CATASTROPHIC GLACIAL OUTBURST FLOODS ON THE UPPER ARKANSAS RIVER, COLORADO

By Keenan Lee

Colorado Geological Survey
Miscellaneous Investigations 98

COLORADO SCHOOL OF MINES

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COVER: *Lidar image of the Arkansas River valley floor near Buena Vista, Colorado, shows scour caused by the third catastrophic glacial outburst flood. Valley floor is covered by boulders and coarse gravels deposited by the second outburst flood. Unscoured surface, far right above highway, is flood gravel from the first outburst flood.*

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INFORMAL TERMS USED IN THIS REPORT

I have defined and used informal names for the floods described in this report as Flood 1, Flood 2, and Flood 3. I have named the postulated glacial lake that led to the floods Three Glaciers Lake.

For clarity and ease of discussion I have used place names that do not appear on U.S. Geological Survey topographic maps. All of these names appear on the geologic maps in this report.

Informal names, locally used:

Big Bend	The Numbers Rapids
Frog Rock	Railroad Bridge
Pine Creek Rapid	Wild Horse Canyon

Informal names, author designated:

Antelope Flats	Kostelic Creek
Behrman Rock	Roberts Flats
BLM Butte	Sailor Mesa
Buena Vista–Nathrop Valley	Sega Mesa
Flood Boulder Flats	Swisher Mesa
Fourmile Gap	Three Glaciers Damsite (Damsite)
Frog Rock Gap	Upper Valley
Kodi Gulch	Wolfe Spillway

OVERVIEW

Three catastrophic floods swept the upper Arkansas River valley and deposited flood gravel at least as far downstream as the town of Salida. The oldest flood took place about 640 thousand years ago (ka), and the two younger floods were comparatively recent and closer together in time, about 130 ka and 19 ka.

These floods occurred during three clearly differentiated glaciations in this area. On the basis of the Rocky Mountain terminology of Richmond (1986), these glacial intervals were, listed oldest to youngest, as follows:

- Sacagawea Ridge glaciation, Marine Isotope Stage (MIS) 16, about 675–621ka;
- Bull Lake glaciation, MIS 6, about 190–130 ka; and
- Pinedale glaciation, MIS 2, about 35–14 ka

The two younger floods originated as glacial outburst floods at the horseshoe-shaped narrows here called the "Damsite" (**Fig. 1**), and the oldest flood likely had the same origin. The glaciers that dammed the Arkansas River flowed down the east flank of the Sawatch Range in the contiguous drainages of Clear Creek and Pine Creek. The glaciers advanced into steep granite walls on the east side of the Arkansas River valley, where the ice thickened and spread laterally, merging into a compound ice dam. The dammed Arkansas River formed a glacial lake, Three Glaciers Lake (**Fig. 2**), which extended about 12 miles (mi.) upstream and was more than 600 feet (ft) deep at the dam. When the dam failed, the lake drained catastrophically. Floodwaters swept away the end moraines at the damsite and transported the debris down valley. Floodwaters spread out in the valley floor below the damsite, until they were funneled into and deepened in the narrow granite reach of Wild Horse Canyon. Bursting out of Wild Horse Canyon, floodwaters again spread out in the wider valley at the town of Buena Vista before being confined in Browns Canyon and spreading out again in the Sand Park area.

Each of the three outburst floods deposited sheets of unsorted flood gravel on the valley bottom. Little remains of the oldest flood gravel, flood gravel 1, except in one area just upstream of Buena Vista and in narrow valley-margin terraces, but the gravels extend as far downstream as Sand Park. Flood gravel 2, the most extensive flood gravel, is more-or-less continuous from the damsite south to Salida, except in two narrow canyons (Wild Horse and Browns) where it was swept downstream by Flood 3. Flood gravel 3, which is more restricted, lies just below the damsite and below the mouths of the two canyons.

The upper Arkansas River valley, as discussed in this report, extends from the headwaters of the Arkansas River north of Leadville to the Bighorn Canyon (Fig. 1) south of Salida. Towns within the valley are, in downstream order, Leadville, Granite, Buena Vista, Johnson Village, Nathrop, and Salida.

This report defines and discusses four reaches of the upper Arkansas River valley (Fig.1), again in downstream order:

- Three Glaciers Damsite, the area around the glacial dams that includes the lower reaches of the tributaries Lake Creek, Clear Creek, and Pine Creek;

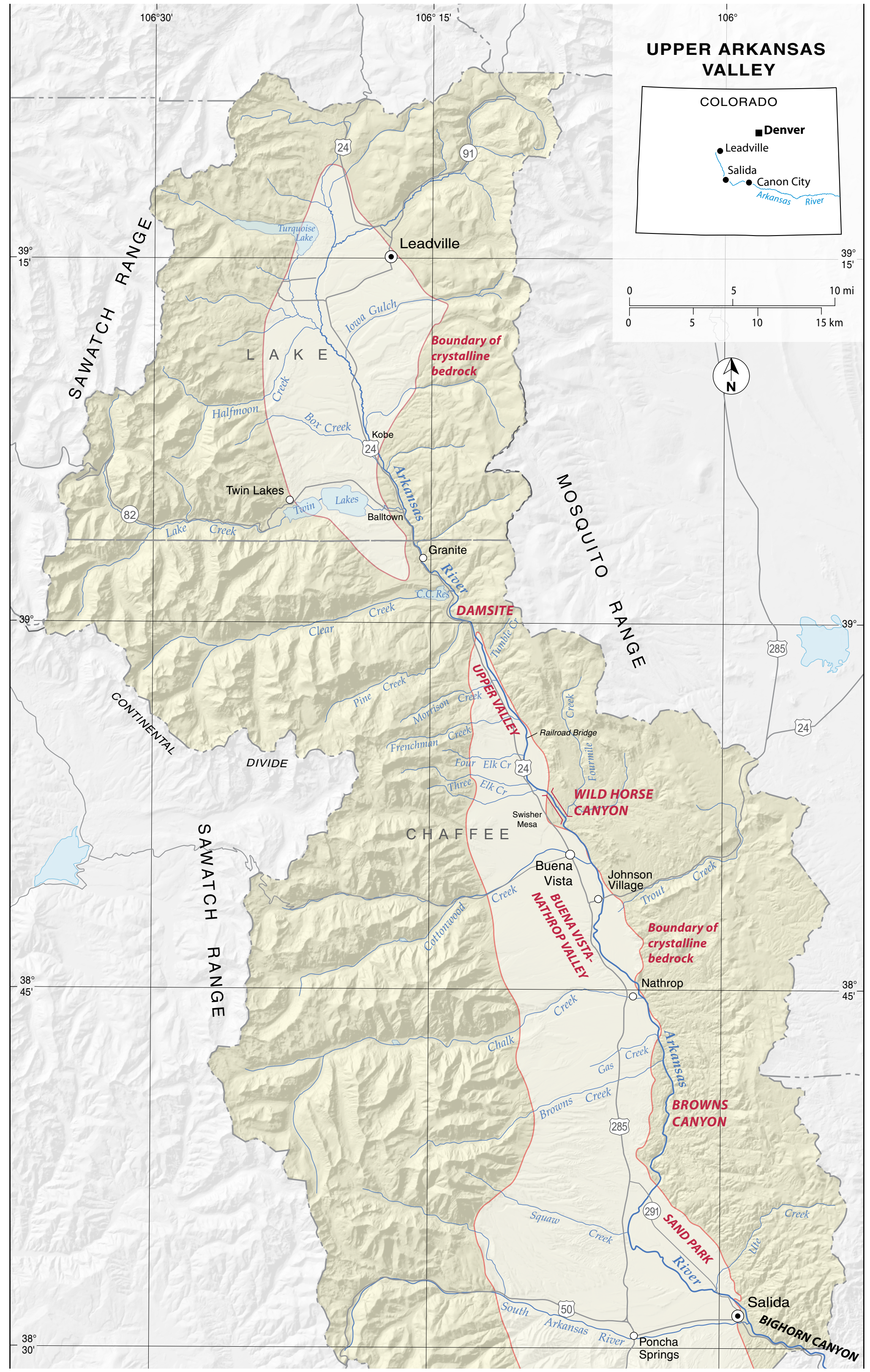

Figure 1 – Upper Arkansas River valley, showing drainages, distribution of crystalline bedrock, canyons of the Arkansas River, and the reaches of the valley discussed in this report.

- Upper Valley, the broad valley from Pine Creek downstream to Wild Horse Canyon;
- Buena Vista – Nathrop Valley, from the mouth of Wild Horse Canyon downstream to Browns Canyon; and
- Sand Park, from the mouth of Browns Canyon downstream to Salida.

THREE GLACIERS DAMSITE

OVERVIEW

Three tributary glaciers reached the Arkansas River near Granite, Colorado (Figs. 1, 2). These glaciers changed the course of the river, formed glacial dams, and impounded Arkansas River waters in a glacial lake. When the glacial dams failed, catastrophic floods poured down the upper Arkansas River valley. Glaciers advanced eastward towards the Arkansas River in each of three contiguous tributary valleys draining the east flank of the Sawatch Range. From north to south, these glaciers were the Lake Creek glacier, the Clear Creek glacier, and the Pine Creek glacier. In the two southern tributary valleys, glaciers dammed the Arkansas River. In each tributary valley, glaciers during three glaciations reached the Arkansas River: the oldest glaciation, Sacagawea Ridge, was about 675–621 ka; Bull Lake glaciation, about 190–130 ka; and Pinedale glaciation, about 35–14 ka.

Glenn Scott (1975) mapped various gravels that contain large boulders in the upper Arkansas River valley and recognized them as evidence for glacial outburst flooding. Scott (1984) postulated four catastrophic floods and suggested that the damsite was probably at Pine Creek.

BEDROCK

Most bedrock in the drainages of the three glacial systems are Precambrian plutonic and metamorphic rocks about 1.7 billion years old; minor amounts of Tertiary plutonic rocks, small exposures of Tertiary volcanic rocks restricted to the headwaters of Lake Creek, and some Tertiary sedimentary rocks are also present (Tweto and Reed, 1973; Tweto et al., 1978; Kellogg et al., 2013; Shroba et al., 2014; Kellogg et al., 2017). Precambrian plutonic rocks are mostly granites, and metamorphic rocks are mostly biotite gneisses. A small mid-Tertiary stock, the Twin Lakes porphyry, intruded Precambrian basement rocks. About 70 percent of the Lake Creek drainage basin consists of plutonic rock, about 15 percent is metamorphic, and about 15 percent is volcanic. In the Clear Creek and Pine Creek basins, 90–95 percent of bedrock is plutonic rock and 5–10 percent is metamorphic rock.

The Twin Lakes porphyry is an easily recognized porphyritic quartz monzonite to granodiorite with conspicuously large orthoclase phenocrysts (Howell, 1919). Because this porphyry crops out in both the Lake Creek and Clear Creek drainages but not in the Pine Creek drainage, it can be used to define the provenance of tills and flood gravels that contain it. The weathering characteristics of the porphyry can be used to provide relative ages of these deposits: the large feldspar phenocrysts are more resistant to weathering than surrounding groundmass, leading to protruding crystals that stand out in progressively greater relief with age.

The Miocene-Pliocene Dry Union Formation consists chiefly of fluvial sands and gravels of rock types from local drainages as well as from upriver, most notably quartzite. Dry Union sands and gravels crop out only in the lowermost part of the Lake Creek drainage.

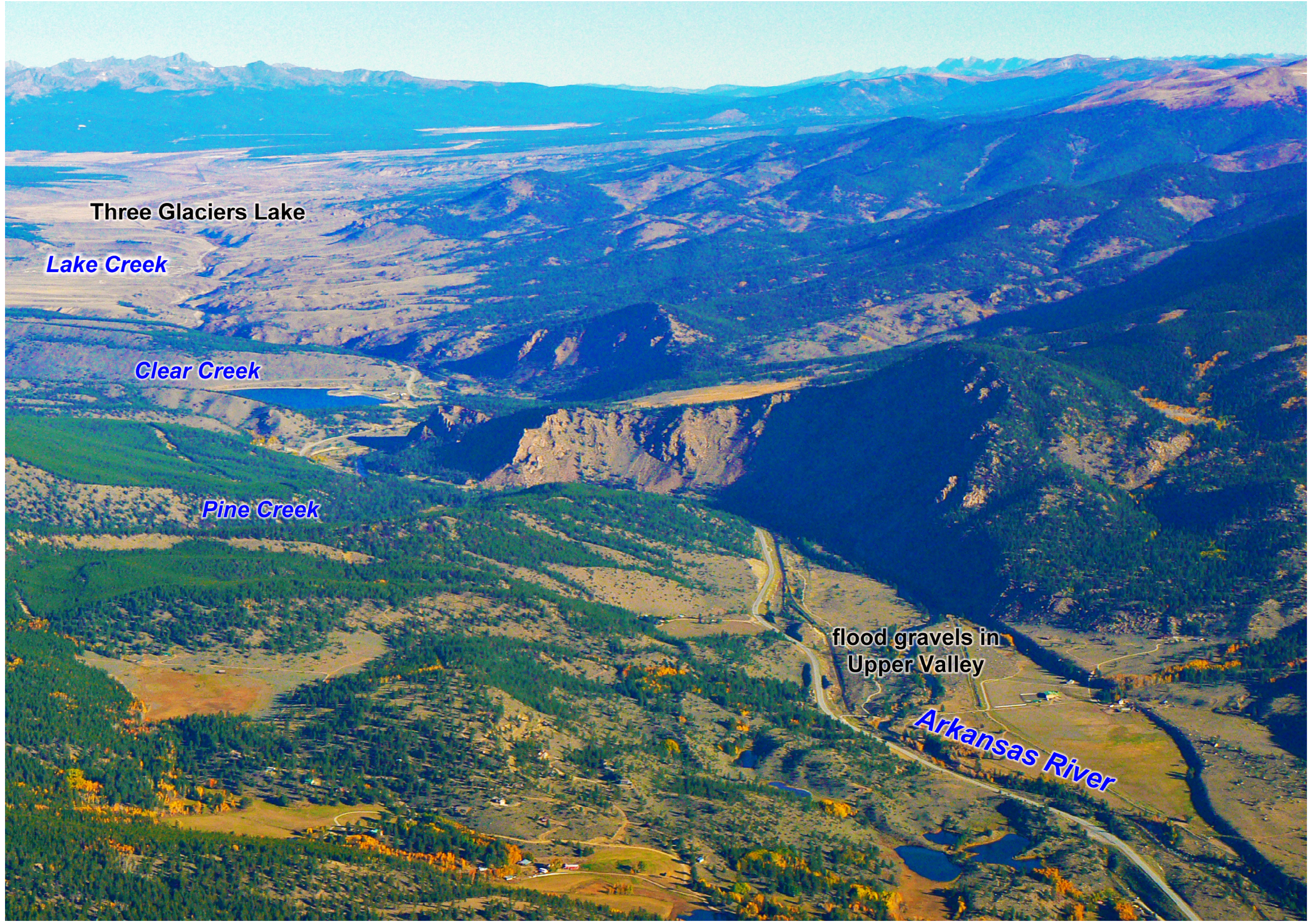

Figure 2 – Three Glaciers Damsite area on the Arkansas River; view to north (upstream) shows area of the glacial lake Three Glaciers Lake.

GLACIAL DEPOSITS

Modern terminology used for deposits of Quaternary age has been in use in this area for some considerable time (Capps, 1909; Shroba, 1977; Nelson and Shroba, 1984, 1998; Shroba et al., 2014).

The age ranges used for these glaciations, however, have not been standardized. Here I follow the usage of Ruleman et al. (2016, his fig. 3), which is based on the work of Lisiecki and Raymo (2005, their fig. 4 and table 3).

- Pinedale refers to deposits of the latest major glaciation, approximately 35–14 ka, MIS 2;
- Bull Lake refers to deposits of approximately 190–130 ka, MIS 6; and
- pre-Bull Lake refers to deposits older than 190 ka. Evidence in the upper Arkansas River valley indicates that pre-Bull Lake glaciation here is about 640 ka, which correlates with the Sacagawea Ridge glaciation (Chadwick et al., 1997; Hall and Jaworowski, 1999; Pierce, 2003), approximately 675–621 ka, MIS 16.

Moraines of three glaciations are recognized in this area. Pinedale-age and Bull Lake-age moraines are found in each of three tributaries—Lake, Clear, and Pine Creeks. Sacagawea Ridge moraines are present in Lake Creek and Clear Creek valleys, and although not preserved at Pine Creek, such deposits crop out in Frenchman Creek, the next glaciated tributary to the south. Sacagawea Ridge moraines were also mapped 30 miles (mi.) to the northwest in the Roaring Fork and Snowmass drainages (Bryant, 1979).

The following sections describe glacial deposits in piedmont portions of each of the three tributary valleys.

LAKE CREEK VALLEY GLACIAL SYSTEMS

Glaciers that flowed down the Lake Creek drainage were larger than glaciers in Clear Creek or Pine Creek valleys, but they probably exerted the least influence on the Arkansas River. None of the three major glacial advances dammed the Arkansas River, although the Sacagawea Ridge glacier probably forced the river to the east.

Glacial landforms and deposits, Lake Creek valley

The oldest glacial deposit, mapped as Sacagawea Ridge till, is a left-lateral moraine (unit st; description of map units is found in Appendix) (**Fig. 3**). The few boulders exposed on the low, rounded moraine ridge are quite weathered. In this till, orthoclase phenocrysts protrude from boulders of Twin Lakes porphyry, whereas similar boulders in younger Pinedale tills generally weather more smoothly (**Fig. 4**). The Sacagawea Ridge till grades into wide outwash terraces that are about 300 ft above the modern Arkansas River (**Fig. 5**).

Because only the left-lateral moraine remains today, the extent of the Sacagawea Ridge glacier cannot be determined. The moraine is concordant with the well-preserved Pinedale moraine, however, so the glaciers may have been about the same size. The Sacagawea Ridge glacier probably forced the ancestral Arkansas River to the east, because the channel of the modern Arkansas River is cut into Precambrian granite—even though extensive and thick deposits of Dry Union Formation sand and gravel are only a few hundred feet to the west, and because Sacagawea Ridge outwash terraces downstream of Lake Creek all grade down to the east toward the modern Arkansas River.

Small remnants of tills have been assigned a Bull Lake-age (Shroba, 1977; Nelson and Shroba, 1998; Shroba et al., 2014). Most of the material was overridden and buried by the Pinedale glacier, but a small segment remains between the Sacagawea Ridge and Pinedale left-lateral moraines, and a short ridge of the distal right-lateral moraine lies outboard of, and contiguous with, the earliest Pinedale moraine (Fig. 3). Once again, the concordance of the remaining lateral moraines indicates that Bull Lake glaciers were approximately the same size as the older and younger glaciers in Lake Creek valley. Cosmogenic ^{10}Be exposure dating of four boulders on the right-lateral moraine yielded an average age of about 130 ka (Schweinsberg et al., 2016). A small outwash terrace grading to the Bull Lake right-lateral moraine is about 150 ft above the modern Arkansas River (Fig. 5).

Three advances of the Pinedale glacier are recognized in the Lake Creek drainage: (1) a minor early advance that was the most extensive, but from which remains the least till (unit pte), (2) the main Pinedale advance that built major moraines about 600 ft above the Lake Creek valley floor (unit pt), and (3) a late advance that spilled over the Pinedale-age right-lateral moraine and extended slightly farther downstream than the main advance (unit ptl). The three Pinedale advances are likely three separate episodes of the main advance, with a slight early retreat, a long period of stasis during which the major moraines were deposited, and a late readvance that locally overtopped the main moraine, extended a bit farther, and then retreated from the Arkansas River valley while depositing nested recessional moraines.

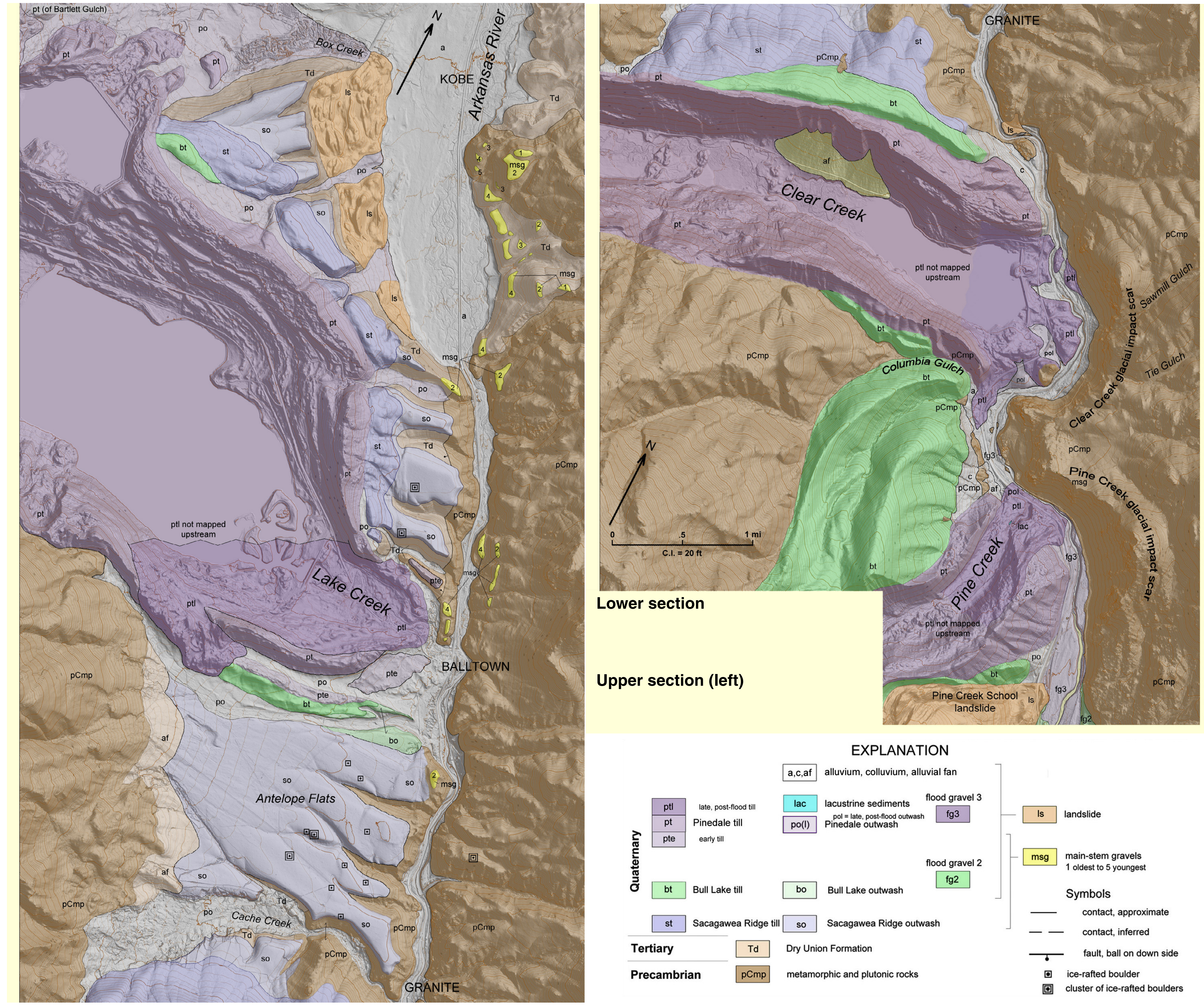

Figure 3 – Geology of Three Glaciers Damsite on lidar base map. Contour interval, 20 ft.

Figure 4 – Boulders of Twin Lakes porphyry on crests of lateral moraines of different ages. Upper panel, boulder on Pinedale moraine; lower panel, boulder on Sacagawea Ridge moraine.

