SOLDIER BAR LANDSLIDE AND SUBSEQUENT LATE PLEISTOCENE LAKES, BIG CREEK, VALLEY COUNTY, IDAHO

ELIJAH KALON EVERSOLE

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SOLDIER BAR LANDSLIDE AND SUBSEQUENT LATE PLEISTOCENE LAKES, BIG CREEK, VALLEY COUNTY, IDAHO

by
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Abstract

The Soldier Bar Landslide, located at the confluence of Goat Creek and Big Creek, Valley County, Idaho, has had a significant impact on the formation of geomorphic features in this tributary to the Middle Fork Salmon River. In this thesis, I analyze these features to infer the history of the temporary lake that formed upstream of the landslide.

Surface mapping, total station surveying, and GPS control on survey base stations were used to correlate and describe spillways, terraces, and shorelines. Four lake levels are recognized upstream of the Soldier Bar landslide: 1372 m (4500 ft), 1325 m (4340 ft), 1280 m (4200 ft) and 1234 m (4050 ft). The highest level was constrained by the highest Goat Creek spillway, and extended upstream ~28 km to the area of Monumental Bar. The Goat Creek and Soldier Bar surfaces are lower, downstream-sloping spillways cut into the landslide debris at elevations of 1372 m (4500 ft), 1325 m (4340 ft), 1280 m (4200 ft) and 1234 m (4050 ft). Rounded fluvial gravels are absent on the upper three spillway surfaces, indicating that they formed as clear water flowed over the top of the dam. This suggests that the first three lakes did not fill entirely with sediment. The lowest spillway surface does have fluvial gravels on its surface, indicating that this lake level did fill with deltaic deposits, at least in the spillway area.

Fill-cut lake shorelines in the Cabin Creek area slope toward the center of the canyon. These surfaces have fluvial gravel and cobbles up to an elevation of 1325 m (4340 ft). The 1280 m (4200 ft) level at Goat Creek is indistinguishably within error from the 1290 m (4230 ft) lake level at Cabin Creek, and demonstrates that a lake stood near this elevation.

At Cave Creek, fine grained sediments deposited over a bedrock strath are correlated with deposition of deltaic bottomset beds into still water at the highest lake level. An optically stimulated luminescence (OSL) age from these sediments reveals that the landslide occurred at least 17.5 ± 1.5 ka BP.

The fill-cut terrace at Taylor Ranch represents deltaic foreset and topset beds deposited into the lowest 1234 m (4050 ft) lake stage. An OSL age from these sediments reveals that the final incision of the landslide dam occurred after 11.3 +/- 0.8 ka BP. Longitudinal profiles of terrace treads show leveling of the stream profile approximately at the inferred lake elevation, suggesting the lake levels persisted long enough to allow fluvial aggradation. Given the minimum and maximum ages, we find that the lake persisted for at least 6000 years.

Chapter 1. Introduction

This thesis documents a canyon blocking landslide dam and associated lake levels in the Big Creek drainage in Valley and Idaho Counties of central Idaho (Figure 1). The Big Creek drainage basin is steep and narrow with a diverse geologic and geomorphic history (i.e., Lund, 2004). Several mapped and unmapped landslides are located in the Big Creek drainage basin. The landslide of interest to this project is the Soldier Bar landslide, which was mapped by Stewart et al. (unpublished maps, 1995-2004) and described by Lifton (2005). This project addresses the degree to which the Soldier Bar landslide controlled the formation of surficial features (spillways, shorelines, terraces, deltaic deposits and tributary delta fans) along the Big Creek drainage.

Geologic and reconnaissance surficial geology by Paul Link and students (2000 – 2006) suggest that the top of Soldier Bar landslide deposit was ~300 m (1000 ft) above the channel at the highest point and impounded a lake that filled to an elevation of 1372 m (4500 ft.) At that level the lake would have reached ~28 km upstream to the Monumental Bar area (Figure 2).

The landslide head scarp is located on the south side of Big Creek, in fractured Mesoproterozoic Hoodoo Quartzite (Figure 3). The toe of the landslide created a ridgeline north of Big Creek, northwest of and above the mouth of Goat Creek basin. Thus, Goat Creek was dammed by the landslide debris and persists today as a hanging valley with the former valley filled to an elevation of 4400 ft.

West of the mouth of Goat Creek, on the north side of Big Creek, sub-horizontal, boulder-strewn benches are cut into the landslide mass at elevations up to 250 m (800 ft)

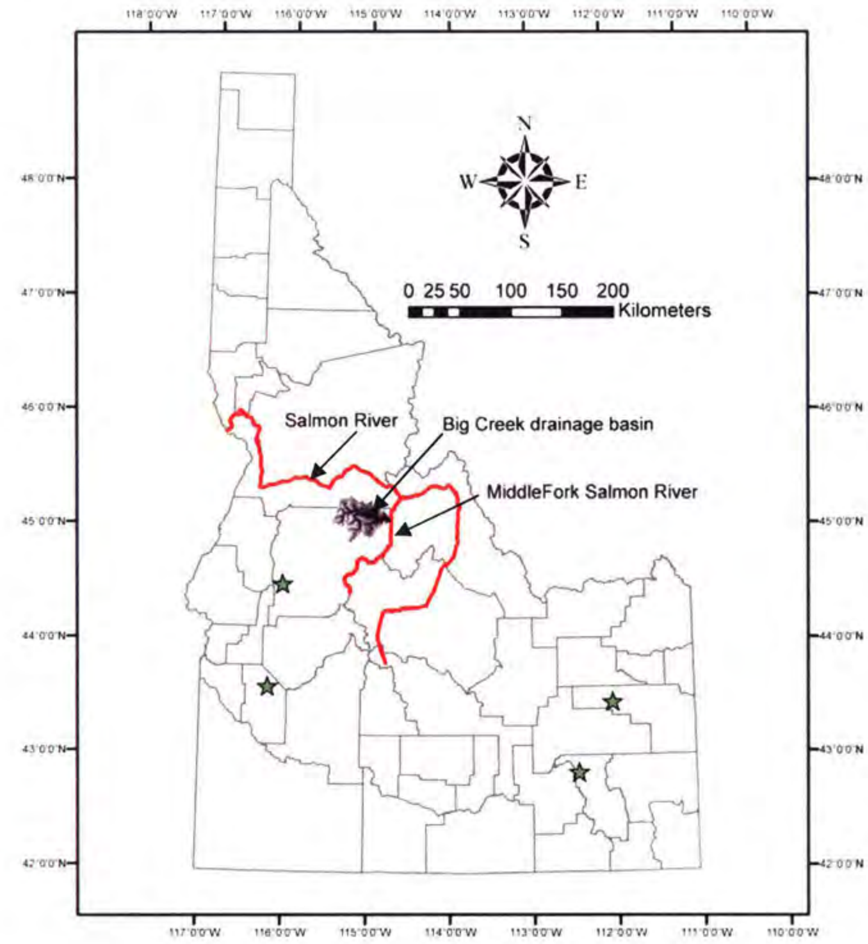
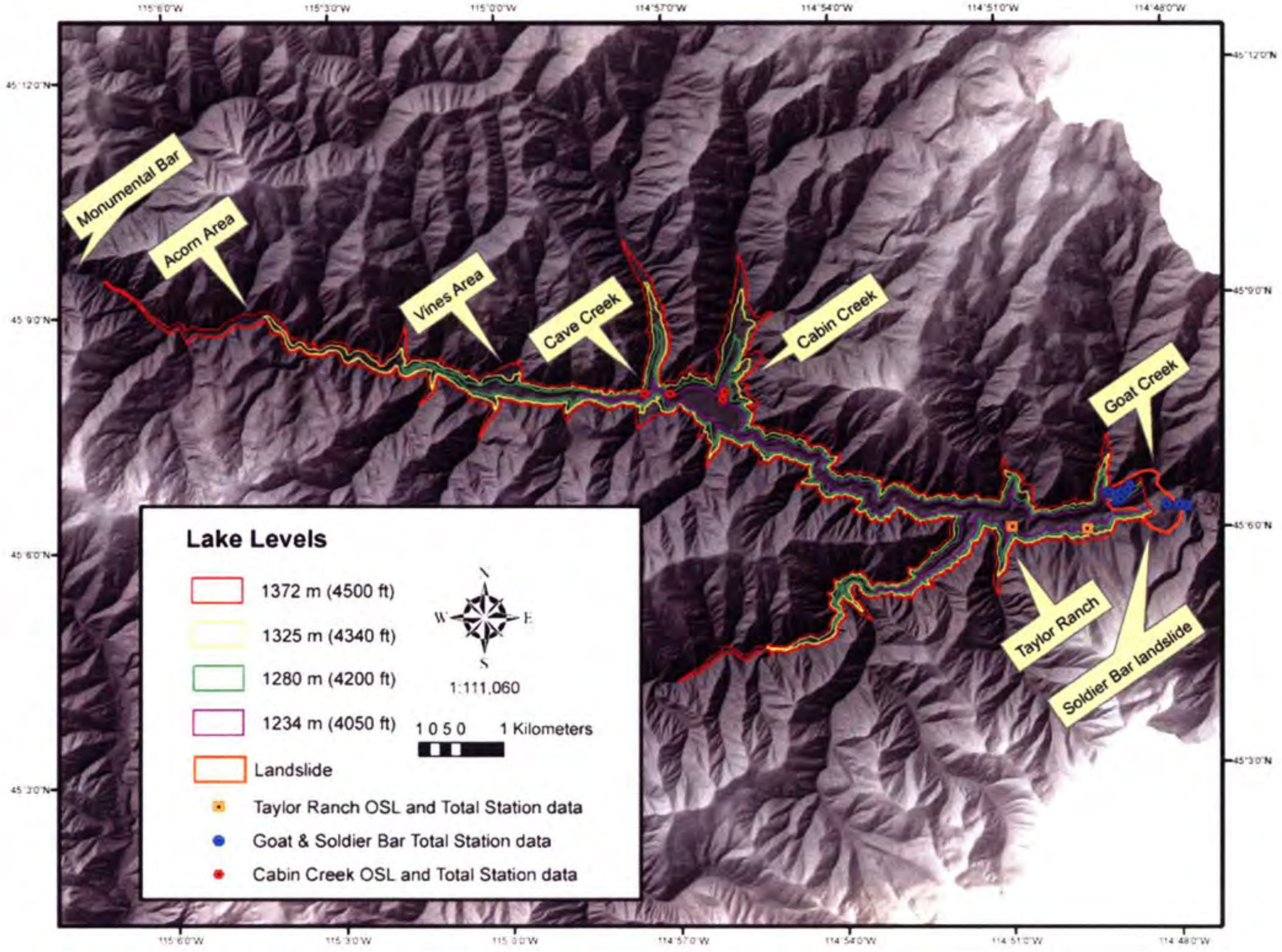


Figure 1. The Big Creek drainage is located in Idaho and Valley counties of central Idaho. The Big Creek drainage is a tributary to the Middle Fork Salmon River which flows into the Salmon River. The green stars are from west to east, Boise, Cascade, Pocatello and Idaho Falls, ID.

Figure 2. Four lake levels filled the Big Creek drainage represented by the red, yellow, green and purple lines. Place names of important areas throughout Big Creek are noted. The Soldier Bar landslide is outlined in orange. OSL sample sites and the locations where the total station was set up are indicated by the orange, blue and red points.



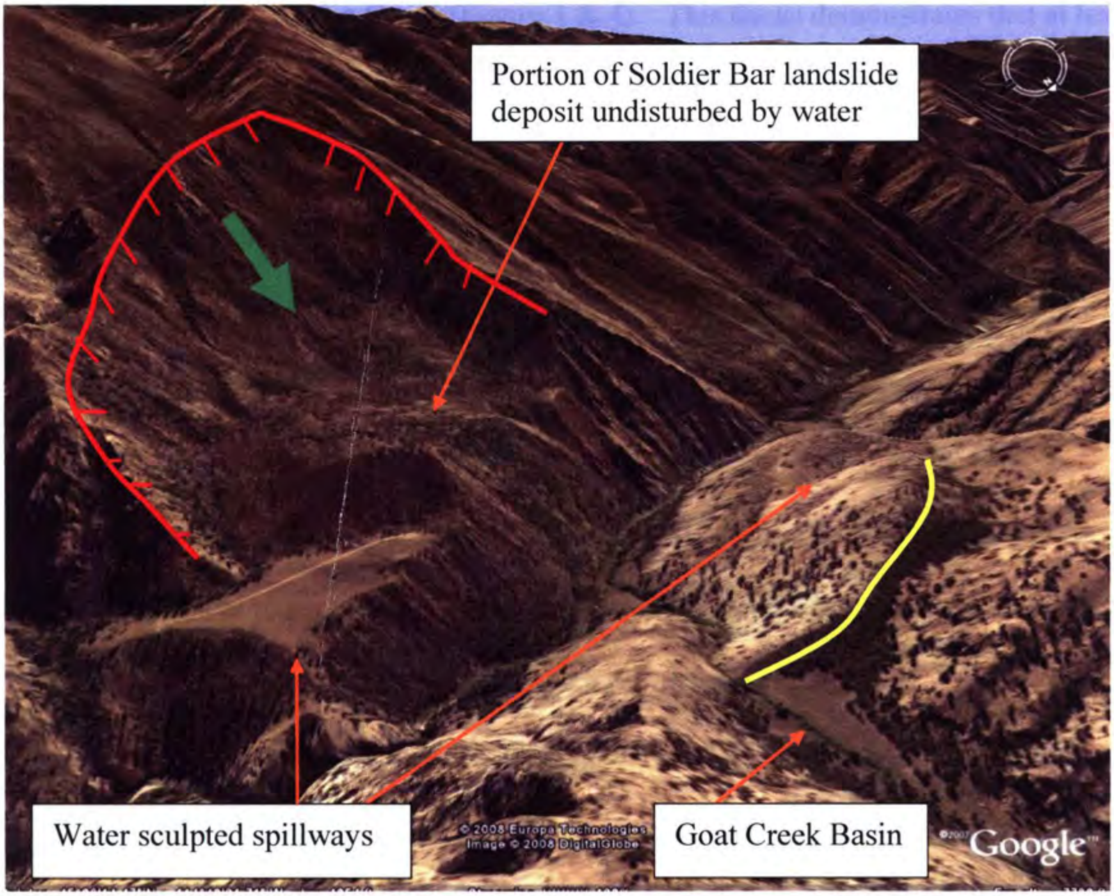


Figure 3. View looking southwest at the Soldier Bar landslide on the south side of the valley with Soldier Bar below the landslide and Goat Basin and the Goat Creek spillways on the north side of the valley. The red line shows the head scarp and the yellow line shows the ridge line formed by the toe of the landslide. The green arrow shows direction of movement for the landslide. Image collected from Google Earth, February 9, 2008.

above the present bed of Big Creek (Figure 3 & 4). This thesis demonstrates that at least four spillways were cut during the downcutting of this dam and that these correspond to four lake levels (Figure 2) represented by upstream geomorphic features, including terraces, shorelines and prograding deltaic deposits (Plate 1).

1.1 Problem Statement

Landslides are a dominant hillslope erosion process in steep, narrow valleys. Large volumes of landslide material ($\geq 10^6$ m^3 (3.5×10^7 ft^3)) in narrow valleys can form dams 10s to 100s of meters tall (Korup, 2006a). A large deep-seated landslide ($\geq 10^6$ m^3 (3.5×10^7 ft^3)) can fill a steep, narrow valley and form an impounded lake (Costa and Shuster, 1988; Korup, 2006a). Intuitively, a landslide of this size may have long-term control on the geomorphic features, sedimentation, and incision rates of the fluvial valley (Ouimet et al., 2007). Furthermore, the effect that a long-lasting ($\geq 10^1 - 10^4$ yrs) landslide-dammed lake has on the formation of geomorphic features is not well understood (Densmore and Hovius, 2000; Korup, 2004; Korup, 2006b; Korup et al, 2006).

