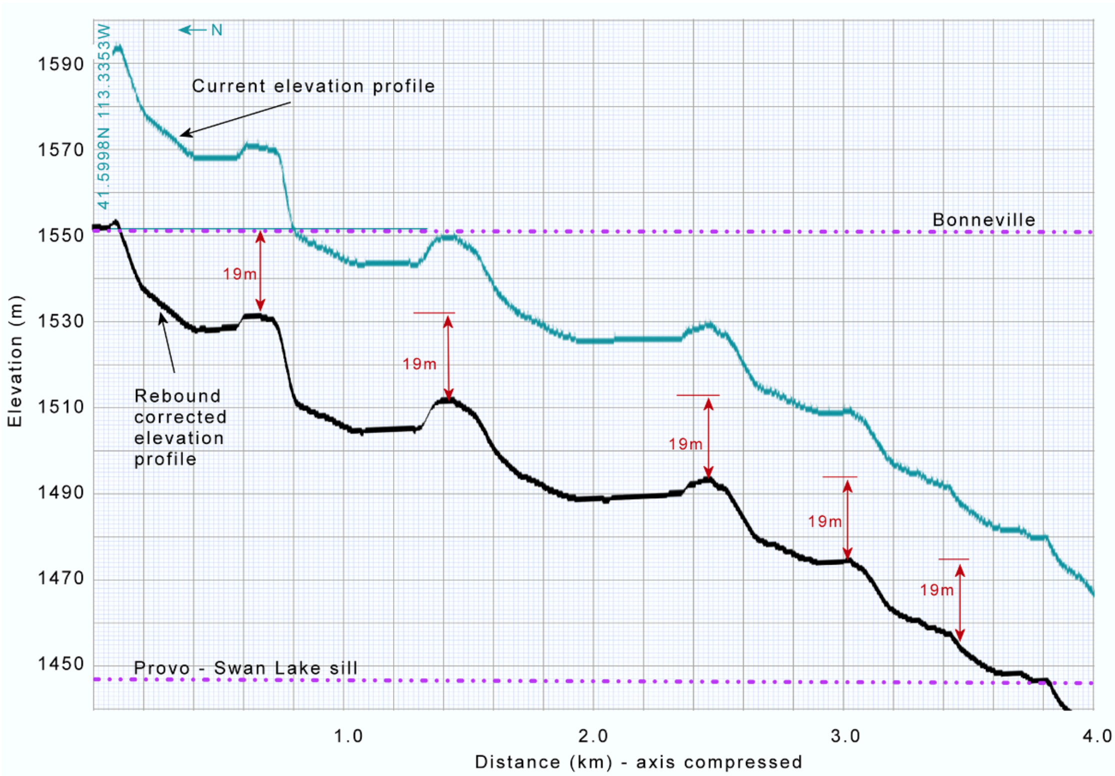

Figure 26. A Google Earth™ elevation profile of the Intermediate Shoreline bars in Matlin Basin. The rebound correction uses the Bonneville and Provo levels as anchor points. The bar height differences are taken at the highest point of each bar. The uniform steps between bars, in addition to the nature of the deposition in each bar, are taken as indicators that they were formed by Isostatic Rebound Pop Seiche (IRPS).

Everyone from Gilbert on has said that these shorelines were formed during a transgressing lake, and logic and the data certainly seem to support that. These are large bars, and it would take a long-static lake level to form each of them. The bars exhibit sediments consistent with a rising lake. The lake regression through these same levels was during the Bonneville Flood and occurred quite rapidly. Most importantly, the ^{14}C dating data of the materials in these bars indicates that they are composed of lake transgression sediment. That the ‘intermediate shorelines’ are transgression features is accepted as an immutable fact about Lake Bonneville. But that is not what happened.

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4.1.3. The Isostatic Rebound Pop Seiche Theory. The intermediate shorelines are not transgression features formed over extended periods, instead, they were formed thousands of years later during the Bonneville Flood and in a short period of time.

During the Bonneville Flood, there was a rapid unloading of the crust and isostatic rebound occurred. Rather than the rebound occurring smoothly, the system was sticky. The rebound occurred in "pops". In engineering terms, it was a regulated system. The load of water in the basin depressing the crust was the regulator. The load was being removed at a controlled rate; the Red Rock Pass weir formation was the controller. When enough weight had been removed, the inherent stickiness or friction in the system was overcome and the crust popped upward.

Judging from the evidence, each pop was not a single jolt but a groundwave shaking that set up a seiche in Lake Bonneville. This radiated out and explains the wave energy distribution seen by Nelson in his work; wave energy was independent of fetch and wind direction. (Nelson, 2015) These standing waves created the striated levels in the bars identified by Schide. The rebound pop lifted the center of the lake, displacing lake water outward to the periphery and thus the perimeter shorelines rose during the pop. This resulted in the bars exhibiting the inwards slope of a rapidly rising lake level. But as soon as the pop ended, the ongoing Bonneville Flood quickly lowered the lake level, preserving the bars in pristine form. This explains why the bars are better preserved than you would expect if they had undergone several thousand years of transgression.

