The late Pleistocene (17 ka) Soldier Bar landslide and Big Creek Lake, Frank Church-River of No Return Wilderness, central Idaho, U.S.A.

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ABSTRACT

Geomorphic mapping coupled with optically stimulated luminescence (OSL) dating reveal the late Pleistocene history and geomorphic development of the narrow canyon of Big Creek, a major tributary to the Middle Fork of the Salmon River in central Idaho. The most prominent feature in the region is the Soldier Bar landslide, which consists of slumped and rotated blocks of Mesoproterozoic quartzite bedrock that slid northward from an arcuate headwall, damming both the east-flowing Big Creek and Goat Creek, a south-draining tributary. Water impounded behind the dam ultimately overtopped the deposit. Overflow laterally eroded a flight of four downstream-sloping spillway terraces into the jumbled landslide deposit at elevations over a range of 450 ft (137 m). These elevations, initially estimated from 1:24,000 topographic maps with 40-foot contours, are 4,500 ft (1,372 m), 4,340 ft (1,323 m), 4,200 ft (1,280 m), and 4,050 ft (1,234 m). At the level of the highest spillway, the narrow lake extended ~17 miles (28 km) upstream from the inferred dam at Soldier Bar, but only impounded 2 km^3 of water. Assuming current river discharge and no seepage, it would have taken only six years to fill the lake to this level.

We use a simple sedimentological model based on the forced regression of fan deltas to interpret the numerous fluvio-lacustrine deposits found along Big Creek. Remnants of alluvial terraces, shoreline deposits, and deep-water lacustrine sediments enable reconstruction of the Soldier Bar landslide dam and the long, narrow Big Creek Lake. Optically stimulated luminescence (OSL) age estimates from deep water sediment just above Cabin Creek indicate a lake level well above 4,160 ft (1,268 m) at 17.1 ± 1.4 ka. Fluvial sands near Taylor Ranch at 4,124 ft (1,257 m) demonstrate that the lake had drained to this level by 11.3 ± 0.8 ka. Today, the slope of Big Creek steepens three-fold immediately downstream of the Soldier Bar landslide knickpoint, suggesting that the landslide event inhibited upstream propagation of the regional incision signal from the Middle Fork of the Salmon River into Big Creek.

KEY WORDS: Big Creek, central Idaho, fluvial terrace, landslide dam, late Pleistocene, optically stimulated luminescence, Salmon River, Soldier Bar landslide, Taylor Ranch.

INTRODUCTION

Historic valley-damming landslides have received considerable attention in the geologic and engineering literature because the outburst floods they can create pose a significant threat to downstream communities (Costa and Schuster, 1988; Costa and Schuster, 1991; Korup, 2002; Ermini and Casagli, 2003; Cui et al., 2009; Xu et al., 2009). Other paleo-landslide studies recognize that over much longer time scales, the integrated effect of many large sediment-delivery events regulate the efficiency of bedrock river incision, thus modulating the pace of landscape development in steep, mountainous landscapes (Korup, 2005; Lancaster and Grant, 2006; Ouimet et al., 2007; Korup et al., 2010; Lague, 2010; Yanites et al., 2011; Egholm et al., 2013). Because these events often occur in narrow canyons, few preserve either the topographic or sedimentological evidence necessary to demonstrate the millennial-scale evolution of a single landslide dam from its inception to its eventual demise. Here, we discuss an example from central Idaho.

Central Idaho, in general, and the Middle Fork of the Salmon River (MFSR), in particular, contain an actively incising landscape, with steep slopes and narrow canyons. The steep terrain of the MFSR is part of the Frank Church-River of No Return Wilderness. One of the only open areas in the narrow, east-flowing canyon of Big Creek is at the mouth of Cabin Creek, the location of the "most remote ranch in America" (Minshall, 2012, 2014). Eight km downstream, Taylor Ranch—a facility of the University of Idaho, but formerly the home of "Cougar Dave" Lewis (1844–1936)—is located on the alluvial fan deposits of Pioneer Creek (Fig. 1). Lewis claimed land for a homestead and built a cabin there in the 1920s (Peek, 2004). Today, Taylor Ranch and Soldier Bar landing strips serve small aircraft and greatly facilitate access to the area. Foot or horse access from upstream is only possible via a 35-mile (56-km) trail from the end of the gravel road and wilderness airstrip at Edwardsburg.

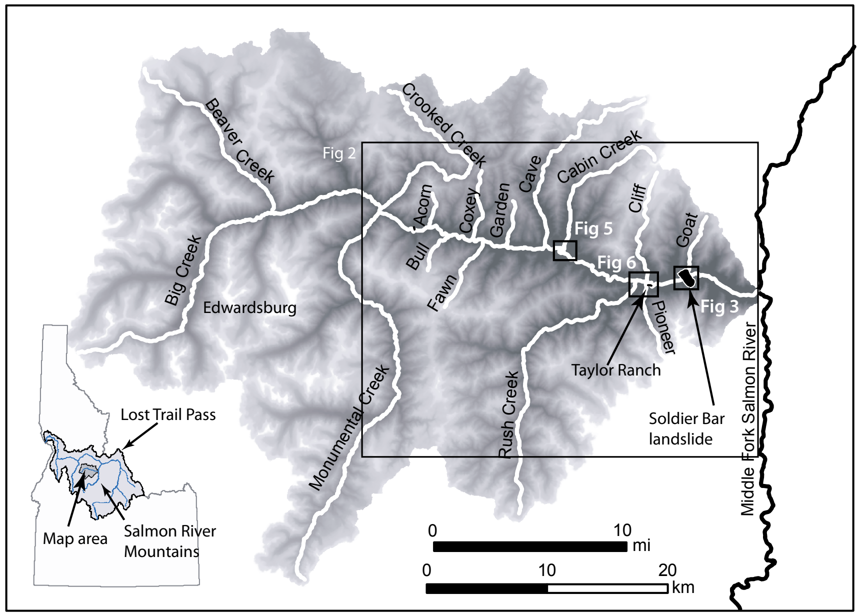

Figure 1. Location of the Salmon River watershed in Idaho, including the outline of Big Creek in the center of the watershed. The elevation-shaded digital elevation model of Big Creek shows the location of tributaries discussed in the text, the locations of other figures, and the location of the Soldier Bar landslide 8 km west of the confluence with the Middle Fork of the Salmon River (MFSR).

We describe the Quaternary geology of the canyon of Big Creek, from Cabin Creek down to the MFSR. We demonstrate that flat or low-gradient shorelines and stream terraces that are cut in unconsolidated sand are found near Cabin Creek and at Taylor Ranch (Figs. 1 and 2). At Soldier Bar, farther downstream, is a particularly spectacular series of low-gradient cut-terraces up to 590 ft (180 m) above the level of Big Creek. These surfaces are cut into jumbled blocks of Mesoproterozoic Yellowjacket Formation and Hoodoo Quartzite, which we interpret as making up the Soldier Bar landslide.