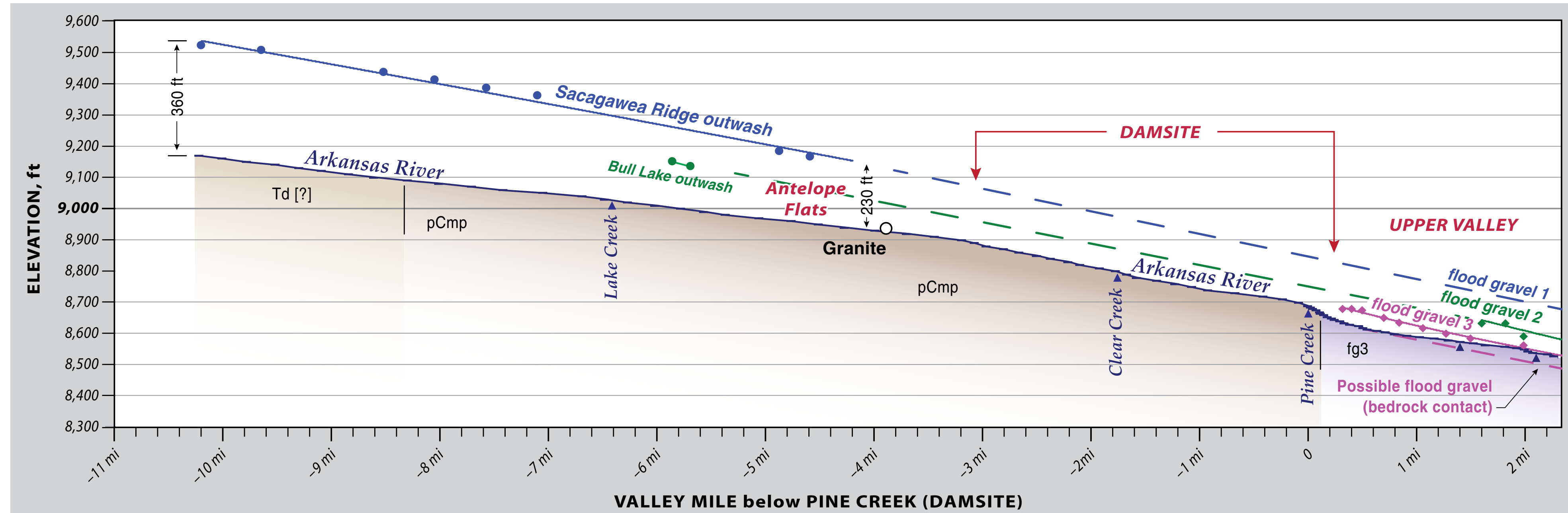

Figure 5 – Longitudinal profile of damsite area showing outwash deposits, flood gravels, and symbols for rock types underlying the Arkansas River channel. Td(?), Tertiary Dry Union Formation(?); pCmp, Precambrian metamorphic and plutonic rocks; fg3, flood gravel 3. ft, feet; mi, miles.

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The early Pinedale glacier left only two small lateral moraines. Along the right-lateral moraine the Pinedale till lies on top of Bull Lake till, and morainal crests of the two are about the same elevation, but Pinedale moraine is differentiated by its more hummocky surface, the greater number of boulders exposed, and the lesser degree of boulder weathering.

The main Pinedale glacier was perhaps larger than the earlier Bull Lake glacier; Pinedale lateral moraines are about 120 to 140 ft higher than Bull Lake moraines, and presumably the base was deeper as well, but it did not extend much farther downstream. As compared with Bull Lake moraines, the main Pinedale moraines have sharper crests and more boulders are exposed along those crests. Cosmogenic ^{10}Be exposure dating of 14 boulders on the right-lateral moraine yielded an average age of 21.8±0.3 ka (Schweinsberg et al., 2016).

A lobe of the latest Pinedale glacier overrode the main Pinedale right lateral moraine in the area where it was unconstrained by bedrock. This lobe may suggest a larger, or at least a thicker, glacier. Alternatively, meltwater may have breached the lateral moraine such that a lobe of glacial ice could pass through. Near the terminus, the latest Pinedale glacier was lower and advanced about a thousand feet farther than the main glacier.

Pinedale outwash (Fig. 3, unit po) is mapped in some outlet channels that clearly originated from the glacier. Mostly the Pinedale outwash and post-Pinedale alluvium have not been differentiated and are mapped together as a single unit (Fig. 3, unit a).

Contribution to glacial dams, Lake Creek valley

No evidence suggests that any of the three Lake Creek glaciers dammed the Arkansas River. The map view (Fig. 3) shows fairly complete end-morainal loops with little truncation, and the east side of the Arkansas River valley opposite the Lake Creek system lacks evidence of glacial abrasion or other effects (Fig. 3). Further support comes from tributaries, mostly unnamed, that flow into the Arkansas River from the east, both upstream and downstream from Lake Creek, that are graded to the modern Arkansas River. Although none of the Lake Creek glaciers appears to have dammed the Arkansas River, the earliest Sacagawea Ridge glacier probably forced the river to the east side of the valley.

CLEAR CREEK VALLEY GLACIAL SYSTEM

Clear Creek is the next tributary south of Lake Creek. Glaciers advancing down Clear Creek valley during Bull Lake and Pinedale time built large, fairly symmetrical lateral moraines, and they dammed the Arkansas River. The Sacagawea Ridge record is limited to the left-lateral moraine, so its full extent cannot be determined, but the glacier that produced that moraine extended to the Arkansas River, and Sacagawea Ridge flood gravels downstream attest to a glacial dam.

Glacial landforms and deposits, Clear Creek valley

A heavily forested, broad rise north of the Bull Lake left-lateral moraine is composed of Sacagawea Ridge till that extends to within 1,100 ft of the modern Arkansas River (Fig. 3). Lack of good exposures precludes conclusive identification of the actual extent of the Sacagawea Ridge glacier, but it may have spread out more than later glaciers after leaving the constraining bedrock valley. Those later glaciers removed any vestige of Sacagawea Ridge tills on the steep bedrock wall on the south side of Clear Creek valley.

The Bull Lake glacier developed an extensive left-lateral moraine that is preserved from about a half mile downstream from the mouth of the bedrock valley almost to the Arkansas River (Fig. 3, unit bt). It is quite similar to the Pinedale moraine in both size and height, but the Bull Lake crest is somewhat more rounded and has fewer exposed boulders. Its left-lateral moraine is truncated at the Arkansas River, presumably by the Bull Lake flood, flood 2. Only a small portion of the right-lateral moraine is exposed (Fig. 3), because the Pinedale glacier overrode its upper and lower ends.

The Pinedale glacier left large, well developed, symmetrical, paired moraines during its main advance, which reached the Arkansas River. Pinedale moraines have sharp crests and expose numerous boulders. Cosmogenic ^{10}Be exposure dating of three boulders yielded an average age of 20.5±0.2 ka (Schweinsberg et al., 2016)

Both lateral moraines show clear truncations near the river, which I attribute to flood erosion during Flood 3. Enough of the distal ends of the lateral moraines remain, however, to show a flaring of the moraines. This flaring is consistent with a widening of the glacier as it advanced into the crystalline bedrock wall on the east side of the Arkansas River valley and its ice thickened and spread laterally.

A distinctive, unique landform was created by the glaciers of Clear Creek, herein called a glacial impact scar (**Fig. 6**). It is a clearly defined erosional zone formed in bedrock at the terminus of a glacier; the zone consists of a very steep, concave (in plan view) cliff of unweathered bedrock cut into an obstructing valley wall on the east side of the Arkansas River valley (Fig. 3). Longitudinal profiles of major eastern tributaries to the Arkansas River reflect the development of this scar; tributaries upstream from Clear Creek all are graded to the modern Arkansas River, whereas those draining into the scar, Sawmill Gulch and Tie Gulch (Fig. 3), are left hanging above the Arkansas River valley floor.

The association of this scar with ancient glaciers in Clear Creek valley is clear; the mechanism of its development is not. One suggestion is that the eastward-flowing glaciers, moving almost perpendicularly into the obstructing granite wall that halted their advance, were deflected both upstream and downstream. The flared, or bulbous, pattern (in plan view) of the lower parts of both lateral moraines (even more pronounced in the Pine Creek valley than in the Clear Creek valley) indicates that the ice thickened and that flow was redirected laterally outward. In order to form such a prominent scar, the glacier must have occupied this position for a substantial length of time, perhaps during several glacial advances.

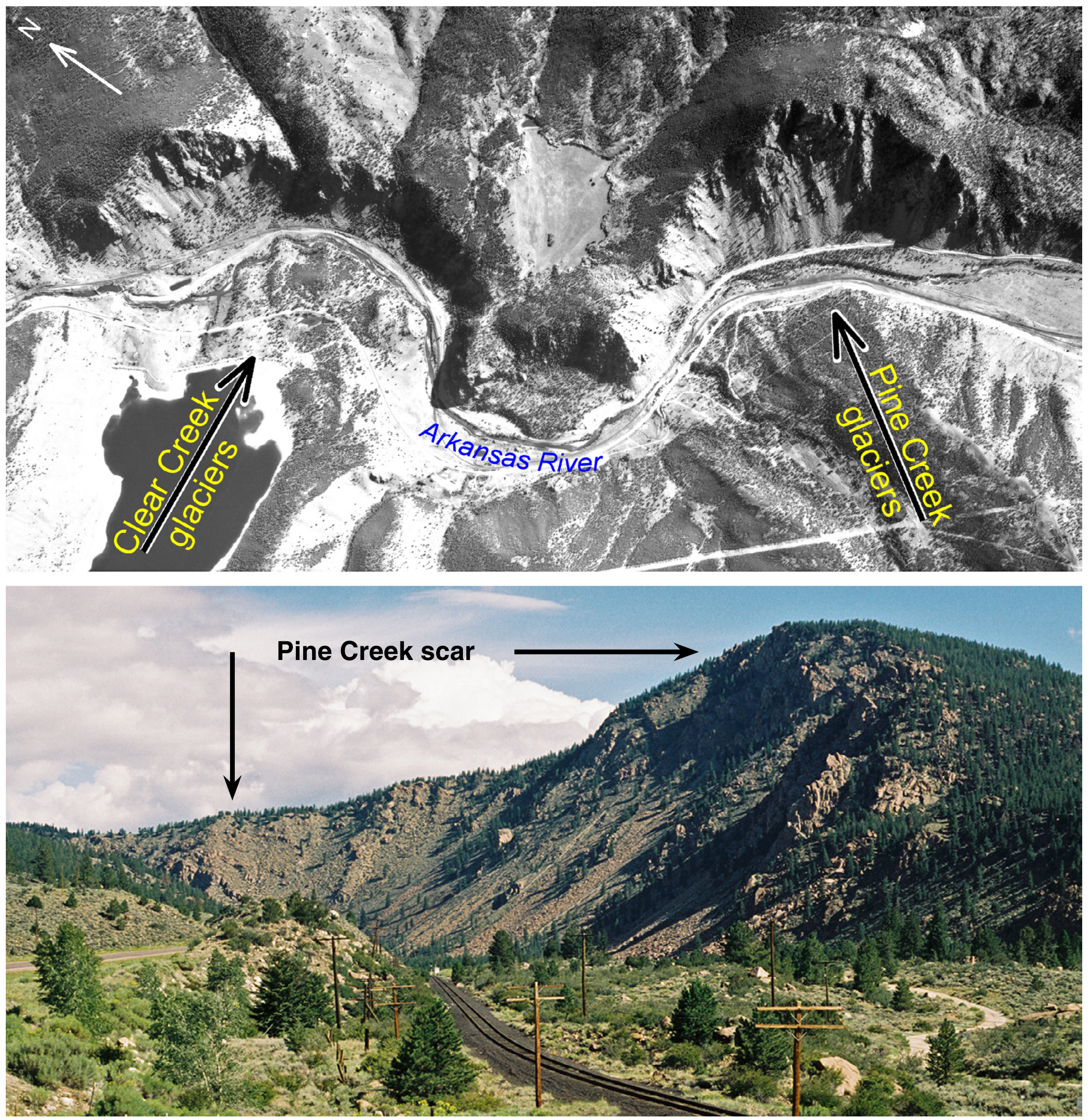


Figure 6 – Glacial impact scars. Upper panel, aerial view of Three Glaciers Damsite scars; lower panel, view north (up-valley) in Arkansas River valley of Pine Creek scar.

Another possibility is that the glaciers forced the Arkansas River against the granite wall, where it repeatedly undercut the slope. A third possibility is that torrential discharges of dammed waters scoured the wall when the glacier dams failed. These three mechanisms, of course, may have acted in concert to shape this distinctive landform.

After the Pinedale flood, Flood 3, the Clear Creek glacier readvanced beyond the truncated ends of the main Pinedale lateral moraines and reached the Arkansas River. This lower, thinner glacier advanced to the east side of the valley, slightly beyond the course of the modern river, without damming the river. The youngest till, visible as two patches of till on the far eastern side of the Arkansas River valley (Fig. 3, unit ptl) extends down to the modern Arkansas River. This till overlies bedrock only a few feet above the river and was deposited after flooding.

Contribution to glacial dams, Clear Creek valley

The Sacagawea Ridge glacier in Clear Creek valley probably dammed the Arkansas River, and glaciers in Clear Creek demonstrably dammed the Arkansas River during Bull Lake and Pinedale glaciations.

Sacagawea Ridge flood deposits are absent above Clear Creek, but Sacagawea Ridge flood gravels are extensive downstream below Pine Creek. The flood gravels are preserved on both sides of the Arkansas River valley, and they extend from just below Pine Creek downstream at least as far as Sand Park. Five miles south of Pine Creek, these flood gravels are overlain by an airfall tuff, identified as Pearlette type O ash by Scott (1975) and now known as the Lava Creek B ash (Izett and Wilcox, 1982). The correlation of this airfall tuff with the Lava Creek B ash was verified by U.S. Geological Survey chemical analysis (Cal Ruleman, oral communication, 2014). In the Yellowstone source area this ash is dated at 639 ka (Lanphere et al., 2002), a date that correlates with the Sacagawea Ridge glaciation. If we assume that these flood gravels were deposited by a catastrophic flood after a glacial dam burst, then the flood was caused by the Sacagawea Ridge glacier in Clear Creek. There is no more favorable site on the Arkansas River than at Clear Creek, and the two later glacial dams are clearly documented here.

The Bull Lake–age glacier in Clear Creek valley dammed the Arkansas River. Bull Lake moraines are large, well-developed lateral moraines that are widely spaced where they were truncated within 1,000–2,000 ft of the Arkansas River. Their crests show no indication, in map view (Fig. 3), of forming an end-morainal loop, and a longitudinal profile of the left-lateral moraine crest shows post-depositional truncation near the river (**Fig. 7**). The crest projects to the modern Arkansas River at an elevation of 9,360 ft, 520 ft above the modern river (profiles and elevations are from lidar data [accuracy ±6 inches (in.)]). One can assume that the glacial lake was higher than 9,360 ft, because the surface of the glacier was higher than its lateral moraine, and when the glacier came in contact with the bedrock valley wall it thickened as well.

A Pinedale-age glacier also dammed the Arkansas River. Well-developed Pinedale lateral moraines extend close to the river, and in map view the moraines bend upstream and downstream. The glacier itself flared when it crossed the Arkansas River, rammed into the bedrock wall on the east side, and glacier ice thickened and widened. The left-lateral morainal crest projects to an elevation of 9,420 ft, or 600 ft above the modern river, similar in elevation to the Bull Lake moraine (Fig. 7).

PINE CREEK VALLEY GLACIAL SYSTEM

Pine Creek glaciers were the shortest glaciers of the three tributaries, but they dammed the Arkansas River just as effectively as did those of Clear Creek. Pine Creek's Bull Lake-age glacier and its Pinedale-age glacier both dammed the Arkansas River. These dams were downstream of the Clear Creek dams, however, so they did not control the elevation of the impounded glacial lake. Bull Lake moraines in the Pine Creek valley differ from those of the other two valleys in being larger than those of the succeeding Pinedale glacier and by forming two separate, although closely positioned, moraines.

Glacial landforms and deposits, Pine Creek valley

The Pine Creek glacial system consists of outer Bull Lake left-lateral moraines and a central pair of Pinedale moraines (Fig. 3). Only a very small sliver of the Bull Lake right-lateral moraine remains, because most of it was displaced by a massive landslide, here called the Pine Creek School landslide. No Sacagawea Ridge till is recognized; it may well be incorporated within the Pine Creek School landslide.

Pine Creek valley was in fact glaciated during the Sacagawea Ridge glacial advance, as evidenced by Sacagawea Ridge moraines north and south of Pine Creek; in addition to the Sacagawea Ridge deposits at Lake Creek and Clear Creek, extensive

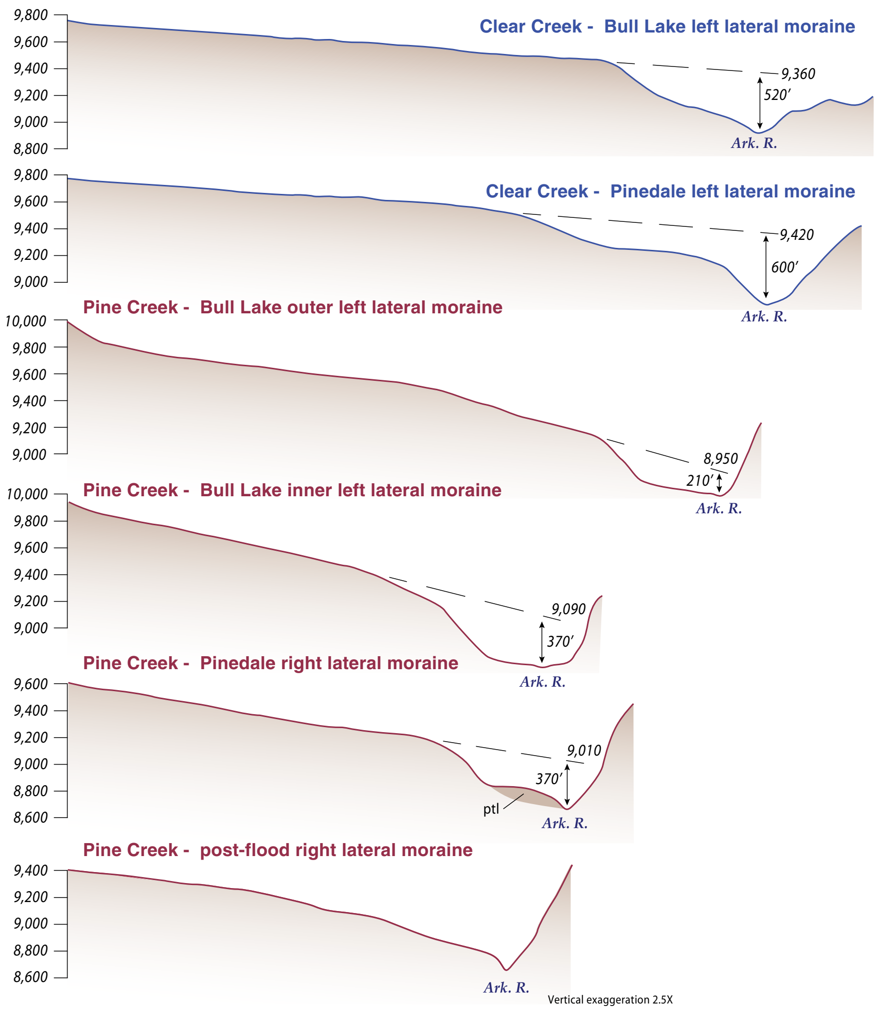


Figure 7 – Profiles along the crests of lateral moraines in the damsite area, projected (along dashed lines) beyond their truncated ends to show estimated heights of moraines, *not glaciers*, at the modern Arkansas River. Ark. R., Arkansas River; unit ptl, late post-flood Pinedale till.

Sacagawea Ridge moraines remain in Frenchman Creek, the next glaciated drainage 5 mi. downstream. The Pine Creek drainage is constrained by granitic bedrock valley walls, so it is not surprising that younger glaciers overrode the older moraines.

Bull Lake left-lateral moraines are assigned that age on the basis of the number of boulders exposed at the surface. Glenn Scott (1975) also mapped them as Bull Lake. Cosmogenic ^{10}Be-exposure dating yielded ages ranging from 3 to 72 ka (Briner, 2009). The two moraines north of Pine Creek possess very similar landform morphology and boulder exposure. Heights are equal, slopes are similar, and the internal volumes of the moraines are similar. They differ from each other only slightly in age and may simply record a slight recession. The outwardly curved shapes of the Bull Lake moraines (Fig. 3) indicate a pronounced flaring of the glacier consistent with impact against the valley wall east of the Arkansas River. The moraines are truncated near the Arkansas River, probably by the Bull Lake flood 2, and also by the later Pinedale Flood 3. Bull Lake glaciers from the valleys of Clear Creek and Pine Creek merged at Columbia Gulch and together formed a compound glacial dam.

Nested inside the Bull Lake lateral moraines are paired Pinedale lateral moraines. These moraines have sharper crests and greater numbers of exposed boulders. Cosmogenic ^{10}Be exposure dating yielded bimodal ages, at 16.6 ± 1.0 ka and 23.6 ± 1.4 ka (Briner, 2009; recalibrated by Schweinsberg et al., 2016). Both Pinedale-age lateral moraines were truncated at their distal ends by the Pinedale outburst flood. As is also true in Clear Creek valley, post-flood till extends down to the modern Arkansas River, recording continued flow of the glacier after the catastrophic flood. Lacustrine sediments about 1,200 ft upstream in the Pine Creek drainage indicate a small proglacial lake that developed in the valley of Pine Creek behind the youngest Pinedale end moraine.

A clearly defined glacial-impact scar developed in the eastern wall of the Arkansas River valley, opposite the mouth of Pine Creek valley. The Pine Creek moraines show a strongly flared (or bulbous) pattern to the moraines, which I interpret as the result of glaciers deforming as they advanced head-on into the bedrock wall just east of the Arkansas River (Fig. 3).

A notch in the ridge crest above the glacial impact scar contains a few cobbles and boulders of mainstem Arkansas River rock types. This notch might represent the pathway of a diverted Arkansas River or a spillway when one (or more) of the Pine Creek glaciers dammed the river, or simply the remnants of an old alluvial deposit. The gravels are at an elevation of 9,415 ft, about 725 ft above the present Arkansas River.

Contribution to glacial dams, Pine Creek valley

Pine Creek glaciers dammed the Arkansas River at least twice and probably three times. The Sacagawea Ridge glacier probably dammed the river. The Bull Lake-age glacier in conjunction with the Clear Creek glacier dammed the river, as did the main advance of the Pinedale glacier. The glacial dams at the mouth of Pine Creek did not determine the elevation of Three Glaciers Lake; that was controlled by the height of the Clear Creek glacier (**Fig. 8**).

A reconstruction of Bull Lake history in Pine Creek valley must rely on the left-lateral moraines, because the Pine Creek School landslide displaced essentially all of the distal right-lateral moraines. The moraine pattern indicates that the glacier flared out strongly as ice impinged upon the bedrock wall in what is now a glacial-impact scar. Lateral flow of ice headward, up the Arkansas River, caused the Pine Creek valley glacier to meet the glacier from Clear Creek valley, essentially buttressing and forming a compound ice dam that determined the elevation of Three Glaciers Lake.

Longitudinal profiles along the Bull Lake moraine crests (Fig. 7) clearly show post-depositional truncation near the Arkansas River from the resulting outburst flood, probably amplified by the later Pinedale-age flood. The crest of the outer Bull Lake moraine projects to the modern Arkansas River at an elevation of 8,950 ft, 210 ft above the river (Fig. 7), and considerably lower than the elevation of the Clear Creek moraine (Fig. 8). The Pine Creek glacier could have controlled the elevation of the impounded glacial lake only if the Pine Creek glacier were considerably higher above its lateral moraines than the Clear Creek glacier.

