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Late Holocene Paleoflood Hydrology of the Snake River in the Lower Hells Canyon, Idaho

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LATE HOLOCENE PALEOFLOOD HYDROLOGY OF THE SNAKE RIVER IN THE LOWER HELLS CANYON, IDAHO

A Thesis
Presented to
The Graduate Faculty
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In Partial Fulfillment
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Master of Science
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by
Kent Carter Allen
November 2020

ABSTRACT

LATE HOLOCENE PALEOFLOOD HYDROLOGY OF THE SNAKE RIVER IN THE LOWER HELLS CANYON, IDAHO

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The Snake River watershed spans a large geographic region from the Rocky Mountains to the inland Pacific Northwest, and a comprehensive paleoflood chronology on the mainstem of the river is key to identifying the frequency and magnitude of large prehistoric floods within the region. We examined and compared four sites of slackwater deposits along a 20-km reach of the Lower Hells Canyon on the Snake River, Idaho. The sites contain evidence of up to 34 paleofloods within the last 1700 years. Stratigraphic breaks, soils, and in-situ plant or archaeological materials demarcate distinct layers that represent discrete paleoflood events. Radiocarbon dates from *in-situ* and transported charcoal constrain the ages of stratigraphic sequences with similar sedimentological characteristics.

The spatially coherent pattern in the paleoflood deposition and chronology over the last 1700 years in the lower Hells Canyon indicates a relatively consistent geomorphic environment in which the accumulation and preservation of paleoflood sediments is not significantly influenced by variations in the morphology of individual sites. This coherence is likely due to a slight widening of the canyon where the bedrock transitions from the hard, accreted metamorphic terrane of Hells Canyon to the basalt of the Columbia Basin, which accommodates the abundant slackwater deposition of fine sand and silt downstream of alluvial fans and in long benches along the channel margins. These geomorphic settings provide longer-term stability or protection of deposits from erosion by channel migration and undercutting from subsequent floods.

Hydraulic modeling of the study reach using HEC-RAS and Lidar data indicates that the flow necessary to overtop the existing deposits is approximately 6,500 m^3 s^{-1} (230,000 ft^3 s^{-1}). The Snake River Flood Terrace has a record of 2-4 large flood events within the last 300 years. Combining this information leads to the conclusion that these four recent prehistoric floods were larger than 6,500 m^3 s^{-1} (230,000 ft^3 s^{-1}) in magnitude. A comparison with the historic record indicates that the largest flood in the 62-year gage record at Anatone, WA of 5,520 m^3 s^{-1} (195,000 ft^3 s^{-1}) in 1974 is insufficient to overtop the Snake River Flood Terrace. However, one of the flood deposits from the last 300 years may be the result of a large flood in 1910 recorded within the 110-year gage record from Weiser, Idaho.

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I dedicate this work to my children, Elliotte and Kamden. With enough determination and perseverance anything is possible.

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CHAPTER I

INTRODUCTION

Paleohydrology, the science of prehistoric floods, has become an effective and recognized tool used to better identify and understand the true paleohydrologic regime of rivers throughout North America and the world. Large prehistoric floods, or paleofloods, generally leave behind evidence such as high-water marks or slackwater deposits. Slackwater deposits consist of fine-grained sediments deposited from suspension in areas of slow-moving water such as alcoves or along the margins of a channel during a large flood event. Given the right conditions, this evidence can persist for thousands of years. Stratigraphic and hydraulic analysis of these slackwater deposits can help identify the frequency and magnitude of prehistoric floods. The Snake River in lower Hells Canyon above the confluence with the Clearwater River near Lewiston, Idaho is a prime candidate for paleohydrologic analysis in that it exhibits many of the geological and environmental factors necessary for slackwater deposition and preservation. Additionally, the relatively short 62-year historic record of discharge on the lower Snake River, Idaho is insufficient to effectively characterize the hydrologic regime of the river, particularly extreme flood events that could negatively affect valuable infrastructure downstream such as cities and hydroelectric dams.

The purpose of this study is to determine the broader spatial and temporal extent of a semi-continuous, 20-km long flood terrace, informally named the Snake River Flood Terrace (Trosper, 2011), that was formed by slackwater deposition along the margins of the Snake River. In addition, this study used one dimensional hydraulic modeling to determine the flood magnitude required to crest the top of the Snake River Flood Terrace.