This study has four objectives: 1) to map the surficial features along the Big Creek drainage; 2) to understand the gradient of spillways located near Soldier Bar, and fill-cut surfaces in the Cabin Creek area and their relationship to one another; 3) to determine the minimum age of the landslide event with optically stimulated luminescence (OSL) dating techniques; and 4) to increase the understanding of the long-lasting effects of landslide dammed lakes on the formation of fluvial geomorphic features.

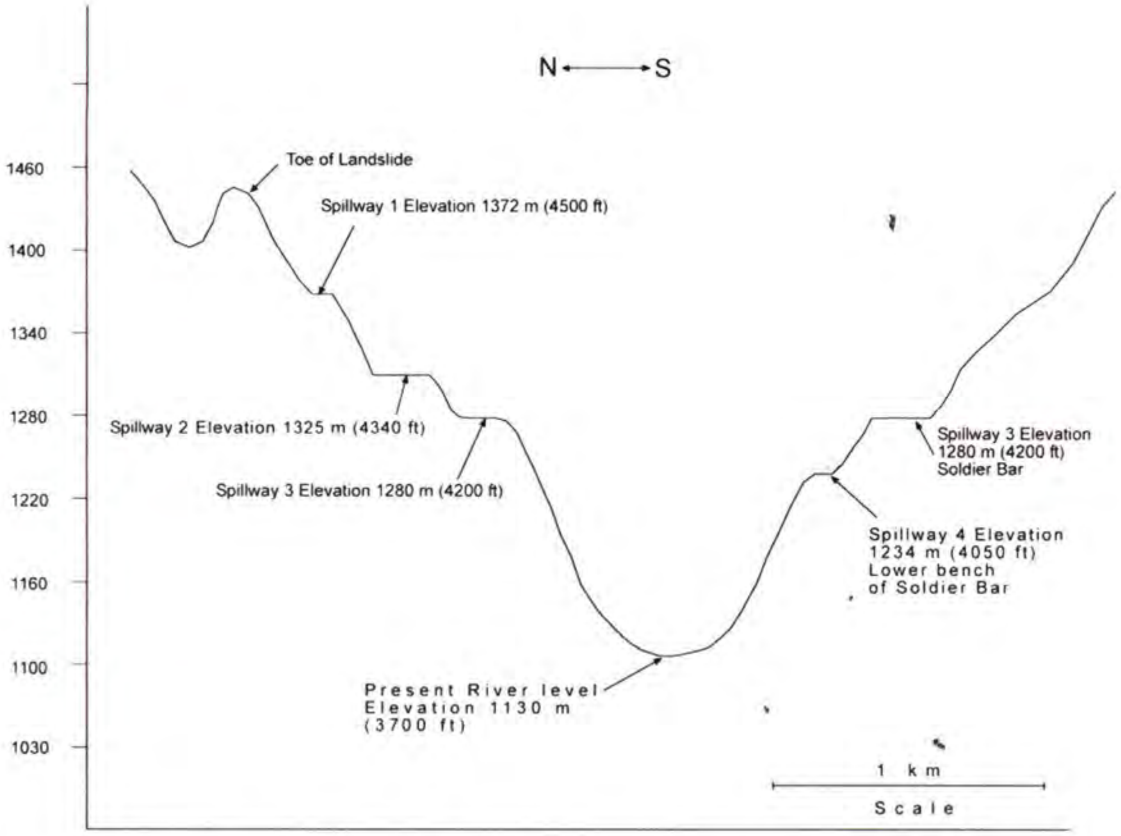


Figure 4. Cross-sectional view of the spillways located near Goat Creek and Soldier Bar.

1.1.1 Hypotheses

This research tests three hypotheses: 1) the Soldier Bar landslide dammed Big Creek, forming a lake; 2) the geomorphic features along the Big Creek drainage reflect the effects of a landslide-dammed lake filled with water or sediment; and 3) the timing of the Soldier Bar landslide was during Quaternary time < 2 Ma.

1.1.2 Approach

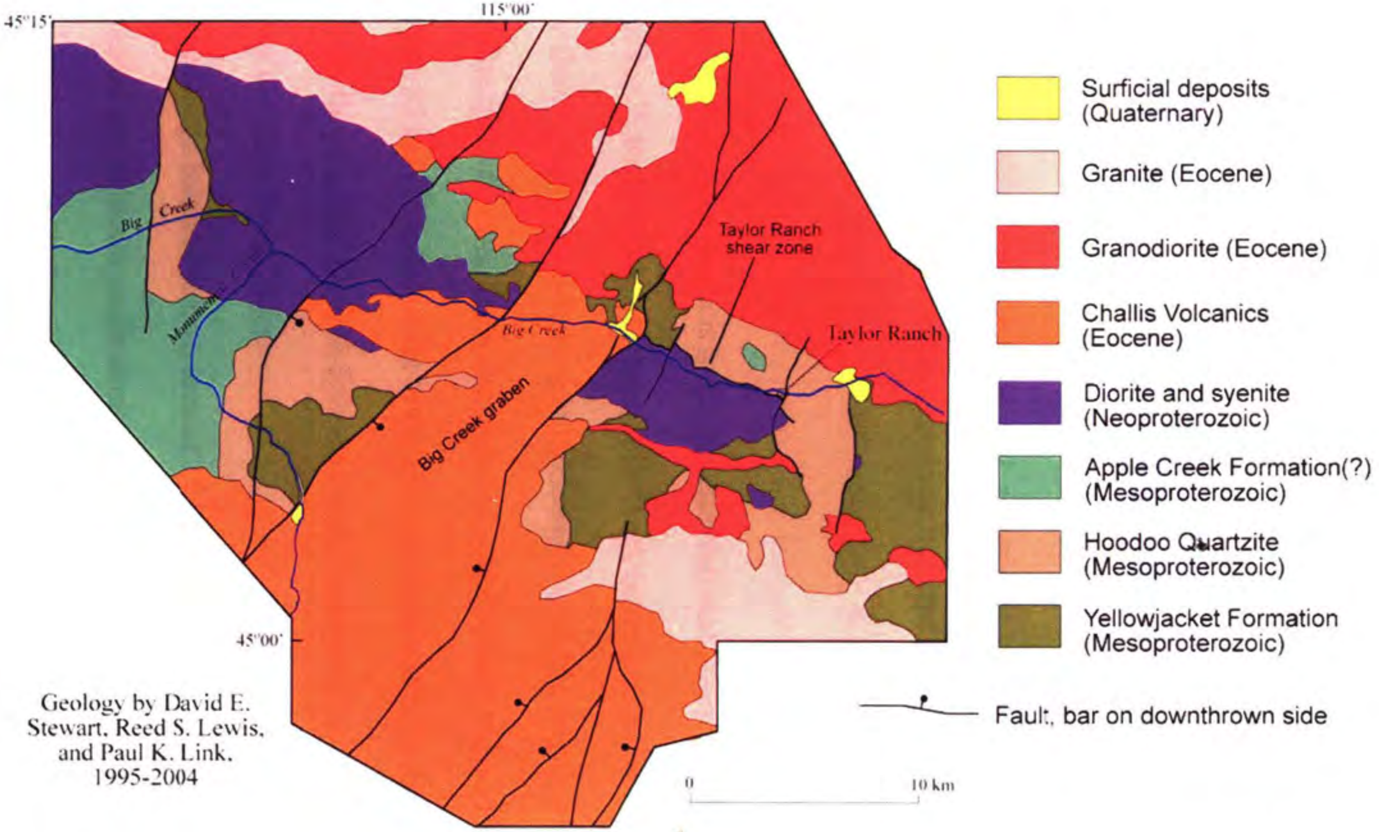
The approach of this study was to map, survey, correlate and date the surficial features in the Big Creek drainage. These techniques provide the basis for understanding how fluvial systems evolve. In this study the elevations of geomorphic features are used to correlate the spillways, shorelines, terraces, and other features to lake levels. Surficial features were correlated using maps, survey data, and elevations of the features to determine whether they are the result of fluvial incision along the Big Creek drainage, or instead are the result of a landslide-dammed lake.

1.2 Setting

1.2.1 Geologic Setting

The geology of Big Creek is compiled as part of the Payette National Forest map at 1:100,000 (Lund, 2004). Stewart et al. (1:24,000 unpublished maps, 1995-2004) mapped in detail the geology of the Big Creek drainage basin (Figure 5). Geologic maps of the Salmon and Payette National Forests have been compiled from several sources (Lund et al., 1999).

Figure 5. Geologic map of Big Creek showing the geologic formations, structures and some surficial deposits. The yellow kidney bean shape under the word Taylor Ranch is the Soldier Bar landslide (Stewart et al.. 1995-2004).



Four major rock groups occur in the Big Creek drainage basin: Mesoproterozoic quartzite and siltite units, Neoproterozoic mafic intrusions, Tertiary (Eocene) intrusive granodiorites, and Tertiary (Eocene) volcanic tuffs and porphyry dikes of the Challis Volcanic Group (Lund, 2004).

Two Tertiary normal faults are mapped in the field area. First, the Eocene Cow Creek fault, a northeast trending, northwest dipping normal fault, is located on the downstream boundary of the Cabin Creek area. Second, a northeast trending, northwest dipping normal fault is located at the location of the Soldier Bar landslide.

1.2.2 Geomorphic Setting

The entire Big Creek drainage basin is in the Payette National Forest and the Frank Church-River of No Return Wilderness Area. Big Creek occupies a narrow (< 1 km wide on the valley floor), V-shaped valley cut in moderately to highly resistant plutonic and metamorphic rocks (Lifton, 2005; Stewart et al., unpublished maps 1995 – 2004). Big Creek flows ~85 km (53 miles) west to east from its headwaters to its confluence with the north-flowing Middle Fork Salmon River, which eventually flows into the Columbia River via the Salmon River.

The Big Creek drainage basin covers an area of 1539 km^2 (591 sq. mi.) Relief between the active channel and adjacent peaks along the river varies from ~900 m (3000 ft) at the headwaters to ~1700 m (5500 ft) near the confluence of the Middle Fork Salmon River. The headwaters of the Big Creek drainage basin have been glaciated during the Quaternary, although glacial features have not been studied in detail.

The Soldier Bar landslide itself is composed of white, thick-bedded Mesoproterozoic Hoodoo Quartzite. The landslide deposit shows northward flowage in oblique aerial views, but only in the spillways west of Goat Creek is the blocky makeup of the landslide revealed. The surface of Soldier Bar, a downstream-sloping water-scoured surface with a high point at 1290 m (4234 ft), and sloping down to 1265 m (4150 ft), lacks rounded cobbles or gravel. Instead it is mantled by small (1 – 4 cm) angular pieces of white quartzite.

The headwall of the landslide is on the south side of the valley with the scarp at the ridgeline (Figure 3). There is approximately 1000 m (3000 ft) of relief between the top of the landslide material and the scarp at the ridge. This allowed the landslide to gain high speeds indicated by the elevation of the toe of the landslide 1460 m (~4800 ft) on the north side of the valley. Since Big Creek is a steep, narrow valley, the amount of material entrained in the landslide filled the valley and dammed Big Creek.

1.2.2.1 Topography and Neogene Uplift of Central Idaho

The Big Creek drainage is a steep narrow valley cut into the high-level central Idaho erosion surface, which formed at some time between 50 Ma and 10 Ma (Sweetkind and Blackwell, 1989). The present valley represents a more rapid phase of down cutting since 10 Ma (Sweetkind and Blackwell, 1989). Furthermore, deeply incised canyons in central Idaho are likely the result of both crustal uplift and a drop in base level due to the incision of Hells Canyon during Pleistocene time (Wood, 1994; Link et al., 2002).

Meyer and Leidecker (1999) conducted a study along the Middle Fork Salmon River where the highest terrace is only 112 m (370 ft.) above river level. They also noted a break in slope at the site of the deep gorge on the lower Middle Fork Salmon River, which indicates an increase in incision during the formation of the gorge. To cut the 300 m deep gorge in the lower reach of the Middle Fork below a 2.63-1.85 Ma surface, they calculated long-term incision rates of 0.12 – 0.16 m/kyr. The incision rates are weakly constrained because they are based on weathering rind age estimates. They also calculated a short-term incision rate of 0.74 m/kyr for 12 m above bank full since 14.5 cal ka.

According to Meyer and Leidecker (1999) the Big Creek region does not contain Quaternary fault escarpments. Therefore, they infer that the effects of tectonism on fluvial response would be limited to distant base-level change and regional rock uplift histories.

Alternating cycles of incision and filling of the riverbeds of central Idaho may be influenced by Pleistocene-Holocene climatic cycles. Although some research documents the uplift or paleoelevations of central Idaho (Axelrod, 1968; Meyer and Leidecker, 1999), few studies have documented climatic perturbations (Pierce and Scott, 1982; Othberg, 1994).

1.2.2.2 Climate and Sediment Delivery

Significant Pleistocene climatic variations influenced deposition of coarse-grained gravels on alluvial fans in east-central Idaho during glacial periods (Pierce and Scott, 1982). Those gravels were deposited in wetter intervals during spring floods and high discharge during summer months. Sediments deposited during the Holocene in east-central Idaho are mainly reworked fine grained loess (Pierce and Scott, 1982). Pierce and Scott (1982) and Othberg (1994) conclude that these changes between coarse-and fine-grained sediment deposition represent a decrease in discharge due to climatic variations between Pleistocene and Holocene periods. These variable patterns of sediment deposition are related in many parts of southern, eastern, and central Idaho.

1.2.2.3 Big Creek Morphology

Lifton (2005) conducted research to determine the relationship between rock strength and valley morphometry in the Big Creek valley. He infers that bedrock strength exerts a strong influence on valley floor width. Throughout the valley, Big Creek flows over thin alluvium and bedrock. The Cabin Creek area is the widest reach (~ 0.5 km wide) of the drainage. The bedrock type in the Cabin Creek area is Eocene tuff of the Challis Volcanic Group. Lifton (2005) found by using the Schmidt hammer that Eocene tuff shows the most variability in rock strength due to the difference in welding intensity and lithification. This has allowed the Cabin Creek area to erode laterally toward the north due to the heterogeneity in the Eocene tuffs. This is due to aspect-controlled freeze-thaw during the winter months and differences in strength of the Eocene tuff.

This study builds from Lifton's observations that there is a headward-migrating knickpoint in Big Creek located near the area of the Big Creek gorge at ~70 km from the headwaters (Figure 6). The headward migration of a knickpoint in a fluvial valley is the result of local or regional base level change and uplift (Meyer and Leidecker, 1999; Korup, 2005). Furthermore, the signal of base level fall is represented by knickpoints propagating up the tributaries of the main stem of a stream.

Convex knickpoints in the longitudinal profile can also be geomorphic implications of landslides (Korup, 2005; Korup, 2006a). A long lasting ($10^1 - 10^4$ yrs) impoundment due to a landslide could cause disequilibrium within the fluvial system by aggradation in the upstream reaches and an incised breach channel formed during lowering of base level in the downstream reaches. The aggradation in the upstream reaches protects the bedrock channel from incision and the breach channel enhances incision in the downstream reaches (Korup, 2006a). Furthermore, the separation between aggradation and the breach channel incision enhances a convex knickpoint in the longitudinal profile and needs to be removed from the profile in order to clearly determine uplift histories.

