Reinterpreted history of latest Pleistocene Lake Bonneville: Geologic setting of threshold failure, Bonneville flood, deltas of the Bear River, and outlets for two Provo shorelines, southeastern Idaho, USA

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ABSTRACT

Geologic, geomorphic, and geophysical analyses of landforms, sediments, and geologic structures document the complex history of pluvial Lake Bonneville in northern Cache Valley, NE Great Basin, and shows that the outlet of Lake Bonneville shifted ~20 km south after the Bonneville flood. The Riverdale normal fault offsets Bonneville deposits, but not younger Provo deposits ~25 km southeast of Zenda, Idaho. Rapid changes in water level may have induced slip on the Riverdale fault shortly before, during, or after the Bonneville flood. Although other processes may have played a role, seismicity might have been the main cause of the Bonneville flood.

The outlet of Lake Bonneville shifted south from Zenda first 11, then another 12 km, during the Provo occupation. The subsequent Holocene establishment of the drainage divide at Red Rock Pass, south of Zenda, resulted from an alluvial fan damming the north-sloping valley. Weak Neogene sediments formed sills for the three overflowing stages of the lake, including the pre-flood highstand. Field trip stops on flood-modified landslide deposits overlook two outflow channels, examine and discuss the conglomerate-bearing sedimentary deposits that formed the dam of Lake Bonneville, sapping-related landforms, and the Holocene alluvial fan that produced the modern drainage divide at Red Rock Pass.

The flood scoured ~25 km of Cache and Marsh Valleys, initiated modest-sized landslides, and cut a channel north of a new sill near Swan Lake. Lake Bonneville dropped ~100 m and stablilized south of this sill at the main, higher ~4775 ± 10 ft (1456 ± 3 m) Provo shoreline. Later Lake Bonneville briefly stabilized at a lower ~4745 ± 10 ft (1447 ± 3 m) Provo sill, near Clifton, Idaho, 12 km farther south. An abandoned meandering riverbed in Round Valley, Idaho, shows major flow of the large Bonneville River northward from the Clifton sill. Field trip stops at both sills and overlooking the meander belt examine some of the field evidence for these shorelines and sills.

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The Bear River, which enters Cache Valley at the mouth of Oneida Narrows, 17 km ENE of the Clifton sill, was the main source of water in Lake Bonneville. It produced 3 sets of deltas in Cache Valley—a major delta during the Bonneville highstand, a larger composite delta during occupation of two Provo shorelines, and at least one smaller delta during recession from the Provo shoreline. The Bonneville delta and most of the Provo delta of the Bear River were subaqueous in Cache Valley, based on their topsets being lower than the coeval shorelines. The Bonneville delta is deeply dissected by closely spaced gullies that formed immediately after the Bonneville flood. The delta morphologies change sequentially from river-dominated to wave-dominated, then back to river-dominated. These unique shapes and the brief, intense erosion of the Bonneville delta record temporal changes in wave energy, erosion, vegetation, and/or storminess, at the end of the Pleistocene. Stops on a delta near Weston, Idaho, reveal many of the distinguishing features of the much larger deltas of the Bear River in a smaller, more concentrated form. We will see and discuss the ubiquitous gully erosion in Bonneville landforms, the nearly undissected Provo delta, the subaqueous topset of the Provo delta, and the wave-cut and wave-built benches and notches at the upper and lower Provo shorelines.

INTRODUCTION AND SETTING

The great Bonneville megaflood in the northeast Great Basin, 17,400 calendar years ago, released roughly half the water from this deep, large pluvial lake (Gilbert, 1880, 1890; Malde 1968; Currey, 1990; Oviatt et al., 1992; O’Connor, 1993; Hart et al., 2004; calibration to calendar years in part from Guido et al., 2007). Approximately 4750 km$^2$ of water drained northward into the Snake River with a maximum discharge of about a million cubic meters per second (Figs. 1, 2, 3, and 4; Malde, 1968; O’Connor, 1993). Massive scouring and redeposition are well documented north of the outlet (Gilbert, 1880, 1890; Malde, 1968; O’Connor, 1993). After the flood, the Provo shoreline in the Bonneville basin was established ~102 m (335 ft) lower than the highstand Bonneville shoreline (Fig. 3).

Gilbert (1880, 1890) identified the threshold at the time of the Bonneville flood at the site of Zenda, Idaho. Gilbert (1890, p. 178) concluded that the outlet of Lake Bonneville at the Provo shoreline shifted south at least 11 km to a position “...between Swan Lake and the Round Valley Marsh” after the Bonneville flood (Figs. 1, 2, 4, 5). Subsequent workers concluded instead that the outlet shifted only 2.5 km south, from Zenda to the modern divide at Red Rock Pass (Ives, 1948; Williams, 1962a, 1962b; Williams and Milligan, 1968; Burr and Currey, 1988; Smith et al., 1989; Godsey et al., 2005; Williams and Milligan, 1968). Early mappers identified a shoreline between 4775 and 4800 ft as the Provo shoreline, whereas later workers favored a lower altitude between 4737 and 4756 ft (Hardy, 1957; Bright, 1966; Link, 1982a, 1982b; Currey and Burr, 1988; Smith et al., 1989; Godsey et al., 2005). Rebound complicates the correlation of shorelines in many parts of the Bonneville basin, but there was little rebound in northernmost Cache Valley because it was at the margin of the lake and shallow (Crittenden, 1963; Bills et al., 1994). The lower shoreline altitude of 4737–4756 ft for the Provo shoreline has a closure far south of the divide at Red Rock Pass, where most workers have interpreted the threshold after the Bonneville flood (Fig. 2; Currey et al., 1984).

The deltas of the Bear River, nearby, have not been mapped nor interpreted in a landscape context, and stratigraphic analyses of the Bonneville delta have produced varied results (Figs. 1, 2, 11, and 12) (Oriel and Platt, 1980; Lemons et al., 1996; Lemons, 1997; Anderson, 1998; Anderson and Link, 1998; Milligan and Lemons, 1998; Milligan and Chan, 1998; Lemons and Chan, 1999). All of these factors, plus our chance discovery of a large relict meander belt 15–25 km south of the original...
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Dune-covered subdeltas, after Provo time
Provo level of Lake Bonneville and 4775 ft (1446 m) shoreline south of deltas
Composite Provo delta of the Bear River below both the 4775 ft (1456 m) and 4745 ft (1446 m) shoreline
Lake Bonneville at its highest shoreline
Swan Lake scour and discharge channel
Bonneville delta of the Bear River and Mink Creek

Figure 1. Map of lake levels within Cache Valley. Deltas of the Bear River are differentiated from other lacustrine deposits. Provo shoreline is simplified west of Cache Valley. RNF—Riverdale normal fault (landslide?). Major structures and locations of other maps are shown.
Figure 2. Digital elevation model delineating the main features of northern Cache Valley. Color schemes are keyed to elevations of the Provo and Bonneville shorelines. Colors are same in the following maps except for minor adjustments to account for rebound. Notice the part of the Swan Lake scour channel that has been filled and dammed by the Holocene fan of Marsh Creek near Red Rock Pass. The tan colors within the Swan Lake scour channel reflect the filling of this area above the altitude of the 4775 ft (1456 m) Provo shoreline.
threshold of Lake Bonneville prompted our detailed reevaluation of this fascinating body of water and its erosional and depositional history.

Much of our work on this topic is presented in a manuscript that is currently in the review process. In that paper, we provide detailed evidence for the two sills, two important shorelines at the Provo level, two discharge channels north of Red Rock Pass, modest-sized landslides, and, most importantly, the possibility of the Bonneville flood resulting from an earthquake on the Riverdale fault zone. In order to limit redundancy, those data and interpretations are summarized here in an abbreviated form, and the evidence for most of these interpretations will be discussed at field trip stops. We present additional data and analysis of the deltas of the Bear River and their relevance for interpreting changing climate in the latest Pleistocene.

**Methods**

We examined landforms of northern Cache Valley on aerial photographs, orthophoto-quadangles, digital elevation models, and topographic maps. Hundreds of topographic profiles and 10-m digital elevation models created in GeoMapApp were analyzed (Figs. 2, 5, 11, and 12). Geologic mapping (Mayer, 1979; Oriel and Platt, 1980; Link, 1982a, 1982b; Link and LeFebre, 1991).
Figure 3.

1500m
1400m
1300m

Adjusted elevation

Age in calendar years before present

~17,800 BP
~17,400 ka

Cave of the Bells

H1?

Derived from Godsey et al. (2005, 2011)
Modification after Benson et al. (2011)

this study

Keg Mtn oscillation?

Swan Lake sill?

Clifton sill

Meander belt is active at this time?