We seek to answer the following: what is the origin of the flat shoreline surfaces in the Big Creek canyon, in particular at Cabin Creek? We posit that the levels at Soldier Bar represent a series of dam spillways that correspond to erosional lake shorelines and datable fine-grained fluvio-lacustrine deposits perched above the canyon floor at Cabin Creek and elsewhere upstream.

Geologic and geomorphic mapping (Figs. 2, 3, 5, and 6, modified from Lifton, 2005; Eversole, 2008; and Stewart et al., 2013) serves as the data for our interpretations. Figure 4 shows elevations of various features on a longitudinal plot of river km upstream. Eversole (2008) showed that just north of Soldier Bar, at the mouth of Goat Creek, is a sequence of cut-surfaces in the quartzite blocks, the elevations of which correspond to upstream shorelines near Cabin Creek. These maps show A) erosional shorelines (topographically flat features cut

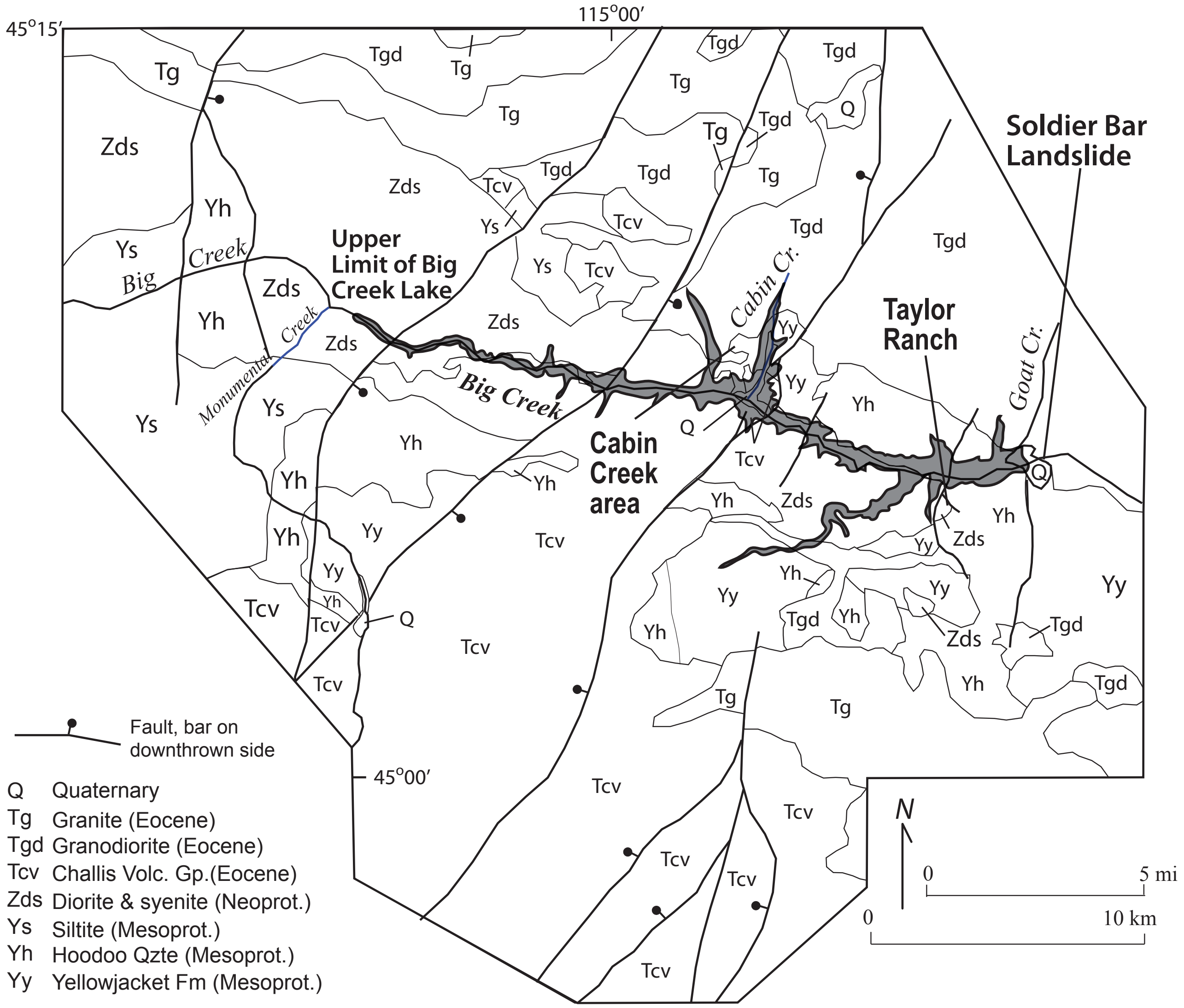

Figure 2. Simplified geologic map of the Big Creek Lake area, after Stewart et al. (2013). Area of map is shown on Figure 1. The maximum area of Big Creek Lake is shaded. The Soldier Bar landslide dam is on the eastern side of the map.

in unconsolidated Quaternary deposits especially at Cabin Creek, Fig. 5); B) spillways (scoured surfaces cut in jumbled blocks of quartzite) at Soldier Bar and Goat Creek (Fig. 3); and C) depositional fluvial terraces, mainly at Taylor Ranch (Fig. 6). The depositional terraces slope downstream at the same gradient as Big Creek, are mantled with cobbles, and are distinct from cut shorelines, which are flat erosional surfaces beveled in unconsolidated sand.

GEOLOGIC SETTING

Big Creek is a large (1,540 km^2) watershed that drains eastward into the MFSR in central Idaho. The canyon is narrow with bedrock walls composed mainly of Mesoproterozoic quartzitic metasedimentary rocks, Cryogenian alkalic intrusive rocks, and Eocene Challis intrusive rocks (Fig. 2) (Lund, 2004; Lewis et al., 2012; Stewart et al., 2013). The quartzitic rocks are included in the Yellowjacket and overlying Hoodoo quartzites. Both sides of Big Creek at Soldier Bar are underlain by megablocks, on the scale of tens of meters to a kilometer, composed of these quartzites. Soldier Bar, one of the only relatively flat topographic surfaces in the steep canyon, is a downstream-sloping depositional surface, high above the modern canyon bottom (Fig. 2).