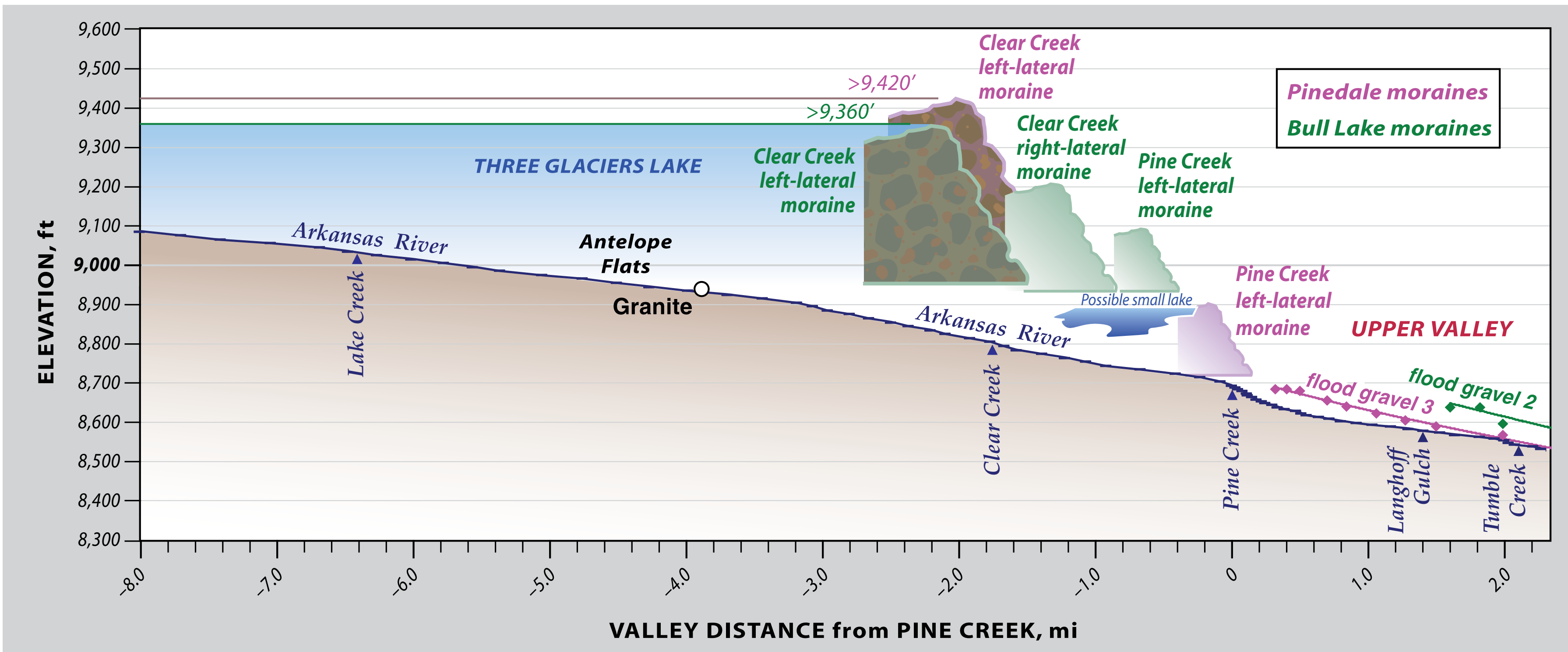


Figure 8 – Positions of Bull Lake moraines (green) and Pinedale moraines (purple) at the damsite.

Pinedale-age moraines, in map view, suggest that the glacier that deposited them also reached the eastern wall of the Arkansas Valley at the damsite. The moraines do not appear to have formed an end loop; their shape suggests a slight flaring, although not as pronounced as the flare of the Bull Lake moraine. Longitudinal profiles along the crests show truncation of the moraines. When projected west to east across the Arkansas River valley, the left-lateral moraine is placed at an elevation of 8,870 ft, 180 ft above the modern river, and the right-lateral moraine is placed at an elevation of 9,010 ft, 370 ft above the modern river (Fig. 7).

The projected elevations of both the Bull Lake and the Pinedale moraines are about 300 ft lower than those of the Clear Creek system, mainly because of Pine Creek's lower position on the Arkansas River. In Pinedale time, a secondary small lake may have been impounded between the two slightly separated glaciers, but the main glacial lake was controlled by the Clear Creek glacier dam.

GLACIAL DAMS AT THREE GLACIERS DAMSITE: SUMMARY

A Sacagawea Ridge glacier dammed the Arkansas River, probably at the Three Glaciers Damsite. No Sacagawea Ridge flood gravels occur above Clear Creek, whereas they are extensive down valley, indicating the dam was at the Three Glaciers Damsite. No other locality in the Upper Arkansas Valley presents any evidence of a glacial dam, no other locality is as favorable for a glacial dam as this site, and it is demonstrated that the last two glacial dams formed at the Three Glaciers Damsite. Dam failure led to catastrophic Flood 1 about 640,000 years ago.

Bull Lake glaciers from Clear Creek and Pine Creek merged to form a large glacial dam. The Pine Creek glacier buttressed the dam, but the upstream face of the Clear Creek glacier controlled the depth of the glacial lake. Elevation of the glacial lake surface was higher than 9,360 ft, and the impounded water was more than 500 ft deep at the dam (Fig. 8). Ice-rafted boulder erratics were deposited in the glacial lake above Clear Creek. When the glacial dam failed about 130,000 years ago, catastrophic Flood 2 tore out the end moraines.

Pinedale-age glaciers likewise dammed the Arkansas River at the mouths of Clear Creek and Pine Creek. The Clear Creek glacier would have held the glacial lake at an elevation of more than 9,420 ft and a lake depth of more than 600 ft (Fig. 8), assuming the glacial dam did not fail before it was overtopped. The Pine Creek valley glacier may have impounded a small lake between the two glacial dams about 400 ft lower (Fig. 8). Failure of the glacial dams resulted in catastrophic Flood 3 about 19 ka.

THREE GLACIERS LAKE

The Arkansas River was impounded to the north behind the glacial dam at Clear Creek and created Three Glaciers Lake. At an elevation of 9,420 ft, the lake would have been more than 600 ft deep at the dam and extended about 12 mi. up the Arkansas River valley (**Fig. 9**). The lake probably filled and emptied during each of the three major glaciations described in this report. The surfaces of Bull Lake-age and Pinedale-age lakes were at about the same elevation, about 9,400 ft, but information about the earliest, Sacagawea Ridge, lake is lacking. No prominent shorelines exist for any of the Three Glaciers lakes, as at lakes Missoula (western Montana) and Bonneville (Utah), probably because (1) Three Glaciers Lake lacked a spillway that maintained a constant lake elevation, thus the lake level rose continuously until the dam failed; and (2) the very limited fetch of prevailing westerly winds inhibited formation of energetic waves capable of forming beach deposits or wave-cut features.

Two large landslides along the shore of Three Glaciers Lake (Fig. 9) provide indirect evidence of the existence of Three Glaciers Lake. These two slope failures were likely triggered by dam failure: when the lake surface dropped catastrophically, the release of high hydrostatic pressures trapped in saturated sediments caused lake banks to fail. The setting of these two landslides thus may be analogous to that of the 1976 Teton Dam failure (Idaho), in which rapid drawdown of a 17-mi-long reservoir caused more than 200 landslides along the shoreline (Randle et al., 2000). The Kobe landslide (**Fig. 10**) has a 2-mi-long crown scarp at 9,400 ft, about the elevation of the probable shoreline of Three Glaciers Lake.

Erratic boulders are observed at several places near the proposed shoreline of Three Glaciers Lake. These boulders are sitting on the ground surface, not incorporated into sedimentary deposits. At one location the boulders are on a weathered surface of Precambrian crystalline rocks east of the Arkansas River (Fig. 9, x symbol), while most boulders are found out on the broad, gently sloping outwash terrace west of the river. I interpret all of these to be ice-rafted boulder erratics (IRBEs) transported by icebergs that probably calved off of Lake Creek glaciers into Three Glaciers Lake. Isolated IRBEs are probably dropstones from icebergs floating in the lake (Fig. 3, dot-in-square symbol), whereas clusters of IRBEs likely represent places where icebergs grounded in shallow water and upon melting deposited their entrained boulders (Fig. 3, dot-in-double square symbol). Icebergs may have transported the IRBEs during any, or all, of the three episodes of lake formation.

One iceberg may have grounded in shallow water along the eastern shore, at about 9,327 ft, leaving an IRBE cluster that contains a boulder of Twin Lakes porphyry, which does not crop out east of the Arkansas River (**Fig. 11**). Two other inferred IRBE clusters on Sacagawea Ridge outwash just north of Lake Creek are at about 9,384 ft and 9,402 ft. Two lower clusters are on Sacagawea Ridge outwash on Antelope Flats, just above 9,200 ft, along with numerous isolated IRBEs at about the same elevation.

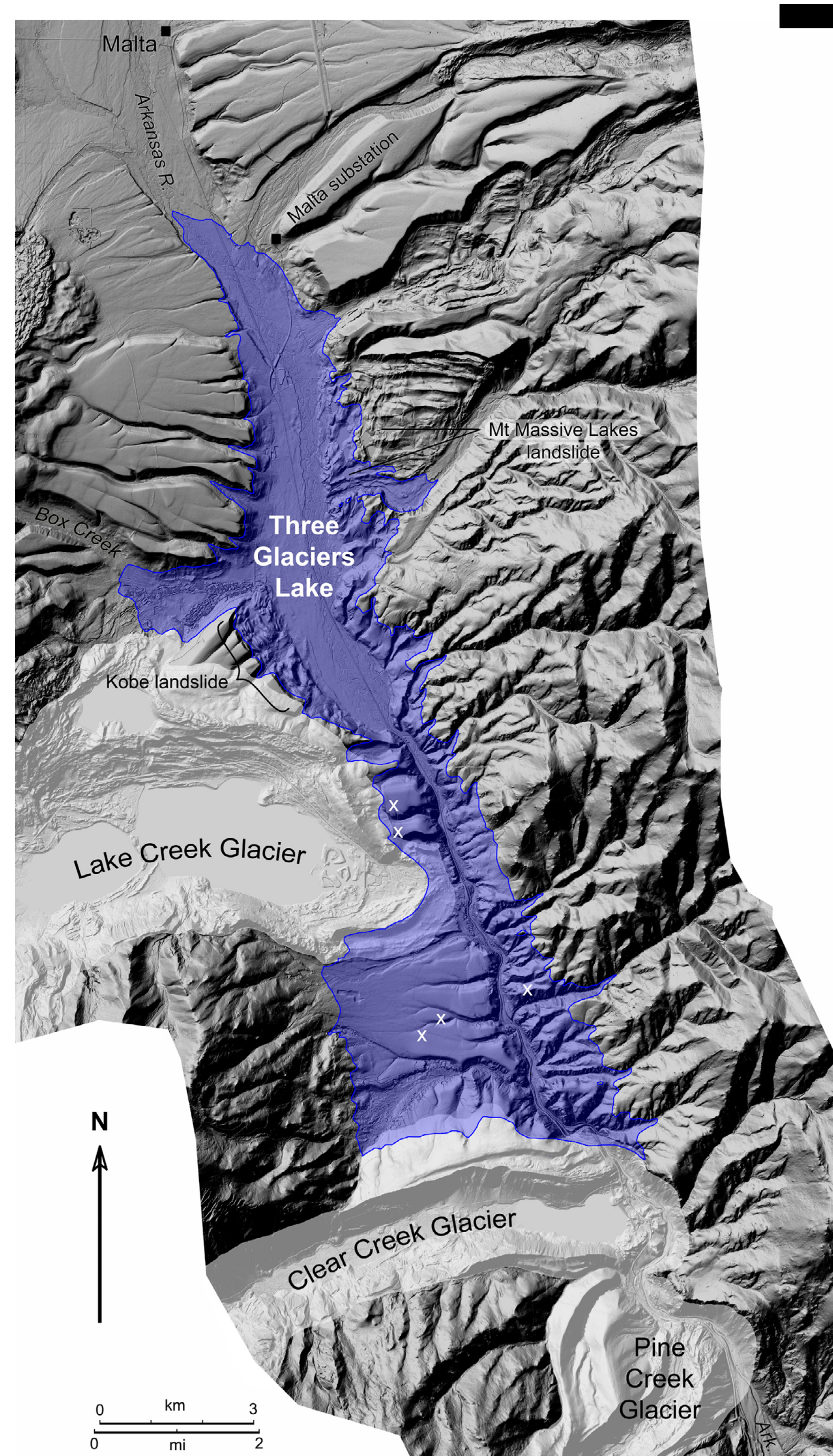


Figure 9 – Extent of glacial lake Three Glaciers Lake shown in blue. The Lake Creek glacier calved off icebergs that rafted boulders to nearshore sites marked by X's. Kobe landslide (western shoreline near mouth of Box Creek) and Mt. Massive Lakes landslide (eastern shoreline slightly farther north) may have been triggered by rapid fall of lake surface when the glacial lake emptied catastrophically.

Figure 10 – Aerial view to the north of the Kobe landslide. Crown scarp (marked by line of trees from lower right to upper left) cuts a Sacagawea Ridge outwash terrace. The rolling topography and closed depressions of the landslide are in Dry Union unconsolidated sands and gravels.

Figure 11 – Cluster of ice-rafted boulder erratics (IRBEs) on Precambrian bedrock near the eastern shoreline of Three Glaciers Lake (location shown in Fig. 9). A boulder of Twin Lakes porphyry (behind end of hammer handle) indicates the iceberg transporting the IRBEs came from across the Arkansas Valley, since the porphyry crops out only west of the river.

Possible lacustrine sediments mantling slopes in the Box Creek embayment (Fig. 9) were mapped between about 9,340 ft and 9,480 ft elevation (McCalpin et al., 2012). The sediments are described as “sand, silt, clay, and minor gravel deposited in shallow water below the shorelines of Three Glaciers Lake”. Along the east shore of Three Glaciers Lake at Mt. Massive Lakes (Fig. 9), between about 9,400 ft and 9,480 ft elevation, shoreline gravels were also mapped on numerous flat hilltops that were interpreted as planed off by wave action (McCalpin et al., 2012).

The left-lateral moraines of Clear Creek glaciers project to elevations of 9,360 ft (Bull Lake age) and 9,420 ft (Pinedale age). These elevations provide minimum elevations for Three Glaciers Lake levels, if we assume that the lake overtopped the dam before the dam failed. IRBE elevations range as high as 9,402 ft, and the Kobe landslide crown scarp is at 9,400 ft. Shoreline features interpreted by McCalpin et al. (2012) were found at elevations between 9,340 ft and 9,480 ft. Taken together, the elevation of Three Glaciers Lake surface, in both Bull Lake and Pinedale times, appears to have been about 9,400 ft.

The mechanism of dam failure is unknown, but huge boulders extending for miles downstream are evidence of catastrophic floods after dam failure that led to rapid discharge of lake waters. The most common failure mechanism for an alpine glacial dam similar to the glacial dams formed in the upper Arkansas River valley (glacier advancing from a tributary drainage into a valley) is outflow through a marginal breach along the contact of ice and the bedrock wall (Walder and Costa, 1996). As the water in glacial Three Glaciers Lake rose, subglacial leakage may have begun at the margin where ice was thinnest. Enlargement of a conduit that led to a subaerial breach may have resulted from thermal erosion and ice calving (Walder and Fountain, 1997). Another possible mechanism for dam failure is flotation. If water depth reached about 90 percent of the thickness of the ice, then the ice dam would become buoyant, allowing deep, high-pressure water to flow under the ice dam and rapidly break it up (Thorarinsson, 1939; Nye, 1976; Craig, 1987).

Peak discharge, calculated by using conservative parameters, for the most recent flood (Pinedale age; Flood 3) has been estimated at 1.63 million cubic feet per second (Brugger et al., 2011). This discharge is about 600 times as great as the historical average annual peak flood of 2,750 cubic feet per second at the glacial damsite (U.S. Geological Survey, 2012). Glacial Three Glaciers Lake likely emptied in less than a day (**Fig. 12**). A wall of ice- and sediment-laden water, deflected by the Pine Creek glacial-impact scar, would have surged down the Arkansas River valley. As the Arkansas River valley widened to the south, floodwater depth diminished but, even so, 2 mi. below Pine Creek the floodwaters deposited a 4 ft long boulder 130 ft above the modern-day Arkansas River.

Erosion was severe at the damsite. Floodwaters tore out the lower ends of moraines and, at Pine Creek, they undercut the downstream lateral moraines enough to bring about the large Pine Creek School landslide. Floodwaters ripped out parts of the granite bedrock river bottom, generating an extremely steep stream gradient at Pine Creek, where the Arkansas River today drops 50 ft in a distance of 1,300 ft, or more than 200 ft per mile. (This drop created the now notorious Pine Creek Rapid, Class V–VI [Staub, 1988], challenged only by expert kayakers and avoided by rafters.)

Farther below the damsite, where the Arkansas River valley begins to widen, erosion was limited to unconsolidated sediments such as the distal moraines at Frenchman Creek (two creeks below Pine Creek; Fig. 3) that were trimmed by floodwaters. No deposits of typical Arkansas River glacial outwash are recognized anywhere in the Upper Valley below the damsite.

Debris—from the end moraines and crystalline rock torn from the river bed and impact scars—rapidly aggraded below the damsite. This debris was spread onto the valley floor as flood gravels tens of feet thick: flood gravels more than 59 ft thick were deposited 2 mi. below Pine Creek, probably in a matter of hours.

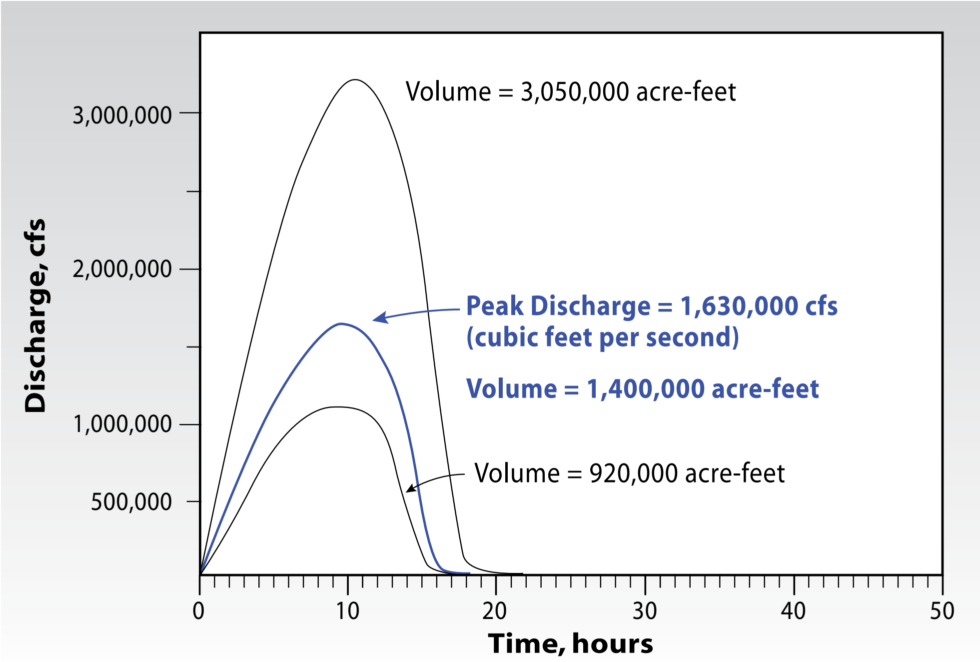


Figure 12 – Flood hydrographs modeled for three different lake volumes. The middle values may be the most likely, but in all cases, Three Glaciers Lake emptied in less than 22 hours (modified from Brugger et al., 2011).

Each of the three catastrophic floods deposited extensive flood gravels. The term "flood gravels," as here used, refers to gravels deposited by catastrophic floods that have discharges orders of magnitude greater than normal floods. Flood gravels are mostly unsorted, unstratified or poorly stratified masses of gravel containing flood boulders. The term "flood boulders," as here used, refers to boulders much larger than those that can be transported by normal floods and thus must have been transported by much larger (catastrophic) floods. There is no definitive size above which a boulder is considered to be a flood boulder, because the size is a function of the local fluvial regime and hydraulic gradient, but the distinction here is made at about 5 ft to 7 ft diameter. Flood boulders in the Arkansas River valley commonly are more than 10 ft in diameter, boulders 20 ft in diameter are not rare, and the largest observed is more than 60 ft long.

No flood gravels have been found in the Arkansas River valley above Clear Creek. Gravels east of the river above Clear Creek contain boulders no larger than about 4 ft long. Two patches of alluvial boulder-cobble gravels on the west side of the river above Clear Creek contain a few boulders in the 5 ft- to 7 ft-long range and one boulder that is 8 ft long. These west-side gravels are opposite steep east-side bedrock walls, and they may have been deposited by strong lake-bottom currents as the glacial lake drained catastrophically. Pardee (1942) demonstrated the role of such currents during the catastrophic draining of glacial Lake Missoula, and Lee (2009) expanded on his work.

In this report, flood gravels are mapped in the Upper Valley, the Buena Vista–Nathrop Valley, and in Sand Park (Fig. 1). Below Sand Park and Salida, the Arkansas River is confined to the long and extremely narrow Bighorn Canyon–Royal Gorge, where isolated flood boulders, but no flood gravels, have been found (the Bighorn Canyon–Royal Gorge reach extends from Salida to Cañon City [Fig. 1, inset map]). At the mouth of Royal Gorge at Cañon City, no flood deposits have been observed.

Alluvial gravels (**Fig. 13**, unit og), high above the flood deposits, are present at many locations in the Upper Valley. None of these gravels contains flood boulders. These high, old alluvial gravels are 100 ft or more above, and older than, the oldest flood deposits. Some of the deposits were mapped as Nussbaum Alluvium by Scott (1975) and as Nebraskan by Scott (1975) and McCalpin and Shannon (2005). Three flood gravels are recognized below the damsite, here called flood gravel 1, flood gravel 2, and flood gravel 3. These gravels are the products of the three catastrophic floods, here called Flood 1, Flood 2, and Flood 3.

UPPER VALLEY, FLOOD LANDFORMS AND DEPOSITS

The broad, flat floor of the Upper Valley between Pine Creek and Wild Horse Canyon (Fig. 1) consists primarily of two relatively flat surfaces that are terraces about 60 ft and about 20 ft above the modern Arkansas River. These terraces are composed of sheets of flood gravels from the second and third catastrophic glacial outburst floods (Fig. 13), flood gravel 2 (units fg2, fg2sr) and flood gravel 3 (unit fg3). A higher flood gravel (unit fg1) caps Swisher Mesa at the south end of the Upper Valley and forms narrow strath terraces along both sides of the Upper Valley about 155 ft above the modern Arkansas River. This gravel is flood gravel 1, deposited by the first catastrophic glacial outburst flood.

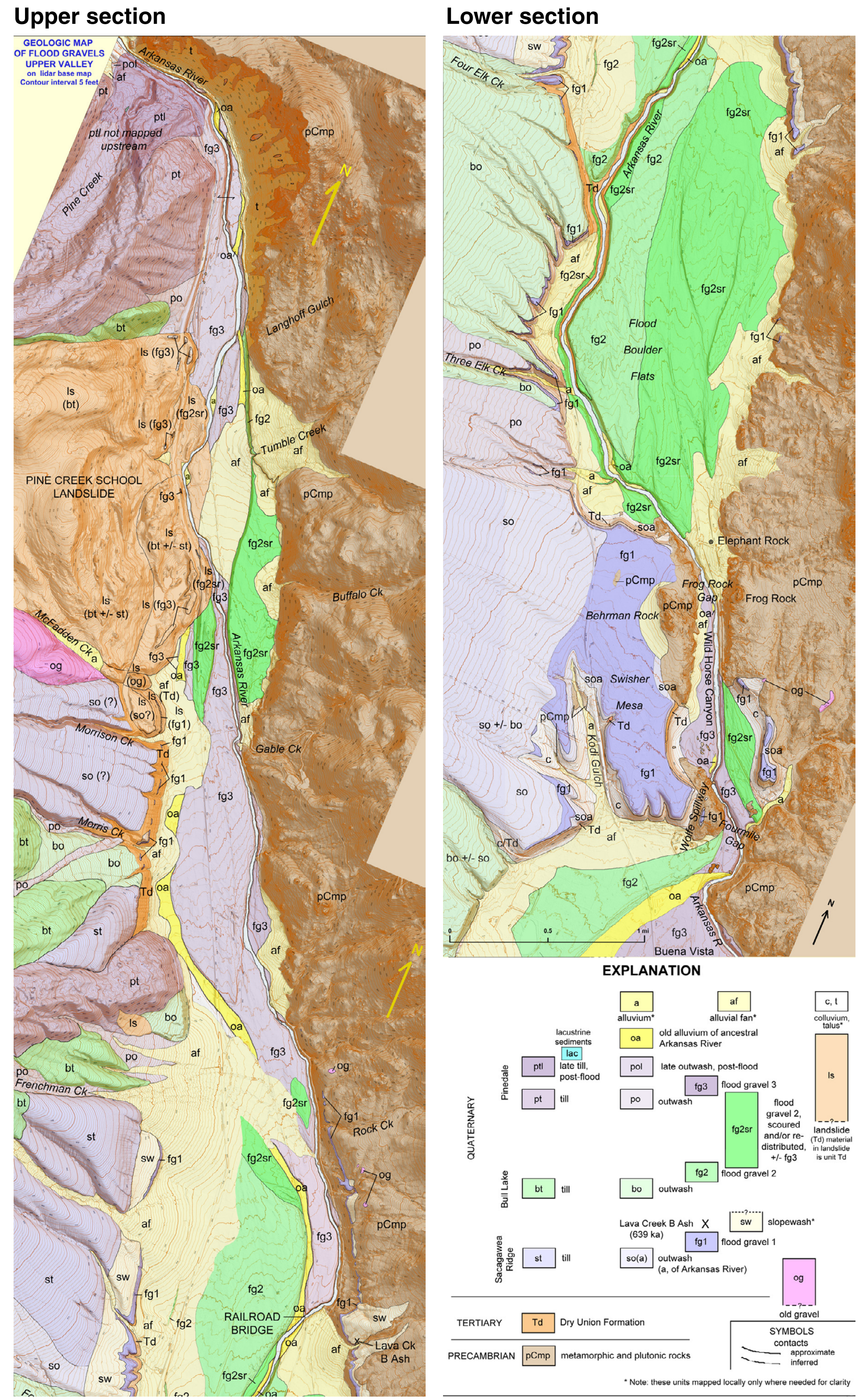


Figure 13 – Geologic map of flood gravels in Upper Valley and Wild Horse Canyon.