Bonneville flood

Provo shorelines

Drier winter/warmer
Wetter winter/cooler

18O (PDB)
δ –12
δ –11
δ –10
δ –9
δ –8

15,000
35,000 30,000 25,000 20,000 10,000

35,000 30,000 25,000 20,000 10,000

15,000

~17,400 ka

1300m

Transgression

1400m

1500m

~17,800 BP

Highest Bonneville shoreline

this study

Keg Mtn oscillation?
Shorelines

The highest Bonneville shoreline is mostly erosional around northern Cache Valley, as wave-cut scarps and terraces, locally with distal wave-built terraces (e.g., Gilbert, 1890) at the bases of small triangular facets. It lies between 5090 and 5120 ft (1551–1561 m) and is very prominent, except in northernmost Cache Valley and southernmost Marsh Valley (Bright, 1963).

After the Bonneville flood, the lake stabilized at a shoreline between 4760 and 4780 ft (1451–1457 m) in northern Cache Valley, the main Provo shoreline of Lake Bonneville. We refer to this higher, older stand as the “4775 ft Provo shoreline” (1456 m) (Figs. 3 and 7). A younger, lower Provo shoreline, between 4740 and 4750 ft (~1447 m), is much more subtle than the higher Provo shoreline around northern Cache Valley (Figs. 3 and 9), and in many areas does not form a clear or continuous shoreline. However, the lower Provo shoreline is well expressed on the Weston delta as a step (~9 m) in the smooth topset of the Provo delta (Fig. 12; Stop 8). The main higher Provo shoreline is 30 ft higher than inferred in most publications after 1970.

North of Red Rock Pass

The divide at Red Rock Pass (Figs. 4, 5, 6, and 8; Stop 3), between Marsh Creek and Cache Valley, separates the Great Basin from the Columbia River drainage basin. The divide was located close to Zenda prior to the Bonneville flood (Gilbert, 1890). It was thought that there had been outflow during the highstand of Lake Bonneville prior to the discovery of groundwater-related landforms in Marsh Valley in the Marsh Creek alluvial fan (O’Connor, 1993; we show below that this is mostly a pediment with fairly thin alluvial and eolian cover). That discovery raised the possibility that Lake Bonneville was closed until sapping
Weakening an alluvial dam near Zenda and initiated outflow and the Bonneville flood (O’Connor, 1993).

We verified and mapped the sapping-related landforms in southern Marsh Valley, and also reconstructed the landscape by projecting the regular pediment and alluvial-fan surfaces related to Aspen Creek (west of Marsh Creek) and Marsh Creek (east and north of Marsh Creek), across the fairly narrow channel cut by the Bonneville flood. Sapping modified the surface of the Marsh Creek pediment and alluvial fan from the altitude of the Bonneville shoreline down to the floor of Marsh Valley (Fig. 6). The reconstructed landforms show that Lake Bonneville probably had an outlet when it occupied its highest shoreline because the high pediments and alluvial fans coalesced at the altitude of the Bonneville shoreline, not above it. The co-occurrence of sapping-related landforms and overland flow is enigmatic. Perhaps it reflects a short period of subsurface throughflow before overland flow was established at Zenda. Possibly the subsurface throughflow reduced the overflow to an intermittent occurrence during high-water years, and thus prolonged the highstand near that level prior to final collapse. Possibly the graded, northwest-sloping pediment surface allowed moderate overflow without downcutting, similar to the Madras canals of India that neither erode nor deposit sediment (Leopold et al., 1964).

A modest volume of landslide material is preserved near the scoured channels in the Red Rock Pass area, but the volume was much less than has been suggested previously (Sewell, cited in Smith et al., 1989). There was an early Bonneville discharge channel at Red Rock Pass, east of Red Rock Butte, that helped to empty the Bonneville basin of water before and during the flood. It was deactivated before the end of the flood.

Our new mapping shows that all but the uppermost few tens of meters of material in the area of the Zenda dam are cemented conglomerate and interbedded silt and sand of the Neogene Salt Lake Formation (Stop 6). Paleozoic rocks do not crop out at the pre-Bonneville divide, so models of the Bonneville flood that involve flow of water through karst in Paleozoic carbonate (J. Stewart Williams, 1967, oral commun. to Oaks; Link et al., 1999) cannot be correct. Quaternary alluvial sediments overlying the pediments thicken and thin in cut-and-fill geometries, and thicken valleyward near Marsh and Aspen Creeks, but do not appear to have comprised much of the Zenda threshold.

Results from South of Red Rock Pass

The northern third of Cache Valley is complex and variable in its geomorphology and bedrock structure (Figs. 1, 2, 5,
Figure 6. Key features of the Bonneville highstand and the Bonneville flood, overlain on a geologic map of southern Marsh Valley, with the divide between Marsh and Cache Valleys and the Bonneville highstand prior to the flood (modified from DeVecchio et al., 2003). Stops 3–6 are in this area.
Figure 7. Color aerial photograph from Google Earth shows locations of Stops 1, 2, 7, and 8, and their relationships to the Swan Lake horst, the Twin Lakes horst block, Round Valley and its relict meander belt, and sills at Swan Lake and Clifton. Note that Swan Lake is a residual low in the Swan Lake scour channel that lies between younger infilling alluvial fans. Blue outlines define the east and west edges of the relict meander belt. White lines denote the east and west edges of scoured terrain, yellow shows the approximate outline of Round Valley, and the white dashed line delineates the highest parts of the Twin Lakes horst. The latter continues east and west in the shallow subsurface according to gravity data (Eversaul, 2004).
6, and 7). We identify five distinct geomorphic zones there, from: (1) the open, former lake bottom of Lake Bonneville south of Preston, (2) the large deltas of the Bear River which have a southern margin 3 km south of Preston and persist north-northwest 12 km to a constriction near Clifton, (3) the Twin Lakes horst block and associated low hills, (4) Round Valley, and (5) the hills and valleys of the Swan Lake terrain in northernmost Cache Valley. Scouring from the Bonneville flood is confined to the Swan Lake terrain and southern Marsh Valley. Shorelines are best developed south of the deltas of the Bear River (see Stop 9). The higher Provo shoreline is mappable as far north as Swan Lake, Idaho (Fig. 2; Gilbert, 1890; Bright, 1963; Stop 2), whereas the lower Provo shoreline is only expressed south of the Twin Lakes horst (Curry et al., 1984). The Twin Lakes hills were an irregular island in Lake Bonneville during the Bonneville highstand and the subsequent higher Provo level (Figs. 2 and 7). Round Valley preserves a marshy low area that once contained a large north-flowing river. The description of the relationships in Round Valley is included here because they require a major re-interpretation of Lake Bonneville.

Pre-Cenozoic bedrock underlies the Twin Lakes horst and the ridges in the Swan Lake terrain. Gravity data (Eversaul, 2004) show where the bedrock is close to the surface in areas of thick surficial cover (see Stops 1–9 for more detail). The Salt Lake Formation is the basin fill that was coeval with slip on the Bannock detachment fault and it makes up the sills of Lake Bonneville (Link, 1982a, 1982b; Janecke and Evans, 1999; Oaks et al., 1999; Oaks, 2000; Janecke et al., 2003; DeVecchio, 2002; Carney and Janecke, 2005; Steely and Janecke, 2005; Steely et al., 2005; Oaks).

Round Valley Terrain, Meander Belt, and Riverdale Normal Fault

Round Valley is bounded by bedrock ridges and a mountain range on three sides, and abuts the foreset of the Bonneville delta of the Bear River on its east side. Its floor is nearly flat, and there is a break in slope around its perimeter that is near the altitude of the higher 4775 ft (1456 m) Provo shoreline. The center of the valley is as low as 4740 ft (1444 m). Most of Round Valley lies between 4745 and 4750 ft (~1447 m) altitude.

Round Valley preserves landforms of an ancient meandering river (Figs. 7 and 9; see Google Earth; Stop 7). The abandoned meander belt in Round Valley has six meander loops, two to three dozen depositional packets of large curving ridges that resemble point bars that were added northward, oxbow lakes, and several tributaries that enter from south to north. The meander belt connects directly into the Swan Lake scour channel at its northeast end (Figs. 2 and 7; near Stop 2). The channel and floodplain of this large river system formed below, and after, the higher Provo shoreline.

