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Cache Valley: A Critical Part of Lake Bonneville Preserves Evidence for a Protracted Bonneville Highstand, Possible Tectonic Triggers of the Bonneville Flood, Liquefaction, and Clustered Earthquakes on the East and West Cache Fault Zones

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ABSTRACT

Geologic, geomorphic, and geophysical analyses of landforms, sediments, and structures in conjunction with new radiocarbon ($^{14}$C) and optically stimulated luminescence (OSL) age determinations document a revised history of flooding and recession of Lake Bonneville in Cache Valley, Idaho and Utah. The presence of wave-cut cliffs in bedrock throughout the Bonneville basin show that the Bonneville highstand was protracted. Triangular facets were cut into bedrock in the footwalls of normal faults, and were steepened significantly by wave erosion at the highest Bonneville shoreline.

Crosscutting relations associated with the Riverdale fault in SE Idaho suggest that a major surface-rupturing earthquake occurred near the Zenda threshold at the north end of Cache Valley around the time of the Bonneville flood (Janecke and Oaks, 2011a, 2011b). Thus, it is likely that fluctuating loads, rebound, and/or pore pressures induced by changing lake levels may have triggered a large earthquake that in turn initiated the Bonneville flood. The flood ended centuries of stable outflow through the Zenda threshold.

G.K. Gilbert (1880, 1890) first observed that the Bonneville flood scour ed a major flood channel from Cache Valley northward that shifted the outlet of Lake Bonneville a great distance southward into Cache Valley. The bedrock sill at the south end of this Swan Lake scour channel became the new threshold for the main 1455 ± 3 m Provo shoreline, 10 m above the commonly accepted altitude of 1445 m (Janecke and Oaks, 2011a, 2011b). The 1445 m contour in northern Cache Valley coincides instead with a lower Provo shoreline (1446 ± 3 m) that was controlled by a second bedrock sill southeast of Clifton, Idaho. The sparse record of shorelines rebounded from the ~1445 m level in Cache Valley indicate that the outlet at Clifton, Idaho, was quickly abandoned when Lake Bonneville reverted to closed-basin conditions. A dry meandering riverbed connects the Clifton and Swan Lake outlets and preserves evidence of the large northward-flowing Bonneville River across Round Valley. The Great Basin's modern divide at Red Rock Pass formed in the Holocene, after Lake Bonneville, when an eastern tributary near the midpoint of the relict flood channel of the Bonneville River built a small alluvial fan across the Swan Lake scour channel and created a subtle drainage divide (Gilbert 1880, 1890; Janecke and Oaks, 2011a, 2011b). Gilbert was the first to recognize that the modern drainage divide at Red Rock Pass is unrelated to Lake Bonneville.

The possibility that an earthquake triggered the Bonneville flood (Janecke and Oaks, 2011a, 2011b) led us to explore the late Pleistocene activity of normal faults in and near Cache Valley. Just west of Cache Valley, the Wasatch fault zone has increased its slip rate since the Bonneville flood (Hetzel and Hampel, 2005; Karow and Hampel, 2010 and citations therein), but little is known about the response of active normal faults in Cache Valley to loading and unloading by Lake Bonneville. To examine the relations between ancient seismicity and lake history, we re-excavated deformed Upper Pleistocene sandy lake beds along a ~50 m by 5 m collapsed north wall of an abandoned gravel pit at the mouth of Green Canyon in Cache Valley, Utah. Utah State University faculty identified two liquefaction events in the outcrop in the 1980s during class trips, and we sought to determine the number, nature, and age of the paleo-earthquakes responsible for the strong deformation there.
Figure 1. View to north-northeast of deltaic sediment of Green Canyon in 1980. Colored units are liquefied masses of event horizons 1-5. Unit 3 was activated a second time in a diapiric mode during event 5. Undeformed cap of alluvial gravel is probably flood related (?), and overlies deformed deltaic sand (s) and gravel (g) from the last pluvial along an angular unconformity. Each green line is an angular unconformity. Lower one-third of exposure contains mostly prodelta fine sand, silt and clay (f=finest). Orange lines are slip surfaces of nested slumps in lateral spreads. Each event bed has a major unconformity at the upper surface (green lines).

The exposure of the paleodelta of Green Canyon is within the boundary between the northern and central Utah segments of the East Cache fault zone (McCalpin, 1994). It is ~25 m to ~170 m basinward, respectively, of two diverging fault strands of the East Cache fault zone, and there might be additional buried faults at lower elevation than the exposure near the main upper Provo shoreline (McCalpin, 1989; this study).