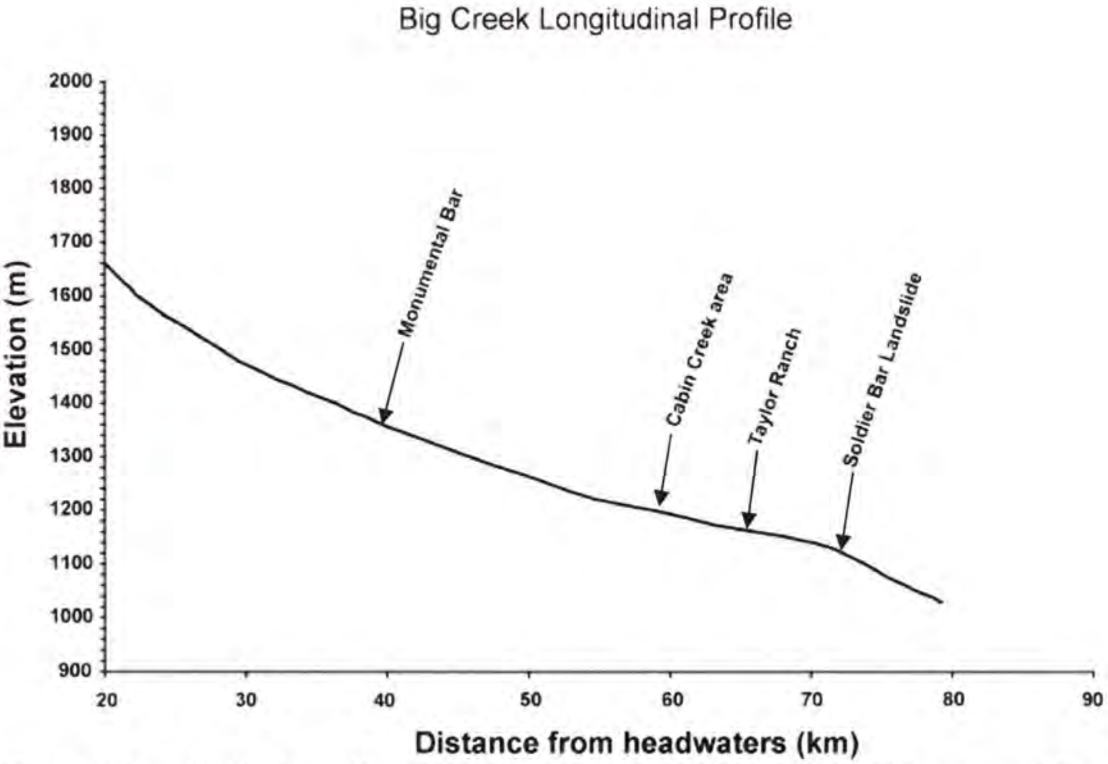


Figure 6. Longitudinal profile of Big Creek showing the locations of Monumental Bar, Cabin Creek, Taylor Ranch and the Soldier Bar landslide which is ~70 km from the headwaters of Big Creek.

Chapter 2. Background

2.1 The Effect of Base Level Rise/Fall on Terrace Formation in Steep Walled Canyons

The formation of terraces in a fluvial valley occurs in many different ways. Terraces form through alternation of aggradation and degradation within a fluvial system. Fluctuations between aggradation and degradation arise from base level rise and fall, tectonic uplift and/or climate change. Gorges, spillways and deltaic deposits also form from the impoundment of the fluvial system (Meyer and Leidecker, 1999; Densmore and Hovius, 2000; Wassmer et al., 2003; Korup, 2004; Korup, 2006a).

Aggradation and degradation depend on the balance between hillslope processes and fluvial processes. The critical threshold of stream power marks the transition between aggradation or incision in the river channel (Bull, 1979). Many factors influence the critical threshold of stream power in a fluvial system. An increase in bed load volume or grain size promotes aggradation, and an increase in discharge or steepening of gradient promotes incision. The external factors that influence deviations in the critical threshold of stream power include changes in base level, rock and isostatic uplift, tectonic changes, knickpoint migration and climatic variations. However, isolation of one of the factors influencing deviations of the critical threshold of stream power for rivers is difficult. Isolation of climatic variations can be determined from fluvial deposits (Bull, 1979; Pierce and Scott, 1982; Othberg, 1994) except in the case of an impounded fluvial system (Densmore and Hovius, 2000; Wassmer et al., 2003).

Deviations from the critical threshold of stream power in a fluvial system lead to incision or aggradation. Incision abandons the floodplain, creating terraces. There are two main types of stream terraces that can form during such deviations, strath and fill-cut terraces. Strath terraces form when a thin veneer of alluvium covers the active channel, resulting in lateral erosion of the river. Lateral erosion promotes slaking, the continued wetting and drying of the bedrock (Montgomery, 2004). Bull (1990) refers to strath terraces as the fundamental tectonic stream terrace. When tectonic uplift takes place, the incision of the river focuses on the weakest spot of the riverbed and vertical incision rather than lateral erosion takes place. Tectonic uplift coupled with incision of the river causes the strath to become elevated above the river. This leaves the tread of the strath elevated above the channel with bedrock exposed in the tread.

A rise in base level or decrease in critical stream power causes the stream to aggrade and sediment to be deposited in the channel. When base level falls, the fluvial system has to incise into the sediment deposited. The initial incision isolates the highest alluvial terrace, which has a depositional, rather than erosional, surface. Fill-cut terraces are isolated above the channel when a drop in base level occurs and the river begins to incise into the fill. Fill-cut terraces tend to form in meanders along the river where sediment traps exist. This type of terrace is formed from the incision into alluvium, leaving the tread of the terrace elevated above the channel with no exposed bedrock in the tread. Instead the tread consists of a thick sequence of alluvium exposed with no evidence of how thick the sequence of alluvium is.

Landslide-dammed lakes can also affect base level rise and fall in the portion of a fluvial system. A canyon-blocking landslide causes base level to rise in the upstream reaches. This causes aggradation to occur in the form of downstream prograding deltaic deposits into the impounded lake. Fill terraces form upstream of the lake. As the dam is incised, base level falls, causing the deltaic deposits to be incised, leaving fill-cut terraces and shorelines isolated above the river channel.

As the landslide is incised, discharge from the impoundment can erode spillways into the landslide material. Natural spillways that form in the landslide material prevent catastrophic failure of landslides by providing a controlled outlet for the impounded water (Costa and Schuster, 1988). These natural spillways form when the toe of the landslide is at a higher elevation than the adjacent bedrock (Schuster et al., 1986).

Prograding deltaic deposits represent one phase of aggradation that took place in association with the damming of Big Creek. As incision into the dam occurred, multiple spillways stabilized multiple lake levels. As the lake level dropped to a new spillway level, Big Creek incised into the deltaic deposits. This incision abandoned fill-cut terraces in the wide reaches and meanders of the river. Further drops in lake level formed subsequent fill-cut terraces lower in the basin.

2.2 Landslide Influence on the Formation of Spillways, Terraces and Shorelines

Landslides are a form of hillslope erosion and can be influenced by fluvial processes. A high rate of incision into the riverbed removes support from the toe of the hillslope and leads to over steepened hillslopes. If weaknesses in rock exist, large portions of the hillslope can slide into the valley. Depending on the landslide volume and the stream's ability to remove sediment, landslide material can block the channel for minutes to thousands of years. This poses a threat to populated areas both upstream and downstream of the landslide. The upstream threats consist of aggradation and flooding during the impoundment. The downstream effects can be devastating if the landslide fails catastrophically and releases a large outburst flood. The geomorphic impact is dependent on longevity, which is controlled by the size, shape, lithology and size of particles from which the landslide is constructed (Costa and Shuster, 1988) as well as the width and the stream power available in the channel.

The triggering mechanisms creating landslide dams can be high rainfall, snowmelt events, earthquakes, or rock weakening (Costa and Schuster, 1988; Reneau and Dethier, 1996; Korup, 2005). When large rock failures occur, the two most common discontinuities that serve as failure planes are jointing and bedding (Costa and Schuster, 1988).

The most likely setting for a landslide to block a channel for hundreds to thousands of years is a steep, narrow valley with rugged topography. A steep, narrow valley only requires a small volume ($\sim 10^6$ m^3) of material to block the channel (Korup et al., 2006). The steep slopes allow the landslide material to reach high speeds. Higher speeds allow the toe of the landslide to travel 10s to 100s of meters up the opposite side of the valley. Furthermore, a steep, narrow valley filled with a landslide composed of rock allows a very tall landslide dam to form (Korup, 2005). The Big Creek drainage has all of the characteristics (a steep, narrow, V-shaped valley, intense erosion rates during the Quaternary and heavily jointed bedrock throughout the valley) that allowed a large landslide to form a tall dam and block the channel for a long period of time (Figure 7).

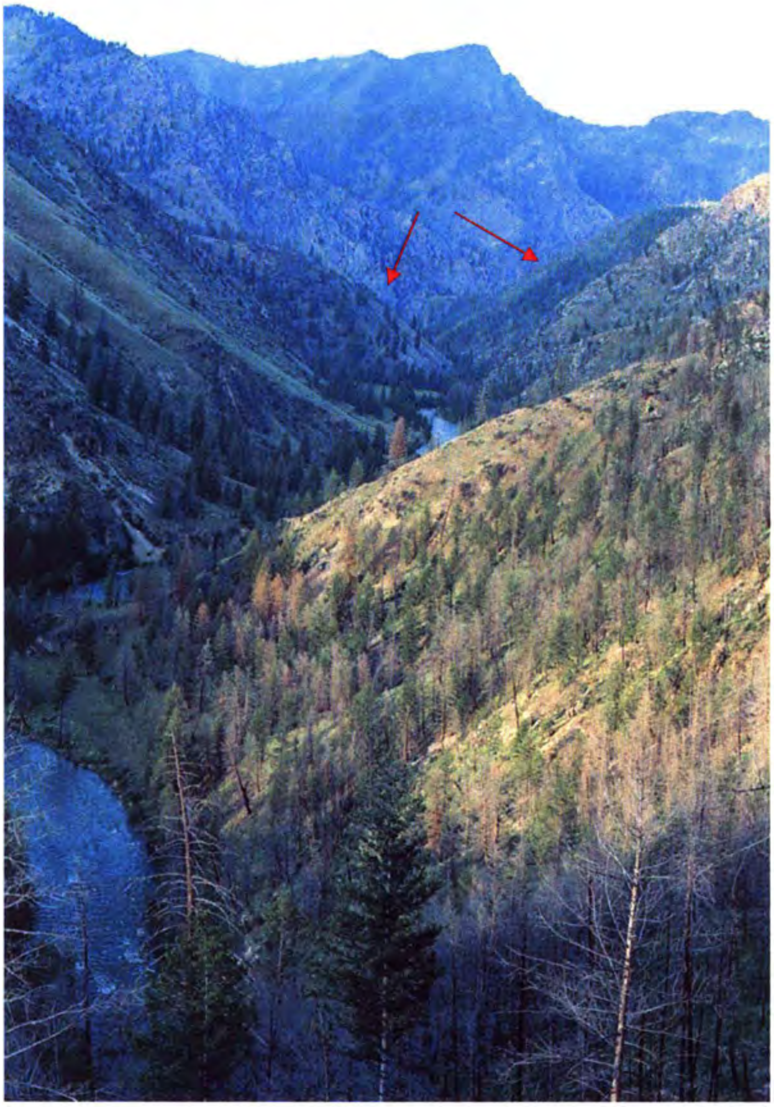


Figure 7. View looking east down Big Creek showing the steep narrow valley with red arrows pointing to the landslide deposit.

2.3 Lakes and Deltaic Fill Deposits in Steep Valley Walled Canyons

The stable Soldier Bar landslide dammed Big Creek and an impounded a large lake. The size of such a lake is dependent on the height of the landslide dam and the valley morphometry (Costa and Shuster, 1988; Wassmer et al., 2003; Korup, 2005). The amount of time the river takes to fill the impoundment is dependent on the discharge of the main stem and its tributaries, the amount of piping and seepage through the landslide material and the morphometry of the impounded basin.

As the lake fills, the upstream reaches aggrade and the river valley fills with deltaic deposits. The amount of aggradation is dependent on the supply of sediment by hillslope erosion and the amount of sediment carried by the main stem and tributaries via suspended load and bed load (Wassmer et al., 2003).

The progradation of main stem and tributary streams into the lake forms Gilbert style deltas from the flow of the river into the standing water of the lake (Figure 8). The shape of the delta and distribution of the sediment flowing into the lake are determined by the shape of the basin, the amount of sediment supplied, sediment grain size, discharge, discharge variability and the density difference between the water flowing into the standing water of the lake (Orton and Reading, 1993). Cold water flowing into warm water is more dense (hyperpycnal) and continues to flow along the bottom of the lake distributing suspended sediment long distances in the form of turbidity currents (Orton and Reading, 1993).

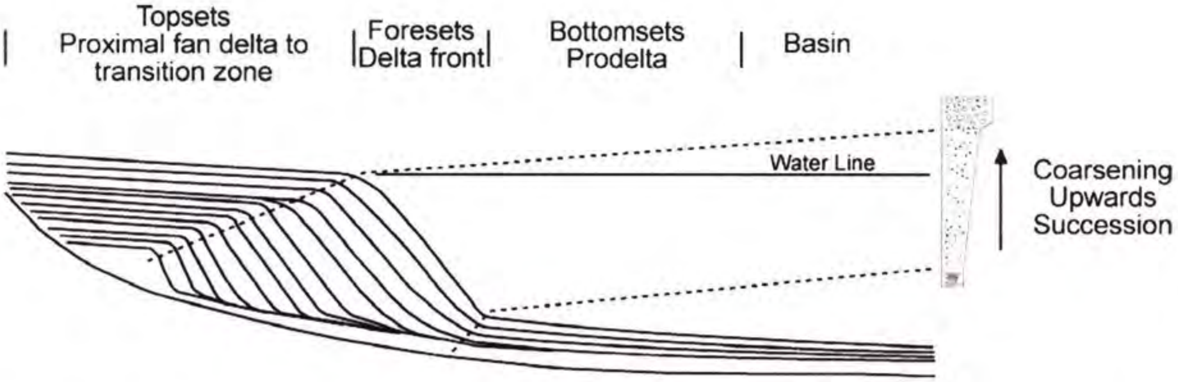


Figure 8. Gilbert type-Delta fan showing locations of topset, foreset, and bottomset bed deposition (Modified from Easterbrook, 1999).

Chapter 3. Methods

3.1 Introduction

In order to document the distribution of landforms and the effects of landslide dammed lakes, four types of data were collected during this research. First, a geomorphic map of all surficial features (terraces, shorelines, alluvial fans, floodplain, landslides, slumps, colluvium, bedrock and talus) from the valley floor to the ridgeline was made along the Big Creek drainage (Plate 1). Second, the elevations and locations of selected geomorphic features were surveyed with a Leica total station to determine the gradient of the surfaces. Third, optically stimulated luminescence (OSL) samples were collected from two areas to obtain age constraints for the timing and duration of the landslide event. Fourth, digital elevation models were used to extract data on the parameters (size, shape and volume) of the landslide dam and the lake levels that formed.

3.2 Mapping

Mapping was conducted during June of 2006 at a scale of 1:24,000 for a ~ 48 km stretch of the Big Creek drainage (Plate 1). Geomorphic maps of Big Creek were made in the field on USGS topographic maps covered with mylar and digitized using ArcMap 9.2 see (Appendix B). Since Big Creek is entirely within the Frank Church River of No Return Wilderness, mapping was done by foot (Figure 9). Mapping was conducted mainly on the north side of the river due to high discharge during the field season. Landforms were delineated from field observations, air photos and map interpretations of contour spacing. Most terrace locations were determined by visual approximation.

Figure 9. Mapping while hiking along Big Creek with clipboard in hand.

Heights of terraces were approximated off topographic maps with either 40 ft or 80 ft contour intervals.