In the remainder of this paper, the phenomenon will be referred to as Isostatic Rebound Pop Seiche or IRPS ("urps").

Bar formation was facilitated in these events because shoreline sediments of the rapidly falling lake were still saturated at depth, so the shoreline would be easily molded by the waves, both sloughing down from above while being built up from below with the incoming waves.

The refuting evidence to this theory would appear to be the carbon dating data associated with these bars. Referring to the climate oscillation timeline presented earlier (Figure 2), the carbon dating evidence in each bar is consistent with the dating of the lake transgression, though the distribution has an incredible level of noise. The noise has been explained as supporting evidence of the huge climate-related level swings. While it might seem patently ridiculous to suggest that all this data is an indication of a short-lived event thousands of years later, it is just that.

During the transgression, the shoreline sediments were laid down at the appropriate levels with the appropriate time stamps and then the lake rose, leaving the lower levels in peace with their time stamps secure and in order and the smooth shoreline of a gradually rising lake. When the Bonneville Flood occurred, it rapidly retraced all those shorelines in reverse sequence, pausing just very briefly at pop intervals to rip up the sediments at each

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pop level in turn and redistribute the old carbon into the new feature of a bar. Each bar received a level-appropriate time stamp, but not a time-appropriate time stamp, the old time stamp was just shuffled and reused. Date reversals would be expected, and they are present. Carbon dating would become a matter of chance, side-by-side buried shells would have two different dates and the time stamp would depend on which was tested.

This brings us to the important question: why did this massive, massive system exhibit such a regular pattern of IRPS in the Intermediate Shorelines? In Figure 26, the Google Earth™ elevation profile has been corrected for a rebound by matching the Bonneville highstand level to 1551m and what I identified as the early Provo level in the elevation profile to the Swan Lake Sill at 1456m, using Red Rock Pass elevations per Janecke and Oaks (2011) as the elevations with rebound removed. The level differences between the bars indicated in the figure are taken as the difference between the highest point of each bar. At the two ends the reference points are the Bonneville highstand and the early Provo level / Swan Lake sill. Nelson, in his PhD thesis. was studying rebound models and used this type of profile of this cove and other bars sites to test a general rebound model. The general model he used resolves the Provo shorelines to a slightly different elevation, whether this is due to the difference between a site-specific model and a general model or simply the result of different identifications of the Provo level is not important. While the exact correction can be debated, it will not materially change the result of this analysis because it is the relative changes that are important.

There are five steps between the Bonneville level down to the early Provo level. Each step was 19m +/- 1m and that was how it sorted out in the first parsing of the data. Even if the steps had varied by a few meters, the consistency between steps is extraordinary. Identifying the controlling variable will provide insight into the behavior of the crust in this area under the effects of isostasy.

First, consider the element of time as the potential controlling variable. As stated earlier, the Bonneville Flood was a controlled system, with the decrease in load on the crust being modulated by the flow rate through the Red Rock Pass weir. At the higher levels, the flow rate through the pass would have been higher, but the level drop is a function of both the flow rate and the volume to be drained at each level. Using the surface areas calculated by Adams and Bills (2016), the volume in the first meter of the Bonneville Flood was 52.11 billion cubic meters and the volume in the last (Provo level) meter of the Bonneville Flood was 38.15 billion cubic meters. While it is possible that the decrease in weir flow exactly matched that, it is unlikely. Lake Bonneville has many shallow arms so there would be a fair amount of variability. Step changes in flow rate would be expected. Time is most likely not the controlling variable.

The second possible controlling element is the total weight of the lake. This is certainly one of the expected controlling variables. The first meter of level loss at the Bonneville highstand represented about 52 trillion kilograms, whereas at the Provo level, the last meter of level loss was 38 trillion kilograms. Total weight loss does not account for the consistency in isostatic rebound pops between the first pop and the last.

The one controlling element which would yield a result just dependent on the level drop is hydrostatic pressure. Mathematically, weight is the product of density, area, and depth. Hydrostatic pressure is just weight divided by area. Area cancels out and what is left is density times depth. At this location, during the Bonneville Flood, the amount of rebound in each pop was based primarily on hydrostatic pressure.

There is a problem with this finding and that is that in the many studies of isostasy and specifically isostasy in Lake Bonneville, the bowing of the crust is dependent on total weight. Total weight was still a factor during the Bonneville Flood, the reason things resolved to hydrostatic pressure in the Matlin cove was probably due to weight distribution in the basin. At the Bonneville highstand, the lake ran up quite high on the steep sides of the mountain ranges of the Basin and Range region. The shallow arms were all to the south. These arms to the south were sufficiently removed from the main body of the lake to be supported locally by the crust. The change in lake surface area during the Bonneville Flood occurred primarily in the somewhat independent southern arms. The area change in the northern portion was minimal and thus the amount of deformation of the crust in the Matlin Basin is resolved to being mainly, not exclusively, dependent on depth.

That the spacing of the intermediate shorelines can be accounted for through simple engineering principles is the final argument as to why these shorelines are the result of IRPS during the Bonneville Flood.