Flood Gravel 1

The largest remaining deposit of flood gravel 1 is at the lower end of the Upper Valley on Swisher Mesa (Fig. 13). Elsewhere, most of these flood gravels have been removed by subsequent erosion, but they are locally preserved in discontinuous strath terraces on both sides of the valley. Their distribution indicates a valley that, at the time that flood gravel 1 was deposited, was about a mile wide and reached a maximum of about 8,000 ft wide at Flood Boulder Flats (Fig. 13). The flood gravels at Morrison Creek on the west side of the valley are exposed discontinuously on a steep, linear slope cut into the unconsolidated sediments of the Dry Union Formation. It is likely that the flood gravels were deposited by the same catastrophic flood that trimmed the steep linear slope on the west side of the valley. South of Frenchman Creek, the flood gravels are almost continuously exposed in a strath terrace with a linear western margin that likely represents the scarp cut into unconsolidated glacial and valley-fill sediments by the floodwaters. On the east side of the valley the flood gravels lie in discontinuous terrace remnants on steep slopes underlain by Precambrian plutonic and metamorphic rocks.

The upper surface of flood gravel 1 is about 155 ft above the modern Arkansas River (**Fig. 14**). The thickness of this flood gravel, which probably varies, is poorly known because the base is rarely exposed on the steep colluvial slopes. At Morris Creek, 35 ft of flood gravels lie on Dry Union Formation. The lowest 5 ft are nonstratified gravels that contain no flood boulders, overlain by about 30 ft of stacked (clast-supported) flood boulders, overlain by slopewash deposits. An old roadcut at Swisher Mesa (Fig. 13), gives some indication of the nature of flood gravel 1 (**Fig. 15**). On Swisher Mesa, the flood gravels lie on a boulder-cobble-pebble main-stem gravel, as much as 30 ft thick, composed of granitic and metamorphic rocks, quartzite, volcanic rocks, and a trace amount of Twin Lakes porphyry. This gravel is interpreted as Sacagawea Ridge outwash of the Arkansas River (Fig. 13, unit soa). A thin veneer of Sacagawea Ridge outwash from the Sawatch Range (Fig. 13, unit so) overlaps the western side of the flood gravels there.

Flood boulders are composed entirely of plutonic and metamorphic rocks; granite is by far the most common rock type. Almost all smaller clasts are also plutonic and metamorphic rocks, but flood gravel 1 also contains minor amounts of volcanic or hypabyssal rocks, quartzite, and Twin Lakes porphyry. Flood gravel on the east side of the valley contains more metamorphic and volcanic rocks and less quartzite.

Flood boulders are sometimes stacked upon each other. Flood boulders as much as 15 or 20 ft long are common, and the largest observed is a granite boulder of dimensions 27 ft x 16½ ft x 10+ ft ("+" indicates the vertical dimension is greater than 10 ft, because the bottom is not exposed). Flood boulder size appears to decrease very little downstream.

Just south of Railroad Bridge (Figs. 13, 14), flood gravel 1 is overlain by volcanic ash (**Fig. 16**), identified by Scott (1975) as Pearlette type O Ash and now called Lava Creek B ash (Izett and Wilcox, 1982), and recently confirmed as Lava Creek B on the basis of chemical analyses by the U.S. Geological Survey (Cal Ruleman, U.S. Geological Survey, 2014, oral communication). This ash, erupted from the Yellowstone caldera, is dated 639 ka (Lanphere et al., 2002). At the type locality in Wyoming

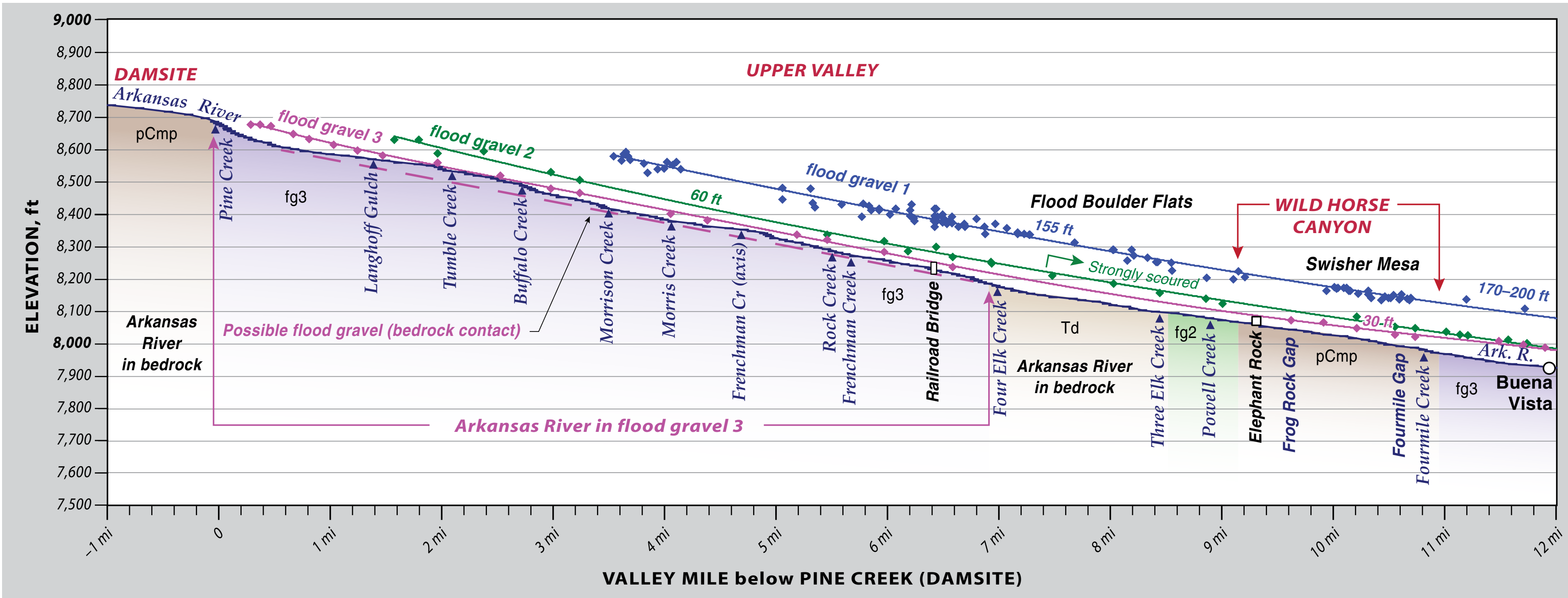


Figure 14 – Longitudinal profile of Upper Valley and Wild Horse Canyon showing three flood gravels and Arkansas River channel lithologies (symbols same as geologic map, Fig. 13).

Figure 16 – Lava Creek B ash, dated at 639 ka, lies above flood gravel 1 near Railroad Bridge (site marked (x) in Fig. 13).

Figure 15 – Flood gravel 1 exposure on east side of Swisher Mesa.

of Sacagawea Ridge-age till, the till is slightly older than Lava Creek B ash (Pierce, 2003). If the same relation holds in the upper Arkansas River valley, then flood gravel here has an age that correlates with the Sacagawea Ridge glaciation, about 640 ka, MIS 16 (Chadwick et al., 1997; Pierce, 2003). These 640 ka flood gravels are the oldest of three flood gravels observed in the Upper Valley, and they represent the first catastrophic glacial outburst flood, Flood 1.

Flood Gravel 2

Flood gravel 2 is distributed from about one and a half miles below Pine Creek to the lower end of Wild Horse Canyon (Fig. 13). The Arkansas Valley appears to have been a few tenths of a mile wide at the north end of the valley, increasing to about a mile wide, and pinching to a few tenths of a mile at the head of Wild Horse Canyon.

Flood gravel 2 now forms a terrace about 60 ft above the modern Arkansas River. Thickness of the flood gravel is 59 ft or more two miles below Pine Creek, and it appears to thin distally to about 15 ft at the entrance to Wild Horse Canyon, although the gravel here may have been thinned by later scour. Where the base is seen, the flood gravels lie on Dry Union Formation.

The terrace deposit is composed of a sheet of flood gravels that shows no internal structure or stratification. The flood gravel contains sand, pebbles, cobbles and boulders. Because of the chaotic mixture of clasts, it is difficult to fully characterize the size of the gravel; median clast size is about 2 ft, and modal size is that of a boulder (≥10 in.). The flood gravel is clast-supported with an openwork texture now mostly filled by sand that may be illuvial. More than 99 percent of the clasts are plutonic and metamorphic rock; the remainder contains trace amounts of volcanic rock and Twin Lakes porphyry. Clasts are mostly round to subround and round-broken. Flood boulders are distributed throughout the thickness of the deposit— at the very base, where it is exposed, and at the exposed surface. Flood boulders are commonly stacked upon each other. At an exposure of flood gravel 2 between Langhoff Gulch and Tumble Creek (Fig. 13), eight of the boulders in a 100-ft-wide exposure are greater than 10 ft long and several are greater than 20 ft long (**Fig. 17**). The largest flood boulder observed is a granite boulder 46 ft x 14 ft x 16+ ft just below Tumble Creek (**Fig. 18**).

It is important to recognize that this is not typical stream sediment deposited during a lengthy time span. Rather, it represents a catastrophic flood event that deposited a thick sheet of flood gravels in a single event, in a matter of hours. The terrace landform that we see today resulted from subsequent erosion. Lack of internal stratification allows for the possibility that the deposit was produced by more than one catastrophic flood.

I consider flood gravel 2 to be the traction bedload of the second catastrophic glacial outburst flood, Flood 2, from the compound glacial dam at Clear Creek and Pine Creek. It is correlated with the second major glaciation, the Bull Lake glaciation (Lee, 2010), MIS 6, about 190–130 ka. Scott (1975) mapped most of this gravel as Older Pinedale outwash, but at the south end of Wild Horse Canyon, he mapped it as Bull

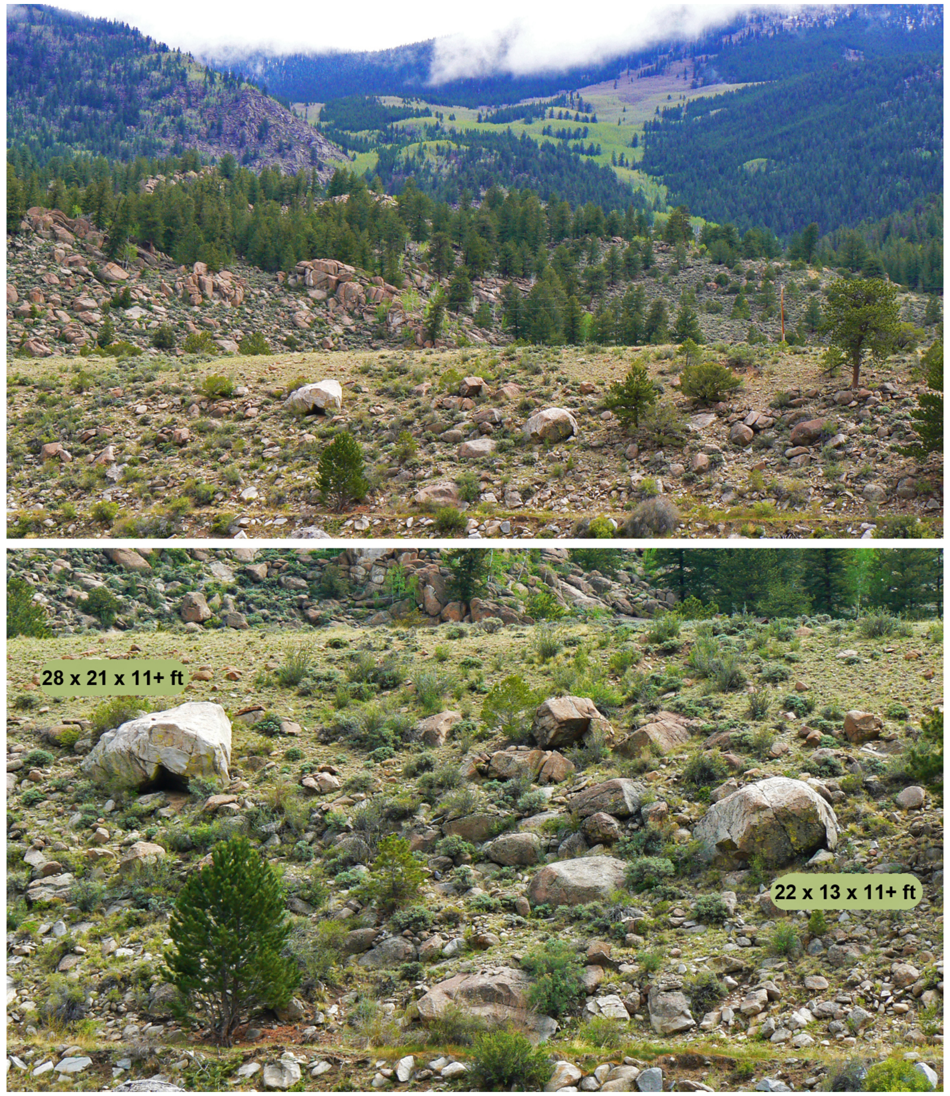


Figure 17 – Exposure of flood gravel 2 at Tumble Creek, two miles below Pine Creek, here is 59 ft thick. Lower panel is a close-up of an area in upper panel.

Lake outwash (Scott, 1975). McCalpin and Shannon (2005) also mapped this gravel as Bull Lake age, and just north of the damsite, gravels at the same height above the modern Arkansas River (50 ft) were mapped by McCalpin et al. (2012) as Bull Lake outwash. Four flood boulders on the surface of flood gravel 2 just below Tumble Creek (Figs. 13, 14) were dated by cosmogenic ^{10}Be at about 21 ka (Schweinsberg et al., 2016). This date is much too young to represent Bull Lake-age (see previous paragraph) exposure and more likely to represent a deposit of the youngest flood (as discussed below).

Flood Gravel 3

Flood gravel 3 underlies the lowest major terrace in the Upper Valley. The flood gravels are distributed continuously from Pine Creek to Railroad Bridge (Figs. 13, 14), with a downstream deposit in Wild Horse Canyon (Figs. 13, 14). The valley floor

Figure 18 – A 46-ft granite flood boulder at the surface of flood gravel 2 near Tumble Creek. Note geologist sitting on top. Relative position of Tumble Creek, Fig. 14.

at the time of Flood 3 appears to have been about a third of a mile wide through much of its length; its maximum width was about a half mile in the Morrison Creek (Fig. 13) reach.

Flood gravel 3 now forms a terrace about 20 ft above the modern Arkansas River. The gravel is at least 45 ft thick just below Pine Creek (Fig. 13), and the thickness elsewhere is at least 20 ft, but the base is nowhere exposed. Clast rock types are similar to those of the older flood gravels—primarily metamorphic and plutonic rocks, with trace amounts of volcanic rocks and Twin Lakes porphyry. The terrace is composed of a sheet of flood gravels in which flood boulders are generally stacked upon each other (**Fig. 19**). Individual boulders often exceed 10 ft long, and the largest observed flood boulder is a granite boulder about 25 ft x 20 ft x 13+ ft.

In addition to the sheet of flood gravels forming the lower terrace, flood gravels considered to be the same age mantle low rises along the west margin of the Upper Valley higher than the main sheet of flood gravels. Patches of flood gravel are up to 18 ft thick, and the base of these flood gravels is not horizontal, but tends to replicate the surface, forming a thin blanket of flood gravel that veneers pre-existing topography. These flood gravels are considered to be bedload and suspension clasts deposited along the valley margins and on low rises in the valley. Among these deposits are boulders and cobbles of Twin Lakes porphyry lying on the Pine Creek School landslide, which does not contain clasts of this lithology, indicating they are flood-transported gravels (**Fig. 20**). The highest of these flood gravels are 130 ft above the modern Arkansas River, or about 110 ft higher than the main sheet of flood gravel 3, and about 70 ft higher than the top of the flood gravel 2 terrace (Fig. 20) (elevations determined by lidar, with accuracies measured in inches).

Figure 19 – Abundant stacked flood boulders on the surface of flood gravel 3 at Tumble Creek.

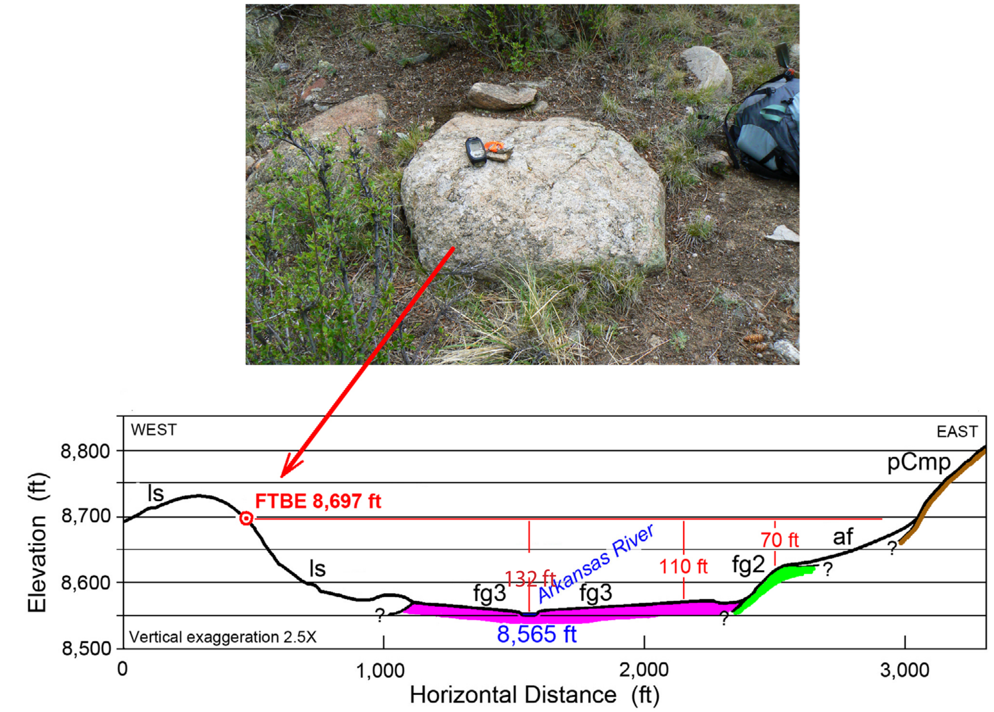


Figure 20 – Flood-transported boulder erratic (FTBE) of Twin Lakes porphyry on Pine Creek School landslide (unit ls). Clasts of Twin Lakes porphyry are not contained in the landslide material, indicating flood transport of this 4-ft boulder. This boulder is at 8,697 ft elevation (determined by lidar). Transverse profile across the Upper Valley shows the relation of FTBEs to the surfaces of flood gravel 2 (unit fg2, green) and flood gravel 3 (unit fg3, red). ft, feet; af, alluvial fan; pCmp, Precambrian metamorphic and plutonic rock.

Flood 3 scoured the surface of flood gravel 2, as shown by the anastamosing channels cut into the gravel (**Fig. 21**). Floodwaters appear to have deposited additional flood gravel containing boulder-size debris on top of the flood gravel 2 terrace as an overwash lobe (**Fig. 22**). Many of these boulders lie on the terrace surface (**Fig. 23**). Three of the flood boulders sampled for ^{10}Be cosmogenic dating that yielded unexpectedly young dates are on this overwash lobe (the fourth is about 0.7 mi. farther downstream). The most probable explanation is that the youngest flood, Flood 3, by depositing new flood boulders and by overturning preexisting boulders, effectively reset the cosmogenic clock for the surface of the older flood gravels. Flood 3 scoured the surface, remobilized older flood boulders, and locally deposited new boulders. By using ^{10}Be and ^{26}Al in cosmogenic dating, such a reset of the cosmogenic clock was identified in massive meter-size boulders that had been overturned by extreme Quaternary floods (Toshiyuki et al., 2014).

Flood gravel 3 was deposited by Flood 3, the third and last catastrophic outburst flood from the glacial dam at Clear Creek. It is correlated with the third, and most recent, glaciation, the Pinedale (Lee, 2010). This flood gravel was mapped as Younger Pinedale outwash by Scott (1975). Four flood boulders on the surface of flood gravel 3 were dated by cosmogenic ^{10}Be at 19.0±0.6 ka (Briner et al., 2010; recalibrated by Schweinsberg et al., 2016).

Controversial age of the upper valley-floor terrace (units fg2, fg2sr)

Scott (1975) mapped the deposits of the upper terrace in the Upper Valley as Older Pinedale Outwash, although he also mapped the upper terrace as Bull Lake in Wild Horse Canyon, as did McCalpin and Shannon (2005). Scott (1975) mapped the lower terrace as Younger Pinedale Outwash. Cosmogenic nuclide exposure dating of four flood boulders from each of the two terraces yielded ages of about 19 ka and about 21 ka (**Fig. 24**) (Briner et al., 2010; Young et al. 2011; Schweinsberg et al., 2016).

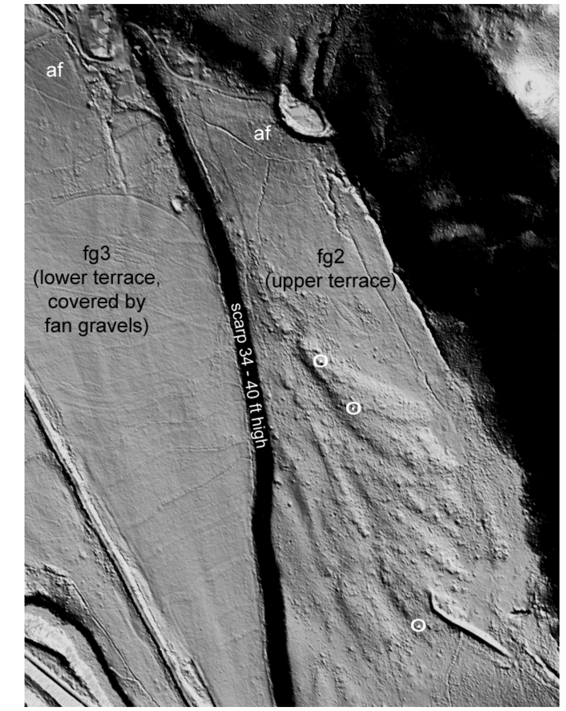
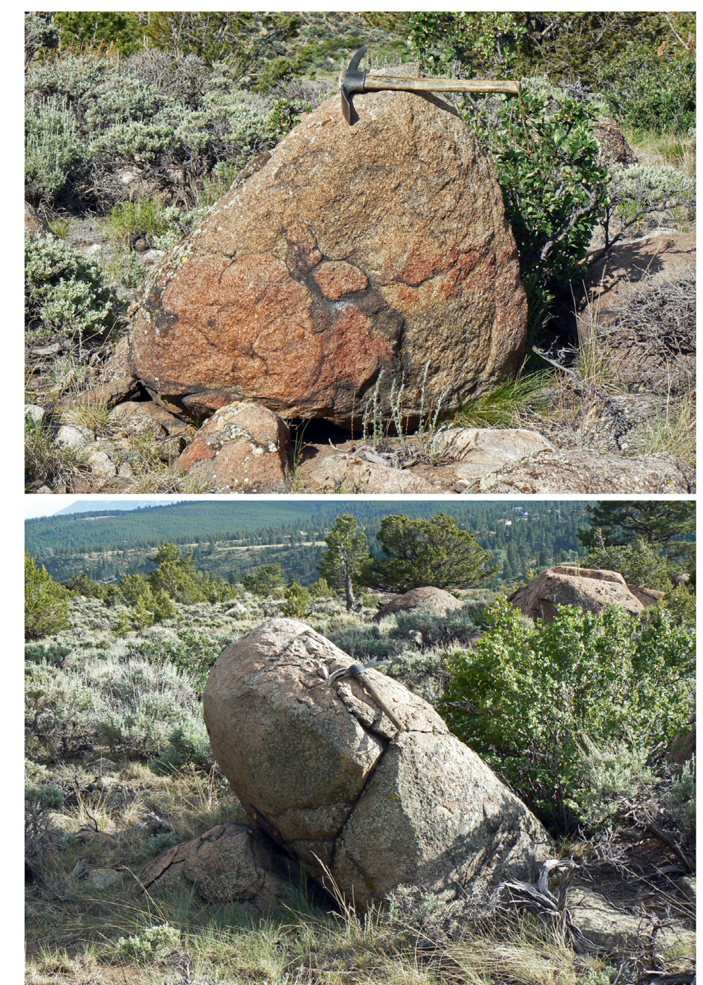


Figure 22 – Lidar image of the valley floor near Tumble Creek showing overwash flood gravels on the surface of the upper terrace of flood gravel 2 (unit fg2). Samples were taken for cosmogenic dating from three circled localities. af, alluvial fan.