The wavelengths of the meanders are ~2.0–2.5 km, and average 2.3 km (7 measurements from Fig. 9), with an average radius of ~0.6 km (Fig. 5). The floodplain produced by lateral accretion is up to ~2.75 km wide, and there are 5–8 accretionary point-bar complexes visible in each meander loop (Fig. 5). The width of the relict channel of the meander belt in Round Valley is ~140 ft (43 m) (average of 12 measurements along the channel courses). The average meander wavelength and average channel width permit other paleohydraulic parameters to be calculated: (1) channel depth ~1.5 m (Dury, 1965); (2) channel slope ~0.1 m/km (Schumm, 1972); (3) mean annual discharge ~6 m³/sec (Schumm, 1972); and (4) mean annual flood ~25 m³/sec (Schumm, 1972). These calculations lie within the data sets shown in Leopold et al. (1964), and the ratio of slope to discharge is within their field for meandering streams rather than braided to straight streams.
Figure 9. Color aerial photograph from Google Earth of the relic meander belt in Round Valley.
The Riverdale normal fault is buried beneath the northeast corner of Round Valley, where a vegetation lineament overlies its probable trace. It separates the more open part of Cache Valley, including the relict meanders in Round Valley, in its hanging wall, from the linear and narrow Swan Lake scour channel in its footwall. To the southeast, it lies near the top of a prominent SW-sloping gravity gradient along the NE edge of the relatively flat floor of Cache Valley (Figs. 1, 2, and 11; Eversaul, 2004; Oaks et al., 2005). Linear gullies are eroded along its trace across the foresets of the highstand Bonneville delta north of the Bear River (see Stop 1). The Riverdale fault lies in the foreset of the Bonneville delta and has a position reminiscent of delta-front landslides (Paolo, 2000; Heller et al., 2001; Paola et al., 2001). We cannot rule out a landslide interpretation but a fault model explains more of the known relationships.

The Clifton sill is at the south end of the meander belt in Round Valley. It coincides with the boundary between undissected fluvial landforms, to the north, and a smooth Provo top-
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Figure 11. Topographic maps of the deeply dissected Bonneville delta of the Bear River (orange), little dissected topset of the Provo delta of the Bear River (greens) and the Riverdale fault zone cutting across foresets of the Bonneville delta (between arrows). Notice that the Provo deposits, shown in green and light blue, are not cut by the Riverdale fault along strike to the north. The profile shows the deep and regular gullies within the Bonneville delta and their complete absence in the Provo delta. Contour interval is 10 m.
Stage 1: Overflow of Lake Bonneville stabilized the position of the lake, and produced a prominent highest Bonneville shoreline. The Bonneville River of Gilbert (1890) was born at this time with an outlet near 1550 m. An earthquake on the Riverdale fault might have started the Bonneville flood, possibly with seiche waves.

Stage 2: Early during the Bonneville flood the Bonneville River in the eastern scour channel cut down ~60 m through the Zenda threshold. Salt Lake Formation was exposed in the floor of the channel.

Stage 3: A landslide from the east blocked the east scour channel, and flow shifted entirely to a channel west of Red Rock Butte.

Stage 4: Recurring landslides into the west channel were washed away as the flood continued. Eventually the flood ended, and a new outlet for the Bonneville River emerged at the Swan Lake area 11 km farther south. Northward flow in the Bonneville River continued within the western channel.

Climate change at the end of the glaciation caused a regression from the Provo shorelines. Stage 5: Immediately after the end of the Provo occupation, the Bonneville River ceased to exist. Its dry river bed (shown in purple here even though it is now dry) had become the new base level for the small tributary streams in the area. Now sediment delivered onto the bed of the dry river by those tributaries was able to accumulate, rather than being carried north by the mighty Bonneville River. Through time the Holocene alluvial fans built up enough topography to block the northward gradient of the dry river bed. Marshes and small lakes, like Swan Lake, formed between the Holocene fans. The largest fan was at the confluence of Marsh Creek and the scour channel because Marsh Creek is the largest stream. Its crest became the modern drainage divide at Red Rock Pass.
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1. Threshold near Zenda, Idaho (~18 ka)
2. Drainage Divide at Red Rock Pass (now)
3. Post-Provo alluvial fan
4. East scour channel
5. West Swan Lake scour channel
6. Pleistocene fan and pediment deposits
7. Pre-Tertiary bed rock
8. Landslide deposits, reconstructed
9. Landslide deposit sculpted by the flood
10. Scoured landform parallel to flow
11. Highest Bonneville shoreline
12. Highest level of sapping features on Marsh Creek fan-pediment
13. Fault scarp and possible fault scarps that may have been modified by flood water
14. Contour on pediment surface
set incised by a few deep, steep-sided gullies, to the south (Figs. 1, 2, and 7).

**Deltas of the Bear River**

The topsets and foresets/bottomsets (delta front) of the highstand Bonneville delta and the composite Provo-level delta of the Bear River form the largest geographic terrain of northern Cache Valley. The foreset-topset contact, which is typically assumed to coincide with shorelines in Gilbert-type sand-and-gravel deltas, is below both the Bonneville and Provo shorelines in these mostly clay-and-silt deltas. There is only one very large delta complex associated with the Provo shorelines, and there is no clear distinction between landforms formed during occupation of the 4775 ft (1456 m) and 4745 ft (1439 m) Provo shorelines (Fig. 3). We therefore treat this composite landform as a single delta, but further study is needed.

Sub-Provo deposits of at least two prior lake cycles, plus transgressive deposits from the rise to the Bonneville highstand could be buried in the subsurface of northern Cache Valley beneath the Provo-level deltas. If so, these deposits reduce the amount of sediment needed to fill in the area beneath the Provo and Bonneville highstand deltas. None of the prior lake cycles significantly exceeded the altitude of the Provo shoreline (McCoy, 1987, as modified in Hart et al., 2004), so there is no ambiguity about the age of the highest deltaic deposits.

**Bonneville Delta of the Bear River and the Riverdale Fault**

The Bear River reaches Cache Valley through a confined bedrock valley ~16 km long at Oneida Narrows, 27.5 km east-southeast of Red Rock Pass (Fig. 1). The highstand Bonneville delta of the Bear River is confined along the northeast edge of Cache Valley and is asymmetric, with more of its surface area north of its inlet where two small creeks contributed sediment to a coalesced delta complex (Figs. 1, 2, and 11). The delta is large, spanning roughly 10 km from its distal point to its inlet into Cache Valley at Oneida Narrows, and 20 km from northwest to southeast. Most of the surface area of the Bonneville delta of the Bear River is in Cache Valley, but a long narrow finger of the delta was first deposited in Gentle Valley and SSW through Oneida Narrows (Fig. 1). Most of that sediment was eroded during and after regression from the Bonneville highstand. Although part of this accumulation may have been swept across the Swan Lake and Clifton sills into the Columbia River Basin, much was probably redeposited into the Provo delta. The highstand Bonneville delta front was originally quite smooth and weakly convex to the southwest. The delta filled in an irregular reentrant in northeast Cache Valley, and then built out into the more open part of the valley, filling it almost halfway from east to west.

Relict erosional gullies dissect the originally smooth delta forest and the distal parts of the topset of the Bonneville delta, both north and south of the presently inset Bear River. The topset is less dissected by the gullies. Gullies are grossly perpendicular to the delta front, except for those that parallel the Riverdale fault, but there is a considerable range of trends in the gullies (Fig. 11). Spacing, widths, depths, and lengths of gullies are very regular. Gullies that head in topsets of the Bonneville delta do not extend into canyons upgradient (Fig. 11).

There is little continuity of the gullies upslope and downslope across the Riverdale fault (Fig. 11). Gullies upslope of that fault trend east-northeast, whereas those downslope of the fault vary, but most have east- to east-southeast trends. Gullies on the highstand Bonneville delta all grade westward to, and end at, the shoreline and adjacent topset of the composite Provo delta of the Bear River. Alluvial fans deposited at the bases of the lower gullies are small, insufficient to contain all of the sediment eroded from those gullies. Most of the material eroded from the gullies must have been reworked and incorporated into the composite Provo delta. The Riverdale fault zone, which is demarked by the gullies that trend across the Bonneville delta, does not cut any of the Provo-age deposits along strike N to S. Thus, the gullies in the Bonneville delta of the Bear River that follow the Riverdale fault are coeval with the Bonneville flood.

**Provo Delta of the Bear River**

**Front, Foreset, and Bottomset of Provo Delta**

The unconfined southern front, at the foreset-topset contact of the lower Provo shoreline, is ~16 km wide, east to west across Cache Valley (Figs. 1, 2, and 12). The change from the gently sloping topset and the steeper delta front (foreset) lies between 1430 and 1439 m (Figs. 2 and 12). This foreset has a very gentle slope southward. The base of the delta foreset coincides with a decrease in slope and a change from slightly more sand-rich sediment of the delta to more silt- and clay-rich sediment of the delta’s bottomset (Web Soil Survey, accessed 30 June 2008; http://websoilsurvey.nrcs.usda.gov/app/WebSoilSurvey.aspx).