Reality is rarely that simple. In Matlin Basin, there are four Intermediate Shorelines, but in other locations, there might be six, eight, or even a couple of dozen. Resolving the Lake Bonneville Intermediate Shorelines between different locations has been a perennial issue in Lake Bonneville research. This is because the Intermediate Shorelines are products of wave action during IRPS events, and those were highly dependent on position in the Bonneville basin and on local topography. Specifically, the differences are due to a mix and match of the following:

a. A seiche in this case is a harmonic response set up by the vibration of the crust popping back up after a decrease in load. At this point, we do not know how fast the pop occurred. The evidence in Lake Bonneville suggests that it was not a single pulse, but that it occurred in somewhat uniform steps and each step was a shaking affair with harmonic vibrations. Matlin Basin suggests that there were five principal steps or pops between the Bonneville and early Provo levels in the center deformation bow. Since a seiche is a harmonic, in the simplest case, those would be standing waves that radiate out from the source of the vibration, or in the case of a bowed crust under Lake Bonneville, the region of greatest deformation of the bow. Side canyons with a straight fetch towards the center of the basin in which the harmonic is established would have clean, large bars. Obstructions and restricted channels would tend to break up the harmonic into smaller waves, creating a series of smaller bars.

b. The isostatic pop shifted water from the deep center to the perimeter. The effect was that the shorelines in the center of the lake moved lower on the slopes and the shorelines on the perimeter got higher. Matlin Basin experienced a rising shoreline during the pops, hence the bar sediments exhibited signs of a rising level. Near the center of the lake, any IRPS bars should show evidence of a falling level and slope towards the lake, or as may be the case on the Newfoundland Mountains, the seiche waves acting on a rising shoreline may have eroded away the bars as quickly as they were being formed.

c. The slope matters and may be a second way of forming bars of different sizes. As a slope flattens out, the seiche breaks up into smaller waves forming smaller and more frequent bars. In a very steep slope, the angle of repose of the material comes into play and two pops can combine into one as a new seiche undercuts the platform formed by the previous seiche until a stable platform is formed.

d. Obstructions can break apart a large seiche pattern into smaller waves. Figure 27 is a Google Earth™ view of bars at a location 25km northeast of the West Desert High School in Partoun, Utah. This is an example where obstructions at the mouth of a cove splintered the seiche waves and left a pattern of main IRPS bars breaking up into a series of smaller bars.

e. After the rapid drop of the Bonneville Flood, the crust had more time to adjust to the sub-Provo level changes. This may have resulted in more frequent and smaller pops. This will be covered in more depth later.