To do this, three sites were selected along the Snake River Flood Terrace that exhibit robust evidence of paleoflood deposition. This study will be added and compared to a previous paleoflood study conducted at Redbird Beach located within the Snake River Flood Terrace to determine how variations in location geometry affect the paleoflood record (Rhodes, 2001; Trosper, 2011). The addition of this study to the Snake River paleoflood catalog will help build a more robust paleoflood history for this reach of the river.

The objectives of this study are to:

1) determine the Holocene paleoflood history of the Snake River in the lower Hells Canyon by describing and dating slackwater deposits at three new sites and one previously studied site located within the Snake River Flood Terrace;

2) compare and correlate the slackwater stratigraphy and chronology among the four sites to assess the effects of local or regional geomorphic characteristics on the accumulation and preservation of slackwater deposits;

3) determine the magnitude of the largest paleofloods identified at these sites using HEC-RAS 1-D hydraulic modeling and compare with historic flood records from upstream gage stations.

The addition of the paleoflood records from the Ten Mile Creek, Dietrich, and Bobcat Bar sites to the findings from previous studies at Redbird Beach, Tin Shed and China Rapids, will improve our understanding of the paleohydrologic regime of the Snake River by extending the flood record and possibly filling in gaps not previously observed. Additionally, comparisons of the geomorphic settings between sites will provide useful information on how geomorphological differences censor the paleoflood record spatially and temporally. This comprehensive paleoflood study will also fill an important spatial gap in the regional flood catalogue because the Snake River covers a large geographic area that spans from the Rocky Mountains to the Columbia Basin. By expanding paleoflood record on the Snake River, this study will enhance the regional paleoflood database that includes the Columbia, John Day, Deschutes, Owyhee, and Salmon Rivers (Chatters & Hoover, 1986, 1992; Hosman, 2001; Hosman et al., 2003; Vandal, 2007; Orth, 1998; Davis & Schweger, 2004). This will allow future studies to refine our understanding of the climatic conditions necessary to cause large floods events in the Snake River watershed and possibly throughout the Pacific Northwest. Additionally, identifying the magnitude of the most recent prehistoric flood events could provide useful information that downstream communities and federal agencies, such as the U.S. Army Corps of Engineers, can use to improve flood mitigation practices.

Paleohydrology and Slackwater Deposits

The Snake River within the lower Hells Canyon (Figure 1) is an ideal location for paleoflood analysis based on characteristics necessary for slackwater deposition as defined by Jarret and England (2002) and Baker (1987). These factors include, but are not limited to, a confined bedrock canyon and an arid to semiarid environment (Jarret & England, 2002; Baker, 1987). Bedrock river channels are preferred for paleoflood studies because they confine large floods, resist lateral erosion, and can remain stable for long periods of time (Ely, 1997). By confining large floods, narrow bedrock channels provide the conditions necessary for significant increases in flow depth and flow speed, causing sediments to be suspended in the high flow velocities and turbulent currents. However, specific geomorphic settings, such as eddy zones, back-water tributaries, and abruptly widening channels, as is the case for the reach downstream of Hells Canyon, reduce flow velocities, allowing fine grain sediments, generally silt and sand, to be rapidly deposited from suspension and form slackwater deposits (Baker, 1987). Due to their high elevation