The southern front of the Provo delta has a smooth, open, concave-south shape (Figs. 1, 2, and 12) that is typical of a wave-dominated delta. A small bend southward in the middle of the delta front at lower altitudes likely resulted from outbuilding of at least one younger delta as the lake fell below the Provo level. The fine sand, silt, and clay deposited by the Bear River in N Cache Valley was easily redistributed by waves and currents, unlike the heavier gravel that dominates deltas at the mouths of steep mountain streams farther south in Cache Valley (Gilbert, 1890).

**Topset of the Provo Delta**

The topset of the higher Provo delta is obscured by fluvial deposits in Round Valley and is interrupted by irregular topography of the Twin Lakes horst (Figs. 1, 2, 11, and 12). Logs of water wells, which penetrate the underlying Salt Lake Formation in some cases, show that most of the sediment in the Provo delta complex is clay, silt, and fine sand. The entire northeast and western edges of the Provo delta complex lap against the older Bonneville delta or bedrock composed of Salt Lake Formation,
Paleozoic or Precambrian rocks, respectively, and the only unconstrained depositional margin is its southern east-trending delta front (Figs. 1, 2, and 12). Deposition was probably rapid at first as voluminous unconsolidated sediment upstream from Provo shoreline was remobilized.

Some of the topset of the Provo delta west of the Twin Lakes horst has faint relict meander scars. Most of the rest of the topset is smooth. Most of it likely formed underwater because the Provo shorelines are higher in altitude around its perimeter (Fig. 1, 2, 11, and 12; Currey et al., 1984).

**Dune-Covered Subdelta(s) below the Provo Delta**

One or two small, lobate, post-Provo deltas were formed by the incising Bear River on the southern edge of the Provo delta during recession below the Provo shoreline (Figs. 1, 2, and 12). Further incision removed large parts of these lobate deltas. Erosional remnants of these deltas are mostly on the east side of the Bear River. Together the post-Provo delta remnants cover ~40 km² southwest of Preston, with the altitude of the higher, northern topset at ~4660 ft (~1420 m) and the high point on the lower, southeastern delta at ~4582 ft (~1397 m). There are younger parabolic sand dunes, formed by winds from the southwest, that obscure much of the post-Provo delta surfaces and some of the distal topset of the Provo delta southwest of Preston.

The post-Provo delta is lobate in plan view, and its convex-south margin differs from the smoother cuspate to gently curving margins of the Provo and Bonneville deltas of the Bear River (Figs. 1, 2, 11, and 12). The dune-covered subdeltas are composed of fine sediment derived from erosion of the adjacent Provo delta, but exposures show significant sand. The post-Provo delta may contain a greater proportion of sand due to winnowing by the Bear River confined within an inset valley. Thus, its lobate, southward-convex shape might be due to an overall increase in grain size plus concentration of deposition in a small area.

**DISCUSSION**

**What Caused the Bonneville Flood: Overland Flow, Sapping, an Earthquake, or a Landslide?**

It is challenging to pin down the main trigger for the Bonneville flood and to develop a definitive test because many processes could have triggered it, and most of the evidence is eroded near the site of failure. Sapping-related dam collapse provides one plausible trigger of the Bonneville flood (O’Connor, 1993). However, incision by overland flow just as easily could have triggered the Bonneville flood, and overland flow during the Bonneville highstand is likely. The cross-cutting relationship between the Riverdale normal fault and the highstand Bonneville foreset deposits of the Bear River raises another intriguing possibility, that a moderate to major earthquake on that fault (or emplacement of a lateral spread with a headscarp at the trace of the Riverdale fault) triggered the flood. After all, the Riverdale fault (landslide?) cuts and deforms deltaic deposits and landforms that predate the flood, yet does not deform any deposits or landforms that postdate the flood. An earthquake on the Riverdale (or other nearby) fault could have produced a seiche wave that overtopped the Zenda dam with high-velocity waters of sufficient volume to destabilize that dam, liquefy the dam, rapidly incise the length of the threshold, or cause other critical damage.

Theoretical considerations suggest that the rapid drawdown of Lake Bonneville could have been a “perfect storm” for triggering reservoir-induced seismicity. Numerous small (and some large) earthquakes develop above the background frequency as bodies of water fill and empty, notably at dams (Gupta, 2002; Telesca, 2010). For this reason, and because the cross-cutting relationships allow it, it also possible that the opposite sequence of events occurred, i.e., that the Bonneville flood unloaded the crust rapidly, and thereby induced slip on the Riverdale fault (landslide?). As ~100 m of water was abruptly removed from the hanging wall of the fault zone, an earthquake may have initiated in response to residual elevated pore pressures and lower vertical loads. Either way, differential loading and unloading is likely to have induced seismicity throughout the Bonneville Basin when Lake Bonneville was rising to its highest levels and during the rapid recession afterwards (Fig. 3).

Evidence of this process is documented in the Salt Lake City and Brigham City segments of the Wasatch fault, which ruptured during the highstand of Lake Bonneville (McCalpin, 2002; McCalpin and Forman, 2002). Some large landslides immediately west of Cache Valley also seem to coincide with this time period (Biek et al., 2003). Trenching and dating of the Riverdale structure are required to test these competing models. There are other possible triggers for failure of the Zenda threshold that are less likely to have been the main trigger for the flood.

**Possible Effect of Climate Change on the Morphology of Deltas of the Bear River**

The contrast of intense and widespread gullying of the highstand Bonneville delta and little or no erosion of the Provo delta complex suggests that the local climate abruptly changed shortly after the Bonneville flood ca. 17.4 cal yr BCE. This change inhibited widespread gullying during the latest Pleistocene and transition into the Holocene.

Prior analyses of the climate in Utah during the last glacial epoch suggested a 15%–30% increase in precipitation relative to the present, so that much of the growth of Lake Bonneville probably was due to increased cloudiness and reduced evaporation in lower air temperatures (Lemons et al., 1996; Milligan and Chan, 1998). Although the total amount of precipitation in the area of Lake Bonneville may not have increased greatly, the snowline in the headwaters of the Bear River in the Uinta Mountains lowered considerably (Munroe et al., 2006). Thus, there was probably an increase in runoff and more sediment (including much fine-grained glacial flour) carried by the Bear River during glacial times. Furthermore, more of the total precipitation probably accumulated as snow. With lower evaporation and more snow...
pack, the frequency and intensity of floods in the springtime should have been greater than at present.

Perhaps dewatering and piping-related gully formation explains the ubiquitous gullies in sediment between the Bonneville and Provo level (Joel Pederson, 2007, oral commun.). If dewatering were important, we would expect to observe theater-shaped and scalloped heads and walls along the gullies that dissect the Bonneville deposits instead of the very regular linear, parallel V-shaped gully systems that formed there. In addition, gully development by dewatering should not be very pronounced in rather impermeable materials such as the tuffaceous parts of the Salt Lake Formation. Hillslopes underlain by tuffaceous Salt Lake Formation have many V-shaped gullies between the Bonneville and Provo shorelines (Fig. 12).

Overall, four processes may have resulted in more erosion of the Bonneville delta than the Provo delta: (1) more rapid exposure of erodable fine sediment during the Bonneville flood, and the inability of plants to rapidly colonize and stabilize the newly exposed hillslopes after the Bonneville flood due to continued cold climate; (2) slightly more precipitation, primarily as snow, during the glacial (and lake) maximum; (3) more intense storms when the continental glaciers were nearby in present northern Idaho and Montana; and (4) more frequent, more voluminous, and more erosive springtime flooding. Some combination of these processes was probably operating.

Wind

Analysis of spits and shorelines built into Lake Bonneville typically indicates strong north winds (Schofield et al., 2004; Jewell, 2007) instead of SW winds (this study). These seemingly contradictory observations may not be in conflict if prevailing SW winds during the summer, like the modern winds, shaped the front of the Provo delta of the Bear River and the later parabolic dunes, but stronger winter storms from the NW were ineffective in northern Cache Valley due to shallow water with small fetch, flanking highlands, and the presence of abundant winter ice across the shallow lake surface in northern Cache Valley.

Other Unresolved Topics Still to Understand

1. The Riverdale fault zone and whether it is a normal fault that ruptured beneath Lake Bonneville, whether it ruptured after the flood, and whether it is perhaps the headscarp of a large lateral spread.

2. The age of the Riverdale structure is critical to determining the trigger for the Bonneville flood.

3. The upper limit of scours of the Bonneville flood, at ~4921 ft (1500 m) in northern Cache Valley, is ~50 m below the Bonneville highstand shoreline.

4. The sill for the higher Provo shoreline at 4775 ft (1456 m) is not preserved, and was probably removed by erosion. This makes it more difficult to determine its original location.