Figure 23 – Flood boulders on the surface of the upper terrace (flood gravel 2).



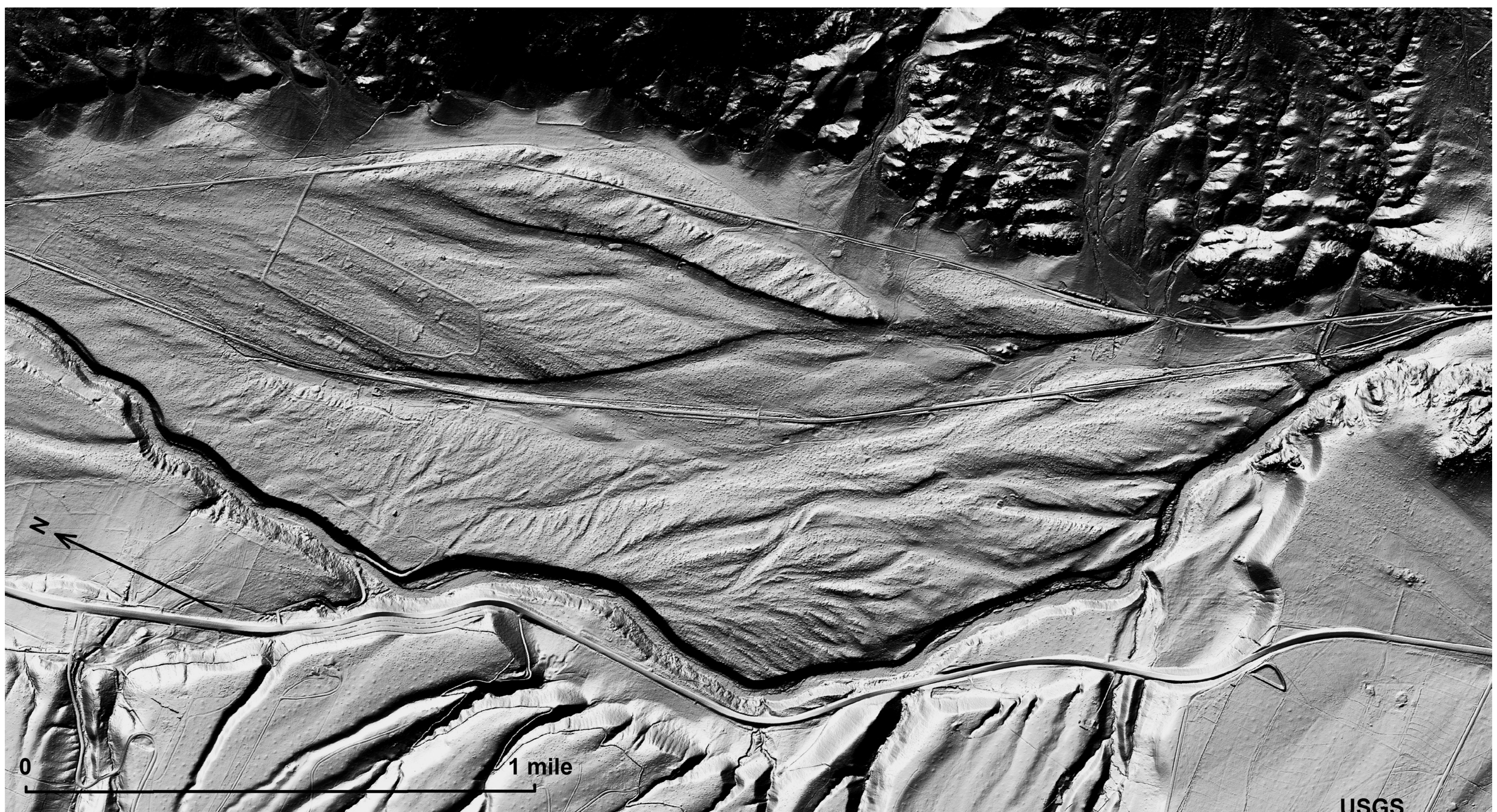


Figure 21 – Lidar image of Flood Boulder Flats shows strong scour of the surface of flood gravel 2.

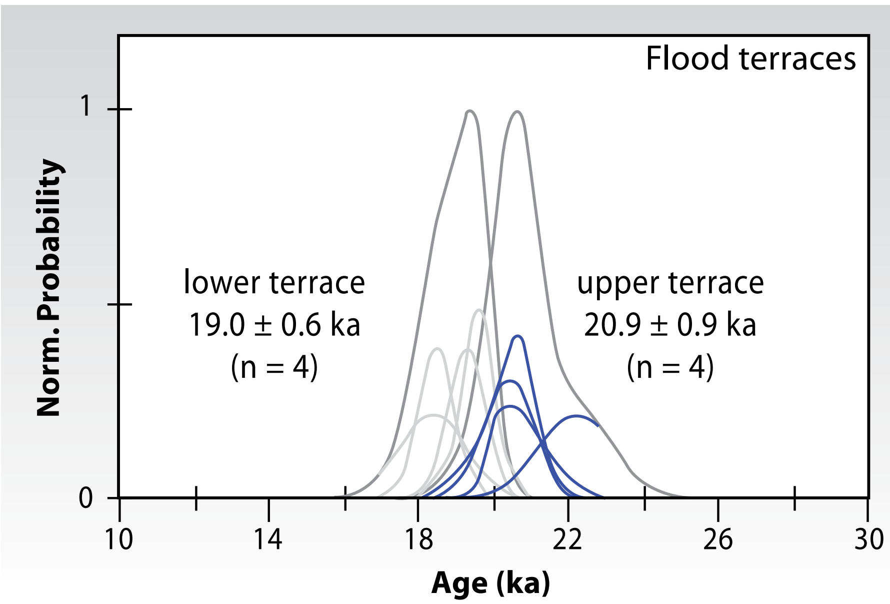


Figure 24 – Exposure ages of eight flood boulders from both terraces (Schweinsberg et al., 2016, Fig. 4).

On the basis of this exposure dating, Young et al. (2011) and Schweinsberg et al. (2016) interpret the flood gravel on the upper terrace as resulting from a flood at about 21 ka and, similarly, the flood gravel on the lower terrace from a flood 2,000 years later, at about 19 ka. This interpretation is difficult to reconcile with the more than 60 ft of downcutting required of the Arkansas River between the two floods (whereas the river had downcut only 95 ft or so in the preceding 500,000 years; see Figs. 14, 20).

This interpretation that both flood gravels are Pinedale age also fails to account for the total absence of Bull Lake flood gravels anywhere below the damsite, despite the fact that the Bull Lake-age moraines were as large as the Pinedale-age moraines in Clear Creek valley, whose glacier dammed the Arkansas River. Bull Lake glaciers were even larger than Pinedale glaciers downstream at Pine Creek and Frenchman Creek (see below).

Glaciers at three different times reached the upper Arkansas River valley. Three distinct flood gravels are evidence for three glacial outburst floods. Parsimony suggests that each glacial advance dammed the river and resulted in an outburst flood, as opposed to the view that Bull Lake glaciers failed to produce an outburst flood (or any outwash at all, for that matter) and that the Pinedale glaciers caused two floods, as proposed by Young et al. (2011) and Schweinsberg et al. (2016).

The exposure ages can be reconciled with the parsimonious interpretation by inferring that flood boulders in flood gravel 2 on the upper terrace were remobilized during Flood 3 and new boulders may have been added to the surface. If the remobilized boulders were not overturned a full 180 degrees, their current top surfaces would have retained some inherited nuclides, yielding a slightly older age (21 ka rather than 19 ka).

Old Alluvium of Ancestral Arkansas River

Swales on the surface of flood gravel 3 contain alluvium in which flood boulders are rare or absent. These channels mark the course of the ancestral Arkansas River following the final glacial-outburst flood (**Fig. 25**). Upstream of Tumble Creek (Figs. 13, 14), the Arkansas River flowed against the east wall of the valley (Fig. 13). A short segment at McFadden Creek (Fig. 13) has main-stem gravels in a channel in flood gravel 3. This channel continues southward on the west side of the valley.

Pine Creek School Landslide

A large landslide, here called the Pine Creek School landslide (unit ls), occupies the western side of the Upper Valley from just below Pine Creek to Morrison Creek (**Figs. 13, 26**). The slide is 1.1 mi. wide along the crown scarp and 2.1 mi. wide along the toe; its length ranges from 1.2 mi. to 1.5 mi. Its calculated area is about 1.9 square miles or 1,200 acres. In most of the slide, a series of slumps preserves some glacial landforms.

The crown scarp is sharp and steep, and throughout its length it is in right-lateral moraines of Pine Creek except for the extreme south end, where it cuts through Dry Union Formation capped by old alluvial gravels (unit oa). The north end of the scarp cuts the Pinedale-age right-lateral moraine of Pine Creek, but most of the material in the landslide is till of probable Bull Lake and Sacagawea Ridge age.

The landslide is younger than the Bull Lake till, or younger than about 130 ka, and at least part of it is younger than till of Pinedale age. A segment of the landslide in the southeast moved and overrode flood gravel 3, so at least part of the landslide was active after Flood 3. Perhaps all or much of the landslide deposit postdates glaciation.

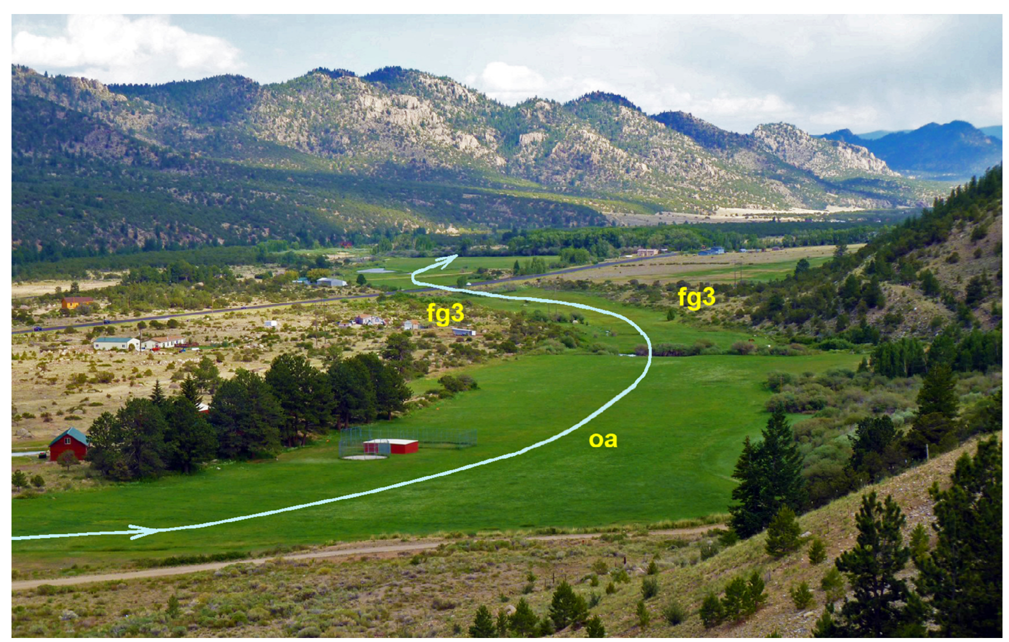


Figure 25 – Old alluvium (unit oa) in swale marks the course of the ancestral Arkansas River in flood gravel 3 (unit fg3).

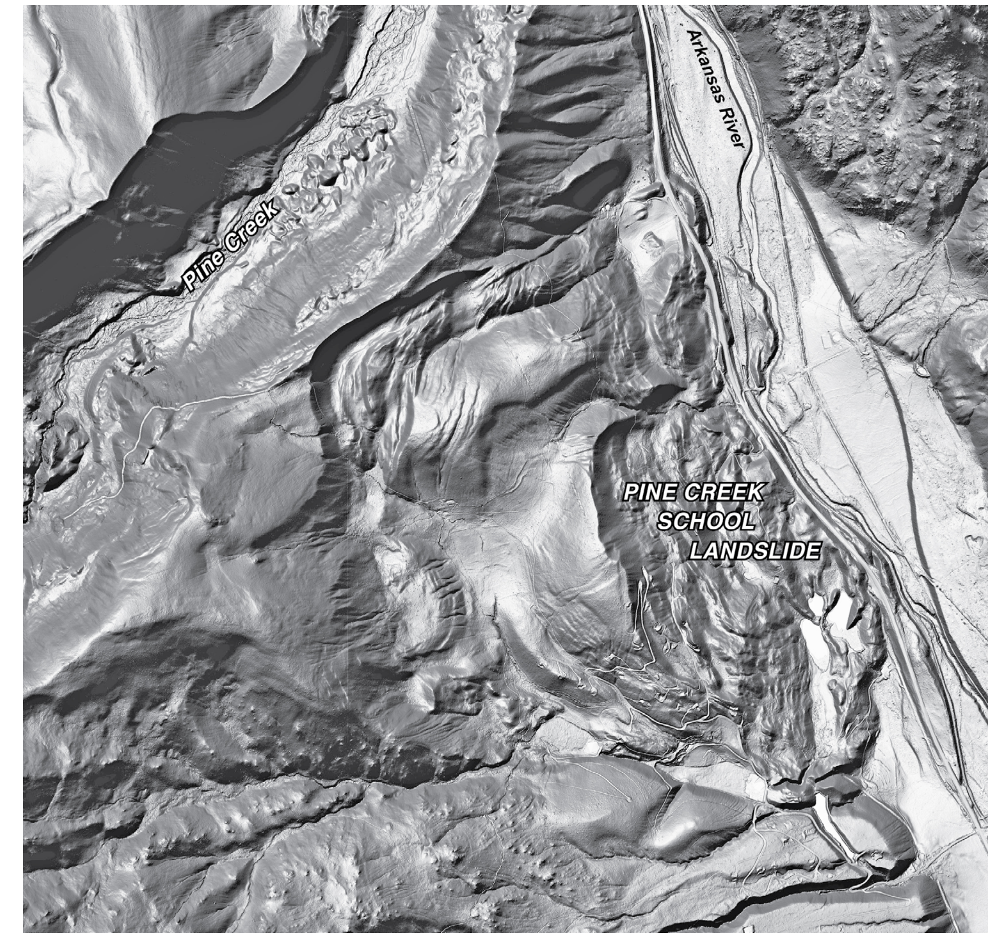


Figure 26 – Pine Creek School landslide displaced most of the right-lateral moraines of Pine Creek.

Frenchman Creek valley glacial systems

Glaciers flowed down Frenchman Creek drainage, 5 mi. downstream from Pine Creek (Figs. 13, 14). Although the drainage basin of Frenchman Creek is smaller than that of Pine Creek, during each of the three main glaciations glacier ice flowed into the Upper Valley (Fig. 13). Although there is no evidence that any of those glaciers dammed the Arkansas River, the Sacagawea Ridge-age glacier was large enough to have done so. The Bull Lake-age glacier, which was perhaps not quite as large, also reached the valley floor and spread out laterally. The Pinedale-age glacier, which was narrower, also reached the valley floor.

Large, widely separated lateral moraines (unit st) indicate that the Sacagawea Ridge glacier spread out on the Arkansas River valley floor once it exited the bedrock-valley constraints. No evidence on the far east-side valley wall indicates that the glacier reached there, and no evidence persists of any lake sediments upstream, so if this glacier managed to dam the river, it was a minor event. Both Sacagawea Ridge-age lateral moraines are truncated at their distal ends, and the linear truncations align with linear scarps immediately to the north cut into Dry Union Formation unconsolidated gravels (Fig. 13, unit Td). Along and just below the truncation are narrow exposures of flood gravel 1 (unit fg1). Catastrophic Flood 1 appears to have cut the distal ends of the Sacagawea Ridge moraines and deposited flood gravel 1 all along the scarp cut into the right-lateral moraine (Fig. 13). Downstream on Swisher Mesa (Fig. 13), flood gravel 1 is at the same elevation as Sacagawea Ridge outwash, and along the west side of the mesa a thin layer of Sacagawea Ridge outwash from the Sawatch Range is on top of the flood gravel (**Fig. 27**).

Wild Horse Canyon

Wild Horse Canyon separates the Upper Valley from the Buena Vista–Nathrop Valley (Fig. 1). The canyon's north and south extremes are marked by two narrow restrictions cut into granite, Frog Rock Gap and Fourmile Gap (Fig. 27). The straight, narrow upper reach of the canyon is about 1,000 ft wide, bounded by granite, whereas the lower reach widens to about 2,600 ft where the river has cut into unconsolidated sediments of the Dry Union Formation (Fig. 27, profile B-B'), before narrowing again to less than 1,000 ft at Fourmile Gap. Only a few deposits of flood gravel 1 remain on the east side of the lower Wild Horse Canyon, on and above Sailor Mesa (Fig. 27). On the west side of the lower canyon, the Arkansas River has cut into extensive deposits of flood gravel 1 on Swisher Mesa. Flood gravel 2 is observed only below Sailor Mesa; elsewhere it has been stripped from the canyon. Flood gravel 3 fills the bottom of the canyon, forming a terrace about 20 ft above the modern Arkansas River.

Flood history of the Upper Valley

Flood 1 (about 640 ka) – Sacagawea Ridge-age glaciers dammed the Arkansas River, probably at Clear Creek and Pine Creek, creating the first glacial Three Glaciers Lake. Flood 1 resulted from the catastrophic failure of that glacial dam about 640 thousand years ago. The flood coursed down a relatively broad, flat valley and spread flood gravels about a mile wide. The main axis of the valley was about the same as the northern part of the axis in the present Upper Valley. However, because Wild Horse Canyon did not exist in Sacagawea Ridge time, the ancestral Arkansas River flowed through a channel on Swisher Mesa at the time of the flood, and some floodwaters moved down the valley east of Swisher Mesa.

In the upper part of the valley, floodwaters cut linear banks along the west bank in Dry Union sands and gravels and in Sacagawea Ridge-age moraines and deposited flood gravels against the lower part of the moraine. On Swisher Mesa, however, the floodwaters spread out and deposited flood gravels on top of Sacagawea Ridge outwash, perhaps because of the additional sediment load eroded from Frenchman Creek glacial deposits.

After Flood 1 (about 640–130 ka) – In the succeeding half-million years, the ancestral Arkansas River changed course in the lower end of the Upper Valley; it abandoned the channel across Swisher Mesa (Fig. 13), now clogged with flood gravels, and cut Wild Horse Canyon. The ancestral Arkansas River also eroded sediments and lowered the valley floor about 100 ft, leaving narrow terraces of flood gravel 1 on both sides of the valley. Numerous large flood boulders were probably let down as lag boulders as the valley deepened and erosion removed matrix from the flood gravel.

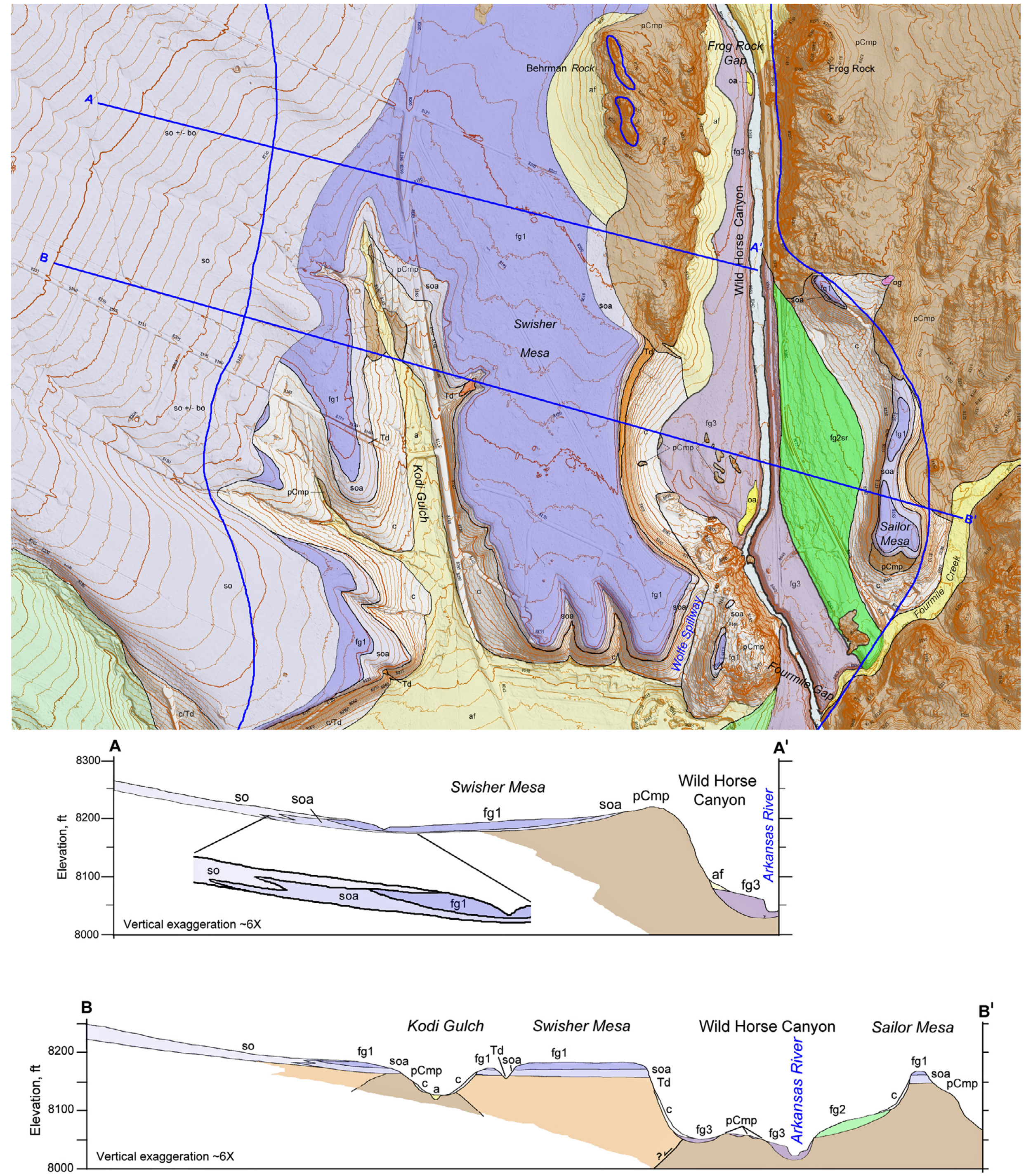


Figure 27 – Geologic map and cross-sections of the Swisher Mesa–Wild Horse Canyon area. Unlabeled curved blue lines on map show probable extent of flood gravel 1. From left to right, so, Sacagawea Ridge outwash; fg1, flood gravel 1; soa, Sacagawea Ridge outwash of Arkansas River; c, colluvium; pCmp, Precambrian metamorphic and igneous rocks; a, alluvium; Td, Tertiary Dry Union Formation; fg3, flood gravel 3; fg2, flood gravel 2.

North of Four Elk Creek, slopewash eroded from banks that were cut into Sacagawea Ridge glacial deposits covered the flood gravels with pebbly sand. On the east side of the valley, similar slopewash on top of the flood gravels is grus eroded from steep granite slopes. South of Four Elk Creek, outwash from Bull Lake glaciers in Four Elk Creek and Three Elk Creek covered much of flood gravel 1.

Flood 2 (about 130 ka) – Bull Lake-age glaciers in Clear Creek and Pine Creek valleys merged and formed a large, 600 ft-high compound glacial dam in the Arkansas River valley that impounded upstream Arkansas River water. When the glacial dam failed, surging floodwaters swept away end moraines of the tributary glaciers and carried their morainal debris down the main valley in Flood 2.

The Upper Valley at this time was slightly narrower and about 100 ft lower than during Flood 1, such that flood gravels from this second catastrophic flood were more concentrated. Just below the dam, flood gravels 59 ft thick are exposed, and boulders carried by the flood typically are stacked one upon another. The extensive flood boulders on Flood Boulder Flats (Figs. 13, 21) in part may be lag flood boulders from Flood 1.