Big Creek sits astride the "Salmon River Arch" of Armstrong (1975), and between the northern Bitterroot and southern Atlanta lobes of the middle and Late Cretaceous (100 to 65 Ma) Idaho Batholith (Kiilsgaard and Bennett, 1995a; Gaschnig et al., 2010, 2011) (Fig. 2). Central Idaho was uplifted and exhumed by tens of kilometers in Paleocene time, prior to Eocene volcanism of the Challis Volcanic Group (Fisher and Johnson, 1995; Kiilsgaard and Bennett, 1995b; Dumitru et al., 2013). Jordan (1994) estimated Late Cretaceous crustal thickness in the southeastern Atlanta lobe of the Idaho Batholith to be 64−52 km. Paleogene erosional denudation thinned the crust and triggered further isostatic response. Sweetkind and Blackwell (1989) used apatite and zircon fission track thermochronology to determine the rate of exhumation and found that from 50 Ma to 10 Ma the batholith was shallowly buried (no deeper than 4 km). This requires rapid uplift in Paleogene time (60−50 Ma), but slow uplift from 50−10 Ma. The deeply incised river canyons are a result of downcutting since 10 Ma.

Significant Neogene uplift in central Idaho created high elevations and deeply cut river valleys. The Salmon River Mountains, especially north of Big Creek, have high, apparently concordant, plateaus that define a Miocene (?) low-relief topographic surface. Paleoelevations, rock uplift rates, and incision rates over various time scales have been estimated in central Idaho (Axelrod, 1968; Sweetkind and Blackwell, 1989; Wolfe et al., 1998; Meyer and Leidecker, 1999; Kirchner et al., 2001). There is order-of-magnitude consistency between regional denudation rates of ~0.1 mm/yr at the 10 ka, 100 ka, and 10 Ma time scales.

GEOMORPHIC SETTING

In the MFSR region, Meyer and Leidecker (1999) estimated an incision rate of 0.12–0.16 m/kyr based on dates from clast weathering rinds and glacial correlations. They concluded that the ~300 m deep inner Middle Fork gorge formed sometime after 2.63–1.85 Ma. Link et al. (1999) suggested that as recently as 3 Ma, the Salmon River may have drained northeast into Montana through what is now Lost Trail Pass on the Idaho-Montana border in the Bitterroot Mountains. Lifton et al. (2009) demonstrated that in the Big Creek canyon near Taylor Ranch, south-facing slopes tend to be less steep, controlled by more frequent freeze-thaw events (e.g., Parsons, 1988; Poulos et al., 2012).

The present Salmon River generally flows north, east, north, and then west (Fig. 1), ultimately draining into the Snake River below Hells Canyon on the Idaho-northern Oregon border, well north of the Snake River Plain. The upper Snake River was captured by the lower Snake River coincident with draining of Pliocene Lake Idaho at 2–4 Ma (Malde, 1991; Wood, 1994; Repenning et al., 1995; Wood and Clemens, 2002). The addition of upper Snake River flow significantly increased the discharge of the lower Snake River. This, plus Neogene uplift, increased the rates of incision, producing a lower base level for the Salmon River drainage, as it was captured into the Snake River system (Meyer and Leidecker, 1999). Such incision in mountain landscapes is manifested by over-steepening of hillslopes, initiation of large landslides, and development of fluvial hanging valleys like Goat Creek (e.g., Bigi et al., 2006; Wobus et al., 2006).

The Big Creek watershed (Fig. 1) drains 1,540 km^2 of mountainous topography ranging in elevation between about 4,600 and 8,530 ft (1,400 and 2,600 m). Because of this wide range of elevations, at the same time that snow accumulates in glaciated upland plateaus and glacial cirques, the low elevations experience intermittent snow cover and winter rain. The local relief of the main stem-bounding hillslopes of the MFSR is typically greater than 1,000 m. Though the Big Creek canyon has a mean slope of ~25 degrees, channel-bounding hillslopes have a mean slope of ~35 degrees. As a consequence of these high gradients, soils are thin or absent and hillslope erosion is dominated by debris flows, rock fall, and deep-seated rotational slumps. The high gradient of the basin also helps distinguish modern coarse clastic river sediment from the fine-grained deposits related to lake impoundment.

The channel slope in Big Creek decreases systematically in the downstream direction, punctuated by anomalous, discrete steep reaches. In the headwaters, Quaternary glaciers eroded an extensive low-gradient reach near the village of Edwardsburg. Near Garden Creek, a small landslide creates an anomalously steep reach (Fig. 4*E*, at 28 km). Geomorphic maps of three critical areas—Soldier Bar, Cabin Creek, and Taylor Ranch—are presented in Figures 3, 5, and 6. The lower 8 km of

Big Creek between Soldier Bar and the confluence with the MFSR is, on average, three times steeper (~0.015) than the river immediately upstream (~0.005).

DESCRIPTION OF THE SOLDIER BAR LANDSLIDE

Soldier Bar is unique in the area, a gently sloping surface high above the Big Creek canyon. The surface is cut into jumbled blocks of quartzite, which we interpret as a landslide (Fig. 3*A*). Soldier Bar was named for an event in the Sheepeater Indian War of 1879 where American soldiers removed Native Americans from the central Idaho mountains. The grave of army Private Harry Eagan, who was shot in both legs August 18, 1879, and died a short time later from those injuries, is on the east end of Solder Bar (Minshall, 2014). The headwall of the Soldier Bar landslide is defined by a north-facing concave depression bounded by bedrock scarps in Mesoproterozoic Hoodoo Quartzite (Fig. 3*A*). A north-striking fault, with Mesoproterozoic Yellowjacket Formation on the east, runs through the landslide headwall. The landslide deposit is composed of large (to tens of meters) angular blocks of quartzite. Locally, a matrix of fine, pulverized rock can be distinguished. The landslide deposit extends northward across the Big Creek canyon to the mouth of Goat Creek, a perched valley ~180 m above Big Creek (Fig. 3*A*, lower right corner). Lower Goat Creek is a broad, low-gradient meadow filled with coarse sediment. The landslide forms the southern lip of the Goat Creek basin.

Four low-gradient erosional surfaces are etched into the remnants of the landslide deposit on either side of the Big Creek valley (Fig. 3*B* and 3*E*). These surfaces are interpreted as spillways. They are at four distinct levels and are inferred to represent progressive incision of the quartzite blocks of the landslide deposit. The spillways on the north side of Big Creek (Fig. 3*C*) are at elevations defined as level-1 at 4,500 ft (1,372 m), level-2 at 4,340 ft (1,323 m), and level-3 at 4,200 ft (1,280 m),. Though no fluvial sediment exists on these terraces, there are distinctive downstream scour marks behind 1–3-m angular boulders of Hoodoo Quartzite.

Soldier Bar is a broad cut-terrace at level-3 at 4,200 ft (1,280 m) (Fig. 3*D* and 3*E*) on the south side of Big Creek. As with the level-3 terrace below Goat Creek, there is no fluvial sediment on this low gradient, downstream-dipping surface. Below it, along the steep trail down to Big Creek, the level-4 terrace at 4,050 ft (1,234 m), is etched into a strath of granodiorite and is mantled with well-rounded fluvial sand and gravel. The presence of these sediments requires that the Big Creek Lake filled with sediment sometime between the abandonment of level-3 and the formation of level-4.