5. Details of the reversal of drainage directions in northern Cache Valley since late Provo time.

CONCLUSIONS

Analysis of landforms on aerial photographs, digital-elevation models, and satellite imagery, consideration of gravity data, analysis of drillers’ logs of water wells, and geologic mapping show that complex relationships in northern Cache Valley and southern Marsh Valley differ significantly from the commonly accepted history of Lake Bonneville. A resistant conglomerate in the Salt Lake Formation and the broad dam-like morphology and northwest slope of the Marsh Creek pediment and alluvial fan may have allowed episodic overflow without significant downcutting prior to the failure of the Zenda threshold. The Bonneville flood may have been triggered by an earthquake on the Riverdale fault, a landslide that had its headscarp along the fault zone, or by seiche waves generated by faulting and/or landslide failure. Other processes probably also contributed to the timing and geometry of the flood.

During the Bonneville flood, the main outflow channel first occupied and cut a curving channel on the eastern side of Red Rock Butte. Later, the flood was diverted entirely into a deeper, straighter channel on the western side of Red Rock Butte, perhaps by a landslide that redirected flood-related incision. Modest but repeated landslides collapsed from hillslopes directly west and east of the scour channel of the Bonneville flood near Red Rock Pass. Voluminous flood water re-excavated scour channels filled by landslides, removed large volumes of bedrock during scouring, and eventually created a fluted and scoured landscape beneath the northern 11 km of the former lake basin of Cache Valley and 14 km of southernmost Marsh Valley. Scours removed soils and loose materials from surfaces in the former lake basin below 4921 ft (1500 m). This altitude is ~177 ft (50 m) below the altitude of the lake when it failed. Scours are only present within the Swan Lake terrain, north of an east-northeast–trending bedrock ridge through Swan Lake, and are notably absent farther south. The scours formed only on and north of the threshold for the higher Provo shoreline of Lake Bonneville.

Wholesale failure of the northern Bannock Range in a megasliding did not occur. The southwest-dipping Riverdale normal fault disrupts downslope gullies in foresets of the Bonneville delta of the Bear River, and likely was coeval with the Bonneville flood. A moderate to large earthquake on this fault might have triggered the Bonneville flood.

Topsets of the highstand Bonneville delta and the two Provo-level deltas of the Bear River formed subaquously at lower altitudes than their associated shorelines. Subaerial parts of the Bonneville delta were upstream in Gentile Valley and within Oneida Narrows. The Bonneville delta of the Bear River was abandoned during the Bonneville flood ca. 17.4 ka. Its foresets and distal topsets were extensively dissected during and immediately after the Bonneville flood by numerous closely spaced, parallel, downslope-trending gullies that excavated 20–45 m of sediment.
The more widespread Provo delta of the Bear River filled all of northern Cache Valley from east to west with fine sediment, and it is barely dissected by younger incised tributaries of the Bear River. The highstand Bonneville delta of the Bear River is slightly convex basinward, perhaps reflecting a stronger riverine influence, whereas the Provo delta is concave basinward, likely due to strong wave action. The erosional event that dissected the highstand Bonneville delta was short-lived, was probably unrelated to rapid dewatering after the Bonneville flood, and was perhaps due to stormier, wetter(?), windier, and more fluctuating erosive conditions of the late Pleistocene. Rapid exposure and initial erosion before colonization by plants also may provide an explanation for the marked contrast between the preservations of surfaces of the Bonneville and Provo deltas of the Bear River.

There are two Provo shorelines in northern Cache Valley. These two lake levels were controlled by two separate bedrock sills. The northward outlet for the Bonneville River (Gilbert, 1880, 1890) that formed immediately after the Bonneville flood was along the Swan Lake scour channel, probably near Swan Lake, atop the NE-trending Swan Lake horst, in the footwall of the Riverdale fault. The Provo shoreline does not persist north of this location (Fig. 2). The Swan Lake sill controlled the level of Lake Bonneville at the more prominent older and higher 4775 ± 10 ft (1456 m) Provo shoreline. Gilbert (1890, 178) came close to predicting the existence of this bedrock sill when he observed that “…the outflowing (Bonneville) river headed…farther south, between Swan Lake and Round Valley Marsh.”

The second, lower Provo shoreline, near 4745 ± 10 ft (1447 m), is more subtle than the higher Provo shoreline. This lower lake stand had a bedrock sill ~23 km south of the original Zenda threshold. We interpret this episode to be shorter than that for the higher shoreline, because a longer occupation would have produced a more definitive shoreline. The Bonneville River flowed north from a second, younger, and lower sill near Clifton, Idaho, into Round Valley. There it meandered laterally and produced point-bar scrolls and a large meander belt and floodplain while flowing northward toward the Snake River Plain. This area is occupied now by a marsh that flows sluggishly southward during high-water years.

During regression of the lake below the lower Provo level, the entrenched Bear River built two successively lower, small deltas into northern Cache Valley. After the lake fell below the lower Provo level and the Clifton sill during the Holocene Marsh Creek built an alluvial dam into the Swan Lake scour channel at Red Rock Pass (Williams and Milligan, 1968). This established the modern drainage divide at Red Rock Pass, 2 km south of its original pre-flood position near Zenda, Idaho. This uneven infilling of the originally north-sloping dry bed of the Bonneville River reversed the flow direction between Clifton and Red Rock Pass. The coincidental repositioning of the modern drainage divide close to its original one near Zenda, Idaho, may explain why Gilbert (1880, 1890) was the only prior researcher to interpret a major southward shift of the outlet of Lake Bonneville during occupation of the Provo shoreline.
Cub River, tributary of the Bear River.

Cub River Road, to east-northeast, joins U.S. Highway 91 where the latter bends to the northwest. Note the absence of a delta at the mouth of the large Cub River Canyon.

Worm Creek is one of four deep post-Provo gullies through Provo delta foresets of the Bear River. This gully is inset below the Provo delta bottomsets southward, where it joins the Cub River. Here U.S. Highway 91 starts to rise up the foresets.

U.S. Highway 91 turns north in Preston, well onto the topset of the Provo delta of the Bear River.

U.S. Highway 91 turns west, where Idaho Highways 34 and 36 turn east-northeast, on Provo delta topset near the north edge of Preston Idaho.

Preston Airport is at the crest of an erosional scarp ~50 ft high, formed by the Bear River during initial recession below the Provo topset. The lower surface to the north and west is likely a strath terrace corresponding to the post-Provo delta ~5 km south.

There is a hot spring on the Bear River here north of the inflow of Deep Creek. Note the highest post-Provo shoreline level along the west flank of this entrenched valley. Numerous slumps, with common earthflow toes and arcuate headscarsps (several historic), mark the steep valley walls where fine-grained sediments of the Provo and Bonneville deltas have failed due to undercutting by the meandering Bear River.

The base of the river-cut scarp, with landslides, here lies at the north edge of the Bear River floodplain. Battle Creek, to the northwest, was site of the Bear River Massacre in 1863. That was the last major attack on Native Americans (Shoshone) by the U.S. Cavalry.

Turn east on side road to Scenic Lookout, at the crest of the river-cut scarp. We have returned to the topset of the Provo delta of the Bear River.

**Stop 1: 4727 ft, 42° 09.176' N and 111° 54.438' W.** This overview stop will be used to orient participants to the landscape. The large mountain ranges are obvious, with the Bear River Range in the east and the Bannock Range in the west. Our stop is at the extreme distal edge of the Bonneville delta of the Bear River and at the upslope edge of the Provo delta of the Bear River. The higher Provo shoreline is a little bit east of us, but is difficult to identify in the field on the deltas.

The Bonneville delta prograded halfway across this part of Cache Valley from the inlet of the Bear River south of Oneida Narrows, after filling that gorge and Gentile Valley just upstream. The landscape occupied by the Bonneville delta is subtle, with its deeply dissected foreset rising immediately east of us, the delta’s topset in the distance (~6 km away and ~100 m higher) and the Bonneville shoreline in the far distances etched across the Paleozoic rocks of low, distant foothills (7–8 km away).

A view from overhead would provide a view of the several tens of gullies eroded into the Bonneville delta of the Bear River and the small number of widely spaced and much deeper gullies that cut into the Provo delta of the Bear River. Also we would see 2–3 deep gullies cut parallel to the Riverdale fault zone 3–4 km east of us. This fault zone (or possible landslide?) does not disturb any Provo-age deposits along strike to the northwest but has a clear and obvious expression across the Bonneville delta (Fig. 11). The cross-cutting relationships show that the fault (landslide?) slipped right around the time of the Bonneville flood. More precise dating is needed to pin this down further.

The flat high terrain underfoot, to the west, to the south of the Bear River, and to the southwest is the topset of the Provo delta of the Bear River. The incision by the modern Bear River is the main modification to this delta since its abandonment at the end of the last pluvial. We were on this topset in the Preston area and will continue driving across it to our next stop. The Provo delta of the Bear River is large, and filled the remainder of northern Cache Valley from east to west with fine sediment.