Floodwaters to the south poured through Wild Horse Canyon. A sharp bend and the narrow Fourmile Gap created a hydraulic dam that backed up floodwaters in Wild Horse Canyon and led to the cutting of the Wolfe Spillway (Fig. 27) across Swisher Mesa.

After Flood 2 (about 130–19 ka) – The ancestral Arkansas River cut down more than 60 ft, leaving the sheet of flood gravel 2 as a terrace (the upper terrace on the modern valley floor). The ancestral Arkansas Valley was now considerably narrower, reflecting the difficulty of eroding thick gravels full of large flood boulders.

Flood 3 (about 19 ka) – When the youngest Pinedale glacier dammed the Arkansas River at Clear Creek, it formed a lake that had about the same dimensions as the Bull Lake-age lake. About 19,000 years ago the dam failed, and the third catastrophic flood deposited a sheet of locally stacked flood boulders in the quarter-mile-wide valley bottom about 6 mi. down to Railroad Bridge (Figs. 13, 14).

In addition to valley-floor traction bedload, the flood also carried flood debris up onto lower valley margins and onto topographic highs on the valley floor, to as much as 110 ft above the top of the valley-floor flood gravel and about 70 ft above the flood gravel 2 terrace surface (Fig. 20). The flood deposited a thin blanket of flood gravel on the Pine Creek School landslide and on eroded remnants of flood gravel 2. Flood 3 may have deposited flood gravels onto the terrace surface of flood gravel 2, or at least reworked the existing surface flood gravels, thus accounting for the anomalously young exposure ages there.

Flood 3 scoured the surface of the flood gravel 2 terrace and produced an anastamosing pattern of scour troughs (Fig. 21). Above Railroad Bridge, such scour troughs are typically only a few feet deep, whereas downstream from Railroad Bridge scour was deeper, and some scour-cut scarps on Flood Boulder Flats are 30 ft high. Perhaps the lack of bedload deposits downstream of Railroad Bridge provided the floodwaters with more erosive power. The isolated patch of flood gravel 3 in Wild Horse Canyon probably was derived from this scour, in essence recycled flood gravel 2.

The Pine Creek School landslide may have been activated, or reactivated, at this time as floodwaters cut into the Pine Creek right-lateral moraines. The landslide's crown scarp cuts the Pinedale moraine.

After Flood 3 (since about 19 ka) – After the last catastrophic flood, the ancestral Arkansas River below the Pine Creek School landslide had a different course from today, with a channel against the west side of the valley. The Pine Creek School landslide failed again, at least the southeastern part. This latest landslide blocked the ancestral Arkansas River and diverted it into what is more-or-less the present course of the Arkansas River (**Fig. 28**).

As the Arkansas River cut its channel down to present levels, it left the most recent flood deposits, flood gravel 3, as the lower terrace.

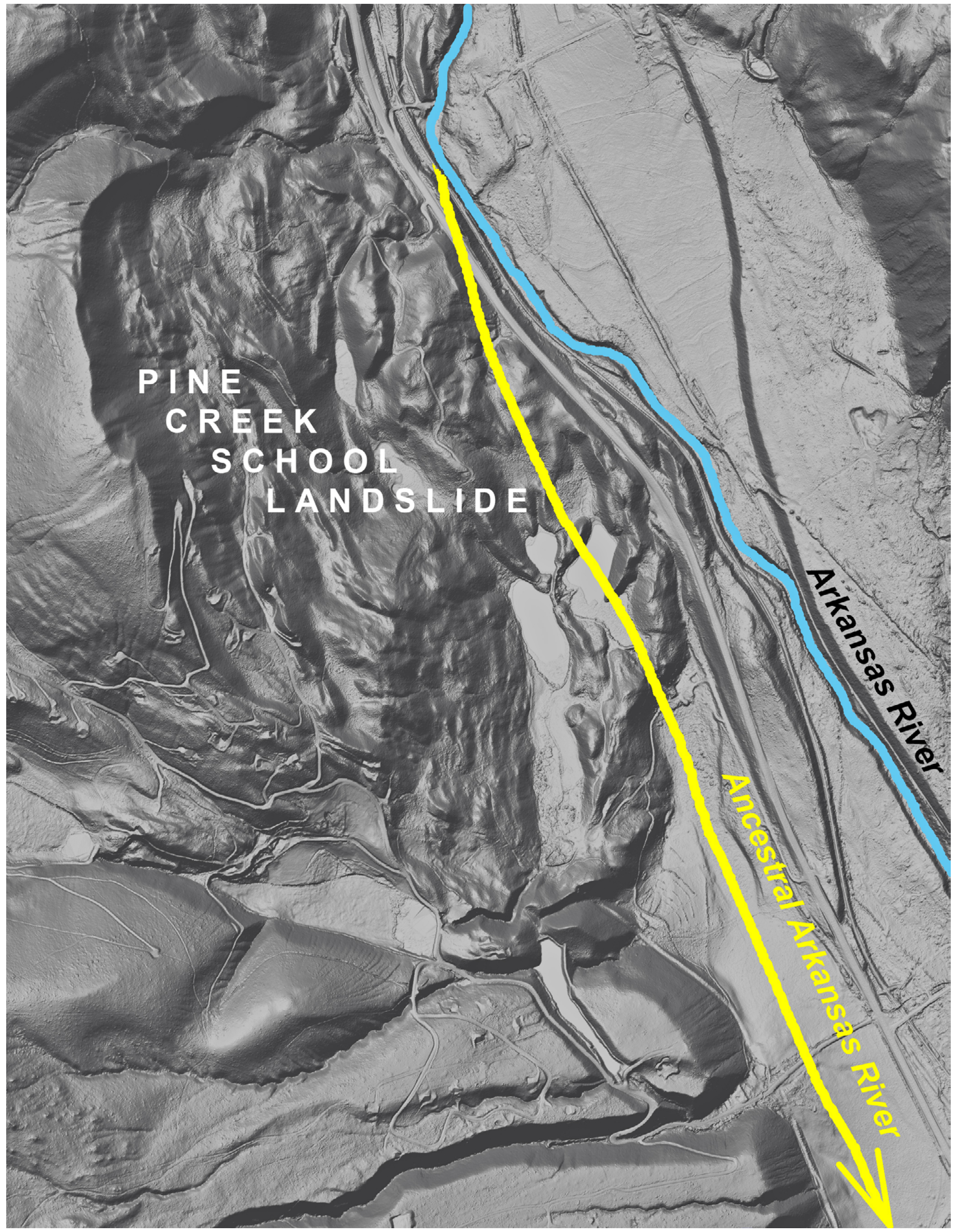


Figure 28 – The ancestral Arkansas River flowed on the west side of the valley before the Pine Creek School landslide blocked and diverted it.

BUENA VISTA–NATHROP VALLEY, FLOOD LANDFORMS AND DEPOSITS

Each of the three flood gravels is present in the Buena Vista – Nathrop Valley. flood gravel 1 has only fragmentary remains, flood gravel 2 is widespread across the valley floor throughout the valley, and flood gravel 3 occurs only as a flood fan at the mouth of Wild Horse Canyon.

Flood gravel 1

Continuous exposures of flood gravel 1 (unit fg1) end at the south rim of Swisher Mesa (**Figs. 27, 29**). Except for a small exposure nearby to the southwest of the mesa, the gravel is not observed again on the west side of the valley between Swisher Mesa and the Johnson Village area to the south. In that area, only discontinuous patches of flood gravel can be traced downstream as far as Thompson Creek. On the east side of the valley, small patches of gravel on Precambrian bedrock extend only as far downstream as Johnson Village. All patches of flood gravel 1 are about 200 ft above the modern Arkansas River (**Fig. 30**).

Flood gravel 2

Flood gravel 2 covers much of the Buena Vista–Nathrop Valley floor (**Fig. 29**, units fg2, fg2sr). Flood gravel 2 is about a mile wide from Buena Vista downstream to Nathrop, where, constrained by the valley, it narrows to about a half mile wide just above the entrance to Browns Canyon. The surface of flood gravel 2 is about 60 ft above the modern Arkansas River (Fig. 30).

Below Buena Vista, the surface of flood gravel 2 is etched with broad areas of shallow scour (Fig. 29, unit fg2) and narrow bands of deep scour (Fig. 29, unit fg2sr). This erosion is attributed to Flood 3. Where the valley narrows toward Browns Canyon, the surface of flood gravel 2 is severely scoured, and below Nathrop the surface of flood gravel 2 is lowered to about 40 ft above the modern Arkansas River.

Flood gravel 3

Flood gravel 3 forms a debris fan at the mouth of Wild Horse Canyon that extends no farther downstream than Buena Vista (Fig. 29, unit fg3). Much of the gravel lies on top of flood gravel 2. Because the two flood gravels are similar, the contact between them is difficult to map with confidence, but it appears that the fan has two lobes, perhaps from two flood pulses.

Flood boulders are abundant at the surface of flood gravel 3. Flood boulders commonly exceed 10 ft in length, and the largest flood boulder observed is about 61 x 31 x 13+ ft (at Rocky Mountain Lumber & Hardware lot on the north side of Buena Vista). This flood boulder is also the largest observed anywhere in the upper Arkansas River valley.

Trout Creek storm-flood deposits

Trout Creek is a major west-flowing tributary of the Arkansas River, draining some 40,000 acres of the Mosquito Range to the east (Fig. 1). The tributary flows into the Buena Vista–Nathrop Valley near Johnson Village (**Figs. 29, 31**), but (at least since the time of Flood 3) it took an indirect route to the Arkansas River. The undisturbed surface of flood gravel 2 (Figs. 29, 31) shows that Trout Creek did not flow directly west to the Arkansas River; rather it flowed south from the mouth of Trout Creek canyon and paralleled the Arkansas River for several miles.

At the mouth of the canyon Trout Creek built an alluvial fan, but beyond the fan to the south the valley floor is an anomalously smooth, very gently sloping, planar surface (Fig. 29; note 5-ft contours on a grade of less than 1%) devoid of boulders. This surface was built mostly by historical storm floods (not catastrophic floods), that issued from Trout Creek (Lee, in press) (**Fig. 31**). The upper Trout Creek watershed was severely stressed by 19th Century deforestation, timber skidding, wagon road construction, and overgrazing; lower Trout Creek was straightened and stripped of riparian vegetation by the railroads. The storm flood deposits are pebbly sand and rare cobbles, from periodic flash floods that flushed out thick grus deposits formed from weathered granitic bedrock in the Trout Creek drainage. The storm flood deposits are more than 6 ft thick at McQuaid Pit (Fig. 31), and historic accounts record a flood that buried a house at Schwanders railway station to a depth of 8–10 ft (Woody, 1935) (**Fig. 32**).

Browns Canyon

Browns Canyon is at the lower end of the Buena Vista–Nathrop Valley (Fig. 1). It is a 7.8 mi. long, deep, narrow canyon cut into Precambrian metamorphic and plutonic rocks. Because much of it is difficult to access, flood events here are incompletely known.

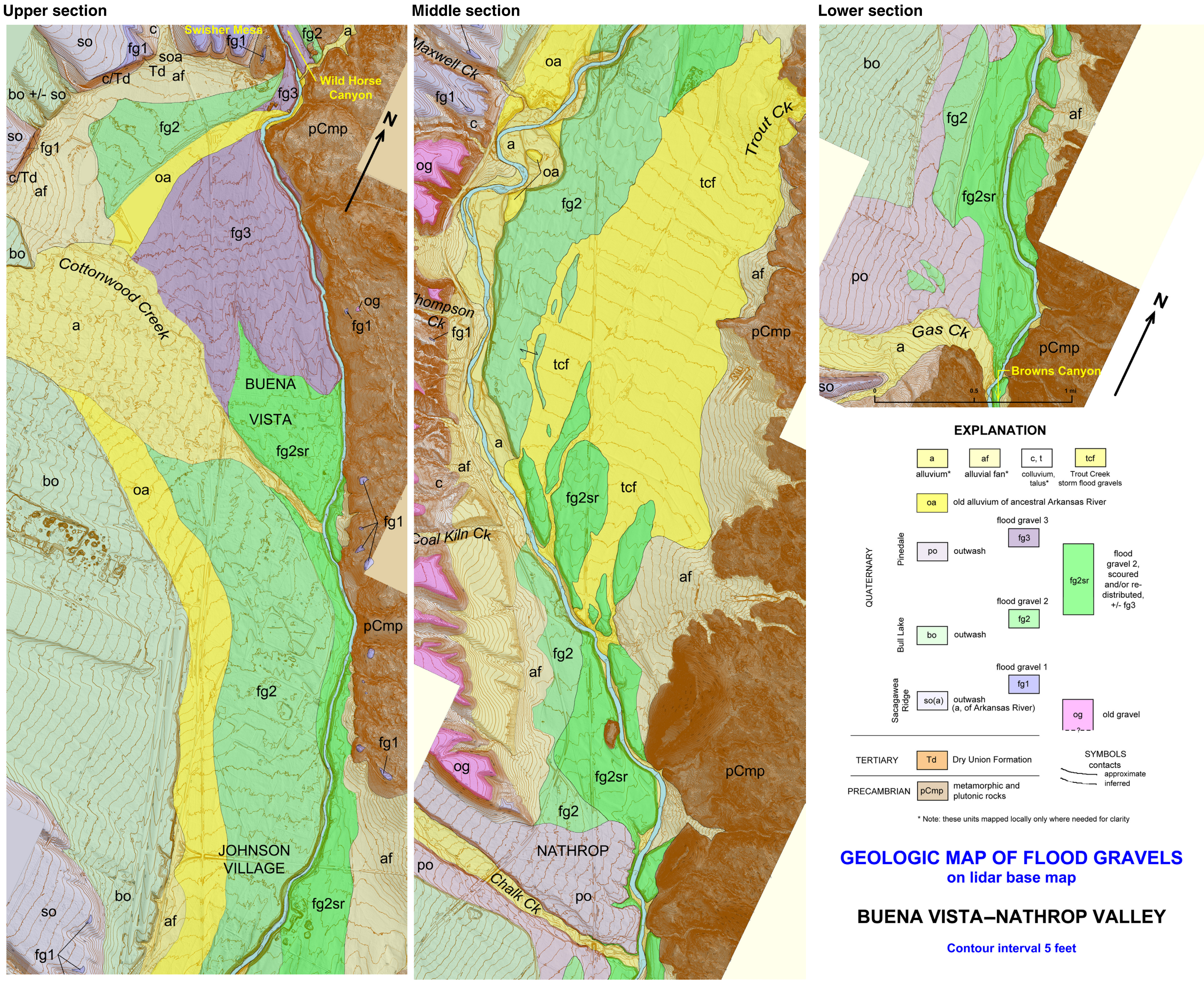


Figure 29 – Geologic map of flood gravels in the Buena Vista – Nathrop Valley.

No flood gravels from Flood 1 or Flood 2 were observed in Browns Canyon. Two isolated patches of flood gravel are mapped as flood gravel 3 (unit fg3) (**Fig. 33**). Remnants of a narrow terrace about 40 ft above the river (unit oa) are present discontinuously along the length of the canyon (**Figs. 33, 34**). The terrace is composed of typical channel gravels that incorporate flood boulders. These terrace deposits represent a former level of the Arkansas River soon after Flood 3.

Each of the three outburst floods likely flushed out extant gravels in Browns Canyon, as well as weathered bedrock boulders, and left in their place only waning-flow flood gravels. Moreover, because the canyon is so narrow and steep (Fig. 33), the Arkansas River following each flood reworked most or all of the waning-flow flood gravels and broke down most of the flood boulders, as the modern Arkansas River continues to do today.

Flood History of the Buena Vista – Nathrop Valley

Flood 1 (about 640 ka) – The record of the first catastrophic outburst flood is sparse and yielded little information on the extent of the flood. The few remaining flood gravels indicate that, at the time of the outburst flood, at least the upper half of the valley was about the same width as it is today.

After Flood 1 (about 640–130 ka) – In the half-million years between the first two floods, extensive stream erosion deepened the valley about 150 ft to about 50 ft above the modern Arkansas River.

Flood 2 (about 130 ka)– Floodwaters discharging from Wild Horse Canyon were deflected off the granite mountainside of Fourmile Gap and cut off the south end of Swisher Mesa (Figs. 13, 29). The flood likewise trimmed unconsolidated sediments along the west side of the valley all the way down to the town of Nathrop (Fig. 1). Flood gravels blanket the valley floor throughout (Fig. 29).

After Flood 2 (about 130–19 ka)– In the briefer interval between Flood 2 and Flood 3, the Arkansas River flowed mostly along the east side of the valley on and along Precambrian crystalline rocks. Downcutting left the surface of flood gravel 2 as a low terrace (today about 60 ft above the river).

Flood 3 (about 19 ka) – Floodwaters scoured and flushed out Wild Horse Canyon and deposited most of the resulting debris below the mouth of Wild Horse Canyon. This debris fan extends south through Buena Vista, and it completely filled the previous channel of the Arkansas River along the east side of the valley. After dropping most of its sediment load, the floodwaters extensively, and locally intensively, scoured the surface of flood gravel 2 downstream of Buena Vista. This scour intensified as the valley narrowed to the south into Browns Canyon.

After Flood 3 (since about 19 ka) – After this outburst flood, the Arkansas River initially flowed west of the debris fan (Fig. 29, unit oa). The river subsequently was diverted to the east side of the valley, where it flowed down to Johnson Village before swinging west to join the channel of the older course at Maxwell Creek. Cottonwood Creek and Chalk Creek (Fig. 29) deposited Pinedale-age outwash and Holocene alluvium onto the valley floor.

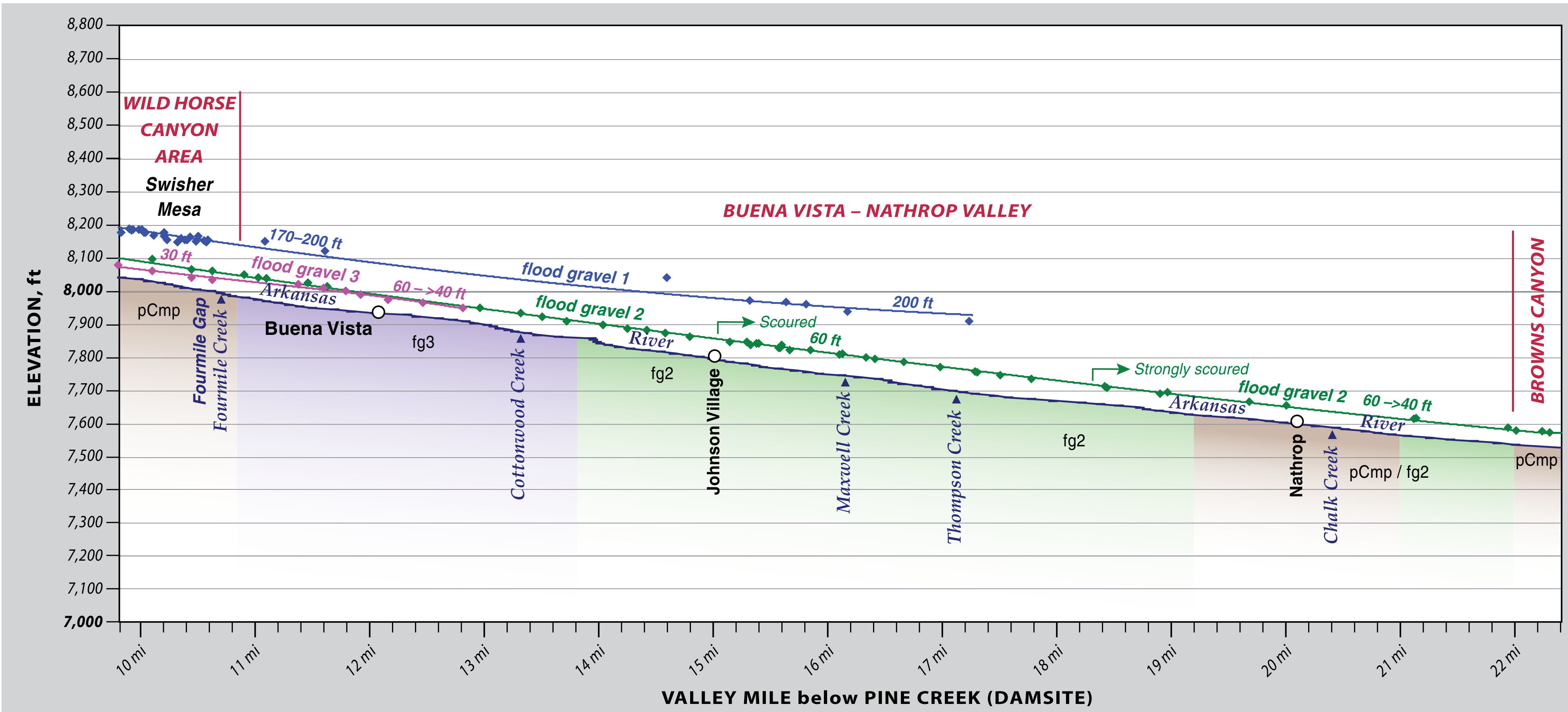


Figure 30 – Longitudinal profile of flood gravels in the Buena Vista – Nathrop Valley.

Intermittent storm floods along Trout Creek transported pebbly sands onto a broad area of the valley floor. Most, and perhaps all, of these storm flood deposits resulted from historical floods.

Figure 31 – Distribution of Trout Creek storm flood deposits (dam was built in 2000).

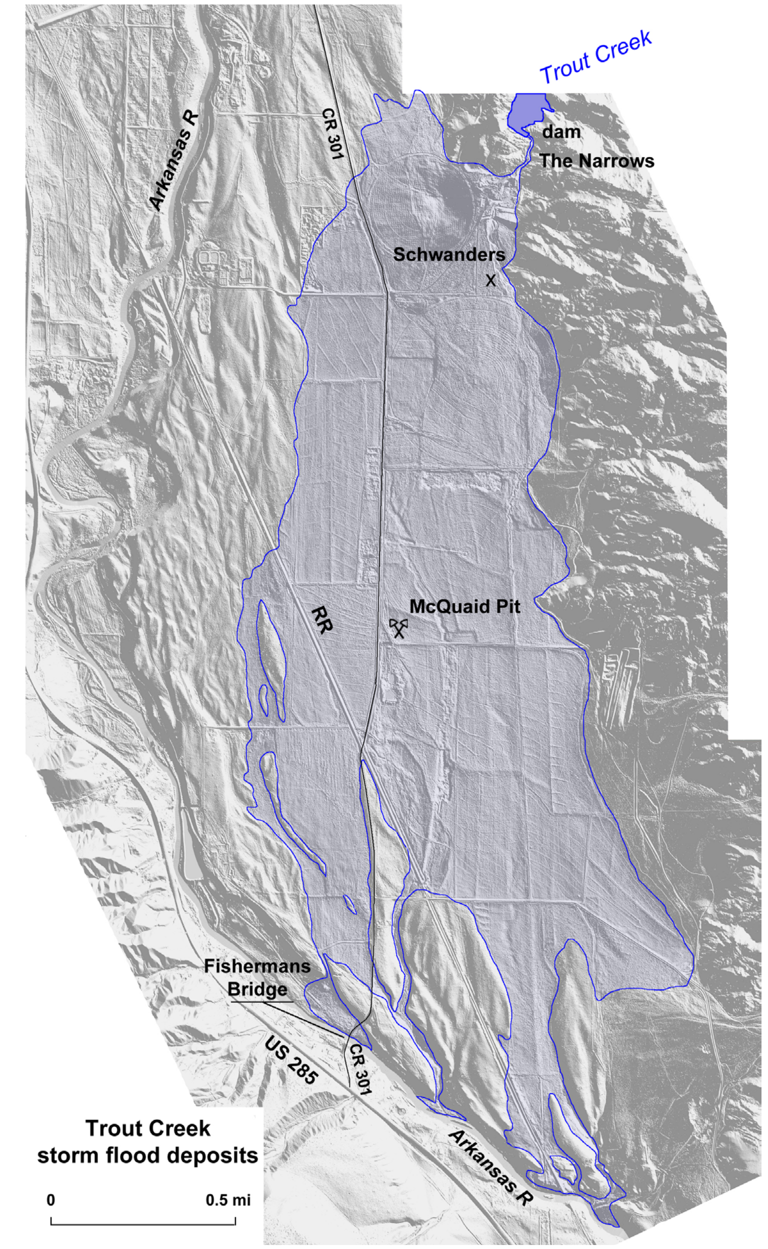


Figure 32 – Trout Creek storm flood deposits buried the G.A. Frisky house and outbuildings near the old Schwanders railroad station (see Fig. 31 for location). Photos taken 20 September 1948. Courtesy of Sam Schroeder, U.S. Forest Service.