LEVELS OF BIG CREEK LAKE

We name the landslide-dammed lake Big Creek Lake. Using the elevations of spillways and the U.S. Geological Survey 10-m digital elevation model, we projected horizontal surfaces upstream and compared elevations of fluvio-deltaic transitions, paleoshorelines, and other base-level controlled features (Fig. 4). Figure 4 shows the forced regression model for production of the various terraces present in Big Creek today. Survey details are in Eversole (2008). Differencing the horizontal surfaces for each lake level from the modern topography, allows estimation of volume of impounded materials (water plus sediment). Elevations were obtained from topographic maps with 40-foot contour intervals. Due to conversion to meters, elevations are only precise to ± 12 m.

LEVEL-1 (4,500 FT; 1,372 M)

Based on the elevation of the highest, level-1 spillway, the Big Creek Lake initially extended over ~28 km upstream (measured along the valley centerline), flooding numerous tributaries, but impounding only about 2 km^3 of water. Assuming flows similar to contemporary river discharge (~0.32 km^3/yr from Olson, 2010), similar valley paleotopography and no seepage through the dam, we estimate that it would have only taken perhaps six years to fill the lake with water. Our ages on lake sediments associated with the damming (see below) suggest that the lake existed during the regional peak of the Pinedale glaciation around 17 ka (Thackray et al., 2004; Easterbrook et al., 2011).

In the upstream area near Monumental Creek (Fig. 1), extensive terraces are found <10 m above the current channel. These surfaces are at the elevation

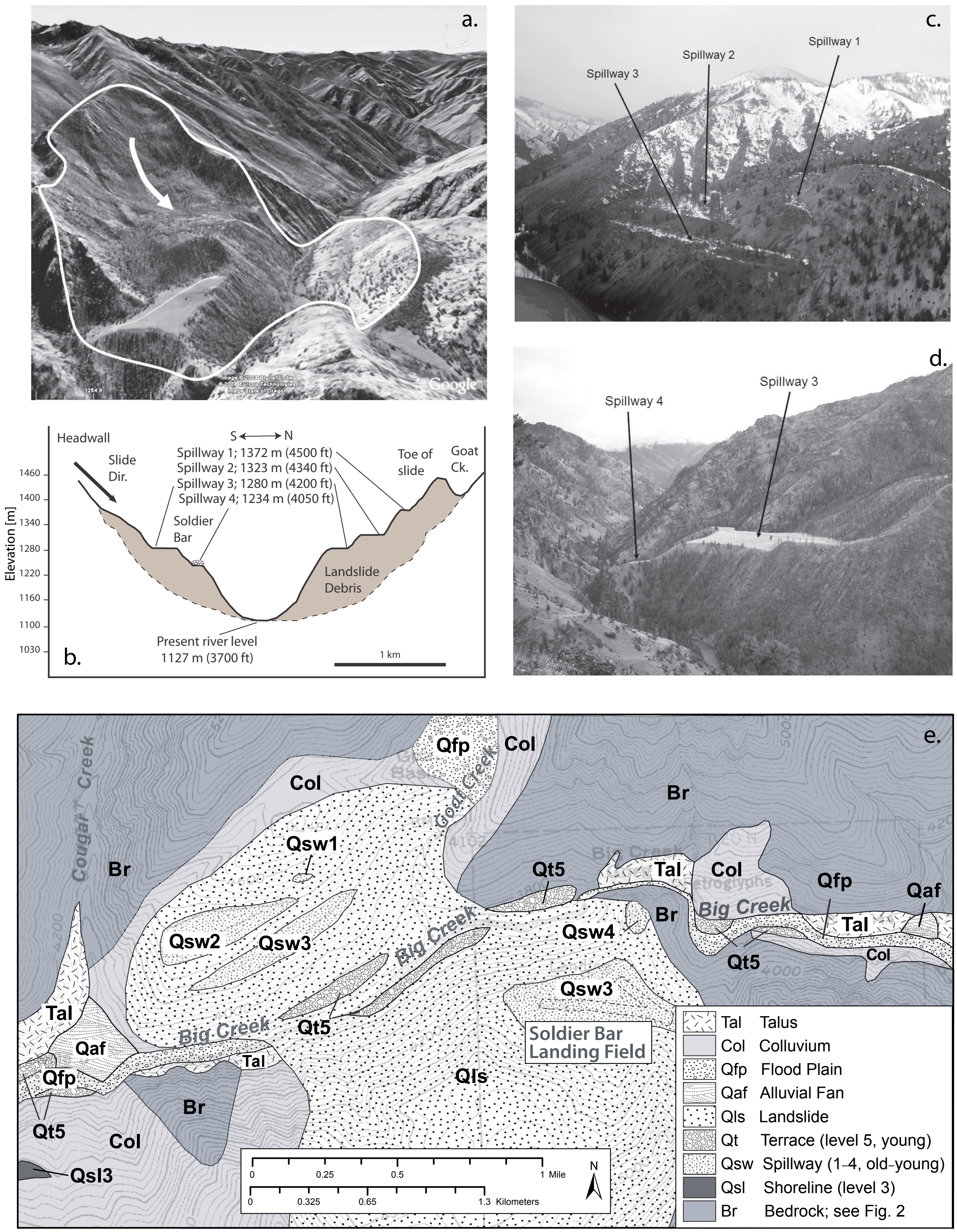
a.
c.
Spillway 1
Spillway 2
Spillway 3
d.
Spillway 4
Spillway 3
Headwall
Slide Dir.
S ⟷ N
Spillway 1; 1372 m (4500 ft)
Spillway 2; 1323 m (4340 ft)
Spillway 3; 1280 m (4200 ft)
Spillway 4; 1234 m (4050 ft)
Toe of slide
Goat Ck.
Soldier Bar
Landslide Debris
Elevation [m]
1460
1400
1340
1280
1220
1160
1100
1030
Present river level
1127 m (3700 ft)
1 km
b.
e.
Qfp
Col
Col
Br
Cougar Creek
Br
Goat Creek
Qsw1
Qt5
Tal
Col
Qfp
Qaf
Big Creek
Qsw2
Qsw3
Big Creek
Qsw4
Br
Tal
Qt5
Col
Qsw3
Tal
Qaf
Big Creek
Qt5
Soldier Bar Landing Field
Qfp
Tal
Qls
Br
Qt5
Col
Qsl3
0
0.25
0.5
1 Mile
0
0.325
0.65
1.3 Kilometers
N
Tal Talus
Col Colluvium
Qfp Flood Plain
Qaf Alluvial Fan
Qls Landslide
Qt Terrace (level 5, young)
Qsw Spillway (1-4, old-young)
Qsl Shoreline (level 3)
Br Bedrock; see Fig. 2