Air Photos were obtained from the Payette National Forest Service in McCall Idaho at a scale of 1:15,600. The air photos were used for areas along Big Creek that were inaccessible by foot.

The Cabin Creek and Goat Creek areas were targeted as areas of interest. The Cabin Creek (Figure 10 A & B) and Goat Creek (Figure 11 A & B) areas were mapped at 1:12,000 for greater detail. The Goat Creek area was chosen because it is the location of the Soldier Bar landslide and associated spillways in the area. The Cabin Creek area was chosen because the area is the widest part of the valley and contains many important surficial features associated with the impoundment.

3.3 Total Station

A Leica total station was used to survey the gradient of all targeted surfaces: spillways, shorelines and terraces. Targeted surfaces were chosen from the geomorphic map based on their accessibility and relationship to the landslide dam and associated lake levels. Surfaces located in three locations were chosen, spillways in the Goat Creek area, shorelines and terraces in the Cabin Creek area and a terrace near Taylor Ranch. These areas were all within six miles of Taylor Ranch.

Base stations were set up for data collection on each surface, in an area with the best possible line of sight to the prism. Four base stations were occupied in the Goat Creek area, with three located on the north side of the valley and one on the south side at Soldier Bar. There were three occupied base stations in the Cabin Creek area. The

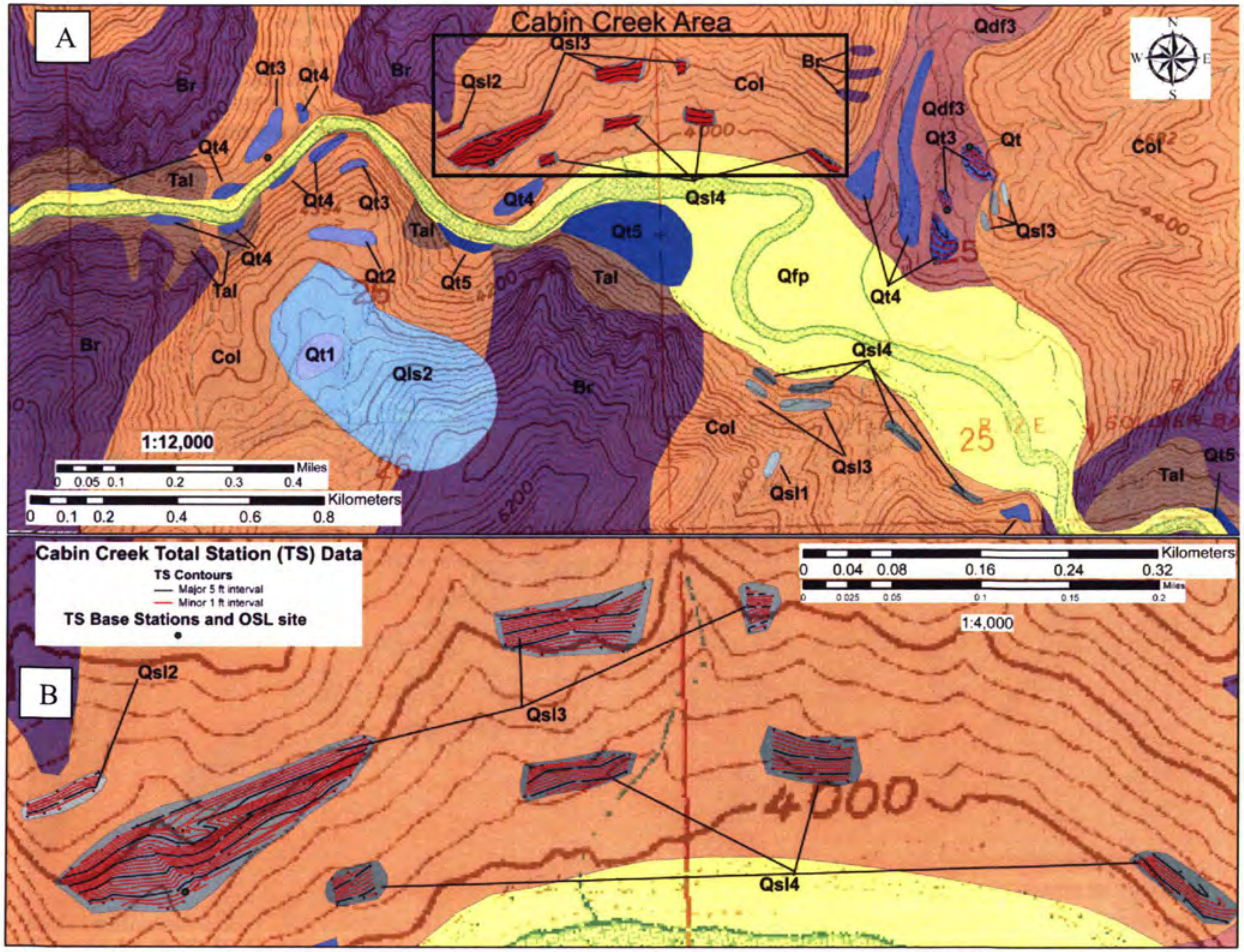


Figure 10 A & B. Total Station data for shorelines in the Cabin Creek area. A) Shows all mapped surficial features in the Cabin Creek area at a scale of 1:12,000 with the total station data outlined by the black box. B) Shows the total station data for the shorelines at a scale of 1:4,000.

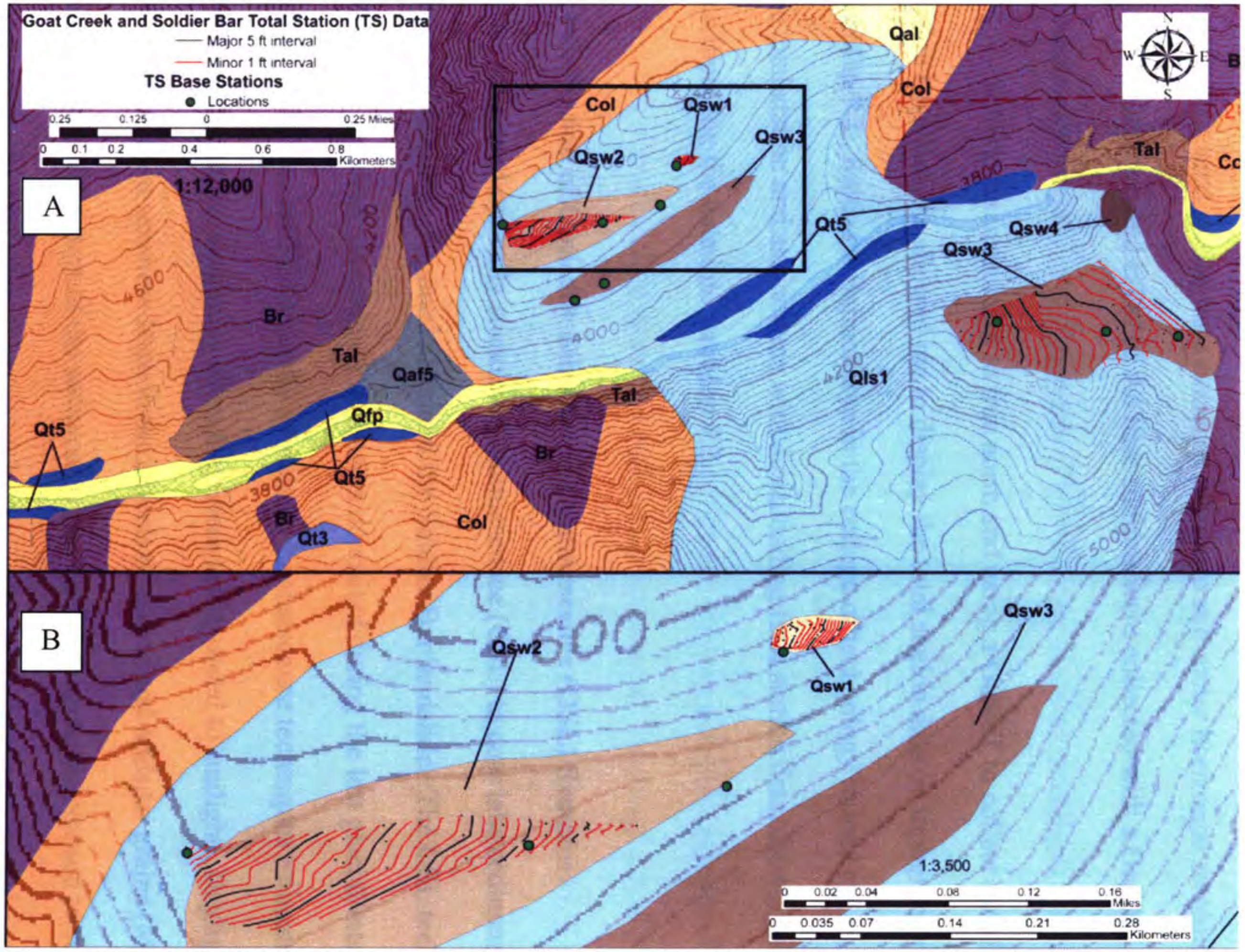


Figure 11 A & B. Soldier Bar area total station data. See Plate 1 for description of map units. A) Shows the mapped surficial features and total station data for Soldier Bar spillway at a scale of 1:12,000. B) Shows upper and middle Goat Creek spillways total station data from black box on A at a scale of 1:3,500.

terrace near Taylor Ranch only required one occupied base station. With the lack of benchmarks in the areas, the instrument was set up to true north at each base station.

A GeoXT handheld GPS unit from the Trimble GeoExplorer 2005 series was used to determine total station base station positions to sub-meter horizontal resolution (Figure 2). The elevation and UTM of the base stations were collected with a Geo XT for more accurate elevations.

Setting the instrument to true north and using a GeoXT to collect data for the total station base stations allowed me to display the total station data on topographic maps in ArcMap 9.2. Rajendra Bajracharya in the college of technology trained me on the use of the total station and assisted me with downloading total station data, drawing the contours and inputting the data into ArcMap 9.2.

3.4 Collection of Optically Stimulated Luminescence (OSL) Samples

We used optically stimulated luminescence (OSL) to date lake sediments deposited in waters impounded behind the Soldier Bar landslide. The OSL technique allows for age determination on sediments deposited during the last glacial/interglacial cycle (Wallinga, 2002). Optically stimulated luminescence techniques estimate the burial age of sediment by measuring when they were last exposed to sunlight. Daylight releases charge from light sensitive traps in the defects of quartz and feldspar grains (Murray and Olley, 2002). Transport of the sediment grains allows them to be exposed to sunlight, which resets the OSL signal. After burial the grains begin to accumulate charge in a measurable and predictable way, allowing for the burial date to be determined (Murray and Olley, 2002).

The procedures used for collecting OSL samples were provided by Dr. Tammy Rittenour of Utah State University. Dr. Rittenour and I processed the OSL samples at the Utah State University Luminescence Lab.

A total of four OSL samples were collected from two locations to obtain the minimum ages of the landslide. Only two of the samples were used to obtain the minimum ages of the landslide event. The other two samples were duplicates of the samples for each area.

3.5 DEM Analysis

A 10 m digital elevation model (DEM) was used to construct the longitudinal profile of Big Creek and determine the volume of the four persistent lake levels as defined by shorelines and terraces in the Cabin Creek area. The longitudinal profile was constructed by Dr. Ben Crosby using a 10 m DEM in conjunction with MATLAB. The data from MATLAB analysis were exported into an Excel spread sheet. From the Excel spreadsheet the longitudinal profile, and the location and elevation of all terraces, spillways, and shorelines were plotted.

The volumes of the lake levels were calculated from a 10 m DEM by using the Spatial Analyst function, raster calculator, in ArcMap 9.2. All calculations are based on the present topography and provide estimates of paleo-lake volumes. A polygon was created to represent the surface of each lake level. Each lake level was set by the elevation of each spillway located near Goat Creek. This allowed me to calculate the volume between the paleo-lake surface and the assumed lake bottom topography (Table 1).

				Lake Dimensions		
Lake Level	Minimum Lake Age	Minimum Lake Elevation (m)	Lake Depth (m) at landslide	Length (km)	Surface Area (km^2)	Volume (m^3)
1	≥17.5 +/- 1.5 ka	1372	~245	~28	22.98	2 x 10^9
2	?	1325	~198	~24	15.07	1.03 x 10^9
3	?	1280	~153	~19	9.32	4.99 x 10^8
4	≥11.3 +/- 0.8 ka	1234	~107	~15	4.93	1.79 x 10^8

Table 1. Parameters of the four lake levels including age, elevation, depth, length, surface area and volume.

3.6 Terrace Profile

The elevation and location of spillways, terraces, and shorelines were plotted on the longitudinal profile in an Excel spreadsheet. The elevations of spillways, terraces and shorelines were plotted using the GeoXT GPS unit and from topographic maps for features that were inaccessible see (Appendix A). The along-stream locations were determined by measuring the features distance upstream from the confluence of Big Creek with the Middle Fork Salmon River. Error for elevations of spillways, terraces and shorelines measured with the GeoXT GPS unit is ± 1 meter (± 3 feet). Error for terraces and shorelines delineated from topographic maps varied from ± 7 m (± 20 ft) on topographic maps with 40 ft contours and ± 14 m (± 40 ft) on topographic maps with 80 ft contours.

Chapter 4. Description of Big Creek Geomorphic Map and Data

4.1 Introduction

The geomorphic features located along Big Creek include aggradational and strath terraces, spillways, shorelines, delta fans, alluvial fans, colluvium, and bedrock. The spillways, shorelines, deltaic deposits and several terraces along Big Creek resulted from the blockage of Big Creek by the Soldier Bar landslide. With the blockage in place, the impoundment filled the drainage for ~28 km (17 miles) upstream of the dam at the dam's highest level of 1372 m (4500 ft). The subsequent discussion numbers the four most prominent lake levels, inferred from spillway elevations as Level 1 (1372 m (4500 ft)), Level 2, (1325 m (4340 ft)), Level 3 (1280 m (4200 ft)), and Level 4 (1234 m (4050 ft)).

Geomorphic features are present at Monumental Bar, Acorn, Vines, Cabin Creek, Taylor Ranch, and Goat Creek; these specific areas are labeled on Figure 2. Each area spans ~ 1 km along the stream. Terraces and shorelines cut into colluvium, bedrock and deltaic deposits characterize these areas. Monumental Bar, Acorn, Vines and Cabin Creek areas represent the upstream extent of each lake level high stand (Figure 2). The Taylor Ranch area is the downstream extent of preserved deltaic deposits.

Total station data collected on spillways in the Goat Creek area and shorelines in the Cabin Creek area show the gradient of these surfaces and support the hypothesis that these surfaces were formed during the impoundment. Coupling the total station data with the geomorphic map allowed me to determine by elevation, the terraces and shorelines that correlate to the four spillways.

4.2 Map Units and Correlation of Surfaces

4.2.1 Landslide

The Soldier Bar landslide is comprised of Mesoproterozoic Hoodoo and Yellowjacket quartzite formations. Particle size and resistance of the landslide material to erosion controlled the longevity of the landslide dam and did not allow catastrophic failure of the dam. The landslide blocked the main stem of Big Creek and the Goat Creek tributary. It covered a $2.8 \times 10^6\ \mathrm{m}^2$ ($3 \times 10^8\ \mathrm{ft}^2$) area, and landslide material was deposited ~ 0.5 km (0.3 mi) upstream to Cougar Creek and ~ 0.5 km (0.30 mi) downstream of the dam past the gorge.