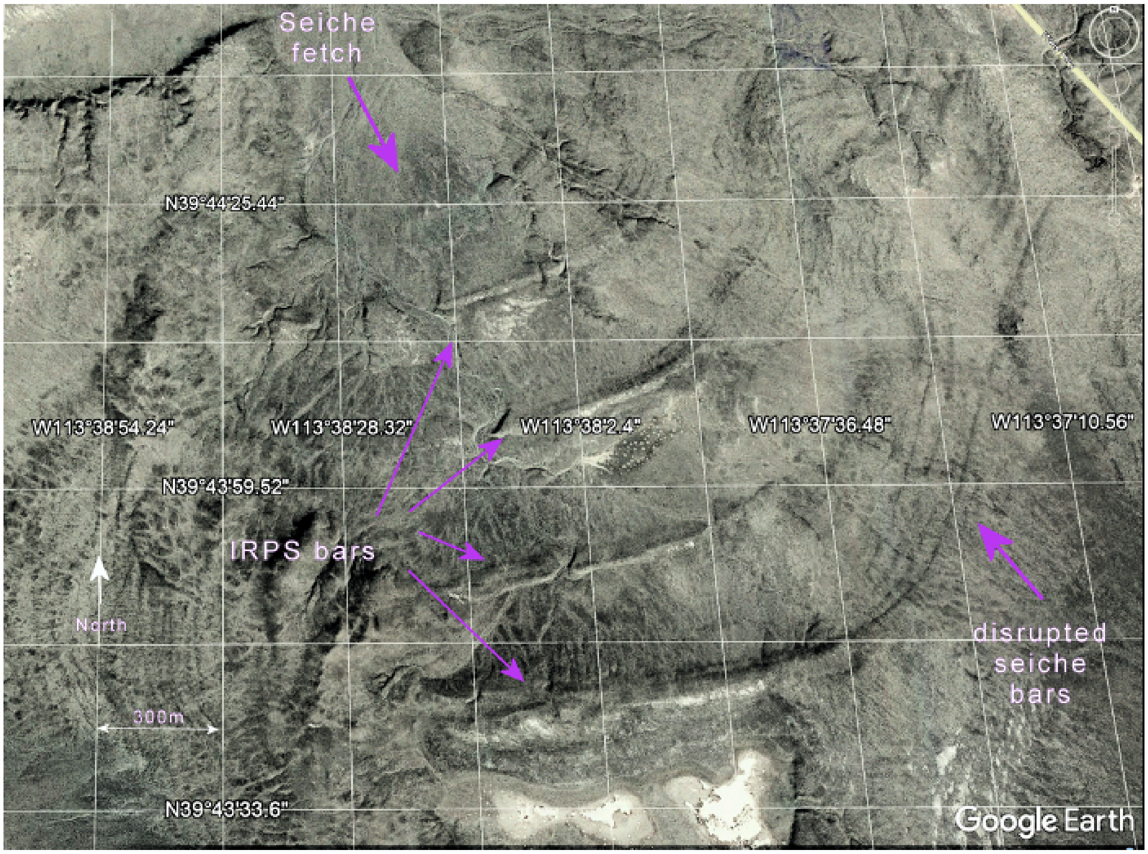

Figure 27. Google Earth™ view of IRPS bars in a cove that splintered into smaller bars due to an obstruction at the mouth of the cove. The straight fetch developed bars consistent with the large steps in the Matlin Basin far to the north. (39°43′48.36″N, 113°37′35.08″W)

4.2. The Provo level Shorelines

The two Provo level shorelines studied by Miller, Oviatt, and McGeehin (Miller, et al.,, 2012), occurred in the short time period after the 15.6-Provo-1455 surging, judging by both their position above the tufa layer and the dating of the sediments.

These particular bars were not a result of earthquake-induced surging. Examining the bars throughout the basin, they do not have the cycle node/antinode variation between the center of the lake and the extremes.

They could be IRPS features or waves from a mid-basin earthquake. However, the most likely candidate would be waves from aftershocks on the Wasatch Fault after the main surging of the Provo level event had subsided.

Miller, Oviatt, and McGeehin postulated that they might be evidence of landslides at the Bonneville outfall near Red Rock Pass raising the level of the lake to establish new shorelines. However, the Bear River Exclusion

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theory presented here has Lake Bonneville hydraulically isolated from Red Rock Pass after the Provo level event and the level in the Cache Valley dropping by 9m.

Another possibility would be that a landslide in the Cutler Narrows allowed Lake Bonneville to rise further after the Bear River Exclusion, however, these bars do not present as consistent standstill shoreline elevations between different locations in the basin even after isostatic rebound is accounted for. These bars are not shoreline bars.

4.3. The Fall-from-the-Provo-level Shorelines

After the S15.6-Provo-1551 event, when the Bear River stopped replenishing the Bonneville basin, Lake Bonneville started a remarkably steady fall from the Provo level. This is evidenced by the regular spacing of shoreline patterns below the Provo level elevation. In the central part of the Bonneville basin, the shape of the basin changes to that of a shallow bowl where the lake volume per unit of depth increasingly becomes a factor. Since the fall is driven by evaporation, time also becomes an important variable. The Bonneville Flood occurred in a geological instant, measured in weeks or months, the Provo regression probably took hundreds of years. The isostatic stress relief was quite gradual and even if the release was sticky, the expectation would be that the intervals would be smaller and thus the steps of smaller magnitude simply because the system had time to adapt.