The distal southern margin of the Provo delta is completely unlike the distal western margin of the Bonneville delta of the Bear River. The Provo delta is concave basinward, whereas the Bonneville delta is convex basinward. This geometry reflects a change from river-dominated deposition during the Bonneville highstand to wave-dominated deposition at the Provo still stand, at least at the delta front. We infer that this contrast in shape and the contrasting degrees of erosion are due to markedly different climates.

The bedrock hills closest to us, in the west and northwest, are the Twin Lakes composite horst block with its faulted mix of Neogene Salt Lake Formation to Neoproterozoic bedrock (Link and LeFebre, 1983). This irregular set of hills pops up through the topset of the Provo delta, and has two northern appendages that are buried just beneath the Provo sediment. The western buried bedrock ridge was the outlet of Lake Bonneville during the brief (?) stillstand at the lower 4745 ft Provo shoreline. The evidence for this interpretation will be discussed at Stop 8, in Round Valley on the far side of the Twin Lakes horst.

We can see some of the sediment of the deltas in cuts along the Bear River Valley. No gravels are apparent in the steep scarps exposed by multiple landslides, and few are recorded in numerous drillers’ logs of water wells. The delta is composed of silt, clay, and some sand in the subsurface. The reddish color of this
fine sediment is inherited from its Tertiary and Mesozoic source rocks in western Wyoming and SE Idaho. Inset remnants visible upstream along the Bear River at the Provo-delta level may be strath terraces in part.

0.2 2 92 Return to U.S. Highway 91. Turn north. Note the proximity of reddish sediment in the foreset of the Bonneville delta of the Bear River northeast of us.

4.0 6 98 At pressurized water pipeline for irrigation, we cross a subtle saddle and buried bedrock of the Twin Lake horst that forms the southeast corner of Round Valley. Relict meanders of the north-flowing Bonneville River lie in the lowest part of the valley, west of us, as we drive north to Stop 2.

6.4 10 108 Stop 2: 4796 ft, 42° 17.658′ N, 111° 59.225′ W. This stop is at a road cut on the east side of the highway and east of the south part of Swan Lake. Most of the exposure is covered because the bulk of the Salt Lake Formation is fine and tuffaceous. Locate the single poorly sorted conglomerate bed of the Salt Lake Formation in the upper half of the outcrop, and trace it laterally to see how it defines a broad, faulted anticline that trends roughly east-west. This anticline in the Salt Lake Formation projects west along the Swan Lake ridge and horst. The ridge coincides with widely scattered exposures of brecciated bedrock all the way up to the base of the Bannock Range in the distance (Long and Link, 2007), and overlies a pronounced gravity high (Kruger et al., 2003). Flood-related scours sliced into the top of this ridge. Scoured hillslopes of the Bonneville flood end along the SSE edge of the Swan Lake bedrock ridge. The flood scraped deep groves into the Swan Lake horst block from south to north—just like a rake scrapes shallow grooves into moist sand.

Scoured landscapes are notably absent farther south (Figs. 7). Twin Lakes horst, just a few kilometers to the south of the scoured landscapes, has magnificent transgressive Bonneville shorelines stacked from top to bottom (some hillslopes preserve ~20 beach ridges) without evidence of later scour. This is striking because Twin Lakes horst is located in the center of the basin that was draining catastrophically during the Bonneville flood, and it lies in the same altitudinal range as the scoured landscapes in the Swan Lake terrain to the north.

The contrast between the pervasively scoured landscape from the Swan Lake horst northward and the rest of the Bonneville basin farther south suggests that scouring developed primarily downstream of the new outlet of Lake Bonneville in the late stage of flooding. For scours of this intensity to form, the landscape must be near or within the outflow channel and thus must be north of the eventual sill for Lake Bonneville after the Bonneville flood.

1. The Swan Lake scour channel starts here and has the morphology of a megaflood-related scour (e.g., Baker, 2009).

2. Its geometry is most consistent with a sill at its south end, not one in the middle at Red Rock Pass (Fig. 10).

3. Notice the irregular topography SW of here. The flood scours might have produced this landscape, but its morphology also resembles a landslide mass and its poor, blocky exposures are similar to those northward toward Red Rock Pass.

This likely was the outlet of Lake Bonneville at the older, higher Provo shoreline, when drainage of the Bonneville River persisted northward along Swan Lake scour channel. The Riverdale fault, downthrown to the southwest, lies buried ~3 km to the south.

Swan Lake is a shallow lake that formed in the Holocene. It is a residual low between adjacent infilling alluvial fans, and drowns a part of the Swan Lake scour channel that was filled less than areas to the north and south (Fig. 7). A piston core (Bright, 1966) at Swan Lake showed 9.55 m (31.3 ft) of Holocene fill here, to ~4730 ft altitude, above Salt Lake Formation. Two water wells within this channel, 4.3 km NNW of this stop, showed two laterally correlatable alluvial gravels separated by 10–13 ft (3–4 m) of clay, to a depth of 101 ft (31 m), near 4678 ft (1426 m) altitude. The base of the lower gravel is ~97 ft (30 m) and 67 ft (20 m) lower, respectively, than the 4775 and 4745 ft shorelines. Thus the sill probably was farther south.

From this stop north we pass by a series of low hills and valleys. Irregular topography here has up to 500 ft (~150 m) of relief, and pre-Quaternary bedrock of all types is close to the surface in many places (Bright, 1963; Link, 1982a).

1.6 6 134 Swan Lake hamlet and country store, is within the Swan Lake scour channel. Fluted terrain to the west, basinward and lower than east-sloping sediment and alluvial fan remnants, is visible to the northwest. Landslide blocks related to the Bonneville flood are common along our route north of here.

3.3 6 140 Stop 3: 4888 ft, 42° 21.172′ N, 112° 02.656′ W. Turn right on Red Rock Road. Turn around at 0.1 mi. Park at base of bedrock hill west of the road. Climb to hillcrest for a view of the scoured landscape produced by the Bonneville flood. North of us is Red Rock Butte, and west of us is Red Rock Pass (~under the overpass). Red Rock Butte to the north consists of Cambrian to Ordovician St Charles Formation (Fig. 13; DeVecchio et al., 2003). Seismic refraction of Williams and Milligan (1968) suggested bedrock at a depth
North of Stop 3 are two scour channels that formed sequentially (?) during the Bonneville flood. The eastern channel, east of Red Rock Butte, has more curvature, formed during the Bonneville highstand, and was active during the early part of the flood. The east scour cut across older Pleistocene sediments along the east wall (Stop 4), but the preserved part of its west wall is durable Paleozoic rocks, and the floor exposes tuffaceous Salt Lake Formation. The Pleistocene sediments vary in thickness. The field relationships may show that downcutting slowed or stopped as more resistant rocks were being exposed in the base of the scour (at an altitude of ~4870 ft [1485 ± 1 m; Fig. 5]). However, some other process probably deactivated this channel, because the tuffaceous facies of the Salt Lake Formation here is weak. The landslide beneath our feet, or an older one in a similar location may have been responsible for deactivating the eastern scour and for diverting flow entirely into the western scour channel (Fig. 13).

The straighter, lower, western scour channel became the only locus for outflow of Lake Bonneville during the last ~50 m of incision in this area. This western channel is better known than the eastern one, and might have been active from the start of the Bonneville flood. Our reconstruction in Figure 13, however, shows another alternative, that the eastern scour was the sole locus of outflow early during the flood and that the western scour replaced it later in the flood.

The western scour became the bed of the Bonneville River, the very large but short-lived north-flowing river that emerged from Lake Bonneville when it was overtopped (Gilbert, 1890). The lake was hydrologically open northward when the Provo shorelines were occupied between ca. 17.4 and 15 cal ka BCE (Godsey et al., 2005).

We are standing on a block of Cambrian Blacksmith Formation within a large landslide that was shed westward (DeVecchio et al., 2003) into the scoured area. Notice that these Paleozoic rocks dip ~30° toward the east-southeast, toward the headscarp in the east. This is one of several prominent landslides of the Red Rock Pass area. We can see other landslides as well from this stop and there are erosional remnants in the scour channel and above the west edge of the western scour channel. We mapped these landslides, and found that they are localized within 1–2 km of the scour channel and are most abundant in the foothills of the Bannock Range (Fig. 13). The area affected by landsliding in the northern Bannock Range (Fig. 4) is much smaller than the >17 km² megalandslide hypothesized by Sewell (cited in Smith et al., 1989). Large areas that Sewell interpreted as landslide are instead stable pediment remnants, distal fan deposits and exposures of in-place Salt Lake Formation (Mayer, 1979; Long and Link, 2007).