There is a small ($1.1 \times 10^5\ \mathrm{m}^2$ ($1.2 \times 10^6\ \mathrm{ft}^2$)) landslide deposit in the Vines area that did not block Big Creek. It is located on the north side of the valley, and was possibly deposited into Level 2. The landslide deposit has a few remnant shorelines cut into the deposit at Level 2 and Level 3. There is also a delta fan deposit from the Garden Creek tributary, which grades into Level 3.

There is a large ($2 \times 10^5\ \mathrm{m}^2$ ($2.2 \times 10^6\ \mathrm{ft}^2$)) landslide in the Cabin Creek area located on the south side of the valley. The landslide deposit did not dam Big Creek and possibly was deposited into Level 1. I infer Level 1 because the deposit does not reach the river and is perched high on the hillslope where only the water of Level 1 would have submerged the lower portion of the landslide deposit.

4.2.2 Spillways

The surfaces near Goat Creek (Figure 12) and Soldier Bar represent five erosional spillways formed by the lake incising the landslide (Figure 4). The surfaces are at four different elevations, indicating four standing lake levels during the incision of the landslide dam (Figure 4). The Level 3 spillway is represented at both Goat Creek and Soldier Bar. Soil horizons are poorly developed and consist of angular pieces of quartzite and a red B horizon (Bill Phillips, personal communication) (Figure 13). The lack of rounded fluvial cobbles on spillways at Levels 1 – 3 imply they were not cut during normal river incision, but were instead cut directly into the landslide material by sediment-free water. This indicates the impoundments upper three lake levels were not completely filled with deltaic deposits; otherwise all of the spillways would contain fluvial sediments transported by the river into the lake. Therefore, the upper three spillways were cut into the landslide material by clear water incising into the landslide dam. The total station data confirm the size and gradients of the spillways (Figure 11 A & B).

4.2.2.1 Upper Goat Creek Spillway

The upper Level 1 spillway is at an elevation of 1372 m (4500 ft.) This spillway has an area of 1,473 m^2 (15,847 ft^2) with a downstream gradient of 0.175% represented by the total station data (Figure 11 B). There are no rounded cobbles or alluvial sediments on the surface of the spillway. Uncommon large (1 – 3 m (3 – 9 ft)) angular quartzite boulders litter the surface; they were possibly eroded out of the landslide

Figure 12. View east from Soldier Bar. The Goat Creek spillways are indicated by the red arrows (Photo Ben Crosby).

Figure 13. Soil Pit on middle Goat Creek spillway consists of angular quartzite and shows minimal soil formation. Pick is ~ 1 m (3 ft) tall for scale (Photo Bill Philips).

material during incision of the landslide or rolled onto the surface from the hillslope above. Vegetation on the surface consists of grasses and sparse Douglas fir trees.

4.2.2.2 Middle Goat Creek Spillway

The middle, Level 2, spillway is at an elevation of 1325 m (4340 ft.) The spillway has an area of 22,233 m^2 (239,191 ft^2) with an undulating downstream gradient of 0.049%. The surface of the spillway has several large (1 – 3 m (3 – 9 ft)) angular quartzite boulders with scours at the base of some of these boulders. The scours at the base of large boulders appear to be paleochannels on the surface. Vegetation on the surface consists of grasses and a large amount of burned and unburned Douglas fir trees.

4.2.2.3 Lower Goat Creek Spillway

The lower, Level 3, Goat Creek spillway is at an elevation of 1280 m (4200 ft). This spillway is long and narrow. The area of the surface is 47,372 m^2 (509,646 m^2) with an undulating downstream gradient of 0.0481%. No reliable total station data were collected on this surface. This surface correlates with the extensive upper Soldier Bar surface on the south side of the valley. This indicates a wide spillway as the water incised through the landslide dam at this level. The surface of the spillway has several large angular quartzite boulders.

4.2.2.4 Upper Soldier Bar

The upper, Level 3, Soldier Bar spillway is at an elevation of 1280 m (4200 ft.) correlating with the lower Goat Creek spillway. The area of the surface is 132,774 m^2

($1,428,435 \text{ ft}^2$). Soldier Bar is ~595 m (1950 ft) long and tapers from ~75 m (250 ft) wide on the upstream side to ~15 m (50 ft) wide on the down stream side. Total station data for this surface show that Soldier Bar is a spillway with a downstream gradient of 0.052% (Figure 11 A). This surface has angular granule and pebble sized white quartzite colluvium and no rounded fluvial cobbles or gravels present on the surface.

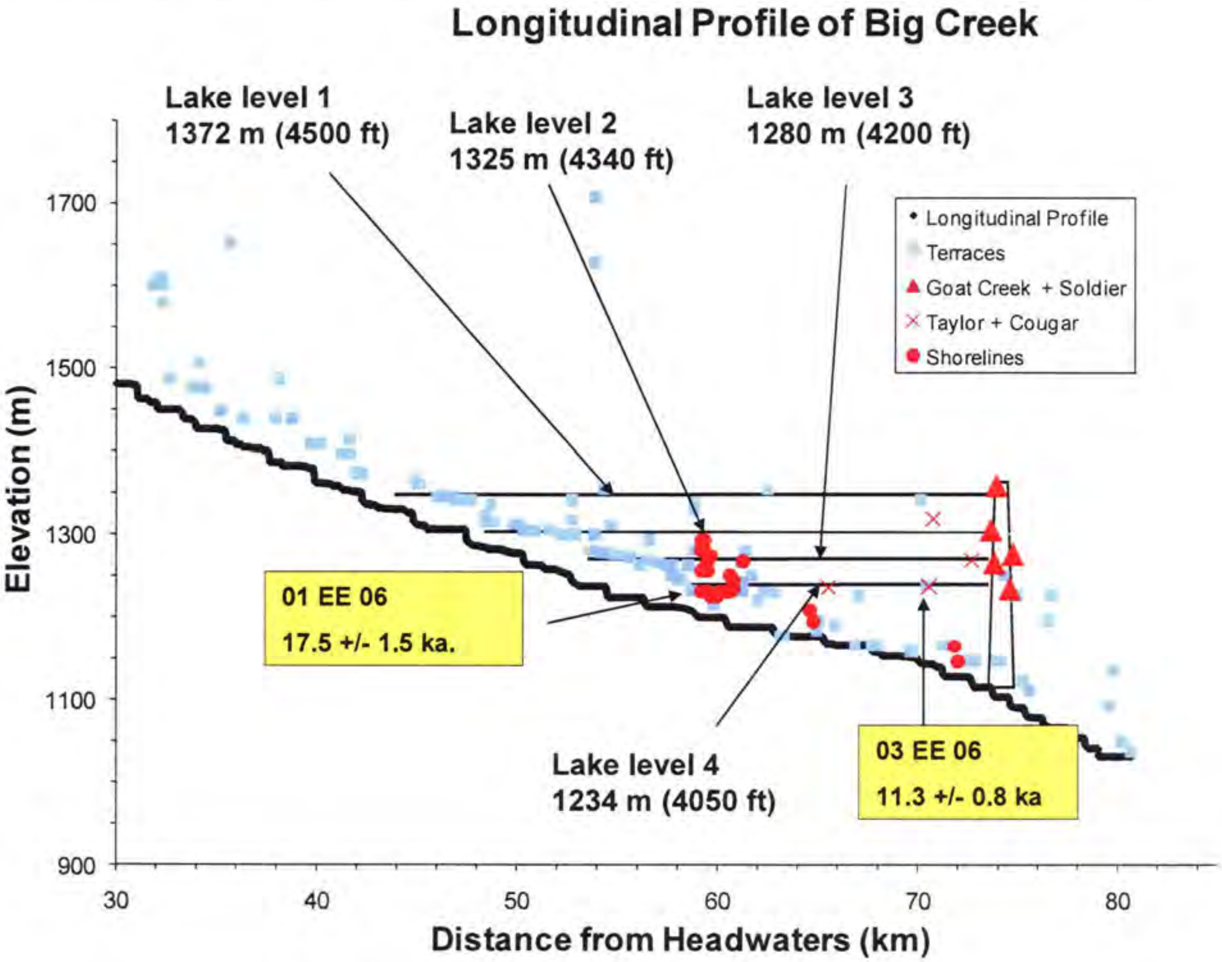
4.2.2.5 Lower Soldier Bar

The area of the lower, Level 4, Soldier Bar spillway surface is ~ $7,297 \text{ m}^2$ ($78,504 \text{ ft}^2$). This spillway correlates with terraces located at Taylor Ranch at an elevation of 1234 m (4050 ft). The surface of the spillway is covered with well rounded fluvial sand and gravel. These sand and gravel deposits are important because they imply that Level 4 was filled with deltaic deposits. The sand and gravel would function as erosional tools contributing to the subsequent incision of the landslide debris.

4.2.3 Lake Levels

The elevation of the Goat Creek and Soldier Bar spillways determine the four distinct lake levels (Figure 2). Upstream of the dam, lake levels are indicated by well-established depositional and erosional features in the Acorn, Vines, Cabin Creek and Taylor Ranch areas. Plotting the spillways, terraces and shorelines by elevation on the longitudinal profile shows how these surfaces diverge from the longitudinal profile into each lake level (Figure 14). The parameters of the lake levels are described below and can be found in (Table 1).

Figure 14. Big Creek longitudinal profile with mapped terraces (in blue), spillways (red triangles), shorelines (red circles), and visited terraces (red x's) plotted. Each lake level is shown by black lines correlated to terraces, spillways and shorelines.



4.2.4 Deltaic Deposits

The upstream extent of waters impounded behind the dam were flooded and filled with prograding deltaic deposits from Big Creek and its tributaries. No full section exposure of deltaic deposits has been directly observed in the field, but they can be inferred from terrace profiles associated with each lake level. The prograding deltaic surfaces are preserved in areas of the Big Creek drainage where sediment deposits were isolated from post landslide incision. Areas where deltaic surfaces are preserved correspond to wide reaches and meanders along Big Creek.

4.2.5 Fluvial Terraces

Sets of terraces at predictable elevations along the Big Creek drainage correlate to the four lake levels. Terraces in the upstream reaches diverge from the longitudinal profile into each lake level with a few prominent terraces holding elevations of each lake level along the profile (Figure 14). Level 4 is well constrained by terraces holding an elevation of 1234 m (4050 ft) along the profile at many different locations, which I discuss below. I infer the terraces that diverge from the longitudinal profile into each lake level represent the subaerial portion of the prograding deltaic deposit and were isolated above the channel as the dam was incised.

A terrace at Level 4 ~ 5 km (3 mi) upstream of the landslide dam, located near Taylor Ranch on the south side of the valley, is a fill feature with thick sequences of fluvial fine sediments, which are ~ 35 – 60 m (120 – 180 ft) thick and coarsen upward into sand and gravel deposits. The Taylor Ranch surface was surveyed with the total station to determine the gradient of the surface. Total station data show the surface to have a slope into the middle of the canyon with a gradient of 0.059%.

There is a paired terrace to the Taylor Ranch terrace cut into a landslide deposit on the north side of the valley at the elevation of Level 4. This terrace has fine sediments on the surface of an unknown thickness. Another terrace cut into the landslide material above the 1234 m (4050 ft) terrace correlates to Level 3.

There is a broad terrace located at the confluence of Rush Creek and Big Creek that correlates to Level 4. The surface of the terrace is covered by fluvial gravel.

There are two prominent terraces at an elevation of Level 4 located in the area between Cabin Creek and Taylor Ranch areas. The first terrace is ~ 2 km (1.3 mi) upstream of Taylor Ranch in the Lobauer Basin area on the south side of the valley. The terrace also correlates to Level 4. The terrace surface is covered by fluvial gravel, which represents deltaic deposits flowing into Level 4. The second terrace is ~ 4 km (2.5 mi) upstream of Taylor Ranch in the Brown Basin area on the south side of the valley and was only mapped visually from the Big Creek trail.

There are two terraces present in the Cabin Creek area on the south side of the valley. The first is ~ 8 km (5 mi) upstream of Taylor Ranch, located at the downstream boundary of the Cabin Creek area at the same elevation as Level 4. Fluvial gravels cover the surface of the terrace and represent deltaic deposits prograding into the Level 4 from the Big Creek main stem. The second terrace is ~ 10.5 km (6.5 mi) upstream of Taylor Ranch, located at the upstream boundary of Cabin Creek. This terrace is at the same elevation as Level 2.

A series of terraces located along the Big Creek drainage are 1 - 3 m (5 – 10 ft) above the current channel. I infer these terraces to represent post-lake incision of Big Creek into aggraded deposits during Holocene time. An example is located upstream of the Vines area showing aggraded deposits in an exposed scarp of the terrace (Figure 15).

4.2.6 Shorelines

Sets of shorelines are located along Big Creek. The main areas where there are an abundance of shorelines are Acorn, Vines, Cabin Creek and Taylor Ranch. These areas represent the location for the input of deltaic sediments from tributaries prograding into the lake. Therefore, many of the shorelines are cut into deltaic deposits and colluvium. The shorelines will be discussed by the areas where they are located along the Big Creek drainage. Each area will be discussed in a downstream direction from Monumental Bar.

4.2.6.1 Monumental Area

The Monumental Bar area is ~ 28 km (17 mi) from the dam, which is the farthest upstream extent that Level 1 filled to. At this location, the lake began to fill with sediments carried by the flowing water into the impoundment. The area represents a beach type environment where deltaic surfaces formed at Level 1. The channel in this area is very narrow and straight where the channel occupies the entire valley floor width (Lifton, 2005). Since the channel in this area is so narrow there are only a few shorelines preserved. Shorelines ~ 3 m (10 ft) above the present channel are located near the confluence of Monumental Creek and Big Creek and appear to slope into the creek rather than downstream.

Figure 15. Excellent exposure of aggraded beds deposited on terrace. This terrace represents post-lake level incision during the Holocene.

4.2.6.2 Acorn Area

The Acorn area is ~24 km (15 mi) from the dam and marks the upstream limit of Level 2. This area is the location of a small landing strip and broad terraces ~ 5-10 m (10 – 30 ft) above the modern channel (Figure 16). I infer that these broad terraces represent a beach environment where remobilized deltaic deposits from Level 1 were redeposited. Downstream, fill-cut terraces and shorelines diverge from the longitudinal profile and the elevation of Level 2. The Acorn area also has a tributary delta fan that prograded into Level 1.

4.2.6.3 Vines Area

The Vines area is ~ 17.5 km (11 mi) from the dam and is the upstream location of the sediment deposition associated with Level 3 (Figure 2). This area is the only place that has remnant shorelines of each lake level, preserved in a large alcove on the south side of the valley, which acted as a sediment trap. I infer that shorelines associated with Level 1 in the area are erosional fill-cut surfaces, because the lake did not completely fill with deltaic deposits. The shorelines are small with a possible gradient toward the stream. The shorelines have very similar characteristics to shorelines in the Cabin Creek area, which were surveyed with a total station.