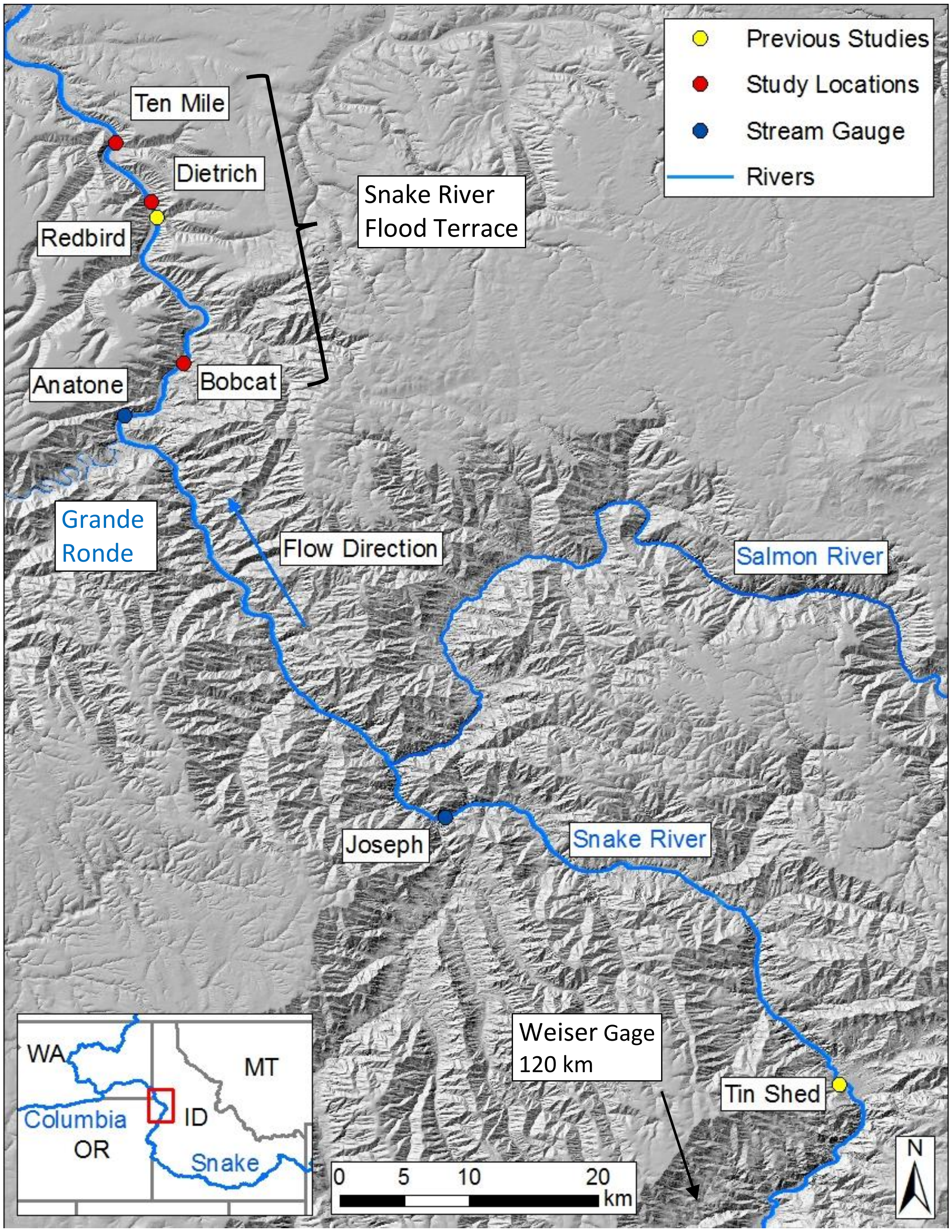

Figure 1. Regional map of the Lower Hells Canyon reach of the Snake River. Red points show the site locations of this study, yellow points indicate the location of previous studies (Rhodes, 2001; Trosper, 2011), and blue points show the locations of the Anatone, Joseph and Weiser stream gages. The bracket indicates approximate extent of the Snake River Flood Terrace and study reach. The inset map shows the location of the study area within the Pacific northwest and its relation to the Columbia and Snake rivers.

within the channel, slackwater deposits are protected and preserved from the erosion of average hydrologic events such as spring runoff. Rivers with semiarid to arid climates are preferred slackwater study locations due to reduced biologic activity. This reduction in biological activity increases the likelihood that the stratigraphy, structure, and organic materials, such as charcoal, within these deposits will be preserved (Baker, 1987).

Preserved sediments at sites of slackwater deposition can be differentiated by variety of structural and visual identifiers. These structures and visual identifiers include stratigraphic breaks, changes in sedimentation patterns, variations in color, and indicators of subaerial exposure such as soil horizons and *in situ* plant material (Kochel & Baker, 1982; Macklin et al., 1992; Ely et al., 1996). One such structure is stratigraphic sequence called a silt/sand couplet. The upper and lower contact of silt/sand couplets are sharp and generally exhibit an inversely graded middle contact that fines upward from silt to fine sand. Each layer of silt, sand, or couplet of silt and sand in a stratigraphic series of slackwater deposits, depending on the depositional pattern of the river, represents a single flood event. Other paleoflood indicators include boulder bars, trim lines, wrack lines, perched debris, tree scares and flood terrace elevation. All are paleostage indicators providing a minimum elevation for the paleoflood that created them (Jarrett & England, 2002).