The west channel bottom is nearly flat due to post-Provo infilling with sediments by the Holocene Marsh Creek (Gilbert, 1890; Bright and Ore, 1987), whereas the east channel was abandoned during the flood, and is entrenched by Marsh Creek. The east channel was not significantly infilled. The modern drainage divide is localized by the slight rise on the radially bifurcated Holocene Marsh Creek alluvial fan (Figs. 4, 8, and 10).

This pre-Bonneville, Marsh Creek alluvium contrasts with the darker, more orange sediment in the west part of this outcrop. These orange sediments are also Quaternary and overlie the fan deposits along a buttress unconformity that dips west toward the channel. One large boulder of the fan sediment was incorporated into the darker sediment and documents the relative age as younger than the alluvium and younger than the eastern scour. The darker sediment is poorly sorted and weakly bedded sand and gravel. It might be an unusually thick hillslope deposit that was shed from the oversteepened east wall of the eastern scour channel. The grain size seems too fine for these to be flood deposit.
This Marsh Creek alluvium and its overlying inclined sediment are in a cut-and-fill relationship with underlying Salt Lake Formation (Stop 6), and thin northward. Be sure to examine the thin gravel lenses for their clasts. We will compare the clasts in these Quaternary gravels with those in Miocene conglomerates at Stop 6. Continue driving east.

0.8 5 236  Head of gully, road bends to north.
1.0 4 240  At road junction, turn west.
1.7 9 249  **Stop 5: 5131 ft, 42° 24.085′ N, 112°04.273′ W.** Proceed west on the gravel road until you are at the top of a west-facing hill-slope. We can see the large, open drainages produced by sapping below the highest altitude of groundwater seeping north from Lake Bonneville. Scalloped drainages with theaters at their heads and margins persist all the way to the valley floor to the northwest, but end upslope a few meters above the altitude of the Bonneville highstand shoreline. Higher on this pediment, dry gullies have V-shaped cross sections typical of fluvial erosion. This groundwater flow and sapping could explain the Bonneville flood, if the basin was closed and sapping weakened the sill and caused it to fail (O’Connor, 1993).

0.5 2 291  At Zenda, Idaho (a few ranch houses) turn west. Note pediment on Salt Lake Formation to west-northwest, with landslides along undercut face in front.

0.2 1 292  At road junction, turn west. Return to Pratt Road junction, and turn north. Note ash in Salt Lake Formation in road cut here. This is late Miocene ash from the Twin Falls caldera along the Yellowstone hotspot track (DeVecchio, 2002; DeVecchio et al., 2003).

0.5 3 300  Downata Hot Springs main building. Park, use facilities, and gather at picnic tables east of the main building for lunch.

1.4 5 305  Return to U.S. Highway 91, turn south, proceed 0.9 mi.

**Stop 6: 4764 ft, 42° 23.021′ N, 112° 04.172′ W.** Park on west side of road at base of a small hill. Inspect the blocks of cemented conglomerate in the road cut and then climb to the top of the hill for a view of the scoured landscape very close to the original threshold of Lake Bonneville before the flood. The Zenda dam would have been ~90 m above us and ~800 m south of here before the Bonneville flood. The flood initiated here, in these fairly weak sedimentary rocks with thin overlying pediment-related Quaternary sediment and loess, after holding fast for long enough to produce a well-defined shoreline across the Bonneville basin. We estimate a minimum duration of at least 500 years for the Bonneville highstand because the ~2000-year occupation of the higher Provo shoreline (Godsey et al., 2005) produced a shoreline of similar intensity. At Stop 7 we will show that an earthquake might have triggered the Bonneville flood.

The hill under our feet is an erosional remnant of a landslide that was shed west into the valley from the oversteepened east wall of the Swan Lake scour and discharge. The landslide was mostly eroded away by floodwaters, by the subsequent Bonneville River, or both. The blocks of cemented conglomerate in this landslide were carried downslope from the in-place conglomeratic Salt Lake Formation from the hillside directly east of us, where it is less accessible. Beds of silt and fine sand alternate with conglomerate and gravel along the entire eastern margin of the scoured channel here, and formed the dam for Lake Bonneville at its highest level. The degree of cementation varies somewhat, but

Our vantage at Stop 5 allows us to see the pediments and alluvial fans along the southern flanks of Marsh Valley. The remnants of two large fan-pediments here truncate folded and faulted Neogene Salt Lake Formation, and head in Aspen Creek (west) and in Marsh Creek (east) (Fig. 4). These were graded to a common base level that is well above the modern streams. Northern Cache Valley contains some smaller remnants of pediments and alluvial fans that graded to a similar higher base level. The Bonneville shoreline is cut lightly into part of this pediment east of Red Rock Pass (Gilbert, 1890) and in northern Cache Valley, so the pediments and Pleistocene alluvial fans exemplify the landscape before the flood.

We used the regular geometry of these surfaces to reconstruct the landscape to a pre-flood condition, and found that the reconstructed saddle was coincident with the highest shoreline of Lake Bonneville, within errors. Therefore, we agree with most prior workers that Lake Bonneville probably had an outlet and was an open lake when it reached its highest altitude at the Bonneville shoreline (cf. Currey, 1982; Currey and Burr, 1988; Currey, 1990; Oviatt, 1997; Oviatt et al., 1992; Currey and Oviatt, 1985). A sapping-related dam failure roughly at the altitude of the highest Bonneville shoreline is an ineffective way to start a catastrophic flood if, as we believe, Lake Bonneville was intermittently flowing out across the Zenda pediment threshold prior to the flood (see also Currey, 1982, and others). The broad, gentle curvature of the surface of the coalesced pediments, their gradual downstream slope, and a resistant conglomerate within the Salt Lake Formation near the low point between the pediments (Stop 6) apparently made this area a surprisingly long-lived (~1.2 k.y.; Godsey et al., 2005) earthen dam for Lake Bonneville.

Note the pediment-covering sediment on Salt Lake Formation across the valley, to the southwest (toe near 5060 ft, rising to ~5250 ft). In distal settings and in cut-and-fill locations, the Quaternary sediment is thicker than the pediment-covering deposits.
these blocks are typical of conglomerates exposed in the channel wall from Zenda northward to the end of the exposures.

Several features show that this landslide transported conglomerates of the Neogene Salt Lake Formation and not Quaternary alluvial-fan deposits, as originally mapped (DeVecchio et al., 2003). In particular, the clast composition is very different from that in the distal alluvial sediment of Marsh Creek exposed at Stop 4, in having many conspicuous reddish and purplish quartzite clasts derived from the Neoproterozoic Brigham Group in the Salt Lake Formation (as we can see at this stop) in contrast to a few white quartzite and much dark to black chert and carbonate clasts in the Marsh Creek alluvial-fan deposits (at Stop 4). Dips in the Salt Lake Formation are low but toward the east throughout this outcrop belt (DeVecchio et al., 2003; Janecke, unpublished mapping). Finally, this conglomerate of the Salt Lake Formation resembles conglomerate beds in a strongly tilted and later eroded subunit of Salt Lake Formation that is interbedded with thick white and silver tuffs in the west wall of the Swan Lake scour channel near Downata Hot Springs (our lunch stop). Ashes that are downsection of the in-place conglomerate, south of our stop, were chemically correlated to 7–10 Ma ashes erupted from the Yellowstone hot spot track (DeVecchio, 2002; DeVecchio et al., 2003).

2.4 5 331 Return south on U.S. Highway 91 to approach to overpass bridge that crosses the railroad tracks. Turn south on Idaho road “D 1.” Note the flat-bottomed and infilled Swan Lake channel to the south-southeast with numerous knobs of flood-sculpted landslide material sticking up. The reddish weathering cavernous cliff of Cambrian limestone west of the road was transported in one of the many modest-scale landslides that initiated during the Bonneville flood (Fig. 13). We speculate that reservoir-induced seismicity from the rise and fall of Lake Bonneville may have helped to destabilize some of the hillslopes during and after the flood.

We will drive south parallel to high remnants of pediments and alluvial fans that are truncated at their toes by multiple east-facing escarpments that could be flood scours, fault scarps, or both. We suspect that most of these are fault scarps of the Dayton-Oxford fault zone because they project into other probable faults, and flood-related scours are lower in elevation, below ~1500 m. The Bonneville flood stripped the landscape of its thick darker soil within all the other scars, thereby exposing light-colored tuffaceous Salt Lake Formation or light pre-Tertiary bedrock.

4.3 9 340 Road trends south, then southeast to a deep gully (Gooseberry Creek) from west, where road turns to south again.