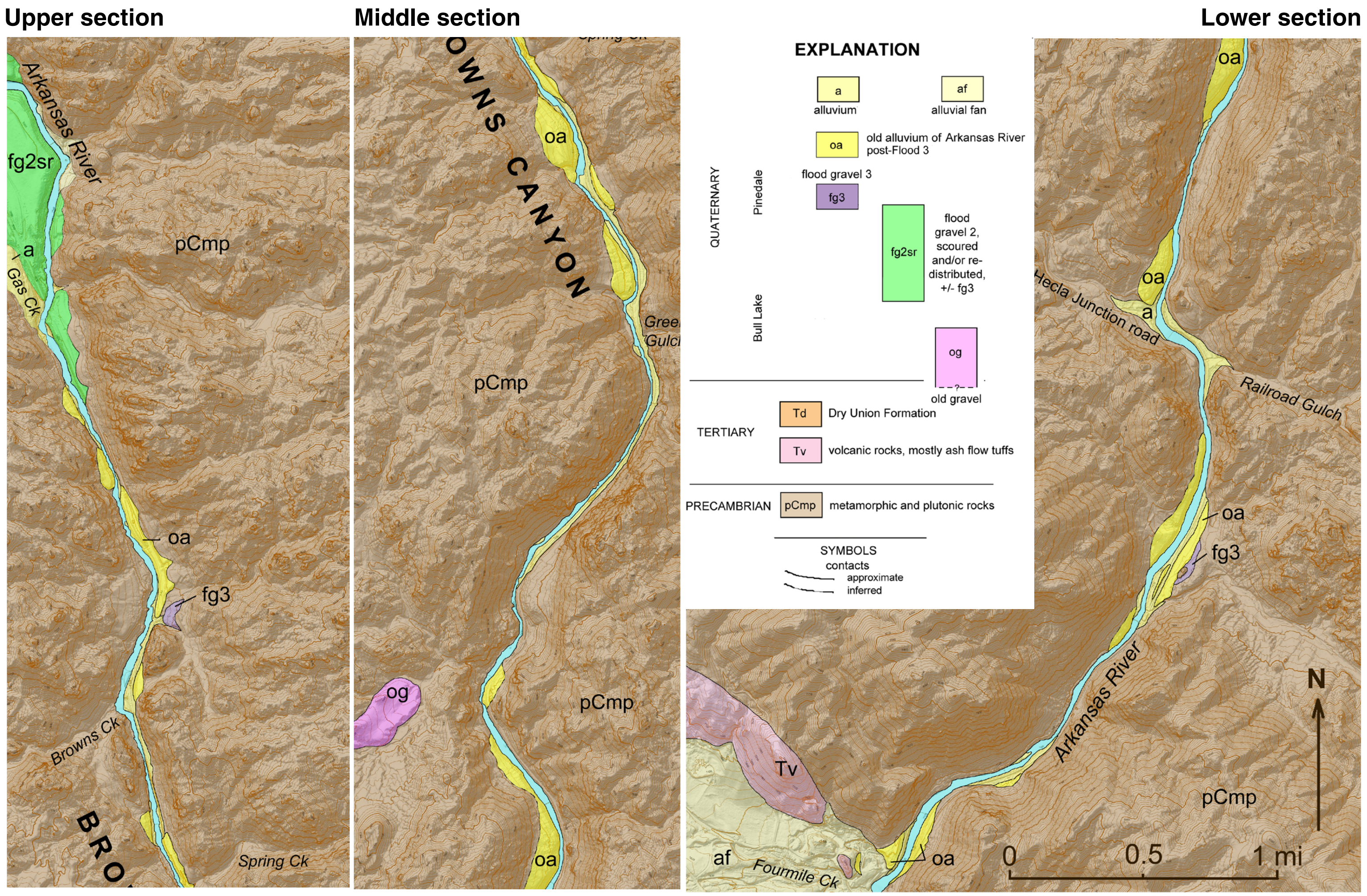


Figure 33 – Geologic map of flood gravels in Browns Canyon. Contour interval, 10 ft.

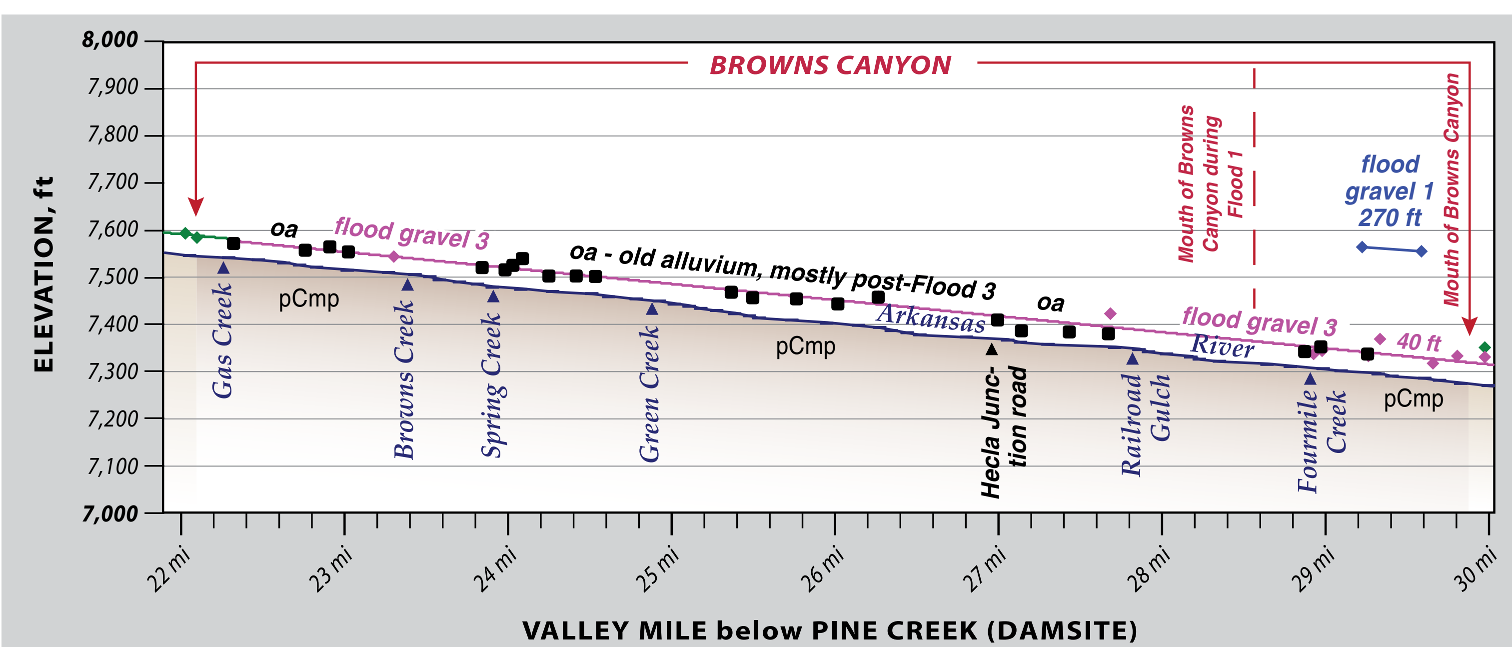


Figure 34 – Longitudinal profile of flood gravels and alluvium in Browns Canyon. pCmp, Precambrian metamorphic and plutonic rocks; ft, feet.

SAND PARK, FLOOD LANDFORMS AND DEPOSITS

Flood gravel 1

Flood gravel 1 deposits (unit fg1; Sacagawea Ridge glaciation) cap Sega Mesa and BLM Butte at the mouth of Browns Canyon (**Fig. 35**), but these gravels are the only deposits remaining in Sand Park, so little is known of the original distribution of the flood gravel. Sega Mesa is composed of Dry Union (unit Td) sands and gravels capped by flood gravels that contain flood boulders near the top. BLM Butte consists of crystalline rock capped by flood gravels similar to those on Sega Mesa.

Flood gravel 1 lies about 270 ft above the modern Arkansas River (**Fig. 36**). Both deposits were mapped as Illinoisan by Van Alstine (1974) and by Scott et al. (1975), although they did not indicate that the gravels were flood deposits. The flood gravels appear to be of Sacagawea Ridge age because they are about 200 ft above flood gravel 2, and because the two closest deposits of Sacagawea Ridge outwash are at a similar height, about 250 ft and 300 ft above the river (Fig. 36).

Fifteen flood boulders total from both deposits have median dimensions of 10 x 6 x 4+ ft. The largest, which is 16½ ft long, has a volume of about 330 cubic feet and a weight of about 30 tons. Modal rock type is granodiorite, with other boulders composed of gneissic granite, ash flow tuff, and biotite gneiss. All of these rock types are found in Browns Canyon.

Flood gravel 2

Flood gravel 2 (units fg2, fg2sr; Bull Lake glaciation) extends over most of Sand Park, and it is the most areally extensive and voluminous of the flood deposits. Abundant, stacked flood boulders form a narrow tongue almost 3 mi. long, covering an area of about 820 acres (Fig. 35, unit fg2 with dot pattern). Thickness of the deposit is unknown, but exposures of 20 ft are common. At the downstream end of the tongue, flood boulders appear to be restricted to the upper third of the flood gravel. The abundance and size of flood boulders decrease notably downstream of this tongue. Flood gravels farther downstream contain flood boulders, but the flood boulders are not stacked on each other. At the farthest downstream extent of flood gravels, in the Butala gravel pit near Salida (Fig. 35), flood boulders are still numerous in the top 10–15 ft of the gravel (**Fig. 37**). Flood boulders are also found in Bighorn Canyon (Fig. 1) below Salida, but from which flood they originated cannot be determined.

Flood boulders are largest near the canyon mouth and diminish downriver, although within the first three miles there is little sorting (**Fig. 38**). From measurements of 31 of the largest flood boulders here, median dimensions are 18 ft by 10 ft by 6+ ft, and median volume is about 630 cu ft, which would weigh about 50 tons. The largest flood boulder is 30½ ft by 19 ft by 12+ ft, with a volume estimated at slightly more than 5,000 cu ft, weighing about 420 tons.

Much of the surface of flood gravel 2 is scoured. A pattern of low swales on the surface of Roberts Flats appears at first to be dendritic but on close inspection is anastomosing (**Fig. 39**), a characteristic of flood erosion (Benn and Evans, 1998, p. 346). Many flood boulders at the surface are almost fully exposed.

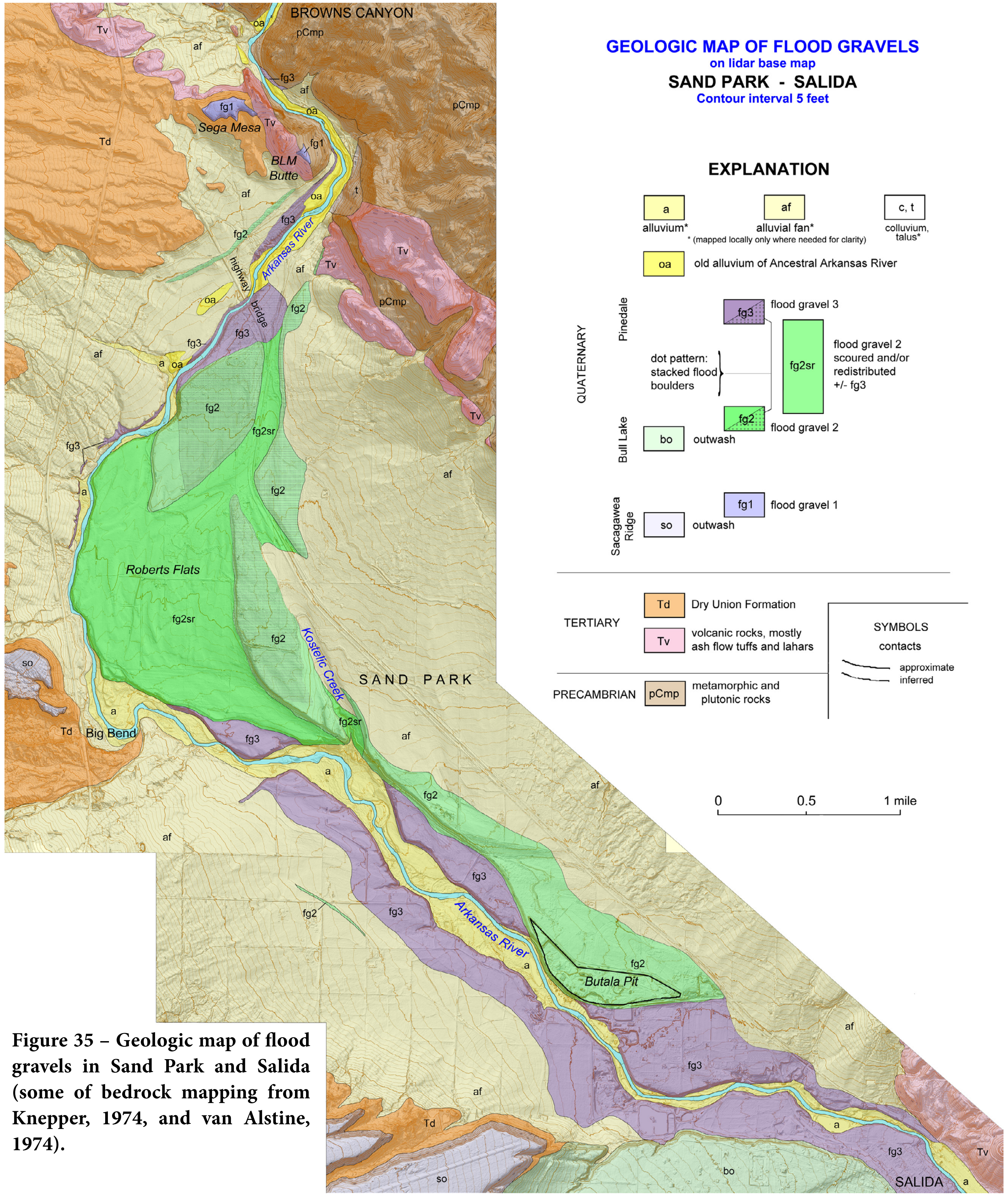


Figure 35 – Geologic map of flood gravels in Sand Park and Salida (some of bedrock mapping from Knepper, 1974, and van Alstine, 1974).

The surface of flood gravel 2 is about 90 ft above the modern Arkansas River at the mouth of Browns Canyon and about the same height near Salida (Fig. 36). Because the surface was later scoured, however, the height varies throughout Sand Park.

Flood gravel 3

Flood gravel 3 (fg3; Pinedale glaciation) is considerably less voluminous and areally less extensive than flood gravel 2. Abundant stacked flood boulders below the mouth of Browns Canyon form a narrow tongue about 1½ mi. long that extends to just below the highway bridge, covering an area of about 230 acres (Fig. 35, unit fg3 with dot pattern). Beyond the highway, flood boulders are entrained in the flood gravels, although they are not stacked, and they extend at least as far downstream as Salida.

Large flood boulders, which are distributed throughout the flood gravel, have no apparent sorting. From measurements of 19 of the largest flood boulders, median dimensions are 19½ x 13 x 5½+ ft, median volume is about 970 cubic feet, and median weight about 80 tons. The largest flood boulder is 33 x 18½ x 10½+ ft, its volume is estimated at slightly less than 5,000 cubic feet, and its weight about 400 tons. These flood boulders are comparable in size to those in flood gravel 2, even though they are less abundant.

Flood History of Sand Park

Flood 1 (about 640 ka) – Catastrophic Flood 1 deposited flood gravels at the mouth of Browns Canyon, but the route through Sand Park is not apparent because of the paucity of flood gravels remaining.

Post-Flood 1 (about 640–130 ka) – A considerable period of time, about 500,000 years, passed without a known catastrophic flood in Browns Canyon. During this time, weathering of the metamorphic and plutonic rocks in the canyon produced numerous rounded boulders. The ancestral Arkansas River incised bedrock at the canyon mouth about 200 ft and established a course east of BLM Butte near its present course.

Flood 2 (about 130 ka) – Floodwaters flushed out Browns Canyon and carried a traction bedload of boulders through the center of Sand Park. Flood boulders were stacked up in the channel through most of the length of Roberts Flats, down nearly to the confluence of Kostelic Creek with the modern Arkansas River. Outside the main channel, flood gravels were spread over a large area (Fig. 35). Flood gravels everywhere contained dispersed flood boulders. Near Salida, Flood 2 waters did not erode all of the Bull Lake outwash but deposited about 15 ft of flood gravel on top of it.

After-Flood 2 (about 130–19 ka) – Following the second flood, the Arkansas River may have flowed from the highway bridge through Kostelic Creek (Fig. 35) for a short period, but eventually it shifted to the west, to approximately its present course. After diversion, the river cut down more than 60 ft, leaving terraces in a broad area east of the Arkansas River and in a narrow area west of the river.

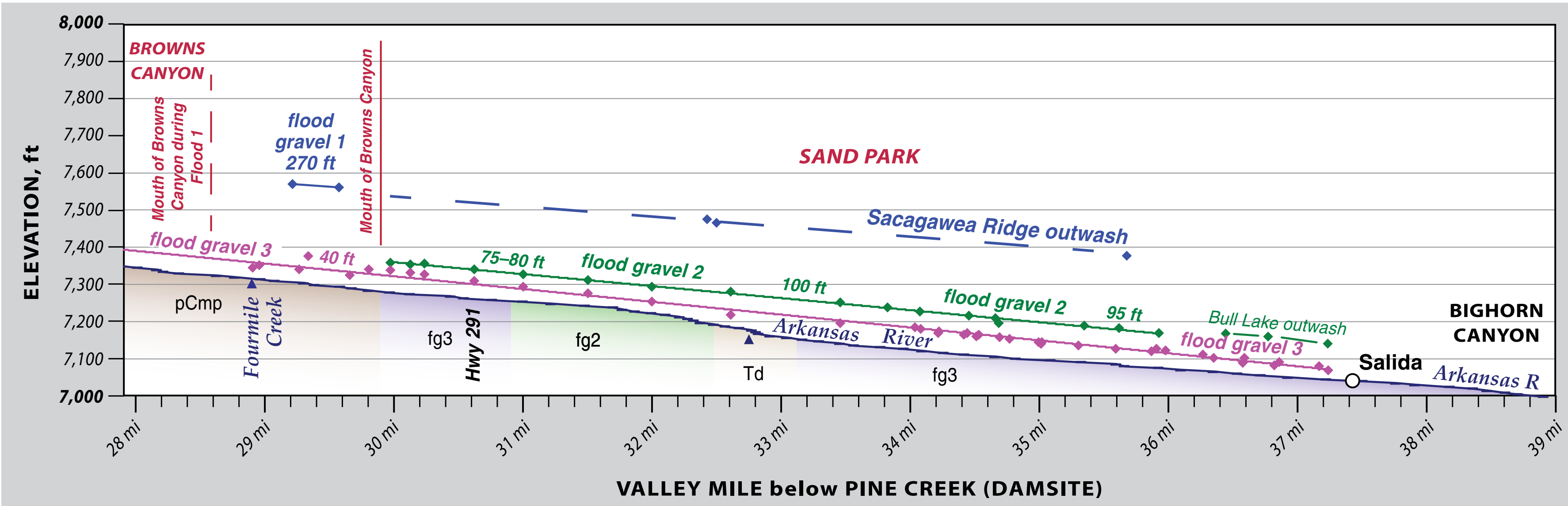


Figure 36 – Longitudinal profile of outburst flood gravels in Sand Park. pCmp, Precambrian metamorphic and plutonic rocks; fg3, flood gravel 3; fg2, flood gravel 2; Hwy, Highway; Td, Tertiary Dry Union Formation.

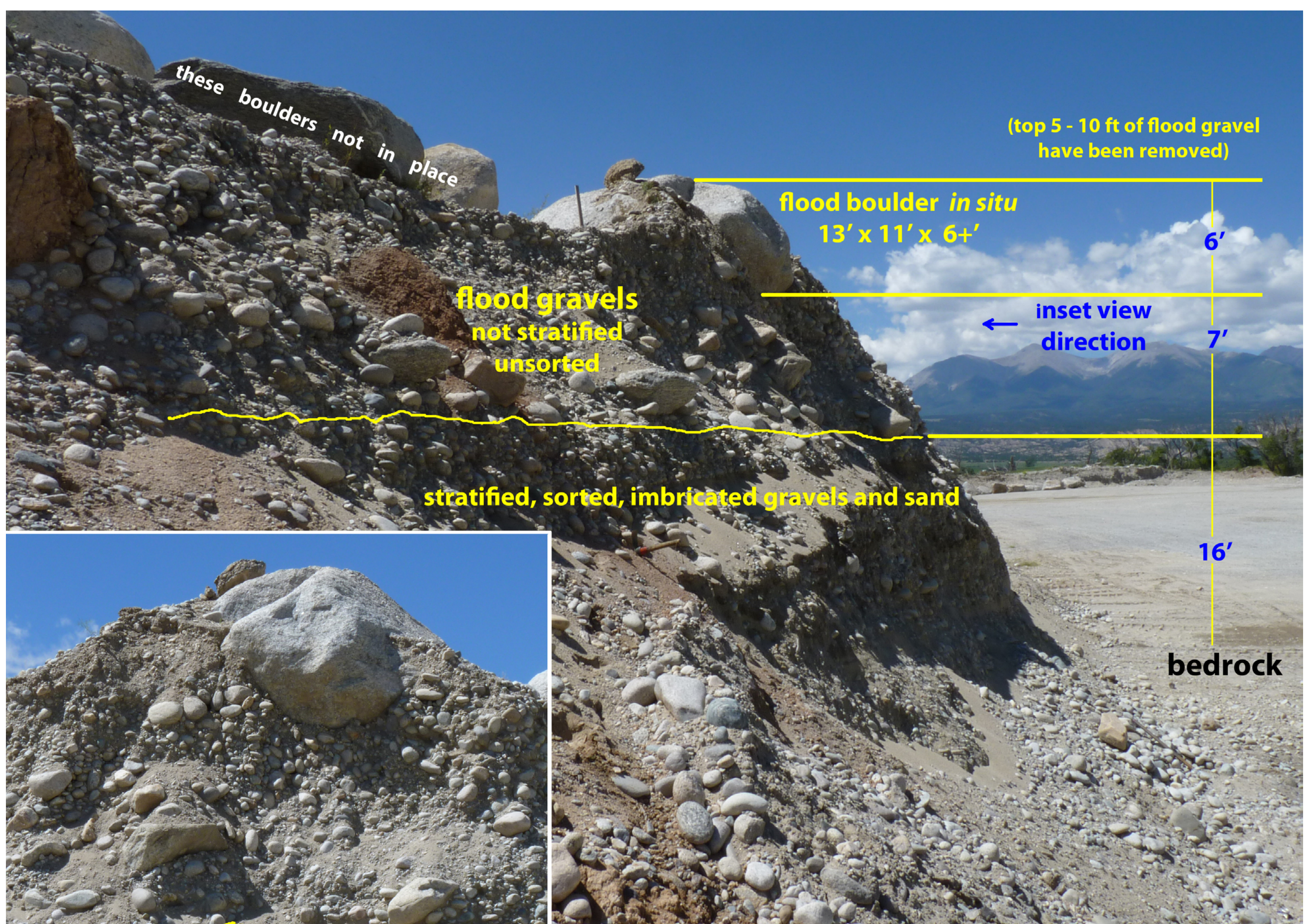


Figure 37 – Flood gravel 2 in Butala gravel pit near Salida (for location see Fig. 35). Flood gravels lie on Bull Lake outwash.

The interval between Flood 2 and Flood 3, which was about 100,000 years, allowed substantially less time to weather bedrock in Browns Canyon than the interval prior to Flood 2. The result was a smaller supply of large boulders available for Flood 3 to flush from the canyon.

Flood 3 (about 19 ka) – Flood 3 carried additional flood boulders out of Browns Canyon, but not nearly as many as had Flood 2. Flood 3 had a discharge similar to that of Flood 2, yet it carried a smaller traction bedload. Waters of this flood, which thus had a greater capacity for erosion, scoured the surface of flood gravel 2. Flood 3 apparently exhumed flood boulders from flood gravel 2, remobilized some of the older flood boulders, and added new flood boulders eroded from the canyon by Flood 3. Floodwaters that in some areas were deeper eroded shallow channels and cut low scarps (Fig. 39, unit fg2sr). The scour pattern seen on much of Roberts Flats resulted from this flood erosion.