Figure 3, facing page. Photographs and geomorphic map of Soldier Bar landslide. ***A***, Google Earth image, view to southwest from east, showing Soldier Bar headwall and spillways. Goat Creek is on the right. ***B***, Schematic cross section in same orientation of Figure 3*A*, showing spillway levels in the Soldier Bar area. ***C***, Aerial view looking northwest at mouth of Goat Creek with spillway levels 1, 2, and 3 on the north side of Big Creek highlighted by an early winter snow. ***D***, View looking south at spillways at level-3 (the Soldier Bar landing field) and level-4. ***E***, Geomorphic map modified from Eversole (2008).

where the level-1 lake level would have intersected the main stem (4,500 ft, ~1,372 m) (Fig 4*A*). If the lake persisted at this elevation, a fluvial-deltaic depositional system would have developed, extending into the lake and causing fluvial aggradation in Big Creek as well as in Monumental and Crooked creeks. The subaerial depositional reaches in Big Creek and the tributaries, adjusted to this level, would have been at significantly lower slopes than the initial channel profile. Low-relief fill terraces extend ~2.5 km up Monumental Creek. We use the downstream extent of fluvial deposits to infer the location of the delta front at any given lake level. Most of the fan delta deposits were eroded away and reworked as lake level dropped and a confined Big Creek incised into and transported the unconsolidated sediments to the next fan delta complex.

In Big Creek canyon, we also observed erosional shorelines (topographic benches notched into hillslopes without fluvial deposits) and tributary delta fans close to the level-1 spillway elevation (4,500 ft, 1,372 m). The coincidence of the elevations of features (Fig. 4*A*) indicates that they formed at one persistent lake level.

LEVEL-2 (4,340 FT; 1,323 M)

At the elevation of the level-2 spillway, the lake extended 22 km upstream to the area near Acorn Creek, and impounded close to 1 km^3. Upstream of Acorn, numerous terraces ~5–10 m above the current channel (Fig. 4*B*) were likely deposited as fluvial aggradation surfaces upstream of the level-2 fan delta. These were initially constructed from coarse sediment remobilized from the incised level-1 fan delta. Downstream of Acorn Creek, depositional alluvial terraces diverge from the modern river profile, persisting at elevations close to the level-2 spillway (4,340 ft; 1,323 m).

These terrace surfaces extend downstream from Acorn Creek for 3 km where a paleo-landslide entered the river from the south. The fact that terraces in the region align with the level-2 spillway suggests that this lesser landslide could pre-date the Soldier Bar event and the terraces in this region are a consequence of deposition in the level-2 fluvial-deltaic complex.

Perched alluvial fans and shoreline features at the level-2 elevation (Fig. 4*B*) are found between Garden and Pioneer creeks. In particular, a large landslide deposit sourced from the west side of Garden Creek is notched by multiple erosional shorelines near the elevation of the level-2 spillway.

LEVEL-3 (4,200 FT; 1,280 M)

At the elevation of the level-3 spillway, the lake extended ~20 km upstream of the dam and impounded no more than 0.5 km^3. Similar to level-2, there are abundant terraces near and upstream of the location where the level-3 spillway elevation would intersect the modern channel (Fig. 4*C*). These alluvial-fill terraces define a consistent, low-gradient surface that likely represents the aggraded terrestrial reach upstream of the delta. Another landslide deposit sourced from the south side of the valley ~4 km upstream of Garden Creek complicates the interpretation of the terraces. We infer that this feature is older than the Soldier Bar landslide based on the fact that it appears to be notched and eroded at similar elevations as the Soldier Bar spillway levels. Numerous erosional shorelines are found near 4,200 ft (1,280 m) on the valley wall south of Garden Creek and in the Cabin Creek area (Fig. 5*A* and 5*C*). Between level-3 and level-4 spillway elevations, there are multiple intermediate shoreline and terrace features (Fig. 4*C*). These suggest that there may have been an intermediate lake level near 4,100 ft (1,250 m) whose spillway is not recognized on Soldier Bar.

LEVEL-4 (4,050 FT; 1,234 M)

Based on the elevation of the level-4 spillway, Big Creek Lake at this stage extended ~15 km upstream and impounded a maximum of 0.2 km^3. There is evidence that Big Creek Lake filled with sediment sometime before or during the time of the level-4 spillway. This evidence includes the fluvial