Deposition of upward coarsening lacustrine deposition in the delta of Green Canyon started before 22.4 ± 0.4 cal kyr B.P. (\(^{14}\)C) with deposition of prodelta clay, mud, and silt, and continued after 20.1 ± 0.3 cal kyr B.P. (\(^{14}\)C) as sand and gravel were laid down in a prograding delta. Nearshore lacustrine deposition is indicated by ripples, cross beds, other sedimentary structures, lacustrine Stagnicola gastropod shells throughout the exposure, and the position of the beds ~40–45 m below the Bonneville shoreline at Green Canyon.

Figure 2. Fault-graded beds of event bed number 2, as it was exposed in the 1980s above a listric slip surface (longest red line). See figure 1 for its position in the exposure. The largest pseudonodule is about 2.5 m across. Fluid escape (white arrows trace sand dikes and sills) created the pseudonodules low in the event layer. The upper two-thirds of the event layer is massive and disaggregated due to protracted shaking and liquefaction. Fault-graded bedding like this is diagnostic of seismic shaking of sediment under a body of water (Rodriguez and others, 2000). View to north-northeast. Red contacts within the event bed separate more deformed above from less-deformed part of the fault-graded bed, below. Note
the fluvial gravel at the top of the outcrop, which might be related to the Bonneville flood.

Fifteen new age determinations indicate early onset of deep lake conditions in Cache Valley at or higher than 1515 to 1510 m (corrected for rebound) (this study and Rittenour and others, 2019). The high altitude of the lake provides additional evidence for Oaks and others’ (2019; this volume) interpretation of Cache Valley Bay. Oaks and others (2019) dated prior lake cycles in Cache Valley, documented their unexpectedly high altitudes, and concluded that Cache Valley was filled by a separate pluvial lake from the main Bonneville basin until the rise to the Bonneville highstand connected them across the Junction Hills. Integration of Cache Valley lake into the main Bonneville basin must postdate the lake beds in Cache Valley that were deposited at higher altitudes than predicted by the Bonneville hydrograph, like the transgressive sediment in the paleodelta at Green Canyon.

We uncovered multiply deformed shallow lake beds and one capping fluvial gravel in the exposure at Green Canyon. Listric faults in the exposure sole into prodelta clay beds beneath the sandy and gravely deltaic part of the succession. West-dipping slip surfaces in the exposure are part of nested lateral spreads, not tectonic faults. Cross-cutting relations are exceptionally clear. The deltaic sediment of Green Canyon was deposited, seismically deformed, and slumped in at least four strong earthquakes under subaqueous conditions in a shallow-water deltaic part of Cache Valley lake. Six 40Ar/39Ar ages on *Stagnicola* sp. shells and three OSL ages are stratigraphically consistent within error, and confirm that the lacustrine sediment was deposited and deformed during ~2–5 kyr of high lake levels prior to the Bonneville flood. The geometry and position in the landscape of a laterally continuous alluvial gravel bed, which overlies the highly deformed sandy lake beds in angular unconformity, suggest that the gravel bed was probably laid down immediately after the erosional stripping of the highest units during the Bonneville flood. The gravel cap may be a flood deposit or barely postdate the Bonneville flood because it predates focused downcutting along the modern channel of Green Canyon Wash that began with the Bonneville flood and occupation of the Provo shorelines ~70 m lower in the landscape. All the deformation in the exposure must therefore predate the Bonneville flood at ~18 ka.

The Green Canyon site exposes three listric slip surfaces of lateral spreads, four sequential thick liquefied units, and less deformed flat and cross-stratified lacustrine and deltaic sediment. Each thick liquefied mass of sand is a different age, yet all of the deformation occurred when the sediment was saturated by the pluvial lake as it approached or stabilized at its highest shoreline. Three of the liquefied units (0.75 to 5 m thick) are localized and displaced in the hanging walls of listric east- and west-dipping slip surfaces of lateral spreads that appear to be coeval with the liquefied fault-graded beds above them. Deposition was ongoing, and produced multiple cross-cutting relations that constrain the relative ages of three similar lateral-spread-liquefaction pairs (LSLP) and one underlying strata-bound liquefied mass (SBLM) that deforms a possible weak geosol. Each LSLP and SBLM formed during a discrete event. Each was subsequently capped by a major erosional surface, upon which 1–2 m of stratified sediment was deposited. The youngest LSLP deformed twice, and its diapirically deformed slip surface records deformation during two strong earthquakes. Seiches likely produced each erosion surface. Truncations at slip surfaces, fault wedges, disconformities and angular unconformities, overlapping sediment, onlapping sediment, sand dikes and sills, and growth strata separate the three LSLP and one SBLM from one another. Less extreme deformation modified the intervening lake beds.