Regional Paleoflood History

Paleoflood investigations can extend the flood history of a river, improve estimates on the frequency of large flood events, and, when possible, determine the minimum magnitude of the largest paleofloods events identified (Chatters & Hoover, 1986; Ely, 1997; Hosman et al., 2003; Harden et al., 2011; Greenbaum et al., 2014);

Kohn et al., 2015.) A paleoflood investigation conducted in eastern Colorado improved upon peak-streamflow regional-regression equations for natural streamflow in the region (Kohn et al., 2015). In addition, numerous paleoflood studies have found that the paleoflood regime of many rivers throughout western North America are more variable than their relatively short historic records indicate. These studies found that this variability is likely due to centennial to millennial scale fluctuations in regional and or global climate (Chatters & Hoover, 1992; Ely, 1997; Greenbaum et al., 2014). A relatively large focus of paleoflood studies completed within the Columbia Basin has been on the catastrophic outburst floods of glacial Lake Missoula (Bretz, 1969; O'Connor & Baker, 1992; Smith, 1993) and Lake Bonneville (O'Connor, 1993) that occurred during the late Pleistocene. Additional Holocene paleoflood studies have been conducted on rivers within the Columbia Basin and Pacific Northwest. These rivers include the Columbia River (Chatters & Hoover, 1986, 1992), the Deschutes River (Hosman, 2001; Hosman et al., 2003), the Owyhee River (Vandal, 2007), John Day River (Orth, 1998), Salmon River (Davis & Schweger, 2004), and the Snake River (Rhodes, 2000; Trosper, 2011).

Late Holocene paleoflood studies conducted on the Deschutes and Owyhee Rivers found geological evidence of high magnitude, low frequency floods, the size of which had not been observed over the last century of hydrologic monitoring on these rivers. In addition, these paleohydrologic studies indicate that the recurrence of large flood events can vary greatly from flood frequency predictions derived solely from historical records (Hosman et al., 2003). In contrast, other paleoflood studies have identified modern floods as large as any in the paleofloods record (Chatters & Hoover, 1986; Vandal, 2007).

Paleoflood studies of this type are useful in that they can improve flood analysis estimates of infrequent, high magnitude floods (George et al., 2020). Improvements in estimation of high magnitude, low frequency floods can help water management agencies such as the U.S. Army Corps of Engineers and the Bureau of Reclamation identify deficiencies in the design of dams, dikes, and other structures affected by flooding (Baker et al., 2002).

Multiple paleoflood studies have identified variability in paleoflood frequency through time. Chatters and Hoover determined that the frequency of large paleofloods on the Columbia River before AD 1020 and after AD 1390 were similar to the historic flood frequencies recorded in the twentieth century. However, they also found that large paleofloods were three to four times more common between 1020 and 1390 A.D. (Chatters & Hoover, 1986). Additional paleoflood studies conducted throughout western North America have identified centennial-scale variations in the frequency of paleofloods (Chatters & Hoover, 1986; Ely, 1997; Rhodes, 2000; Greenbaum et al., 2014). These studies concluded that this variability in paleoflood frequency is likely caused by shifts in climate.

Previous Snake River Studies

Prior to this study, two paleoflood studies (Figure 1) have been conducted in the Hells Canyon reach of the Snake River (Rhodes, 2001; Trosper, 2011). Rhodes used geologic evidence within slackwater deposits to identify a 5000-yr record of more than 22 paleofloods at the Tin Shed and China Rapid sites. The paleoflood record at these sites also showed a hiatus in paleoflood activity from 1319 - 510 BP. A comparison of historic flood and climate records led Rhodes to conclude that low-pressure weather systems derived from the Northern Pacific are the primary mechanism for large winter and spring floods that created the paleoflood record observed at the Tin Shed and China Bar sites within Hells Canyon on the Snake River. Winter storms in the form of low elevation rain on snow events and or rain on frozen ground events that cover a large geographic area likely produce the largest floods on the Snake River because the bulk of the precipitation is discharged from the system as surface water. Large spring runoff events can also produce large floods but not in at the same scale as large as winter rain on snow events because snowpack generally melts slowly over a long period time and also recharges ground water tables.