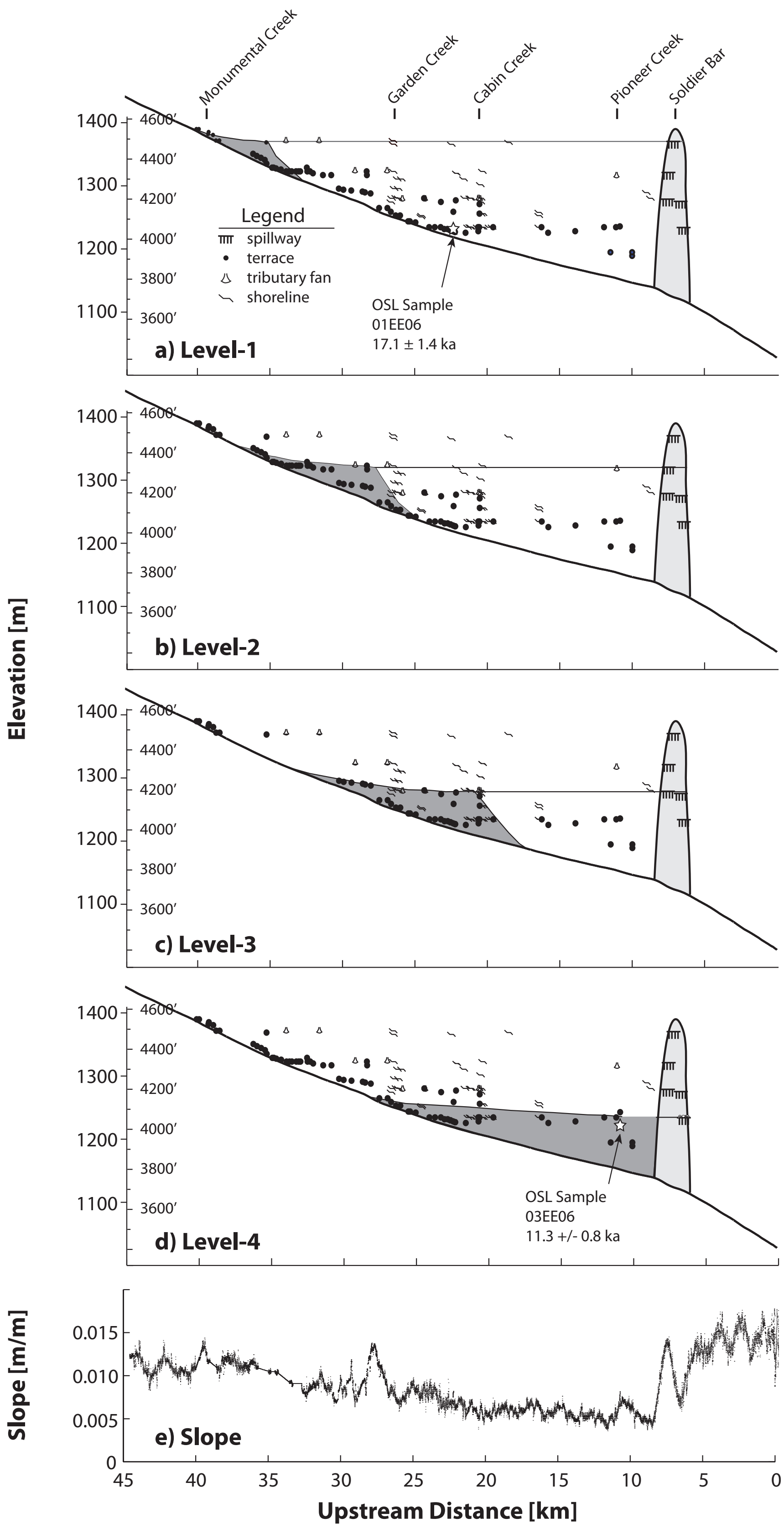

Figure 4. Longitudinal profiles of Big Creek, starting from the confluence with the Middle Fork of the Salmon River. Profiles include place names, sample locations, and, in each diagram, the lake surfaces, spillways, terraces, tributary fans, and shorelines. Level lines or stream profiles are drawn at each level (***A–D***). We assume that the longitudinal profile during the impoundment is similar to today's profile (thick black line). Upstream shaded region shows the expected extent of the main stem fan delta complex. Note that it increases in volume over time. For simplification, no deep water accumulations are shown. ***E***, Point wise measurements of channel slope showing the 3-fold increase in channel slope downstream of the Soldier Bar landslide.

gravel-topped spillway and also the presence of alluvium-topped terraces in the reach between Cabin and Pioneer creeks (Figs. 4*D* and 6). This type of deposit forms upstream of the fluvial-deltaic transition. This implies that this reach of the river was fluvial at level-4.

OPTICALLY STIMULATED LUMINESCENCE GEOCHRONOLOGY

We use optically stimulated luminescence (OSL) to date lake sediments deposited upstream of the Soldier Bar landslide. The OSL technique provides an age estimate of the time since sediment was last exposed to sunlight, which resets the luminescence signal by releasing stored charge in crystal-lattice defects in quartz and feldspar grains (Huntley et al., 1985). After burial, the grains are removed from sunlight and begin to accumulate a luminescence signal due to exposure to radiation from the surrounding sediment and incoming cosmic radiation. In

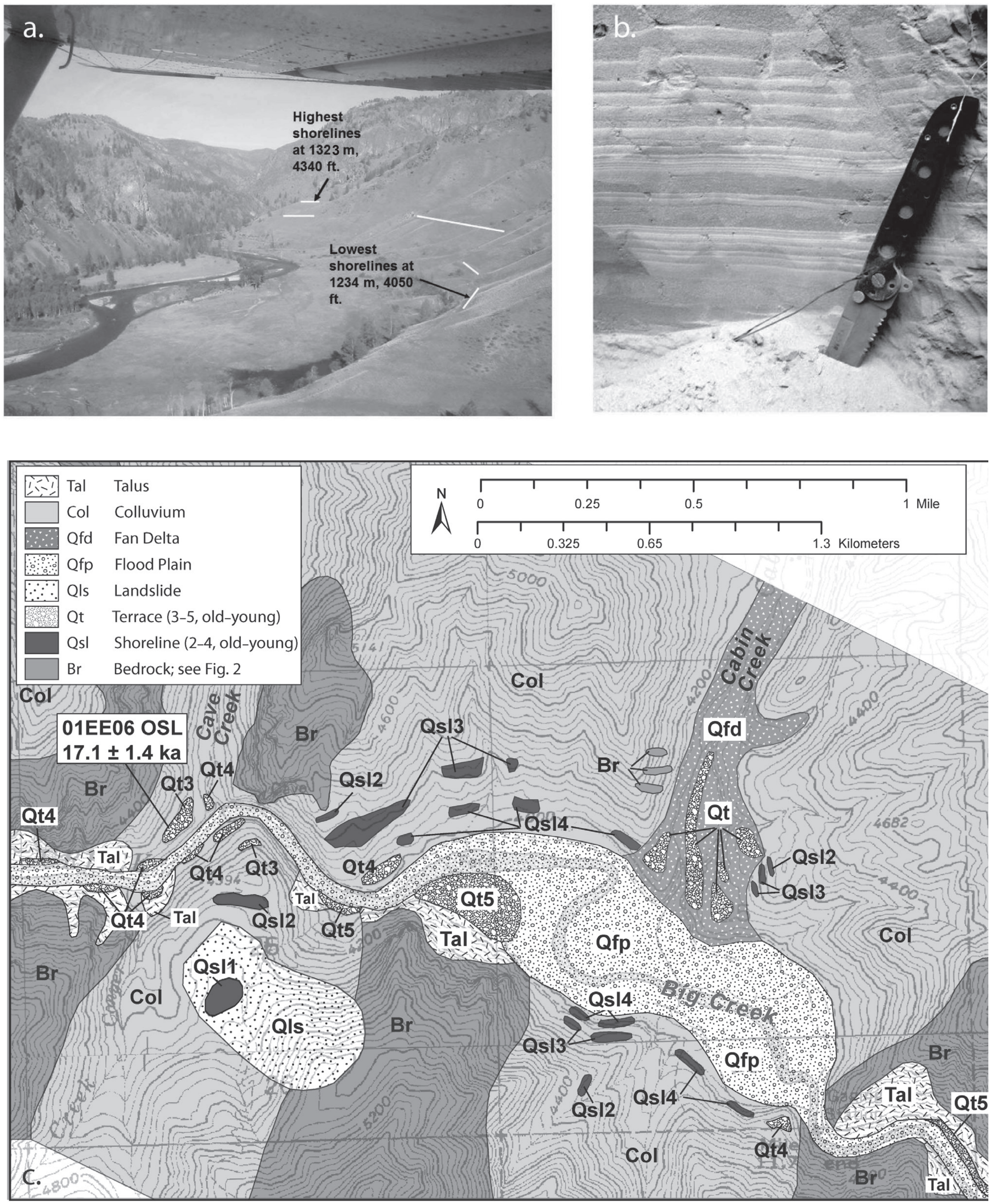

Figure 5. Cabin Creek area. ***A***, Aerial view looking west at the mouth of Cabin Creek, showing shorelines cut in lake beds. ***B***, Graded sand to silt couplets from mouth of Cave Creek. These sediments produced an OSL age of 17.1 ± 1.4 ka (Sample 01EE06). ***C***, Geomorphic map (after Eversole, 2008) of mouth of Cabin Creek, showing OSL sample site for fine-grained sample.

the laboratory, the measured equivalent dose (De) is directly proportional to the length of burial and the dose rate environment the sample has been exposed to during burial.