4.2.6.4 Cabin Creek Area

The Cabin Creek area is ~ 13.5 km (8.5 mi) upstream of the landslide dam. The north side of the valley in the Cabin Creek area was surveyed with a total station to characterize the gradient of the shorelines. The gradient of the shorelines is toward the

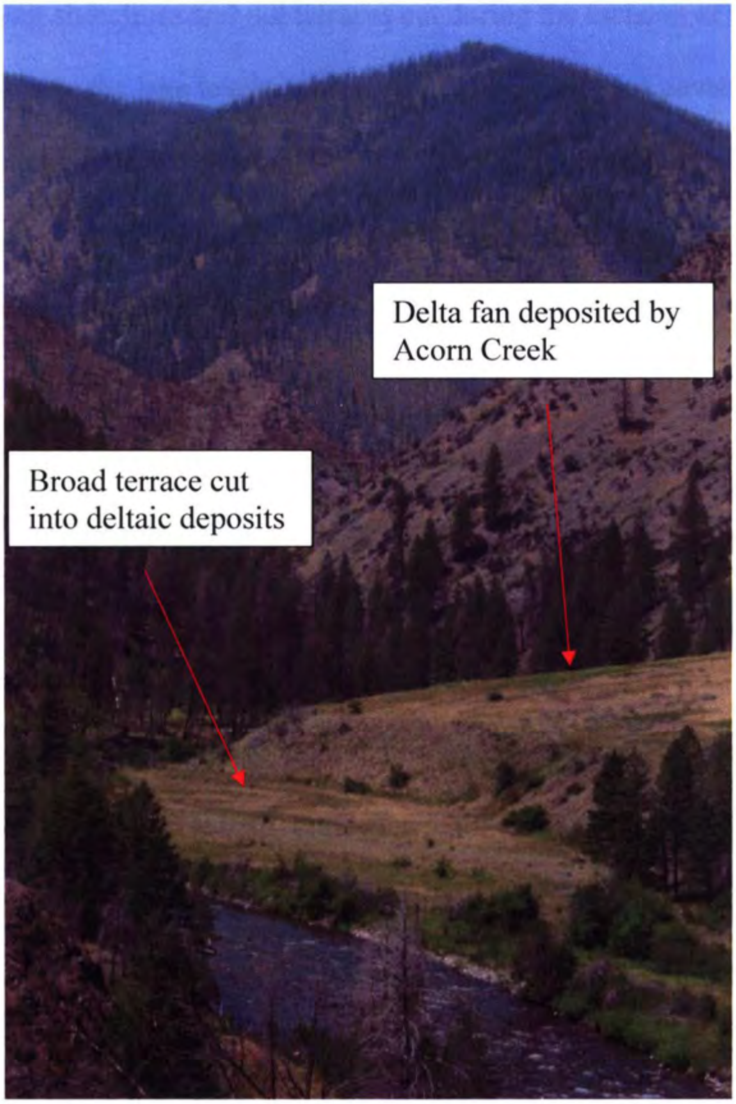


Figure 16. View looking southwest in the Acorn area represents the upstream reach of the 1325 m (4340 ft) lake level and a delta fan deposited into the 1372 m (4500 ft) lake level.

river rather than in the downstream direction (Figure 10 A & B). Because of this, I infer that they are fill-cut shorelines and not terraces cut during the incision of Big Creek. This represents areas where the lake levels persisted. The shorelines are covered with fluvial gravel and cobbles up to an elevation of Level 2. The well rounded cobbles present range from 2 – 10 cm (1 – 2 in.) in diameter with sands and gravels filling the interstices. Alternatively, the shorelines could be degraded fluvial terraces.

There are several prominent fill-cut shorelines on the south side of the valley. These surfaces were not surveyed due to inaccessibility during the 2006 field season. Abundant gravels are present on the surfaces with occasional cobbles.

4.2.6.5 Taylor Ranch area

Taylor Ranch is built on an alluvial fan formed by the Pioneer Creek tributary after the landslide dam was breached. I infer the alluvial fan to be post-landslide because it formed below Level 4. The Taylor Ranch area has only a few remnant fill-cut shorelines. They are only located on the south side of the valley at the same elevation as Level 4.

4.2.7 Alluvial and Delta Fans

The geomorphic map shows that the elevations of the majority of tributary mouth fans between Soldier Bar and Monumental Bar correlate with inferred lake levels. Thus, they are likely from tributaries that prograded into the lakes. Delta fans are described here by tributary location from upstream to downstream. Acorn creek has a delta fan that prograded into Level 1. A delta fan located at the mouth of Coxey Creek prograded into

Level 2. A delta fan at the mouth of Garden Creek, in the Vines area, formed into Level 2 and Level 3. Cabin Creek has a much wider valley floor; therefore, a delta fan prograded into Levels 2, 3, and 4. The Cabin Creek delta fan was probably remobilized as each lake level fell during the incision of the dam.

Prominent prograding delta fans into Level 4 characterize the confluence of Cabin Creek and Big Creek. At the mouth of Cabin Creek there are three terraces cut into the delta fan. These surfaces were surveyed to determine their gradient and relationship to Big Creek. The gradient is in the downstream direction with Cabin Creek. This indicates that Cabin Creek rather than Big Creek formed the surfaces during incision of the landslide and lowering of the lake levels.

Alluvial fans are present at the mouths of many small tributaries flowing into Big Creek. The alluvial fans are not graded to any of the lake levels and are below the lake levels. The timing of alluvial fan deposition is most likely post-impoundment in the areas downstream of Monumental Bar. Alluvial fans formed in the areas above Monumental Bar are inferred to have continually formed from before the landslide event to the present. This is inferred from the size of the alluvial fans and because they are located above the lake levels. Cougar Creek, ~ 1 km (0.62 mi) upstream of the Soldier Bar landslide has formed an alluvial fan during post-lake levels. Taylor Ranch is built on an alluvial fan that was formed by Pioneer Creek. Cliff Creek across from Taylor Ranch has also formed a small alluvial fan during post landslide history.

Chapter 5. Geochronology and Sedimentation of Deltaic Sediments Along Big Creek

5.1 Introduction

The Soldier Bar landslide caused the local base level within the Big Creek drainage to rise, allowing the drainage to partially fill with sediment. The amount of sedimentation into a lake is difficult to determine (Hewitt, 1998; Costa and Shuster, 1988; Korup, 2004; 2005). Therefore, the amount of sediment that filled the lake basin can only be speculated by the elevations and locations of remnant sediment deposits. Remnant sediment deposits were preserved in wide and meander reaches along the river. Sediment transport into the lake levels in the upstream reaches led to the formation of many geomorphic features including; terraces, shorelines and delta fans while incision of the landslide took place. As lake levels fell during the incision of the landslide, deltaic deposits were remobilized by lowering of local base level in Big Creek.

5.2 Optically Stimulated Luminescence (OSL) Sampling Procedure

For optically stimulated luminescence studies, samples need to be collected at least ten feet below the surface of the terrace (Rittenour, personal communication). Since the scarp of terraces constantly erodes, getting underneath the tread of the terraces was difficult. Therefore, the samples were collected by digging laterally into the scarp of the terrace (Figure 17 A & B). This was done to avoid sampling eroded material from above i.e., sediments that have been disturbed by bioturbation and plant roots. All of these factors can lead to a much younger age then the actual age of formation of the terrace

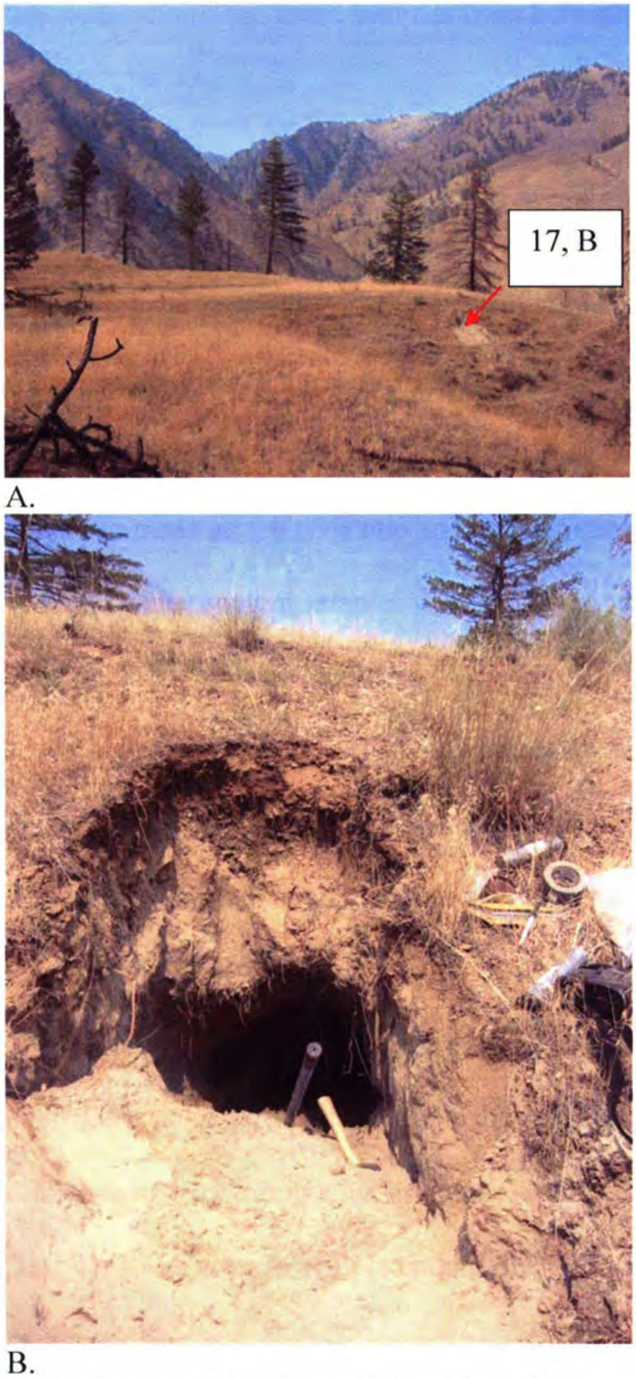


Figure 17 A and B. These figures show the OSL sampling site on the terrace near Taylor Ranch. A) Figure 17 A shows the location in the scarp of the terrace where the OSL sample was collected. Figure 17 B shows the hole excavated into the scarp of the terrace. The hole is ~ 2 m (6 ft) deep into the scarp.

(Rittenour, personal communication), but intact samples from beneath the terrace tread can produce valid ages.

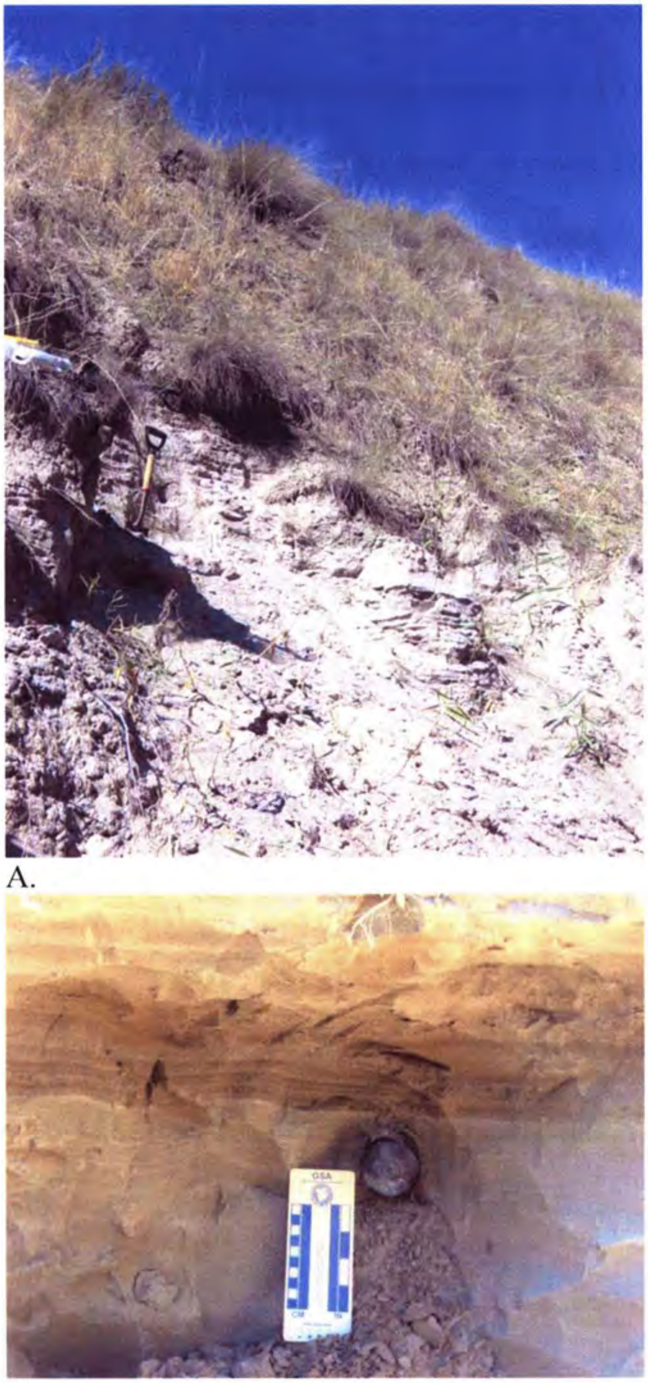
For each sample, I recorded the stratigraphy and the burial depth of the deposits along with latitude, longitude and elevation. Each OSL sample was collected with an 8 in. long, 2 in. diameter PVC tube to protect the sediments from light exposure. The ends of the PVC tube were also capped to keep the sediments from light exposure. Another sample of the sediment was collected in a film container to measure water content of the deposit along with a sample to measure the dose rate and mineral composition of the sediments. The dose rate and water content samples were collected within a 30 cm (11 in) radius around the PVC tube.

Sampling in the Cave Creek area was easy due to the nearly vertical face on the exposure and being adjacent to the Big Creek trail. The sample was collected one foot into the slope to insure the sediments had not experienced bioturbation or exposure to sunlight (Figure 18 A & B).

Sampling on the terrace near Taylor Ranch was not as easy as the Cave Creek area. The scarp of the terrace is not a vertical face due to degradation since formation. Therefore, sampling was done by excavating a horizontal six-foot deep hole into the scarp (Figure 17 A & B). This was done to sample undisturbed sediment deposited during the formation of the surface.

5.3 Sample Site Descriptions

We sampled fine laminated sediments distinguishing annual or surging under flow of suspended sediment carried by the river into the lake in the area of Cave Creek. The



A.

B.

Figure 18 A and B. Figure (A) shows where figure (B) was collected in the deposit. The scarp located between the shovel and the scale in figure (A) was excavated 18 inches into the face.

grain size of the sediments is silt to fine sand with centimeter scale laminations and ripple marks (Figure 19). The fine grained lacustrine sediments are ~ 5 -10 m (15 – 30 ft) thick and deposited on bedrock ~ 10 – 15 m (30 – 45 ft) above the river. The sediments coarsen up from the silt to sand to gravel and cobbles on the terrace tread. I infer that these represent bottomset beds deposited into the lake.

The Taylor Ranch terrace is constructed of a thick sequence ~40 – 60 m (120 - 180 ft) of sands and gravels. The lower 35 – 60 m (110 – 180 ft) of the deposit has alternating beds with grain sizes ranging from fine to coarse sands. The upper 5 m (~15 ft) of the deposit has alternating beds of coarse sand to gravel. I infer that these represent foreset and topset beds prograding into Level 4 because of the grain size and the fact that they coarsen up into gravel on the terrace tread.

Figure 19. Lacustrine sediments deposited in the Cave Creek terrace are fine grained graded beds and contain fine laminations and ripple marks. These sediments are excellent for OSL dating techniques. Length of knife handle is ~ 5 in (Photo by Ben Crosby).

5.4 Interpretation of OSL Results

The OSL samples from the fine sediments below terrace surfaces indicate the minimum age of the Soldier Bar landslide is late Pleistocene ~ 17.5 ± 1.5 ka (Table 2). The minimum age of the final incision of the dam is late Pleistocene ~ 11.3 ± 0.8 ka (Table 2). These ages determined the minimum length of time the landslide was in place to be ~ 6.2 ± 1.5 kyrs.

The age of 17.5 ± 1.5 ka was obtained from the Cave Creek sediments (Table 2). The fine sediments, laminations and current ripple marks indicate that the sediments were deposited as bottomset beds into a delta at Level 1 or 2. This location would have been an environment where the current was unable to transport the sediment but still influence the sediment enough to form ripple marks.