After Flood 3 (since about 19 ka) – After the final catastrophic flood, the Arkansas River cut channels through the youngest flood gravels (unit fg3) just below the canyon mouth, in the process breaking down flood boulders and leaving coarse gravels dotted with few flood boulders (Fig. 35, unit oa). Such deposits show that the Arkansas River, upstream of the highway bridge, was broader than it is today or that it migrated laterally (or both). Downstream of the bridge, alluvial fans obscure most of its course.

The Arkansas River then cut down into the youngest flood gravels (unit fg3). It incised about 30 ft along the reach down to Big Bend (Fig. 35) and about 60 ft deep below there.

Alluvial fans that developed since Flood 3 now cover much of the surface of Sand Park, and as a result some flood history there is lost. This loss is noted particularly in the area west of the Arkansas River, where east-flowing streams erode unconsolidated sands and gravels of the Dry Union Formation and transport them down to the modern river.

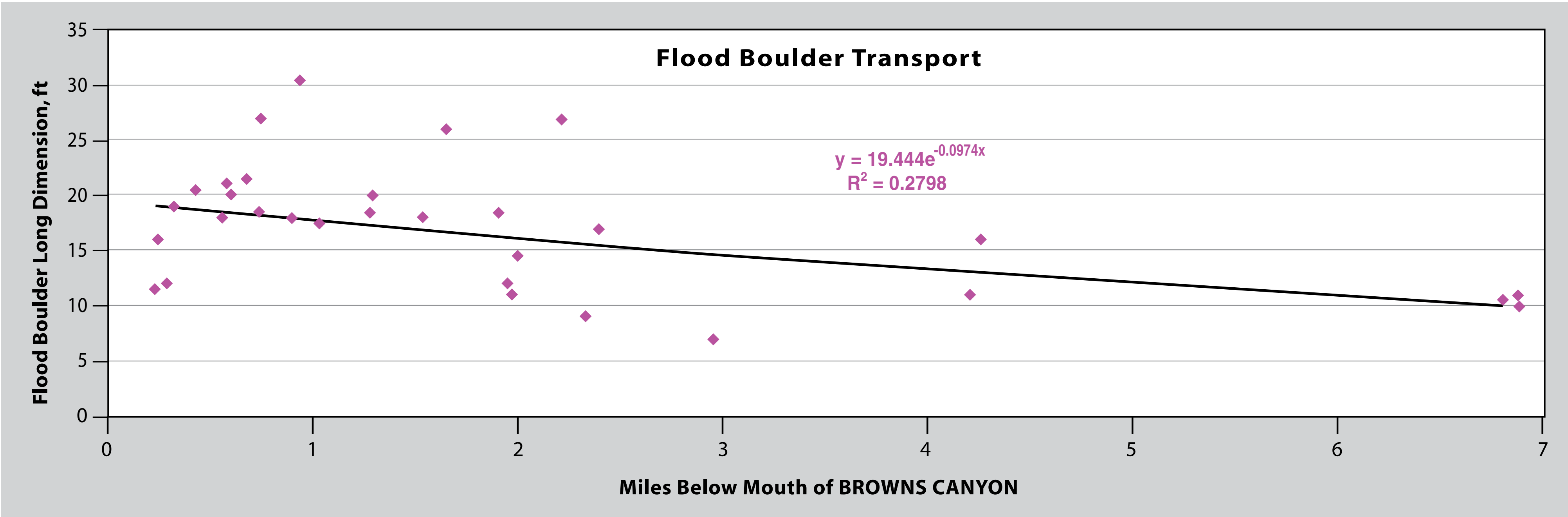


Figure 38 – Largest flood boulders in flood gravel 2 just below the mouth of Browns Canyon.

Figure 39 – Anastamosing scour pattern on the surface of flood gravel 2 at Roberts Flats.

HISTORY OF OUTBURST FLOODS IN THE UPPER ARKANSAS RIVER VALLEY

Glaciers advanced three times down tributary valleys from the Sawatch Range and dammed the Arkansas River at a point here named the Damsite. The tributary valley glaciers that created these glacial dams flowed out of Clear Creek and Pine Creek valleys (north to south). When the glacial dams failed, three catastrophic outburst floods swept down the upper Arkansas River valley.

Sacagawea Ridge Glaciation and Flood 1 (about 675–640 ka)

Sacagawea Ridge glaciers flowed eastward down tributaries of the Sawatch Range, west of the Arkansas Valley, and four of them reached the Arkansas River. No glaciers from the Mosquito Range, east of the valley, reached the Arkansas River.

The Lake Creek glacier, although it did not dam the Arkansas River, diverted the Arkansas River from its more westerly position in unconsolidated sediments to the east onto Precambrian crystalline rocks.

The Clear Creek glacier probably did dam the Arkansas River. The glacier's advance was arrested by a high granite wall that closely bounded the river channel on the east. The record here is incomplete because of subsequent glaciations, but no other glacier in the Arkansas valley upstream of Clear Creek was capable of damming the river, and the only flood gravels in the Arkansas River valley are downstream from the mouth of Clear Creek valley.

The Pine Creek valley glacial record is also incomplete, but a Sacagawea Ridge-age glacier may have reached the Arkansas River, on the basis of an extensive Sacagawea Ridge-age glacier to the south at Frenchman Creek.

It is uncertain whether the Frenchman Creek glacier dammed the ancestral Arkansas River, but even if it did, the dam's effect on flooding likely was felt only locally, because the main glacial dam formed by a Sacagawea Ridge-age glacier lay upstream at the mouth of Clear Creek valley.

About 640 ka, failure of the Sacagawea Ridge-age glacial dam led to a catastrophic outburst flood, Flood 1.

Floodwaters coursed down the relatively broad, low-gradient Upper Valley, which was about a mile wide through most of this reach, and cut a linear bank in unconsolidated sediments along the valley's west side. Flood gravels (unit fg1) were deposited across the valley floor on Swisher Mesa and downstream at least to Johnson Village. The main source of flood gravels was the washed-out end moraines of Sacagawea Ridge-age at the mouths of Clear, Pine, and Frenchman Creek valleys, and pieces of bedrock ripped from the dam abutments. Floodwaters deepened Browns Canyon, flushed large weathered bedrock boulders out of the canyon, and deposited flood gravels at the mouth of the canyon in the upper part of Sand Park. Discharge of Flood 1 is unknown, but it likely was about the same magnitude as the discharge of later floods, about 1½ million cubic feet per second.

After-Flood 1 (about 640–190 ka)

Lava Creek B ash from the Yellowstone caldera was deposited in the region, including the top of flood gravel 1; the age of the ash is 639 ka, which dates the flood to about 640 ka.

During the half million years between Floods 1 and 2, the Arkansas River deepened its valley about 100 ft. Much flood gravel 1 was removed, but many of the flood boulders likely remained as lag to be incorporated into flood gravel 2. The ancestral Arkansas River was diverted from its channel on Swisher Mesa, now filled with flood gravel, and cut Wild Horse Canyon.

Bull Lake Glaciation and Flood 2 (about 190–130 ka)

Bull Lake-age glaciers from Clear Creek and Pine Creek merged and formed a large, thick compound glacial dam that impounded the Arkansas River. A glacial lake formed above the dam that is estimated to have been about 12 miles long and more than 600 feet deep at the dam.

When the glacial dam failed, the lake emptied catastrophically. The surging floodwaters spread out in the Upper Valley, were funneled into Wild Horse Canyon, spread out in the Buena Vista–Nathrop Valley, and were funneled into Browns Canyon before spreading out in the very wide valley of Sand Park. At the lower end of Wild Horse Canyon, Fourmile Gap created a hydraulic dam that backed up floodwaters, leading to the formation of a spillway on Swisher Mesa. Discharge through the canyons was sufficient to flush the canyons of large weathered bedrock boulders and finer sediment.

Flood gravel 2 was deposited on the valley floor throughout the Upper Valley, likely incorporating lagged flood boulders from flood gravel 1. The gravel is more than 59 ft thick just below the dam. Flood gravel 2 also mantles most of the valley floor in the Buena Vista–Nathrop Valley and in Sand Park. Peak discharge was probably about the same as Flood 3, about 1½ million cubic feet per second, because the dam at Clear Creek was at about the same elevation.

After Flood 2 (about 130–35 ka)

The Arkansas River deepened its valley about 50 ft. The valley widened little, however, so the sheet of flood gravel 2 was left as a broad terrace, now the upper terrace on the modern valley floor.

Pinedale Glaciation and Flood 3 (about 35–19 ka)

About 20 thousand years ago, a Pinedale-age glacier in Clear Creek valley dammed the Arkansas River. A glacier in Pine Creek valley also dammed the river, but it impounded only a small, lower lake, whereas the considerably higher and upstream Clear Creek glacier dam controlled the main glacial lake.

About 19 ka, the most recent glacial dam at Clear Creek failed, and the lake drained catastrophically within hours, with peak discharge estimated at 1,630,000 cubic feet per second (Brugger et al., 2011). Outburst floodwaters immediately topped the lower dam at Pine Creek, leading to its failure as well.

Floodwaters deposited debris on the valley floor, on low rises, and at valley margins as much as 70 ft above the flood gravel 2 terrace surface. The surface of flood gravel 2 was deeply scoured, and its upper gravels were redistributed, and mixed with new flood gravels.

In the Upper Valley, flood gravel 3 was deposited, as a coherent unit, only as far as Railroad Bridge. Downstream from the bridge, the now more-erosive floodwaters deeply scoured the terrace of flood gravel 2 across Flood Boulder Flats. Debris from this erosion, along with weathered bedrock boulders from the walls of Wild Horse Canyon, was dumped at the mouth of the canyon as a flood fan on top of flood gravel 2 at Buena Vista. In the Buena Vista–Nathrop Valley, flood gravel 3, as a coherent unit, does not extend beyond Buena Vista.

Floodwaters below Buena Vista scoured the terrace of flood gravel 2. Scour became more severe as the valley narrowed above Browns Canyon and the waters became deeper. Sediment and weathered bedrock boulders were flushed out of Browns Canyon, and most of this debris was deposited just below the canyon mouth in Sand Park. Beyond where much of the coarse gravel load was deposited, the enhanced erosive power of the floodwaters then scoured the surface of flood gravel 2 across Roberts Flats.

A simulation of Flood 3 that used a hydraulic model shows the distribution of floodwaters in the upper Arkansas River valley (**Fig. 40**). The effects of the hydraulic dams created at Wild Horse Canyon and Browns Canyon are clearly shown.

After Flood 3 (since about 19 ka)

Glaciers in Clear Creek and Pine Creek valleys, which continued to flow briefly after Flood 3, advanced beyond the truncated end moraines washed out by Flood 3, but they did not dam the Arkansas River.

Just below the damsite, the Arkansas River changed course soon after Flood 3. As the Arkansas River cut its channel, it cut down into flood gravel 3 as much as 54 ft without exposing the base of that unit, and it left the most recent flood gravels, flood gravel 3, as the lower terrace.

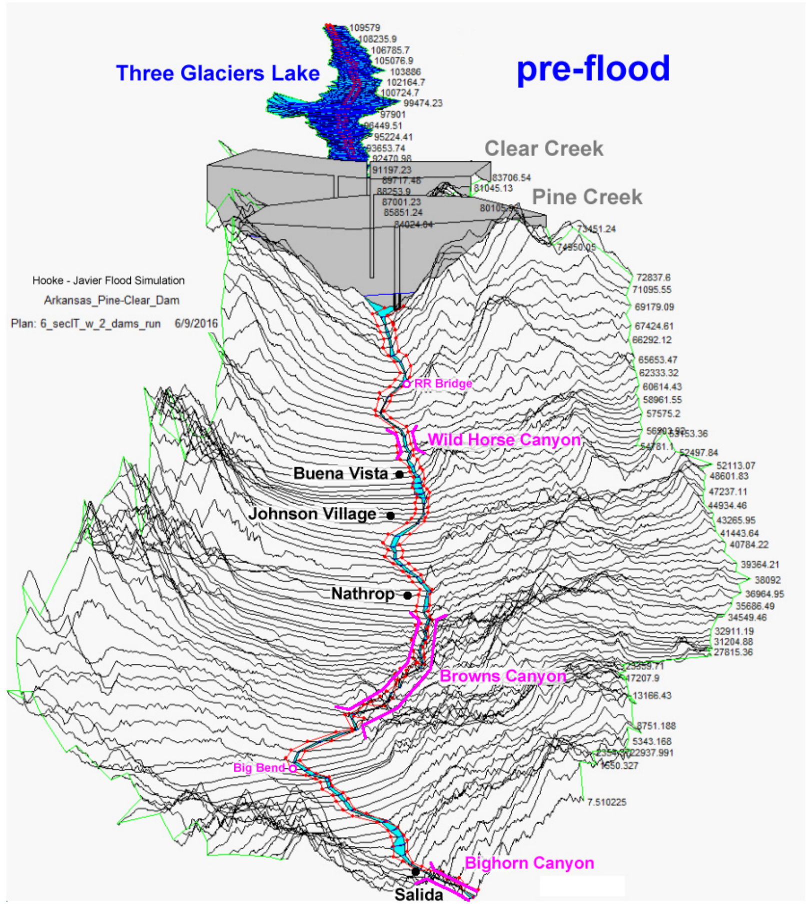
The Pine Creek School landslide failed again—at least the southeastern part, blocked the Arkansas River at Buffalo Creek (Fig. 13), and diverted the river to the east side of the Upper Valley into its more-or-less present course. At the mouth of Wild Horse Canyon, the Arkansas River originally flowed to the west side of the Buena Vista–Nathrop Valley. Subsequent diversion at the canyon mouth moved the Arkansas River into its current channel.

In historic times, flash floods in the Trout Creek drainage deposited a sheet of pebbly sand over the Arkansas Valley floor.

Tributary streams built extensive alluvial fans along the valley margins.

Legacy of the Glacial Outburst Floods

A prominent legacy of the catastrophic floods is the abundance of large flood boulders in relatively low-gradient reaches of the Arkansas River. These boulders created numerous rapids that spawned, and maintain, a thriving rafting and kayaking industry (**Fig. 41**). These same flood boulders, however, are spread over large areas of valley bottom that would ordinarily be prime agricultural land, precluding cultivation. Today such areas are experiencing residential development, in many cases with attractive, dramatic flood boulder landscaping (**Fig. 42**). Residents here may not be aware, however, that they are in the 100,000-year floodplain.



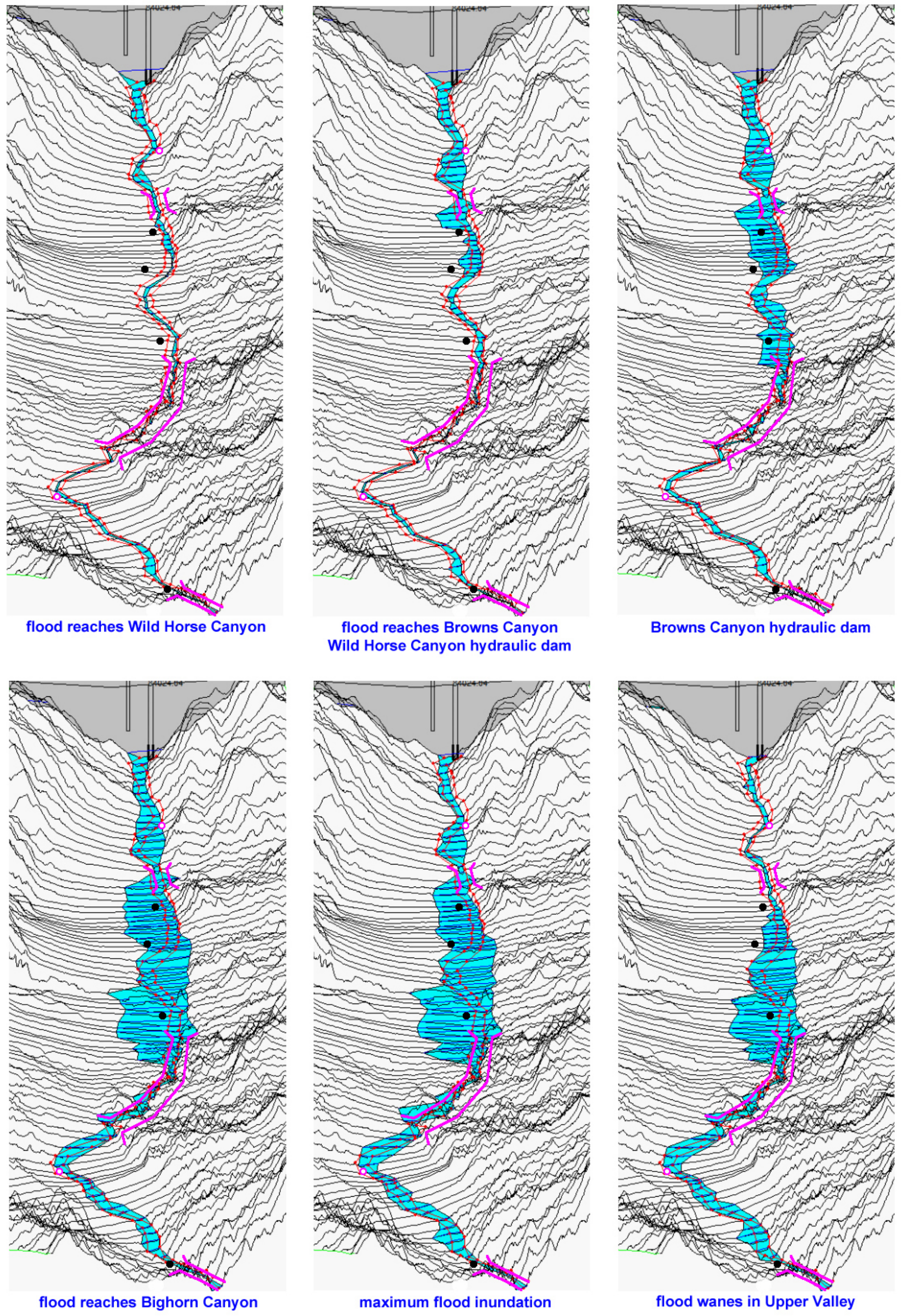


Figure 40 – Simulation of Flood 3 in the upper Arkansas River valley by Roger LeB. Hooke and Xavier Allegre. Time-lapse snapshots demonstrate the effects of hydraulic dams created at Wild Horse Canyon and Browns Canyon. The simulation utilizes a gate-opening module in the US Army Corps of Engineers HEC-RAS open-source software. To generate the flood, a gate in a dam at the location of the Pine Creek glacier is opened rapidly, simulating overflow of the dam followed by erosion of a breach. Courtesy Roger LeB. Hooke.

Figure 41 – Rafting and kayaking through flood boulders in The Numbers Rapids.

Figure 42 – Flood boulder landscaping in Sand Park.

AKNOWLEDGEMENTS

In the 1970s, Glenn Scott helped the faculty at the Colorado School of Mines Geology Field Camp set up a surficial geology field problem still being taught today. Glenn taught me much about the Quaternary geology of Colorado and engendered my interest in glacial processes. When I first recognized flood boulders below Browns Canyon and started this study, I learned that Glenn already knew of the floods, and he kindly provided me a copy of his report (Scott, 1984).

I appreciate discussions in the field with Eric Leonard, Karl Kellogg, Cal Ruleman, Ralph Shroba, Jim McCalpin, Jason Briner, Roger LeB. Hooke, and numerous participants of field trips through the valley. Our interpretations don't always agree (we're geologists), but the interchanges were always fruitful. Lidar data acquired by the U.S. Geological Survey in 2010 were an invaluable aid in mapping subtle landforms and creating accurate maps. Many landowners in the upper Arkansas River valley graciously provided access to their properties, some of them numerous times.

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APPENDIX

List of Map Units and Description of Selected Map Units

SURFICIAL DEPOSITS

Glacial Deposits and Glacio-fluvial Deposits*

pt(l)	Till of Pinedale Glaciation (l, late stage clearly post-flood in Clear Creek and Pine Creek drainages)
po	Pinedale outwash (not differentiated from more recent alluvium along Arkansas River)
bt	Till of Bull Lake Glaciation
bo	Bull Lake outwash (from glaciers in the Sawatch Range)
st	Till of Sacagawea Ridge Glaciation (Pre-Bull Lake)
so	Sacagawea Ridge outwash (Pre-Bull Lake) from glaciers in the Sawatch Range
soa	Sacagawea Ridge outwash (Pre-Bull Lake) from the Arkansas River

Lacustrine Deposits

lac	Lacustrine sediments: laminated sands and silts, deformed by slumping; occurs only in one deposit in Pine Creek where it was deposited in a late-stage (post-flood) proglacial pond

Alluvial Deposits, Unrelated to Catastrophic Outburst Floods

tcf	Trout Creek storm flood deposits: sandy pebble gravel - pebbly sand spread over the Arkansas valley floor below Trout Creek; most from historical flash floods (e.g.- 8 July 1890, 10 Sept 1919, 25 July 1923) that deposited up to 10 ft of sediment in a single flood
a	alluvium, deposits older than modern Arkansas River floodplain deposits**
af	alluvial fan deposits**
c	colluvium**
t	talus**
sw	slopewash: sand and fine gravel transported by running water not confined to channels that cover outer margins of flood gravel 1 terrace
oa	old alluvium of Ancestral Arkansas River: normal river alluvium that incorporates occasional flood boulders; marks a former course of the Arkansas River channel cut into flood gravel 3, since abandoned; in Browns Canyon forms terraces commonly about 40 ft above modern channel
og	old gravel; pre-glacial gravels high on valley margins; on west side of the valley they are pediment-like sheets of gravel derived from the Sawatch Range; on the east side of the valley they occur only as isolated, small patches of main-stem alluvium on Precambrian bedrock

Catastrophic Flood Deposits

fg3	flood gravel 3: mostly unsorted, unstratified gravels indistinguishable from flood gravel 2 except by position; flood boulders abundant, and often stacked, below damsite and below the two canyon mouths; deposits more restricted than fg2 – coherent deposits of flood gravels below damsite extend only about seven miles, below Wild Horse Canyon fg3 is a fan-like deposit, in part on top of fg2, that extends only about 2 mi., below Browns Canyon, flood boulders abundant and stacked for only about 1 mi.; flood boulders as large as 61 x 31 x 13+ ft; thickness as much as about 50 ft below damsite; height above modern Arkansas River about 20–40 ft, except on the Buena Vista fan where it reaches 60 ft and in Sand Park where it is 40–55 ft; Pinedale age, MIS 2, about 19 ka
fg2sr	flood gravel 2 scoured and redistributed, +/- fg3: this is an unconventional map unit, representing deposits of mixed ages; mostly fg2 subsequently modified by severe scour with redistribution of surface fg2 materials by Flood 3, with some addition of flood gravels 3; scour patterns generally anastomotic, ranging from gentle scour (e.g., Roberts Flats [Fig. 39]) to severe erosion (e.g, Flood Boulder Flats [Fig. 21])
fg2	flood gravel 2: mostly unsorted, unstratified gravels except in wide valley reaches where lenses of stratification may occur (such as Vasquez Pit near Johnson Village); flood boulders abundant, and often stacked, below damsite and below the two canyon mouths; distant from canyon mouths may overlie outwash (such as Butala Pit near Salida); flood boulders as much as 46 x 14 x 16+ ft; thickness as much as 70 ft observed; surface about 60 ft above modern Arkansas River in Upper Valley, about 40 ft just above Browns Canyon, and 75–100 ft in Sand Park; probable Bull Lake age, MIS 6, about 130 ka,
fg1	flood gravel 1: poorly exposed flood gravel seen only on steep colluvial slopes; recognized by ubiquitous flood boulders; extent of fg1 clearly visible in Upper Valley and on Swisher Mesa, but only isolated patches in Buena Vista–Nathrop Valley, and two small patches below the mouth of Browns Canyon; overlies Sacagawea Ridge outwash of Arkansas River on Swisher Mesa; flood boulders as large as 27 x 16½ x 10+ ft; height above modern Arkansas River about 155–200 ft in reaches upstream of Browns Canyon, about 270 ft in Sand Park; Sacagawea Ridge age, MIS 16, about 640 ka

Volcanic Ash**

x	Lava Creek B Ash

BEDROCK

Td	Tertiary Dry Union Formation**
Tv	Tertiary volcanic rocks***
pCmp	Precambrian Metamorphic and Plutonic Rocks**

*	for detailed description, see Shroba et al., 2014
**	for detailed description, see Kellogg et al., 2013, and Kellogg et al., 2017
***	for detailed description, see Van Alstine, 1974, and Kellogg et al., 2017