Two OSL samples were collected from sediments deposited upstream of the Soldier Bar landslide to constrain the age of the landslide and lake. Each OSL sample was collected with a 20-cm long, 5-cm diameter capped PVC pipe to protect the sediments from light exposure. Other samples of the same sediment were collected for water content and dose-rate determination. OSL analysis followed the single-aliquot regenerative-dose technique (Murray and Wintle, 2000) using 2-mm aliquots of quartz sand. Dose rates were calculated using elemental concentration and conversion factors of Aitken (1985, 1998) and include water attenuation and cosmic contribution (Prescott and Hutton, 1994) (Table 1).

CAVE CREEK SAMPLE

Sample 01EE06 OSL returned an age of 17.1 ± 1.4 ka (Table 2). It was collected from below a terrace ~100 m southwest of the confluence of Cave Creek with Big Creek, on the north bank at an elevation of 4,160 ft (1,268m) (Fig. 5*C*). The sample site is immediately west of the broad valley near Cabin Creek, where numerous lake shorelines are visible (Fig. 5*A* and 5*C*). At this location, lateral erosion by Big Creek has exposed a 60-foot (~18-m) section that includes 30 to 50 ft (9–15 m) of bedrock at the base topped by 15–30 ft (5–9 m) of coarsening upward sediment ranging from silt to cobble. Our sample comes from ~15 ft (~5 m) below the terrace surface in fining upward rhythmites (Fig. 5*B*). These centimeter-scale sand to silt beds contain current ripple marks and are interpreted as density-current deposits (turbidites).

TAYLOR RANCH SAMPLE

Sample 03EE06 OSL returned an age of 11.3 ± 0.8 ka (Table 2). It was collected from a terrace deposit ~1,000 ft (305 m) southeast of Taylor Ranch (Fig. 6) by excavating horizontally 6 ft (2 m) into the east-facing erosional scarp of a terrace deposit. This terrace tread (4,134 ft, 1,260 m) is ~300 ft (91 m) above the current river and is constructed of ~130–180 ft (40–55 m) of coarsening upward sands and gravels. The lower part of the deposit has alternating beds of fine to coarse sands. We sampled 10 ft (3 m) below the surface in alternating beds of coarse sand to gravel that we interpret as topset beds prograding into the lake (Fig. 4*D*). This terrace is located downstream of the outlet for Pioneer Creek and is, thus, not remnant of that debris fan, but instead is related to deposition in Big Creek.

INTERPRETATION OF GEOMORPHIC AND GEOCHRONOLOGIC DATA

The OSL data constrain the timing of the formation and degradation Big Creek Lake and its eventual demise. Our observations support the following sequence of events:

1. Before 17 ka, the Soldier Bar landslide filled the valley and dammed Big and Goat creeks with

Table 1. Dose rate information for OSL ages.

Sample #	USU #	Depth (m)	$H_2O\%$[1]	U (ppm)[2]	Th (ppm)[2]	$K_2O\%$[2]	Rb_2O (ppm)[2]	Cosmic (Gy/ka)[3]	Dose Rate (Gy/ka)[4]
01EE06	USU-099	5.0	6.7	2.20 ± 0.2	12.00 ± 1.1	2.76 ± 0.07	118.7 ± 4.7	0.12 ± 0.01	3.53 ± 0.22
03EE06	USU-101	3.0	2.6	3.70 ± 0.3	19.40 ± 1.7	3.58 ± 0.09	151.5 ± 6.1	0.16 ± 0.02	5.27 ± 0.24

[1] In-situ moisture content.

[2] Radioelemental concentrations determined by inductively coupled plasma-mass spectrometry (ICP-MS) and ICP-atomic emission spectroscopy (ICP-AES) techniques by ALS Chemex, Reno, Nevada.

[3] Contribution of cosmic radiation to the dose rate was calculated by using sample depth, elevation, and longitude/latitude following Prescott and Hutton (1994).

[4] Dose rate is derived from elemental concentrations (see Table 2) by conversion factors from Aitken (1985, 1998).

coarse, erosion-resistant debris, resulting in the formation of an impounded Big Creek Lake.

2. Water filled the lake to a level above 4,500 ft (1,372 m), raising base level for the main stem Big Creek and all its tributaries. Coarse sediment moving down tributaries was deposited in Gilbert-style fan deltas while alluvial aggradation extended up the tributaries. Fine sediment was deposited in deeper turbiditic zones on the lake bottom (Fig. 5*B*; Sample 01EE06; 17.1 ±

Table 2. OSL information.

Sample #	USU #	Description	# aliquots[1]	Equivalent dose(Gy)[2]	Dose rate (Gy/ka)[3]	OSL Age (ka)[4]
01EE06	USU-099	laminated lake sediments, Cave Creek; UTM11T, 660611E; 4999584N	23 (35)	60.41 ± 13.74	3.53 ± 0.22	17.1 ± 1.4
03EE06	USU-101	deltaic sediments on terrace, Taylor Ranch; UTM11T, 669317E; 4996417N	21 (25)	59.71 ± 14.00	5.27 ± 0.24	11.3 ± 0.8

[1] Number of aliquots used for age calculation, number of aliquots measured in parentheses. Rejection criteria follow those in Rittenour et al. (2007).

[2] Age analysis using the single-aliquot regenerative-dose procedure of Murray and Wintle (2000) on 2-mm aliquots of 75−125 µm quartz sand. Preheat and cutheat temperatures were 240°C and 160°C held for 10 seconds. Equivalent dose (De) calculated from the mean of accepted aliquots. Error reported at 1-sigma standard error.

[3] Dose rate is derived from summed contribution from radio-elements and cosmic contribution, taking into account attenuation by water.

[4] OSL age calculated by dividing the equivalent dose by the dose rate. Error on age is 1-sigma standard error.