The age of 11.3 +/- 0.8 ka was obtained from the Taylor Ranch terrace at an elevation of 1234 m (4050 ft) (Table 2). The thick sequence of the sand and gravel beds is inferred to represent the result of a delta prograding into Level 4. This location would have been an environment in which deposition took place proximal to the input of sediment into Level 4.

The OSL dates sampled at Cave Creek and Taylor Ranch represent minimum ages for the formation and filling of the impoundment. There is a possibility that the fine lacustrine sediments deposited in the Cave Creek area were not deposited during the highest lake level stand. If the fine sediments were not deposited into Level 1 then they were deposited into Level 2. I infer the sediments to be deposited into Level 2 because transport distance of the sediments would be less than if they were deposited into Level 1.

The two locations, Cave Creek sediments and Taylor Ranch terrace, offer an excellent sequence of fine sediments and ease of accessibility for the use of OSL dating techniques.

			OSL Age Information			
Sample #	USU #	Description	# aliquots	Equivalent dose (De), Gy	Dose rate (Gy/ka)	OSL Age (ka)
01 EE06 OSL	USU-099	laminated lake seds.	23	60.41 ± 13.74	3.45 ± 0.22	17.5 ± 1.5
03 EE06 OSL	USU-101	deltaic seds on terrace	21	59.71 ± 14.00	5.27 ± 0.24	11.3 ± 0.8

			Dose Rate Information								
Sample #	USU #	Location	Depth (m)	Grain Size (μm)	H_2O%*	U (ppm)	Th (ppm)	K_2O%	Rb_2O (ppm)	cosmic (Gy/ka)	Dose Rate (Gy/ka)
01 EE06 OSL	USU-099	Big Creek, ID	16.2	75-125	6.7	2.20 ± 0.2	12.00 ± 1.1	2.76 ± 0.07	118.7 ± 4.7	0.04 ± 0.004	3.45 ± 0.22
03 EE06 OSL	USU-101	Big Creek, ID	3.0	75-125	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

Table 2. OSL age and dose rate information.

- * In-situ moisture content.
- Error on De is 1 standard error.
- Error on age includes random and systematic errors calculated in quadrature.

Chapter 6. Discussion of Geomorphic History

6.1 Introduction

The following discussion is divided into five sections. The first addresses the Soldier Bar landslide, and the next two sections discuss the geomorphic features, lake levels associated with the dam and estimates for the filling of the lakes with water and sediment. Finally, I discuss the geomorphic impact caused by the dam and make suggestions for future work in Big Creek.

6.2 Landslide

The Soldier Bar landslide dammed Big Creek for at least 6,000 years during the late Pleistocene – early Holocene. The minimum age of the landslide event is constrained by an OSL age from the lacustrine sediments at Cave Creek of ~17.5 +/- 0.8 ka. Maximum age of final lake drainage is constrained by an OSL age from deltaic sediments at Taylor Ranch terrace, of 11.3 +/- 0.8 ka.

As mapped by Stewart and others (1995 – 2004) the Soldier Bar landslide consists of the Mesoproterozoic Hoodoo and Yellowjacket Quartzite formations. Sub-horizontal joints in the bedrock dip at a low angle to the northwest. These joint planes and a north-striking fault are the two most likely failure planes that allowed for the movement of the large rock mass.

The two most important causes of landslides in a steep, narrow valley are excessive precipitation and earthquakes (Korup, 2005; Costa and Schuster, 1988). I infer that a possible trigger for landsliding in the Big Creek valley was a wetter Pleistocene climate (Pierce and Scott, 1982). Allowing for increased rainfall and spring snow melt runoff, this would increase ground-water recharge and increased spring discharge of Big Creek. I infer the increase in discharge and groundwater recharge weakened the hillslope allowing for failure along joint planes. This has a big effect on shallow landslides, but less effect on deep-seated landslides.

Earthquakes are also possible triggers. Big Creek lies within 100 km (62 mi) of several major active faults at the Sawtooth, Lost River, and Lemhi Ranges.

Meyer and Leidecker (1999) describe a landslide-dammed lake on the Middle Fork Salmon River near the mouth of Big Creek. They obtained a radiocarbon date of ca. 14.5 cal ka on lacustrine marls, in the upper portion at 20 m (60 ft) thick sections of lacustrine sediments. The lakes are broadly coincident in space as well, as the Middle Fork landslide dammed lake reached an elevation less than 30 m (100 ft) below the Soldier Bar landslide.

6.3 Lake Levels

The landslide dam caused base level to rise and the upstream portion of Big Creek to form a lake that filled to an elevation of 1372 m (4500 ft). The dam was incised in at least four stages during the > 6,000 years the dam was in place. The four spillways located near the Goat Creek area and shorelines in the Vines and Cabin Creek areas represent persistent lake levels at times of spillway stabilization.

The time to fill Level 1 with water, with a volume of 2 km^3 (0.48 mi^3), was calculated using three scenarios (Table 3). I used the area of the Big Creek drainage basin above the landslide dam (1462 km^2 (562 mi^2)), which is ~95% of the entire

Scenareo	Discharge	Volume of impoundment	years to fill basin
	[km^3/yr]	[km^3]	[yrs.]
Current discharge	0.3193	2	6.3
Half current Dishcarge	0.1596	2	12.5
Tenth current discharge	0.0319	2	63

Table 3. Scenarios to fill Level 1 with water.

drainage basin. The first scenario uses the recent discharge data from 1944 to 1958 of 0.3193 km^3/yr (1.13×10^{10} ft^3/yr). In the first scenario, Level 1 would have filled within 6.3 years after the landslide dam was in place. In the second scenario, using half of the recent discharge the lake would have filled within 12.5 years. In the third scenario, the lake would have filled within 63 years using a tenth of the recent discharge. These scenarios were calculated by assuming the pre-landslide valley was similar to the present valley topography.

The reason for three scenarios is that during late Pleistocene time, discharge rates were probably quite different than current discharge rates. All three scenarios show that Level 4 filled quickly when compared to the duration of the landslide dam.

I also tested four scenarios for the time to fill each lake level entirely with deltaic deposits was calculated using a range of erosion rates 0.25 – 1.5 mm/yr (.0098 – .059 in/yr). Two additional scenarios were calculated to determine the amount of time it would take deltaic deposits to fill half and one third of the lake level volumes with the same range of erosion rates (Table 4).

Field evidence and the calculated time indicates that Level 1 filled ~ 1/3 of the 2 km^3 (0.48 mi^3) basin with an erosion rate of 0.5 – 1.0 mm/yr (.020 – .040 in/yr) (Figure 20 A). Filling the lake 1/3 full would have taken ~ 900 years. This is shown in the Vines area by what I infer to be foreset beds of fluvial sand and gravels coarsening upward on shoreline surfaces at an elevation of 1372 m (4500 ft). I infer that fine grained bottom set beds were deposited into the Cave Creek area.

Lake level	Erosion Rates		Basin Area	vol. of sed. per year	vol. to fill	yrs to fill entire basin	yrs to fill 1/2 of basin	yrs to fill 1/3 of basin
	mm/yr	km/yr	km^2/yr	km^3/yr	km^3			
1	**1.50**	**0.0000015**	**1462**	**0.00219**	**2.00**	**912**	**456**	**304**
1	**1.00**	**0.000001**	**1462**	**0.00146**	**2.00**	**1368**	**684**	**456**
1	**0.50**	**0.0000005**	**1462**	**0.00073**	**2.00**	**2736**	**1368**	**911**
1	**0.25**	**0.00000025**	**1462**	**0.00037**	**2.00**	**5472**	**2736**	**1822**
2	1.50	0.0000015	1462	0.00219	1.00	456	228	152
2	1.00	0.000001	1462	0.00146	1.00	684	342	228
2	0.50	0.0000005	1462	0.00073	1.00	1368	684	456
2	0.25	0.00000025	1462	0.00037	1.00	2736	1368	911
3	**1.50**	**0.0000015**	**1462**	**0.00219**	**0.50**	**228**	**114**	**76**
3	**1.00**	**0.000001**	**1462**	**0.00146**	**0.50**	**342**	**171**	**114**
3	**0.50**	**0.0000005**	**1462**	**0.00073**	**0.50**	**684**	**342**	**228**
3	**0.25**	**0.00000025**	**1462**	**0.00037**	**0.50**	**1368**	**684**	**456**
4	1.50	0.0000015	1462	0.00219	0.24	109	55	36
4	1.00	0.000001	1462	0.00146	0.24	164	82	55
4	0.50	0.0000005	1462	0.00073	0.24	328	164	109
4	0.25	0.00000025	1462	0.00037	0.24	657	328	219

Table 4. Scenarios for the time to fill the entire, 1/2, and 1/3 the volume of each lake level with deltaic deposits using four different erosion rates. These calculations assume the volume to fill with sediment is empty at time of filling each lake level. Thus, these are certainly overestimating the volume to fill and thus overestimating the time to fill the basin.

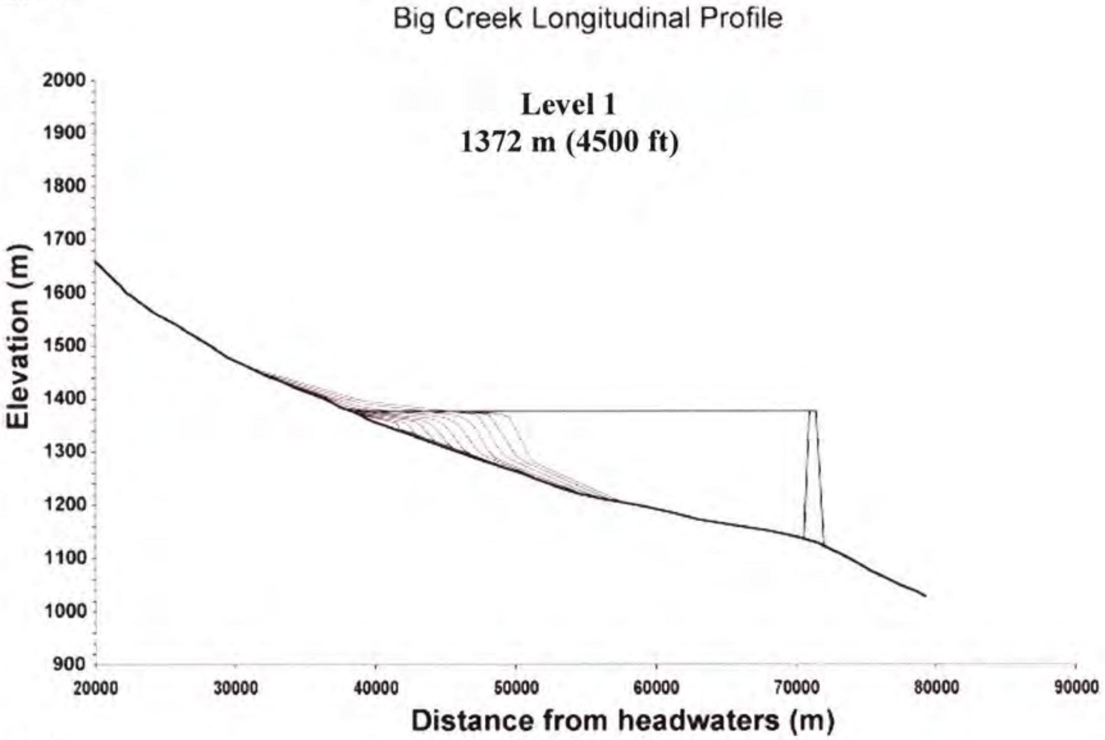
I infer that Level 2 filled ~ 1/3 of the ~ 1.0 km^3 (.24 mi^3) volume of the basin based on topset and foreset beds of rounded fluvial gravel and cobbles present on the hillslopes in Cabin Creek up to elevations of 1325 m (4340 ft) (Figure 20 B).

Filling the volume of Level 3 to 1/3 of the volume at an erosion rate of 0.5 – 1.0 mm/yr would have taken ~ 230 – 450 years. I chose 0.5 – 1.0 mm/yr as the erosion rate because it is a conservative estimate and the amount of time is reasonable. The majority of sediments deposited into this lake level would have been remobilized sediments from Levels 1 and 2.

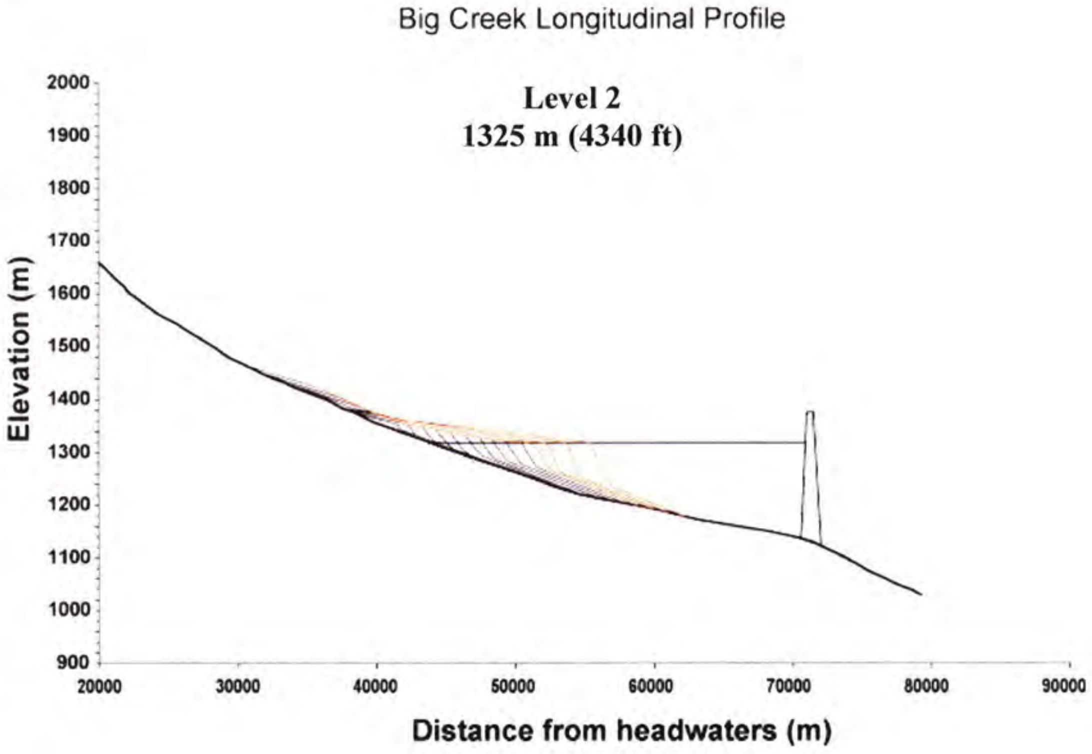
I infer that Level 3 filled ~ 1/2 of the 0.5 km^3 (0.12 mi^3) volume, and maybe more based on the amount of sediment deposited as foreset beds on the terrace located at Taylor Ranch (Figure 20 C). This is due to the amount of sediment input from the Cave, Cabin and Rush Creek tributaries flowing into Level 3 as well as remobilized sediment from Levels 1 and 2. The time for this lake level to have filled half its volume is ~ 350 – 170 years.

Level 4 filled entirely with deltaic deposits (Figure 20 D), deduced from the rounded fluvial gravel on the lower Soldier Bar spillway and the short amount of time to fill the entire lake basin. At most this lake level would have taken ~ 650 years to fill using the lowest estimated erosion rate. Considering the amount of sediment being remobilized from deltas in Levels 1 – 3 by the river as the dam was incised and the amount of sediment already present from the existence of Level 3 makes it plausible this lake level was completely filled. I infer that Levels 1 – 3 never completely filled with deposits considering the time it would take to fill the entire basin based on the calculations and the evidence mentioned above about the spillways.