Trosper (2011) conducted a geoarchaeological study with the lower reach of Hells Canyon to determine how large paleofloods on the Snake River affected human occupation and the preservation of archeological materials on the flood terrace at Redbird Beach. Trosper (2011) identified four progressively younger sets of slackwater strata at Redbird Beach that revealed a complex paleoflood chronology. Analysis of the two oldest slackwater sections identified a 2300-year record that contained evidence of as many as 30 large paleofloods; the two younger, lower-elevation insets recorded approximately 200 smaller floods (Trosper, 2011).

Regional Setting

The Snake River, the largest tributary of the Columbia River, drains an area of approximately 280,000 square kilometers (108,000 square miles) that covers mostly southern Idaho and parts of Montana, Utah, Nevada, Wyoming, Oregon, and Washington (Figure 1). The Snake River Basin is bounded by the Rocky Mountains to the northeast, the Basin and Range province to the south, and the Columbia Basin to the northwest. The

Snake River headwaters begin in the Rocky Mountains of Yellowstone National Park in Northwestern Wyoming. From there the river flows southwest tracing in reverse the path of the Yellowstone Hotspot through the Snake River Plain of southern Idaho. Near the border of southeastern Oregon and southwestern Idaho the Snake River cuts north through Hells Canyon. The 160 km reach of Hells Canyon is bounded by the Oxbow Dam to the south and the confluence of the Clearwater with the Snake River to the north. This study is located on a 20-km reach of the Snake River directly downstream of the confluence of the Grand Ronde River in lower Hells Canyon (Figure 1). From the Clearwater River, the Snake River flows west through the Columbia Plateau to its ultimate convergence with the Columbia River in southeastern Washington.

Climate

Lower Hells Canyon exhibits a semi-arid climate that averages of 326 mm (13 in) of precipitation annually. This high desert environment is greatly influenced by the rain shadow effect caused by the Cascade Mountains in Western Oregon and Washington. Approximately 45 percent of annual precipitation falls within the months of November through January with only 9 percent falling between July and September. Temperature range from 0 ^{o}C (32 ^{o}F) to 33 ^{o}C (92 ^{o}F) at the bottom of Hells Canyon (Tisdale et al., 1969; Johnson and Simon, 1987; Rocklage et al., 2001). From late fall to early spring cool, moist weather systems derived from the North Pacific created storms that impact the Snake River drainage. During the summer months, systems of high pressure develop which greatly reduce precipitation (Ross and Savage 1967; Rhodes, 2001; Rocklage et al., 2001). The increase in precipitation during the winter months suggest that large floods are more likely to occur during this period within the Snake River basin.

Vegetation

Vegetation varies greatly due to complexities in topography and soils throughout Hells Canyon which blend together to form a mosaic of vegetation types that include grassland, shrubland, riparian, and coniferous forests environments (Tisdale, 1979; Rocklage et al., 2001). Riparian vegetation observed at each of the sites of study include, black hawthorn, syringa, hackberry and black cottonwood. Cheatgrass and bunch grasses dominate the surface of the terraces along with a variety of sagebrush species and infrequently observed ponderosa pine. Historically, the presence of woody shrubs, sages and trees is likely the source of *in situ* charcoal and carbonized plant material observable within the stratigraphy that can be sampled for radiocarbon dating analysis to constrain the age of slackwater deposition.

Geologic Setting

The upstream end of the 20-km study reach begins downstream of the confluence of the Grande Ronde River with the Snake River in lower Hells Canyon. Here the Snake River canyon widens as the bedrock transitions from the hard, accreted metamorphic terranes of Hells Canyon to the relatively softer basalt of the Columbia Basin. The upstream Hells Canyon region primarily consists of metamorphosed oceanic crust and volcanic island arcs originating from the ancestral Pacific Ocean that accreted via subduction against the North American continent during the late Mesozoic (Vallier, 1998).

During the middle Miocene, fissures opened in northeastern Oregon and southwestern Washington and erupted enormous amounts of basalt across northern Oregon, central and eastern Washington, and Western Idaho. These eruptions occurred multiple times from approximately 18-12 Ma, creating the many basalt layers of the Columbia River Basalts (CRBs) that compose the Columbia Plateau. The basalts layers that make up the canyon walls and channel of the Snake River within the study reach are from the Grande Ronde Group of the CRBs that erupted approximately 15 Ma (Vallier, 1998).