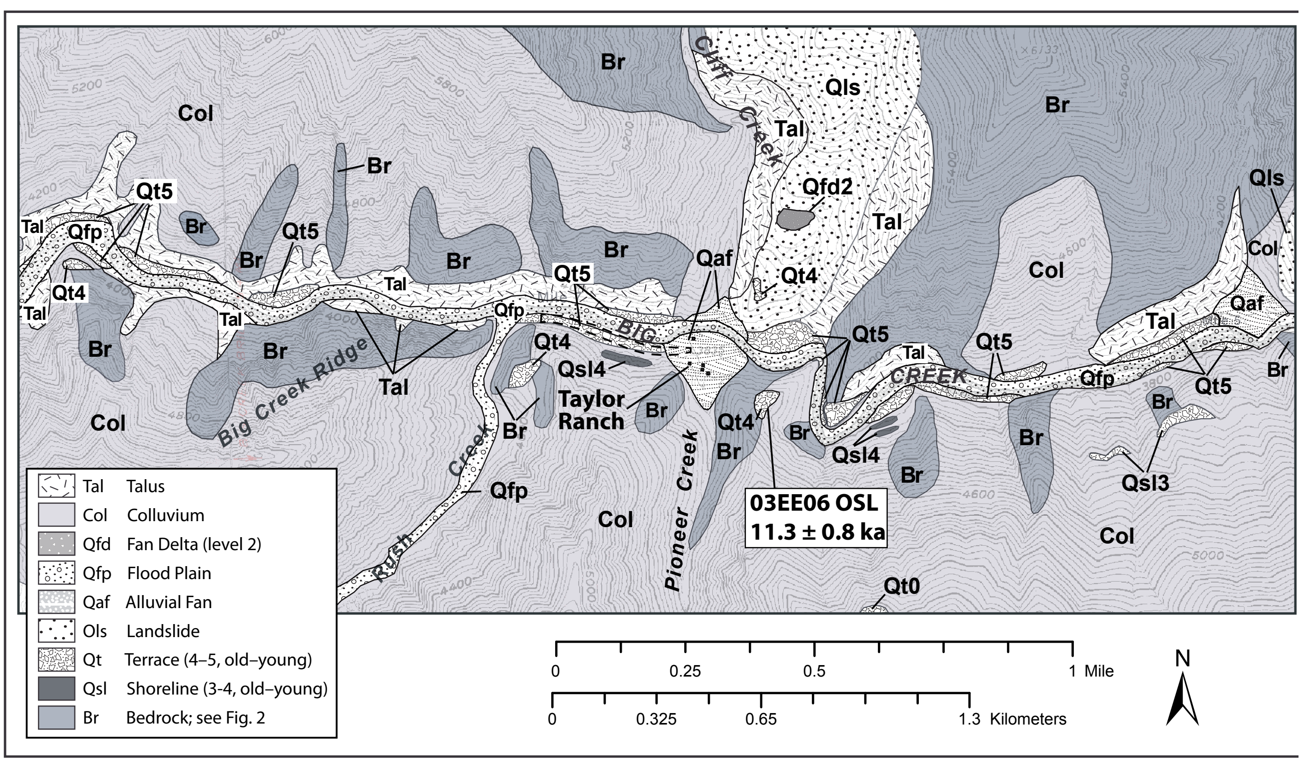

Figure 6. Taylor Ranch area. Geomorphic map after Eversole (2008). Note the location of the OSL sample (03EE06) from the level-4 terrace that produced an age of 11.3 ± 0.8 ka.

1.4 ka). In the upper reaches of the main stem (Fig 4*A*), a similar Gilbert-style steep-fronted fan delta is predicted to have extended into the impoundment. It is important to note that in both the main stem and tributary channels, subaerial alluvial deposition on the upper part of the fan delta occurred at transport-limited alluvial slopes that were significantly lower gradient than channels cut in bedrock.

3. After 17 ka, the landslide deposit was eroded in discrete, episodic drops in base level that stabilized long enough to support the formation of erosional shorelines (as seen at Cabin Creek, Fig 5*A*). At least four of these episodic drops are preserved in Soldier Bar spillways and erosional shorelines at 4,500, 4,340, 4,200, and 4,050 ft (1,372, 1,323, 1,280, and 1,234 m) (Fig. 3). Drops in base level also drove the incision of the main stem and tributary fan deltas, redepositing sediment into fan deltas controlled by the next lower stable lake level (Fig. 4). These forced regressions are preserved as abandoned terraces and incised remnants of the previous fan delta surface.
4. Before 11.3 ka, river sediment filled the shrinking lake (Fig. 4*D*). It was during this late stage that Sample 03EE06 (11.3 ± 0.8 ka) from Taylor Ranch was deposited (Fig. 6) as the front of the fan delta approached within 3.5 km of the landslide dam.
5. Once sediment overtopped the impoundment (as supported by the presence of coarse alluvial sediment on the level-4 spillway), the availability of fluvial boulders as tools accelerated erosion of the landslide deposit. Sediments impounded behind the failing dam were progressively transported downstream by Big Creek, only leaving small remnants plastered to the steep canyon walls. The erosional nature of the modern stream explains the poor preservation of lake-floor sediment, which must have been washed downstream during times of high springtime fluvial discharge. The difference between the two OSL ages provides a minimum duration of the Soldier Bar landslide of >6 k.y. (~17–11 ka BP).
6. During the duration of the Soldier Bar landslide as a dam to Big Creek, regional signals of fluvial incision were unable to propagate upstream, overall decreasing long-term rate of channel incision. While the landslide deposit and the impounded sediments were being incised, local, short-term channel lowering rates upstream of the dam would be significantly elevated above the background, regional rate. Today, the bedrock-floored, main stem channel at Soldier Bar has incised through the landslide deposit, and it is close to its original elevation before the landslide. A small inflection in the river profile just upstream of the landslide (Fig. 4*E*) suggests that the MFSR incision signal has begun to propagate up Big Creek. The knickpoint lies at the contact between the remnants of the coarse landslide debris to the west and granodiorites to the east. Future vertical incision of the knickpoint in Goat Creek would result in the formation of an epigenetic gorge (Ouimet et al., 2007).

CONCLUSIONS

These findings are compatible with recent work on terraces and landslides in the MFSR (Meyer and Leidecker, 1999) and the South Fork of the Payette River (Pierce et al., 2011), confirming the important role of landslides in modulating river incision in this region. Our observations of landslide-derived extensive terraces found at varying elevations suggest that caution must be exercised when using the age and heights of ancient fluvial surfaces to infer bedrock incision rates. In the case of Big Creek, terrace formation and abandonment processes are entirely independent of bedrock incision. The ages of landslide-derived terraces are valuable in understanding landslide triggers as well as the temporal evolution of impoundments.

Meyer and Leidecker (1999) provide a radiocarbon age of 14.5 cal ka for marly lake sediments deposited upstream of a 61-m tall landslide deposit located in the MFSR just downstream of Big Creek. This age permissively overlaps with our constraints on the Big Creek Lake—that is, younger than 17 ka. If the lakes were coeval, no sediment was bypassing the Soldier Bar dam, and the Middle Fork dam would have remained unfilled longer than if Big Creek were flowing with its normal sediment load. The impounded water in the Middle Fork would have extended upstream into Big Creek, but not far enough upstream to interact with the Soldier Bar dam.

The initiation mechanisms for both the Soldier Bar and Middle Fork landslides are not known, though both regional seismicity and late-glacial warming and slope saturation are possible causes. Both landslides formed close to the time of maximum or near-maximum Marine Isotope Stage 2 glacial advance in the Sawtooth Mountains, just before 16.9 ka, when precipitation was higher than today and hillslopes less stable (Thackray et al., 2004; Easterbrook et al., 2011). The other smaller landslide features noted along Big Creek may have similar causes, or could have been initiated as the filling of Big Creek Lake raised pore pressures in rock fractures, initiating rotational or translational sliding during the time of impoundment. This same driving mechanism has been observed during filling of man-made impoundments (e.g., Kilburn and Petley, 2003).

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