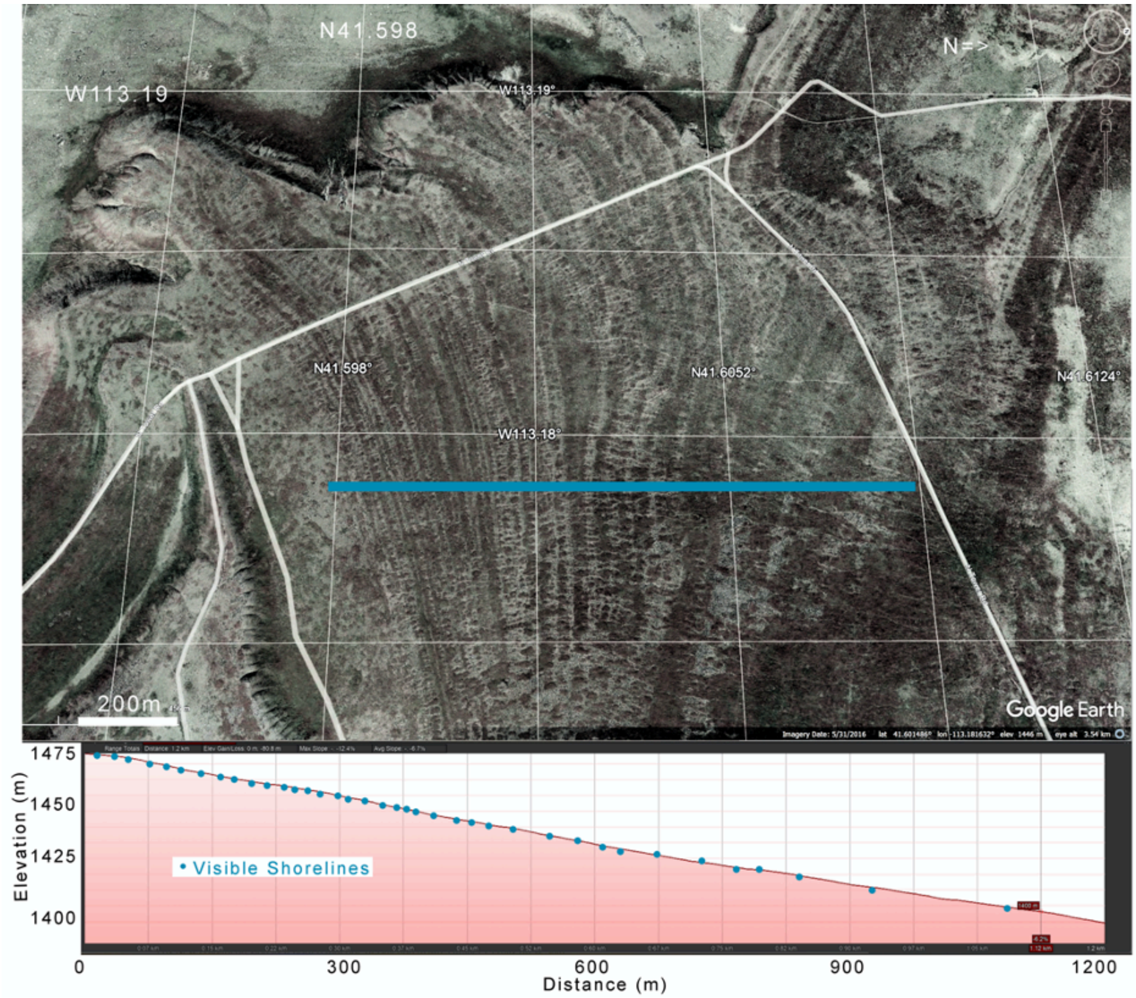

Figure 28. Google Earth™ view of bars on the north side of the Hogup Mountains from the fall from the Provo level. The bars are formed in expanding intervals even though the slope in this area is constant. The bars appear to be dependent on the weight of the lake removed and are thought to be resulting from IRPS. (41°36′N, 113°11′W)

The sub-Provo level has examples of large bars, but for the most part, the change in the appearance of shorelines below the Provo level is dramatic. A location at the northern end of the Hogup Mountains just west of the northern arm of the Great Salt Lake was chosen for study because it is an area with an approximately constant slope and with well-defined bands. At this location, the bars appear in the Google Earth™ view as a series of narrow stripes, almost like ripple marks in the sand. (Figure 28). The shorelines are too fine to be resolved on a Google Earth™ profile, so they were identified visually and plotted. There is a pattern to the shorelines; they are not due to random storm events. Unlike the Bonneville Flood IRPS, the steps are not uniform across the range. The intervals increase as the level drops. This suggests a relationship between these

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shorelines and lake volume, which equates to the weight depressing the crust: at lower lake levels the basin flattens and a greater step change in elevation is required to provide the same decrease in the volume of water.

If the shorelines below the Provo level were climate-related, then this regular pattern would represent an annual cycle since other climate patterns are just not that consistent. This would mean that the 74 meters studied here dropped in 38 years and at an accelerating rate. That exponentially increasing rate would have had the fall from the Provo level to the Great Salt Lake level occur in less than 100 years just by evaporation. The odds are against these as being climate-related shorelines.

It is possible that the bar spacing is simply an erosion feature of a falling lake where a harmonic is set up by how the lake interacts with the shore: waves cut into the slope until it forms a platform and then the platform diffuses the wave energy until the lake drops enough to start to erode a new platform. The problem with that concept is that this type of erosion would remain constant for a constant slope, and that is not true for this location.

As with the Bonneville Flood shorelines, the shorelines in the fall from the Provo level appear to be due to the effects of isostatic rebound. The rebound continued to occur in steps during the much slower fall from the Provo level, though the step pattern changed, reflecting the shape of the basin. As the level drops, the basin flattens, so a greater elevation change is required to achieve the same change in load. Note that the location studied in Figure 28 was selected because it has a relatively constant slope through the elevation range, to fairly reflect that the increasing spacing is not due to local contour effects.

With these smaller steps, any seiche generated would probably be of limited amplitude.

The fine pattern of shorelines visible here yields some other interesting information about this time period:

a. The climate was relatively consistent as far as the direction of prevailing winds and was not much different from what occurs in the region today. The location studied on the north side of the Hogup Mountains has little fetch to the northwest and none to the south. Prevailing winds in this area come from the northwest and large storms are preceded by strong winds from the south. In other areas of the lake that are more exposed to strong winds from the northwest and south, a much coarser pattern of shorelines is all that remains, intermediate shorelines were probably overrun by large storm events.
b. This specific location is a spit deposit from earthquake-induced surging during the Provo level event. This is evident on the western edges (top of Figure 28). This left the location with a clean surface, devoid of conflicting earlier shorelines and with a soft sediment that could be easily molded.
c. The unbroken record of shorelines in this area supports the findings by McCalpin et al. in a 1996 Brigham City trench study and in a 1999 Salt Lake Valley trench study. They determined that there was an aseismic interval along the Wasatch Fault following the Bonneville Flood. If there had been other major earthquake