During the Pleistocene approximately 14,500 years ago, the high stand of pluvial Lake Bonneville breached the divide between the Bonneville basin and Snake River watershed near Red Rock Pass, Idaho. The resulting catastrophic outburst flood with a maximum peak discharge of approximately 1.0 million cubic m/s swept west across the Snake River plain downstream through Hells Canyon, the Columbia River Gorge, and finally the Pacific Ocean (O'Connor, 1993). The Bonneville Flood contributed to the modern morphology of Hells Canyon through depositional and erosional processes that deepened the channel and left behind massive fluvial structures such as flood terraces and boulder bars. In some places these Bonneville flood structures create a depositional environment where younger slackwater deposits are deposited and preserved in the upper reaches of Hells Canyon (O'Connor, 1993; Rhodes, 2001).

Historically, the supply of sand necessary to form slack water deposits in lower Hells Canyon is from the quartz-rich granite batholith located in the Salmon River Watershed, the metamorphic rocks of upper Hells Canyon, and the igneous rocks of the Snake River Plain in Southern Idaho. However, the sand supply from southern Idaho has been cut off since construction of the Hells Canyon Dam in 1967. Thus, sand is scarce in the upper Hells Canyon upstream of the confluence of the Salmon River. Sand supplies appear to be sufficient to form slackwater deposits in the lower reaches of Hells Canyon due to sand recharge derived from the Salmon River and Grande Ronde River watersheds.

Snake River Flood Terrace

The Snake River Flood Terrace is approximately 20 km in length and is located on the east bank of the Snake River (Figure1). Geographically, the Snake River Flood Terrace first appears downstream of the confluence of the Grande Ronde River and extends downstream approximately 20 km to Asotin, WA. The Snake River Flood Terrace is discontinuous in the upper 10-12 km of the study reach but becomes continuous and easily traceable for the last 8-10 km. The flood terrace is approximately 6-8 meters above the Snake River during summer flows that average approximately 500 cubic m/s (20,000 cubic ft/s).

Initial fieldwork for this study identified multiple potential study locations along the Snake River Flood Terrace. These sites primarily contain slackwater deposits of fluvial silt and sand layers interbedded with alluvial and colluvial basalt clasts that eroded from the walls of the Snake River Canyon. Of the multiple sites identified along the study reach, three sites of slackwater deposition were chosen for this study (Fig. 1). The Ten Mile Creek study site is located at the north end of the study reach approximately 9 km upstream of Asotin, WA. The Dietrich site is located approximately 5 km upstream (south) of Ten Mile Creek and approximately 1km downstream of previously studied paleoflood site at Redbird Beach (Trosper, 2011). The third study site, Bobcat Bar, is located approximately 10 km upstream from the Redbird site. A second paleoflood study was conducted on the Snake River at the Tin Shed and China Rapid sites (Rhodes, 2001). The Tin shed and China Rapids sites are located in the upper Hells Canyon approximately 90-km upstream of the Snake River Flood Terrace study reach that contains the Ten Mile Creek, Dietrich, Redbird Beach, and Bobcat Bar sites.

CHAPTER II

METHODS

Site Characteristics

Site reconnaissance and fieldwork for this study was conducted during the summer field season of 2015. Three sites of paleoflood deposits were identified and described using a combination of methods that include field observations and geochronology. These sites were chosen for this study based on ease of access and observation, slackwater deposit height, distribution within the channel, and similarities in geomorphic settings. Undercutting by the river has formed nearly vertical cut banks in the terrace that clearly exhibit the layered stratigraphy of the slackwater deposits. Selected sites were either accessible by road or kayak via the Snake River Road on the Washington side of the river. Sites with tall exposures of slackwater deposition were preferred because they should contain a more complete paleoflood record of the Snake River. Sites that contained a mixture of depositional facies, such as alluvial and colluvial deposits, were not selected for this study. Site distribution was also a factor for site selection; two sites were selected at the far upstream, Bobcat Bar, and downstream, Ten Mile Creek, ends of the 20-km study reach. A third site, Dietrich, was chosen to compare with the adjacent, previously studied Redbird Beach site (Trosper, 2011). Each site of slackwater deposition identified within the study reach appeared to be part of the Snake River Flood Terrace that makes up much of the Idaho bank within this reach of the Snake River. This would suggest that these sites have similar geomorphic settings which, in turn, could indicate that they have similar paleoflood histories. However, slight differences in geomorphic settings could influence the deposition and preservation of paleoflood deposits which would lead to differences in the temporal distribution, frequency, and magnitude of paleoflood events between study sites.