1.8 4 344 Turn left (east) into driveway at 9766 North Westside Highway, proceed uphill on a private drive belonging to Mr. Dennis Brisco.

Stop 7: 4965 ft, 42° 16.507′ N, 112° 00.720′ W. The stop is located near the southern margin of the Swan Lake horst block, overlooking Round Valley, south of us. Our location is within an area that was scoured and modified by the Bonneville flood to form N-S trending scours and ridges. A short distance west of here there is no clear evidence for scouring in the 50 m below the high Bonneville shoreline. Meanders are visible in the lowest part of Round Valley below us to the south (Fig. 9). These large relict meanders have wavelengths of 2.3 km, and match the size of those produced by the Pleistocene Bear River (Fig. 12). The meander belt is at an altitude of 4745 ft (1446 m), and is distinctly below the higher main prominent Provo shoreline in northern Cache Valley, the 4775 ft (1456 m) shoreline. Therefore a separate, lower, and probably later Provo shoreline is indicated by these relationships. We will examine the lower 4745 ft (1446 m) shoreline at Stop 9 in the Weston, Idaho, area.

0.3 2 366 Return to Idaho road D-1, turn left; note road crest ~4948 ft at road cut in Salt Lake Formation just southeast of well at Stop 7. Quartz-rich rock was encountered at 82 ft in the well at the home on the hill east of the road. Road bends to southwest at canal. Note view southeast of formerly north-flowing meanders in Round Valley. Between here and Clifton, cobbles and boulders of foliated green rocks are common at the surface. They are mostly phyllite, derived from the Neoproterozoic Pocatello Formation in the cliff faces to the west. In a well log at 7375 North Westside Highway, a surficial unit composed of this material 29 ft thick, perhaps a landslide deposit, was identified as “basalt.”

6.6 8 352 Clifton, Idaho.

1.3 4 368 Turn right (west) and drive a short distance across a canal and stop at entrance to a small sand and gravel pit for an overview of the Clifton sill area.

Stop 8: 4766 ft, 42° 10.017′ N, 111° 59.828′ W. Stop and look around at the locked gate of a small borrow pit, west of the west side canal. In the gravel pit and to our west is faulted Salt Lake Formation (the white and silver sediment) in fault contact with Neoproterozoic metasedimentary rocks (Carney and Janecke, 2005; Carney et al., 2003). These rocks are tilt bocks in the hanging wall of the Bannock detachment fault.

The Twin Lakes composite horst is the low set of hills east of here, and they separate Round Valley from the rest of Cache Valley. These low hills are largely between the Provo and Bonneville shoreline, and have closely spaced beach ridges along many of
their exposed hillslopes. There is a thin carapace of these lake beds on complexly faulted Neoproterozoic Pocatello Formation, Brigham Group quartzite, Paleozoic carbonates, and much Late Cenozoic Salt Lake Formation (Link and LeFebre, 1983).

This Twin Lakes composite horst block consists of two crossing fault blocks in a T-shaped geometry overall, with a chubby P-shape above ground level. One sub-horst is a narrow NW-trending bedrock ridge of Proterozoic rocks (Link, 1982a, 1982b; Link and LeFebre, 1983).

We infer the Clifton sill at the narrow valley here, where the Bannock Range and Twin Lake horst block come closest to one another. This unremarkable looking place separates northward-merging tributaries in the north from southward-merging tributaries in the south. Gravity data show shallow bedrock beneath this area (Eversaul, 2004). Locations of sparse logs of water wells are poorly documented across this area. However, shale of the Salt Lake Formation was reached at 129 ft (39 m) near the west margin, and hard clay was reached at 136 ft (41 m) near the east margin. The top of the Salt Lake Formation may be higher in both wells. Incision by younger streams is dissecting the topset of the Provo delta of the Bear River in the south, but has not begun to incise north of the sill. This is one of several geomorphic contrasts across the sill.

4.3 7 414 In south part of Dayton, at junction with Idaho Highway 36 West, turn southwest. 5.2 8 422 Idaho Highway 36 turns west. Continue south. Note older, higher Provo topset on Weston delta, near 4782 ft altitude here. 0.4 1 423 Stop 9: 4747 ft, 42° 2.245’N 111° 58.898’W. Curve to east, and descend to younger, lower Provo shoreline. Park on north side of Depot St., southwest of the Latter Day Saints church. The Dayton-Oxford fault lies west of Idaho Highway 36 northwest of Weston and forms the east face of Rattlesnake Ridge. The step down to the east located west of the church is the 4745 ft Provo shoreline, and it is cut into the topset of the Provo delta of Weston Creek. This stop and alternate Stop 9 show the 4745 ft shoreline in particularly well-expressed locations.

Alternate Stop 9: 42°01.449’ N 111° 58.807’ W. A better location for viewing both the higher and lower Provo shorelines is south of Weston on a gravel road at these coordinates; however this stop might not be used due to time constraints. Stop here on the topset to the Weston delta and look around to see the 4745 ft shoreline due west of you at 42° 01.461’ N 111° 58.897’ W. This is below the main higher 4775 ft shoreline visible on the hillslopes to the south. The two shorelines are 52–56 ft (16–17 m) apart vertically in this location. The Bonneville shoreline is also clear southwest of this location along the northeast flank of Bergeson Hill. Notice that the hillslope between the Bonneville and higher Provo shoreline is riddled with small steep gullies that trend downslope, gullies are closely spaced, and this intense erosion end downslope at the higher Provo shoreline with its distinctive wave-cut cliff and basinward bench. These gullies cut into Salt Lake Formation and its fairly thin Quaternary cover.

Continue east, then south to Utah state line. Road becomes Utah Highway 23. To west are Big and Bergeson Hills, which contain faulted Salt Lake Formation, an anticline near the crest of Bergeson Hill, and local east-dipping Ordovician Garden City Formation and brecciated Paleozoic rocks near normal faults. Farther south, note shorelines in the west, and, past Trenton, black Ordovician-Silurian Fish Haven Formation dipping ~75° east, but dipping west with minor underlining Eureka Quartzite near the Provo shoreline north of the borrow pit that is ~0.5 mi south of 9400 North. Then gray quartzite (Neo-proterozoic?) dipping west appears, near the Provo shoreline, south of the borrow pit and a distinct NW-striking gully. All pre-Cenozoic rocks are overlain by Miocene-Pliocene Salt Lake Formation in a north-plunging syncline along the crest of Newton Hill (which is also called Little Mountain).

Stop 10: 4495 ft, 41°52.501’ N, 111° 56.889’W. Pull into old county road–gravel storage area east of Utah Highway 23, at bend. East-west geologic section with logs of 3 water wells and 2 oil wells encountered thin Quaternary deposits over thick Salt Lake Formation over possible Eocene Wasatch Formation over white quartzite over Neoproterozoic metasedimentary rocks, the latter near 6200 ft (east) and 5200 ft (west), perhaps evidence for extent of the Bannock detachment fault south to this latitude. Second (south) gravel pit has abundant and varied Neoproterozoic quartzite with no obvious source, distributed in two foreset sequences separated by a well-developed buried paleosol. Relations to the west with a gently south-sloping gravel bench (~4830 ft in south rising to ~4980 ft in north), between the highest Bonneville shoreline and the Provo shorelines, are unclear. However, the gravels below the paleosol may belong to the older Pokes Point or Little Valley lake cycle, and those above probably belong to the Bonneville or perhaps to the Little Valley lake cycle if it reached this height (Scott et al., 1983; McCoy, 1987; Oviatt et al., 1987;
Oviatt et al., 1999). Dating by optical stimulated luminescence is in progress.

Continue south on Utah Highway 23 to near crest. Turn south on 4800 West. Take care crossing the northeast-trending railroad track to south. Note Cutler Narrows to west, where Bear River exits Cache Valley westward. There were four sites along the Cache Butte Divide where water could flow from west to east at the Bonneville highstand, at the start of the Bonneville flood, but only one, Cutler Narrows, when the lake level fell below ~5000 ft altitude (Maw, 1968; Oviatt, 1986a, 1986b).

Utah Highway 218. Turn east toward Smithfield. Cross buried trace of the Dayton-Oxford fault close to here. Flat valley floor consists of bottom set muddy deposits of Lake Bonneville.

Road begins to rise from ~4420 ft to ~4450 ft, near east end of the sewage lagoons, onto a sand levee built by Bear River atop the lake-bottom sediments. We cross the Bear River east of the Amalga cheese plant (north). An oil well drilled there reached carbonate bedrock between 5200 and 5500 ft (total depth). Small solifluction lobes form each spring in the sandy levee slopes along the Bear River here.

Smithfield town center. Turn south on U.S. Highway 91 at stoplight.

Arrive on the west side of Riverwoods Convention Center ~5–6 p.m.

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