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events along the Wasatch Fault during the fall from the Provo level, even small surging events would have disrupted the continuous record in the level range of Figure 28. This is an important data point in our overall understanding of how isostatic depression and rebound affected the Wasatch Fault. During transgression, the crust depression appears to have collected the slip on the Wasatch Fault into a few, very large, multi-segment earthquakes. Collected is probably not the best word, since crust depression probably forced an earlier slip on all the segments than would have occurred with simple plate tectonic stress buildup. As the lake level, and thus the load on the crust dropped during lake regression, the isostatic rebound appears to have off-loaded the stress on the fault enough so that it took a long aseismic period for the tectonic stresses to reload and trigger another earthquake. (McCalpin and Forman, 2002, McCalpin 2002)

The findings regarding IRPS are important because there are areas of the globe undergoing deglaciation today. If the crust depression in those regions is just gradually relieving, then there is not a problem. But if the crust has a sticky response, the resulting pop might form an IRPS in glacial lakes and that could result in a catastrophic failure of natural dams, endangering communities below. A recent article by Scientific American estimated that 15 million people live in areas at risk due to the potential of a failure of natural dams retaining glacial lakes. (Harvey, 2023)

5. The ramifications of the Lake Bonneville / Wasatch Fault Theories

5.1. The Wasatch Fault and the risk of a multi-segment event

In this paper, the large earthquake-induced surging events have consistently been referred to as being caused by multi-segment earthquakes, where the post-Bonneville norm for seismic events on the Wasatch Fault seems to be unsynchronized individual segment failures.

The reason the five Lake Bonneville earthquake events named in this paper are probably multi-segment events are these:

a. The scale of these events. These were massive, basin-wide events. The Bonneville Flood earthquake event resulted in surging in the far corners of the lake: Little Cottonwood Canyon, Red Rock Pass, and Keg Mountain.
b. During the Holocene, a major earthquake occurs somewhere on the Wasatch Fault every few hundred years. But on any given segment (such as the Salt Lake segment) the interval is measured in thousands of years. There may have been small individual segment earthquakes during the Bonneville timeframe, since in the Benson core there were over 50 laminated layers in the sediment core, and these could have come

from storm events or from a single-segment seismic event. Though the frequency in the thousands of years supports the concept that the major displacements along the fault were collected into single multi-segment events.

c. Others have suggested the possibility of long aseismic intervals during the Bonneville period (McCalpin, 1999, McCalpin and Forman, 2002). The tectonic stresses continue to build during these intervals and the greater the accumulated stress, the greater the chances of an event on one segment carrying over to the adjacent segments.
d. Basalt ash eruptions are an integral part of the stress relief system associated with plate movement. The one-to-one correlation between basalt ash eruptions with these large surge events supports the concept that these were extraordinary events.

The larger question is whether the heavily populated Wasatch front is vulnerable to a multi-segment failure today. In a single-segment event, emergency support can be obtained from adjacent areas. A multi-segment event would overwhelm emergency services and shut down the key infrastructure for the whole region. Electricity, water, natural gas, roads, and communications would all be affected for an extended period.

There are two possibilities:

a. The multi-segment earthquakes were a product of the Lake Bonneville isostasy and Lake Bonneville is gone for the relevant time frame.
b. There are two cycles on the Wasatch Fault, the first is a shorter cycle of shallower, single segment earthquakes and the second is a much longer cycle of deeper, multi-segment earthquakes.

In reviewing the various trench studies of the Wasatch Fault scarps, there does not appear to be compelling evidence that there has been a post-Bonneville multi-segment event. This means that at least the last 15ky have not seen a multi-segment event, whereas during the Lake Bonneville period, the longest interval between events was about 10ky, and most intervals were shorter. One possibility is that the underlying pattern of multi-segment earthquakes is still there, and lake isostasy just forced it into a higher frequency. A supporting data point to this is that as the lake rose, the time between multi-segment events shortened. This is a topic that requires the consideration of a larger group of individuals with a variety of fields of expertise.

5.2. The risks of underwater faults

The literature has an unfortunate mixing of terms when it comes to the impact of earthquakes on bodies of water. As an engineer, I am inclined to differentiate these effects by the resolution of forces:

Seiche – A harmonic response in a closed body of water produced by an external force. In an earthquake-induced seiche, this is due to the vibration caused by the fault slip. A seiche was reported in Hebgen Lake in the

1959 Montana earthquake, and these occur regularly in swimming pools in California. The larger the body of water, the more intense the event required to set up a seiche. The IRPS events in Lake Bonneville were basin-wide and were the manifestation of an isostatic pop. The first IRPS event during the Bonneville Flood lifted close to 50 trillion kilograms of water possibly around 5 meters, or about the energy of forty-nine first atomic bombs.

Shock-type tsunami – This is the water-hammer effect. When a column of water is dropped, potential energy is converted to kinetic energy and since water is essentially incompressible, this is transmitted as a high-velocity shock wave, traveling at 800km/hr. The energy generated is related to the height of the water column dropped and the distance it drops. When talking about the ocean and its great depths, this is a lot of energy. In Lake Bonneville, it would have been a lot less. The ~500km wavelength of a shock-type tsunami is far greater than the width of Lake Bonneville, and that would break up any cycle development. While a shock-type tsunami would be expected in any body of water, it would not have been the dominant effect in Lake Bonneville.