All three sites had easily accessible, tall exposures of stratigraphy that were primarily composed of slackwater deposits which were found downstream of alluvial fans. A comparison of the stratigraphic record and the geomorphic setting of the Ten Mile Creek, Dietrich, and Bobcat Bar sites with those described in a previous study conducted at Redbird Beach (Trosper, 2011) was used to help determine if the paleoflood record is consistent across the length of the Snake River Flood Terrace (Figure 1).

Stratigraphic Analysis

The sedimentary layers that represent individual paleoflood events within slackwater deposits can differ between watersheds, locations on the same river, or even within a single deposit depending on the variability of individual flood characteristics and the geomorphic setting of each location. According to Kochel and Baker (1982), each unit in a vertical stratigraphic series identified as a slackwater deposit represents a single flood event, with discrete flood events distinguished by abrupt stratigraphic breaks, changes in sedimentation patterns, variations in color, and indicators of subaerial exposure such as soil horizons and in situ plant material at stratigraphic boundaries (Kochel & Baker, 1982). However, other depositional processes are capable of depositing layers within a stack of slackwater deposits. These include but are not limited to colluvial deposits derived from erosion of the basalt canyon walls, alluvial deposits from adjacent upstream intermittent tributaries, and aeolian deposits or erosional features. Stratigraphic layers that did not meet the criteria for a slackwater deposit were not interpreted as flood events.

Examination of slackwater deposits at Ten Mile Creek, Dietrich, and Bobcat Bar revealed that the primary depositional pattern of stratigraphic layers on the Snake River downstream of Hells Canyon is of the form of silt/sand couplets. These couplets exhibit a sharp upper and lower contact with an inversely gradational contact between the lower silt and the overlying fine sand. Previous studies have interpreted slackwater deposits composed of individual layers of silt, sand, and couplets of silt and sand as single flood events if the boundary between these layers exhibits the characteristics described earlier that indicate a period of subaerial exposure between deposits (Ely et al., 1996; Rhodes, 2001). Based on these criteria, this study will interpret distinct individual layers of silt, sand, and couplets of silt and sand as discrete events produce by flooding of the Snake River.

The stratigraphy of the Ten Mile Creek, Dietrich, and Bobcat Bar study sites were described with the purpose of identifying the number of paleofloods that created the vertical sequence of slackwater deposits. Each site of slackwater deposition was described from the surface of the terrace downward to the bottom of the exposed cut bank surface. Distinct stratigraphic units at each site of slackwater deposition were described in the field using physical characteristics, which include depth within the stratigraphic column, color, grain-size, and stratigraphic boundaries. The depth to the top of each stratigraphic unit was measured and recorded in meters with zero being the surface of the flood terrace. The color of each unit was determined with the Munsell soil color classification system. The representative grain size of each stratigraphic unit was determined in the field from visual and tactile observations. Stratigraphic boundaries of each unit were also examined in the field to determine if they were sharp, gradational, wavy, convoluted, and or intermittent. Characteristics used to differentiate distinct flood units were changes in sediment color, abrupt changes in grain size, and evidence of subaerial exposure such as bioturbation of the upper contact and or the upper portion of the sediment layer and concentrations of organic material such as charcoal or preserved plant matter observed between the contact separating two stratigraphic units (Kochel & Baker, 1982; Macklin et al., 1992; Ely et al., 1996). An initial determination of the number of flood units present at each site was made in the field. However, the final number of flood events at each site was determined in the lab through the carefully examination of field notes and the creation of detailed stratigraphic columns.

Age Analysis

Samples of organic materials, such as charcoal, were collected and described from throughout each stratigraphic column with the purpose of constraining the age of each stack of slackwater deposits. Information collected in the field for each sample included the depth in meters from the surface, the stratigraphic unit it was collected from, if the sample was collected at a contact or from within a stratigraphic unit, a physical description of the sample, and if the sample appeared to be *in situ* or transported. Samples for radiocarbon analysis were initially described in the field and later reevaluated in the lab prior to dating to determine if they were *in situ* or emplaced during deposition.