The most extreme deformation is expressed in fault-graded beds that are 1–5 m thick. The similarity between the LSLP and SBLM in the Green Canyon pit and secondary deformation generated by the 1934 M 6.6 Hansel Valley earthquake (McCalpin and others, 1992) indicate that seismic shaking is the most likely explanation for the five largest deformational events recorded at the mouth of Green Canyon. The smaller deformation features may have formed during subsequent aftershock sequences. Other evidence for a tectonic trigger includes the presence of small fault wedges, alternating brittle and ductile deformation, brittle fluid-escape structures, buried scarps, sand dikes, erosion of each fault-graded bed, and angular unconformities. We propose that five separate moderate to large earthquakes shook and
liquefied the sediment between ~22.4 ka and the Bonneville flood (~ 18 ka; age from Miller, 2016). Those earthquakes probably ruptured the nearby central or northern segments of the East Cache fault because other gravel pits lack liquefied sediment in coeval deposits elsewhere in Cache Valley.

If we are correct that each liquefaction and major diapiric re-liquefaction event records a moderate to large earthquake when a deep pluvial lake filled Cache Valley, then the adjacent part of the East Cache fault zone generated at least five major earthquakes during the last pluvial between about 22.4 ka and the Bonneville flood at about 18 cal kyr B.P. The paleoseismic data of McCalpin (1994) documents one additional earthquake along the East Cache fault zone as Lake Bonneville paused at the Provo shoreline. The temporal clustering of the ≥ 6 syn-Bonneville paleoearthquakes, their strong spatial association with the East Cache fault zone, the paucity of deformation at the site after the Bonneville flood, and the absence of liquefaction in coeval sediment elsewhere in Cache Valley, are all consistent with a high frequency of liquefaction-inducing earthquakes along the central or northern segment of the East Cache fault during the transgression and highstand of the pluvial lake in Cache Valley. A single mid-Holocene earthquake that occurred ~ 4–5 ka is the only earthquake known to have ruptured the East Cache fault zone during the Holocene (McCalpin, 1994). Altogether, there has been a significant decline in earthquake frequency since the deep-water phase of the Bonneville lake cycle along the East Cache fault zone.

The low earthquake frequency along the Utah part of the East Cache fault zone documented here in the Holocene is in marked contrast to the history of the West Cache fault zone and the Wasatch fault zone; those western fault zones generated numerous Holocene earthquakes (Black and others, 1999, 2000; Solomon, 1999; Hetzel and Hampel, 2005; Ellis and Jänecke, 2018). We explain the opposite earthquake histories of the East and West Cache fault zones as the consequence of opposite flexural stresses induced by the loading and later rebound produced by pluvial lakes along an upper monoclinal hinge (near the East Cache fault zone) and along a lower monoclinal hinge (near the West Cache fault zone and the Wasatch fault zone) at the eastern margin of Lake Bonneville and Cache Valley lake. Lateral changes in loading within Lake Bonneville and Cache Valley lake could explain clustered earthquake activity by changing the loading stresses in the crust, by modulating rebound-related stresses, and/or by raising the pore pressure along the slip surfaces with circulating groundwater. Similar processes might explain the rough coincidence of the Bonneville flood and the last major earthquake on the Riverdale fault zone in northern Cache Valley (Jänecke and Oaks, 2011a, 2011b).

The West Cache fault zone ruptured at least three times in the Holocene (Black and others, 1999, 2000; Solomon, 1999), and a fourth Holocene earthquake is likely because it displaces Holocene marsh deposits on the floor of Cache Valley along newly identified traces of the Cutler Reservoir segment of the Dayton-Oxford fault zone (Ellis and Jänecke 2018). This fault segment links the Wellsville, Junction Hills, and Dayton-Oxford faults with one another (Jänecke and Evans, 2017; Ellis and Jänecke, 2018; Jänecke and others, 2019). Holocene scarp slips along most of the new traces nearly double the length of active fault traces mapped in the West Cache fault zone. At least one additional surface-rupturing earthquake is needed to explain the plethora of Holocene fault scarp on the floor of Cache Valley. Altogether these data suggest that the West Cache fault zone and the Wasatch fault zone, were positioned near the lower monoclinal hinge of the flexurally bending lithosphere, and both have been particularly active since Lake Bonneville disappeared.
Figure 3. New traces of the West Cache fault zone identified using lidar by Ellis and Jänecke (2018) on the floor of Cache Valley. Fault zones are up to 1 km wide and contain both east- and west-dipping traces. Geophysical datasets support this interpretation (Evans and Oaks, 1996). The Dayton-Oxford fault is much longer than previously known, connects with both the Junction Hills and Wellsville faults, and joins these other faults to form a very high fault scarp in Mendon, Utah. Jänecke and Evans (2017)
identified a small subset of these faults.

Figure 4. Conceptual model of enhanced extension along the East Cache fault zone during the last pluvial. Rebound during the Holocene caused the western faults to be more active than the eastern fault zone.

REFERENCES


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