Surge-type tsunami – when one side of a body of water is changed in elevation, the water must flow to achieve a new equilibrium. Momentum is the key. The surge has to be accelerated by gravity, so it is slow to start, but in a large body of water, that is a lot of mass put in motion. In a basin, the surge will overshoot the equilibrium point in the first slosh. If the basin gets shallower as the edge is approached, the energy gets concentrated, and the overshoot is exacerbated. There has been a lot of modeling done on shock-type tsunamis, but based on what happened in Lake Bonneville, a surge-type tsunami may be the more important hazard in certain situations.

The speed of the surge is one-tenth that of a tsunami, or around 80km/hr. With acceleration and deceleration at the extremes, the surge cycle in Lake Bonneville would have been measured in hours.

Displacement-type tsunami – this occurs when objects fall into a body of water. Landslides or calving blocks of ice typically cause this type of tsunami. It is only mentioned here to be comprehensive in terminology.

5.3. Human occupation of the Bonneville Basin

Evidence of early human occupation of an area is easily erased by the elements of time. Consequently, any evidence of humans in a region has to be considered as potential evidence of a more widespread presence. Early humans have consistently proven to be highly mobile.

Human footprints found in the area of White Sands National Park, New Mexico have been dated to between 23kya and 21kya (cal), around the time of the last glacial maximum and while Lake Bonneville was still in transgression (Bennett, et al. 2021). This dating has been questioned because of the risk of carbon reservoirs distorting the results (Madsen, et al., 2022), however, Pigati et al. maintain that this dating is robust because they checked their dating against “geologic, hydrologic, stratigraphic, and chronologic evidence” (Pigati, et al., 2022). In the current paper, the work of Bennet and Pigati is assumed correct because they used multiple factors to assess their timing. That early date supports the concept of a broader presence of humans in the western United States at a time when Lake Bonneville was still in transgression.

Large bodies of water would be attractive areas for early human occupation since they provide water in the winter, and they are a natural draw to game. The shores of Lake Bonneville would have been a logical location for human settlement.

In a 2021 paper Goebel et al. reported on trench studies conducted in the Bonneville Estates Rockshelter, an erosion feature cut into a rock outcrop at the Bonneville highstand on the western edge of the Bonneville Basin (Goebel, et al., 2021). They found evidence of human occupation a little less than 15kya (cal), at a time when Lake Bonneville had commenced its rapid climate-based fall from the Provo level. At the lowest extent of their excavation, they found an unmodified mammal long-bone fragment and dated it at 18.476kya cal. The fact that the bone was “unmodified” suggests that it was not the product of hunting and butchering. The dating places the limit of their excavation at a time 1ky before the Bonneville Flood, and probably during the last stages of the lake’s transgression to highstand. The Rockshelter may have been uninhabitable at highstand.

A deeper excavation of the Bonneville Estates Rockshelter might be warranted since it is one of the few locations which might have trapped the evidence of pre-highstand occupation.

Earthquake-induced surging in Lake Bonneville, or other Pleistocene Lakes in the Great Basin, would have been catastrophic for early inhabitants of the region and the S17.4-Bonneville-1551 surge would have destroyed evidence of their presence if they had settled in the logical locations where streams of side canyons and basins emptied into the lake. The oral history carried by survivors would have delayed resettlement. Once the level reached the Great Salt Lake level, the water was no longer suitable for drinking or fishing, so humans would tend to settle in areas further from the hazards of earthquake-induced surging.

5.4. The lessons from the Bear River Diversion

The exclusion of the Bear River from the Bonneville basin during the Provo level occupation resulted in a loss of about 40% of the inflow to the lake. The lake level plummeted at an unprecedented rate and this fall was only arrested when the flow was restored.

A 2016 white paper by researchers from Utah State University estimates that human activities have reduced the net river inflows into the Great Salt Lake by 39% since 1847 (Wurtsbaugh, et al. 2016). Agriculture represents 63% of that, with the remainder going to industrial, residential, and commercial consumption (Ibid, 2016). The

Great Salt Lake sees anomalously wet years, 2023 for example, but the trend of the last few decades led to a record low in 2022.

Lake Bonneville disappeared after 30ky due to a 40% reduction in inflow. Human activity has diverted 39% of the inflow to the Great Salt Lake and the lake level is dropping.

In a flat basin such as the Great Salt Lake's a small drop in level results in a very large loss in surface area. This exposes more of the mudflats. Those mudflats contain concentrated heavy metals and other toxins from tens of thousands of years of accumulation. Anyone who has lived in the heavily populated areas to the east of the lake knows that winds from the west can pick up this mud and even on just a hazy day deposit a thin coating of mud on a previously clean car. Air quality is an issue.

Snow in the Wasatch and Uinta Mountains is the principal source of water for this region as well as being the reason for Utah's well-deserved reputation among skiers for the 'greatest snow on earth'. Lake-effect is one of the reasons for the deep snow in these mountains. Lake-effect is dependent on the lake surface area. Lake-effect is a type of feedback loop, and a falling lake level puts us on the wrong side of that phenomenon.