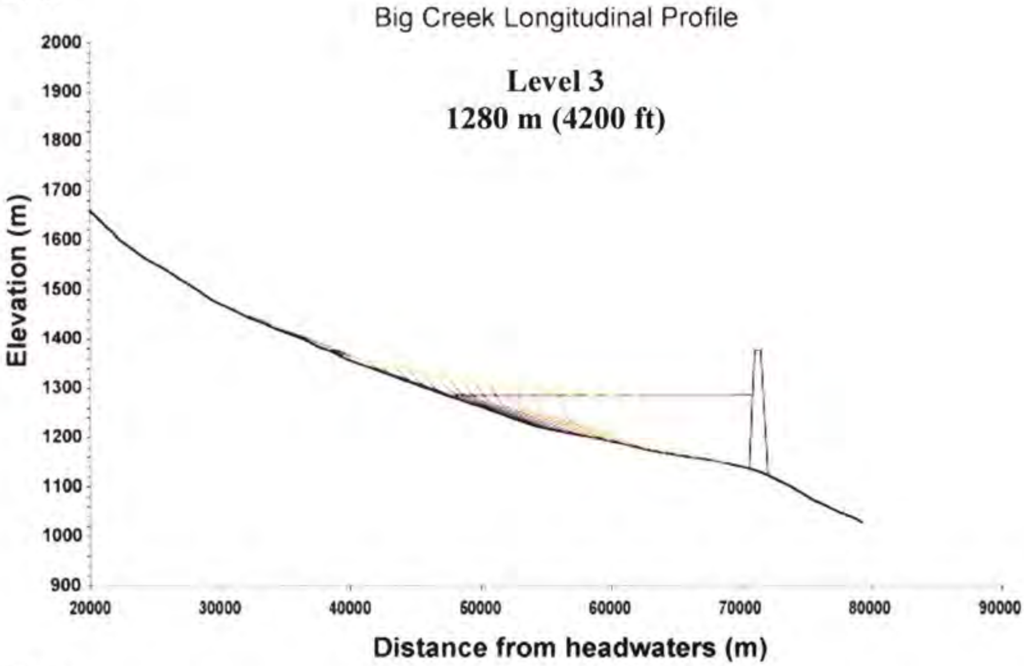
20 A


Big Creek Longitudinal Profile
Level 1
1372 m (4500 ft)
Elevation (m)
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
20000
30000
40000
50000
60000
70000
80000
90000
Distance from headwaters (m)

20 B


Big Creek Longitudinal Profile
Level 2
1325 m (4340 ft)
Elevation (m)
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
20000
30000
40000
50000
60000
70000
80000
90000
Distance from headwaters (m)

20 C



20 D

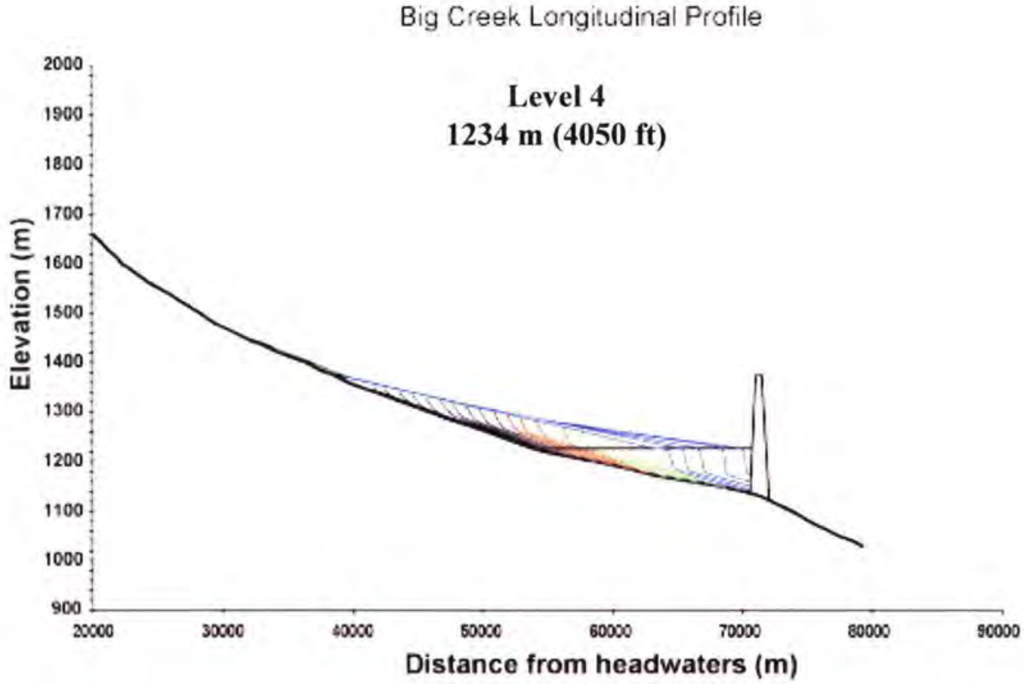


Figure 20. Diagrams A – D show filling scenarios of each lake level with delta fans. A.) Shows the filling of lake level 1 1/3 full. B) Shows the filling of lake level 2 1/3 full and the unconformity from remobilization of sediments from lake level 1. C) Shows the filling of lake level 3 1/2 full and the unconformity from remobilization of sediments from lake levels 1 and 2. D) Shows lake level 4 completely filled with delta deposits and the unconformity formed from remobilization of sediment deposited in lake levels 1-3.

The calculations do not take into account that aggradation would have also taken place in the area upstream of the lake levels. Aggradation upstream of the lake levels would decrease the amount of sediment delivered to the basins and increase the amount of time it would take to fill the lake levels with sediment.

6.4 Geomorphic Features

The geomorphic map and longitudinal profile of Big Creek shows the many surficial features that formed as a result of and correlate to the impoundment of Big Creek. These include spillways, shorelines, terraces, deltaic deposits and other landslides throughout the Big Creek drainage. Many of the terraces and shorelines are fill-cut in origin because they were cut into deltaic deposits and colluvium as lake levels dropped.

Shorelines in the Vines, Cabin Creek and Taylor Ranch areas represent the elevations of the four lake levels. The surfaces of the shorelines are covered by fluvial gravel and cobbles, which were deposited by the deltaic deposits prograding into the lake levels from Big Creek. The gradient of the shorelines indicated by the total station data is toward Big Creek rather than in the downstream direction. This indicates that the surfaces in Cabin Creek are probably shorelines rather than terraces formed during the incision of the Soldier Bar landslide.

Tributary alluvial fans are present throughout the Big Creek drainage. Alluvial fans, such as the fans formed by Pioneer Creek, Cliff Creek and Cougar Creek, were deposited below all four of the lake levels during post landslide incision. I infer this based on their elevations and relationship to lake levels from the geomorphic map.

Tributary delta fans were deposited into the lake levels. I interpret delta fans based on their elevation and relationship to the lake levels. The difference between alluvial fans and delta fans is the depositional environment in which they were formed. Alluvial fans were formed by tributaries depositing sediment onto a sub aerial surface at the mouth of a river and delta fans were formed by tributaries depositing sediment into a body of water.

6.5 Conclusions

The Soldier Bar landslide had a significant impact on the geomorphology of Big Creek as indicated by the spillways, shorelines, deltaic deposits and the length of time the landslide was in place. The Soldier Bar landslide caused a rise in base level and aggradation that persisted in Big Creek for at least 6,000 years.

6.6 Future Work

The triggering mechanism for the landslide is unknown and difficult to determine. Further geologic mapping and sedimentology of the landslide must be done to understand the geotechnical parameters of failure for the Soldier Bar landslide.

In order to obtain an age for the timing of the landslide event cosmogenic dating could be done by collecting samples from the top and toe of the landslide deposit. Additional optically stimulated luminescence ages could be obtained from other sediments on terraces throughout Big Creek in order to better constrain the ages of the landslide and lake filling event.

The incision and uplift histories of Big Creek would increase the knowledge of Neogene drainage changes in central Idaho related to the migration of the Yellowstone Hot Spot and Basin and Range extension. This excellent record of fluvial dynamics and incision rates over the last 100 ka or longer may allow estimates of long-term incision rates for central Idaho.

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APPENDIX A: TERRACE DATA

Features, such as terraces, spillways, and shorelines, were plotted on the longitudinal profile using the elevations and locations determined from GeoXT acquisitions and topographic maps. The horizontal error in GeoXT acquisitions is within one meter (~3 ft). The error for plotting features determined from the topographic maps is ~ 7 m (20 ft) on maps with 40 ft contour intervals and ~ 14 m (40 ft) on maps with 80 ft contour intervals. Locations of features were determined using meters upstream from the confluence of Big Creek and the Middle Fork Salmon River see table below.

Distance from mouth (m)	Elevation (m)	Location of Surface
0.0	1036	
160.9		
321.9		
482.8	1049	
643.7		
804.7		
965.6	1134	
1126.5	1091	
1287.5		
1448.4		
1609.3		
1770.3		
1931.2		
2092.1		
2253.1		
2414.0		
2574.9		
2735.9		
2896.8		
3057.7		
3218.7		
3379.6		
3540.5		
3701.5		
3862.4		
4023.4	1225	

4184.3	1195	
4345.2		
4506.2		
4667.1		
4828.0		
4989.0		
5149.9	1109	
5310.8		
5471.8	1122	
5632.7		
5793.6	1225	
5954.6	1280	Upper Soldier Bar 3
6115.5	1235	Lower Soldier Bar 4
6276.4		
6437.4	1250	
6598.3	1146	
6759.2	1146	
6920.2	1280	GCLS 3
7081.1	1324	GCMS 2
7242.0	1372	GCHS 1
7403.0		
7563.9		
7724.8		
7885.8	1146	
8046.7	1267	
8207.6	1146	
8368.6		
8529.5		
8690.4	1146	shoreline
8851.4	1164	shoreline
9012.3		
9173.2		
9334.2		
9495.1	1164	
9656.0		
9817.0		
9977.9	1317	
10138.8	1234	tayter
10299.8	1237	
10460.7		
10621.6		
10782.6		
10943.5	1158	
11104.4	1158	
11265.4		
11426.3		
11587.2	1341	
11748.2		

11909.1		
12070.1		
12231.0		
12391.9		
12552.9		
12713.8	1164	
12874.7		
13035.7	1164	
13196.6		
13357.5		
13518.5		
13679.4	1225	
13840.3	1164	
14001.3		
14162.2		
14323.1		
14484.1	1189	
14645.0		
14805.9		
14966.9		
15127.8	1234	plane turn around
15288.7		
15449.7		
15610.6	1195	
15771.5	1183	
15932.5	1195	Shoreline
16093.4	1207	Shoreline
16254.3		
16415.3		
16576.2		
16737.1		
16898.1		
17059.0		
17219.9		
17380.9	1177	
17541.8	1177	
17702.7		
17863.7	1228	
18024.6		
18185.5	1353	
18346.5	1230	
18507.4		
18668.3	1219	
18829.3		
18990.2	1250	mouth of cabin area
19151.1		
19312.1	1280	
19473.0	1268	Shoreline above brown

19473.0	1265	yellow
19473.0	1241	between B & Y
19473.0	1231	Brown
19633.9		
19794.9	1231	
19955.8	1234	Shoreline S side
19955.8	1244	Shoreline S side
20116.8	1231	Shoreline N side
20116.8	1250	Shoreline N side
20277.7	1231	Shoreline N side
20438.6		
20599.6	1231	Shoreline N side
20760.5	1225	Shoreline N side
20921.4	1213	
21082.4	1225	Shoreline N side
21082.4	1274	Shoreline N side
21243.3	1231	Shoreline N side
21243.3	1256	Shoreline N side
21243.3	1268	Shoreline N side
21404.2	1259	Shoreline N side
21404.2	1280	Shoreline N side
21404.2	1292	Shoreline N side
21565.2	1231	Shoreline N side
21565.2	1256	Shoreline N side
21565.2	1280	Shoreline N side
21565.2	1292	Shoreline N side
21726.1		
21887.0	1280	S side
21887.0	1329	S side
21887.0	1338	S side
22048.0	1231	S side
22208.9	1262	Cave Cr.
22369.8		
22530.8	1244	S side
22691.7	1245	N side
22852.6	1250	S side
23013.6	1250	N side
23013.6	1262	N side
23174.5		
23335.4	1262	S side
23496.4		
23657.3	1265	N side
23818.2		
23979.2		
24140.1	1292	S side
24301.0	1268	S side
24462.0		
24622.9	1262	N side

24783.8		
24944.8		
25105.7	1271	Vines S side
25105.7	1271	N side
25266.6		
25427.6		
25588.5		
25749.4	1274	Vines S side
25910.4	1274	N side
26071.3	1311	S side
26232.2		
26393.2	1277	S side
26393.2	1353	S side
26554.1	1277	N side
26715.0		
26876.0	1298	S side
26876.0	1628	Mile Hi N side
26876.0	1707	Mile Hi N side
27036.9	1280	S side
27197.8		
27358.8		
27519.7		
27680.6		
27841.6	1298	S side
28002.5	1317	S side
28002.5	1341	S side
28163.5	1298	S side
28324.4	1298	S side
28485.3	1298	N side
28646.3		
28807.2		
28968.1		
29129.1	1305	Coxey Hole N side
29290.0		
29450.9		
29611.9		
29772.8	1305	N side
29933.7		
30094.7	1305	S side
30255.6		
30416.5	1305	Soft Boil Bar N side
30577.5	1311	S side
30738.4		
30899.3	1311	S side
31060.3		
31221.2		
31382.1		
31543.1		

31704.0		
31864.9	1314	S side
32025.9	1335	Hard Boil N side
32186.8		
32347.7	1314	N side
32347.7	1323	S side
32508.7		
32669.6		
32830.5		
32991.5	1341	N side
32991.5	1341	S side
33152.4	1341	S side
33313.3	1341	N side
33474.3		
33635.2		
33796.1	1341	AcornS side
33957.1	1344	N side
34118.0		
34278.9		
34439.9	1344	N side
34439.9	1344	S side
34600.8		
34761.7	1344	N side
34761.7	1344	S side
34922.7		
35083.6		
35244.5		
35405.5		
35566.4	1359	S side
35727.3	1359	N side
35888.3	1366	S side
36049.2		
36210.2		
36371.1		
36532.0		
36693.0		
36853.9		
37014.8		
37175.8		
37336.7		
37497.6		
37658.6		
37819.5		
37980.4		
38141.4		
38302.3		
38463.2	1372	Monumental N side
38624.2	1372	S side

38785.1	1375	N side
38946.0		
39107.0	1396	N side
39107.0	1414	S side
39267.9		
39428.8		
39589.8	1396	N side
39750.7		
39911.6		
40072.6		
40233.5		
40394.4		
40555.4	1408	N side
40716.3		
40877.2		
41038.2	1408	N side
41199.1		
41360.0		
41521.0		
41681.9		
41842.8		
42003.8	1439	S side
42164.7		
42325.6		
42486.6		
42647.5	1487	S side
42808.4	1439	S side
42969.4		
43130.3		
43291.2		
43452.2		
43613.1		
43774.0		
43935.0		
44095.9		
44256.9		
44417.8	1442	S side
44578.7		
44739.7		
44900.6		
45061.5	1652	S side
45222.5		
45383.4		
45544.3	1448	S side
45705.3		
45866.2		
46027.1		
46188.1		

46349.0	1475	Copper Camp N side
46509.9		
46670.9	1506	N side
46831.8	1475	S side
46992.7	1475	N side
47153.7		
47314.6		
47475.5		
47636.5		
47797.4		
47958.3		
48119.3	1487	N side
48119.3	1487	S side
48280.2		
48441.1	1579	S side
48441.1	1600	S side
48602.1	1609	N side
48763.0		
48923.9	1600	S side