6. Conclusions / Summary of Findings

- 6.1 The Wasatch Fault has experienced five multi-segment earthquake series over the last 45 thousand years. There is a one-to-one correlation with the known, major basalt ash eruptions in the basin during this period. There may have been long aseismic intervals between these events. Isostatic deformation by Lake Bonneville and its effect on the Wasatch Fault may have been both the cause of the aseismic intervals and the trigger for the multi-segment events.
- 6.2 Alternately, there may be a longer-term pattern of multi-segment earthquakes on the Wasatch Fault. While this is unlikely, it would represent a significant concern in this heavily populated area. Studying the long-term frequency of basalt ash eruptions in the basin and a deeper sediment core may provide insight into this pattern.
- 6.3 The earthquake-induced surging in Lake Bonneville provides a record of this type of surging-type tsunami hazard and this needs to be considered in addition to shock-type tsunami and seiche when reviewing the hazards of underwater faults in other areas of the world. This not only applies to lakes but may also be relevant in ocean locations where a fault parallels a coastline.
- 6.4 The Bonneville Flood was caused by a multi-segment, earthquake-induced surge-type tsunami 17.4kya. The discontinuity on the Marsh Creek alluvial fan 30m above the Bonneville highstand is a remnant of the Bonneville Flood, and not the 'only visible section of a suspected normal fault in the area' as previously

thought. This initial surge cut the March Creek obstruction down to the late Zenda threshold which allowed the Bonneville Flood to proceed after the initial surge.

- 6.5 G. K. Gilbert's Intermediate Shorelines of Lake Bonneville between the Bonneville and Provo levels are not transgression standstills or drops, but rather lake regression features during the Bonneville Flood. This paper calls the phenomena Isostatic Rebound Pop Seiche (IRPS). This new theory provides important information:
- a. The crust rebound was sticky in nature and not a smooth release of strain.
- b. The rebound occurred in highly regular steps. The pattern of steps was dependent on the weight removed and on the basin topography.
- c. IRPS may explain features in Lake Lahontan and other Pleistocene lakes of sufficient mass to exhibit isostatic effects.
- d. Hazards associated with IRPS may be present in glacial lakes forming in regions undergoing deglaciation. IRPS could cause natural dams to fail.
- 6.6 The climate history of the Bonneville Basin needs to be revisited with the long-held "climate oscillations" removed.
- 6.7 The Heinrich stadials did not cause dry conditions in the Bonneville Basin and a rapid drop in the lake level as previously assumed. Recent research by others that these were wetter periods is supported by this paper. Surprisingly, there appears to be a link between stadials and multi-segment earthquake events. A rapid increase in isostatic load due to Lake Bonneville's level rising during a wetter period may have been the trigger of an overstressed fault. The McGee team linked the Heinrich stadials to the Pacific Hadley circulation. (McGee et al., 2018) That work requires more attention.
- 6.8 There has been a long-term debate on whether there were early and late Provo levels and there is clear data supporting each theory. This paper resolves that and explains the very rapid drop of this massive lake from the Provo level to the Great Salt Lake level. Provo shoreline sediment formed a natural dam in the Cutler Narrows. An earthquake dropped the lake outflow level in Cache Valley, isolating that area from Lake Bonneville and short-circuiting the flow of the Bear River such that it was immediately excluded from the hydraulic balance of the main Bonneville Basin. Deprived of 40% of its incoming water, the lake level fell due to evaporation. A later earthquake in Cache Valley resulted in surging and seiche which overtopped and destroyed the Cutler Narrows dam, restoring Bear River flow to the Great Salt Lake basin and stabilizing the level close to where it remains today.
- 6.9 During the Lake Bonneville transgression, the sediment record suggests instances of collapse of subterranean aquifers potentially resulting from isostasy. At Blue Lake in the Bonneville Basin, this would manifest as a dramatical outflow from the existing spring and result in increased sedimentation and a local

drop in the local Total Inorganic Carbon content of those sediments. These have been termed 'Water Events' in this paper. This hypothesis is just one of many possible explanations for these Water Events.

- 6.10 The boulder field on the side of the south lateral moraine at the mouth of Little Cottonwood Canyon is evidence of a tsunami in what is now a desert climate area far from any ocean. Sometimes an innocuous feature can hold a wealth of information. This warrants a geological marker just to pique the interest of those in the area, and to remind everyone that sometimes science comes down to someone bicycling by and wondering why that rock field seems a bit off.
- 6.11 This paper provides additional evidence supporting the author's previous finding that the "grabens" in the area between Big Cottonwood Canyon and Little Willow Canyon in the Salt Lake Valley are actually fissures at the top of an underwater shift of massive areas of glacial till deposits at the time of the S17.4-Bonneville-1551 earthquake-induced surging. The G.K. Gilbert Geological Park at the mouth of Little Cottonwood is eventually going to need the educational panels updated, the actual story is a lot more interesting. That story includes the Bell Canyon terminal moraine splitting during the event and the glacial lake at that location flushing down through the rapidly forming gap leaving a distinctive debris wall. A popular hiking trail goes up through that fissure and the hikers are oblivious to the dramatic event that formed their path.

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