In situ carbonized plant material and charcoal was sampled from the contact between two slackwater deposits. The presence of charcoal and or carbonized plant material located at the contact between two units indicates a period of subaerial exposure sufficient in length for woody plants such a sagebrush and other brush to grow to maturity. Later, these woody plants burned, the resulting charcoal left on the surface of the flood terrace was then buried and preserved by the sediments deposited by the subsequent flood. Alternately, charcoal identified at the contact between deposits could have been deposited by a nearby wildfire. This charcoal would have been carried aloft by a wildfire to later fall on the surface of the flood terrace where is was buried by the next flood. *In situ* charcoal is generally angular and easily broken into flaky pieces. This could suggest that the charcoal is derived from sagebrush or other woody plants that would have grown on the surface the terrace between floods. Transported charcoal was observed as large coherent chunks that were rounded during transport and deposited within a slackwater flood unit. Ages derived from transported charcoal are assumed to be older than the deposit it is sampled from because the charcoal is sourced from a tree or shrub that lived an unknown amount of time before being burned. These chunks of charcoal are then picked up by the next flood(s) which deposits the charcoal within a slackwater deposit.

Samples of *in situ* charcoal were given priority over charcoal samples that appeared to have been transported and deposited by a flood. Radiocarbon ages derived from *in situ* charcoal found at a contact between two paleoflood layers provide a maximum age for the overlying flood event and a minimum age for the underlying event. In contrast, charcoal that is transported and later deposited by a paleoflood could be significantly older than the flood because the charcoal was on the surface or in transit within the river system for an unknown amount of time before being deposited (Ely, 1993).

Thirty-two samples of charcoal and carbonized plant material collected and described in the field were later prioritized for radiocarbon analysis in the lab. Once each sample was identified as *in situ* or transported, they were prioritized by location within the stratigraphic column. *In situ* samples located nearest to the top and bottom of a stratigraphic column were given priority over transported samples collect from the same site to more accurately constrain the timing of slackwater deposition at each study locations. The next priority was *in situ* samples located near the middle of each stratigraphic column. These samples were chosen in the hope of identifying chronological differences in the depositional pattern observed at Ten Mile Creek and Dietrich sites. Samples of charcoal and carbonized plant material were weighed and processed to remove sand or modern carbon contaminants. Ten samples of charcoal and or carbonized plant material prioritized and sent for analysis by Direct AMS located in Bothell, WA using Accelerator Mass Spectrometry (AMS) in accordance with standard procedure (Brock et al., 2010).

Hydraulic Modeling

Hydraulic modeling was conducted to determine the minimum discharge requirements to overtop the Snake River Flood Terrace. This was accomplished using ArcMap 10.3 software, HEC-RAS and HEC-GeoRAS hydraulic modeling software, and Lidar data obtained for the study reach. HEC-RAS is a one-dimensional steady state hydraulic modeling program that is used to simulate the elevation of water within a defined river channel. ArcMap 10.3 along with the HEC-GeoRAS tool were used to define the river channel constants necessary for the HEC-RAS software to run properly. Channel constants required for HEC-RAS include the channel center line, left bank and right bank lines, flood plain lines, and 114 cross sections. Cross sections were placed at intervals of approximately 100 m in straight sections of the river and in intervals of approximately 50 m in sections of the river where it narrows, widens, and or curves. The variables required for HEC-RAS are the flow volume in cubic feet per second and a Manning's *n* roughness coefficient for the channel and overbank areas on each side of the channel. A Manning's *n* of 0.03 was used for the over bank areas and 0.02 was used for the main channel.

Lidar data for this project was collect by the U.S. Army Corps of Engineers as part of the Columbia River Light Detection and Ranging (LiDAR) survey project (U.S. Army Corps of Engineers, 2010) Lidar data for the study reach was collected on November 21, 2010. Because LiDAR does not penetrate water, the Lidar data used in this study includes the water surface of the Snake River on the day it was collected. When the LiDAR data was collected on November 21, 2010, the discharge of the Snake River was recorded at approximately 422 cubic m/s (14,900 cubic ft/s) at the USGS gauge station located upstream of the study reach near Anatone, WA (U.S Geological Survey, 2015). HEC-RAS modeling was run over the top of the lidar data. Thus, any discharges used to calibrate the model had 422 cubic m/s (14,900 cubic ft/s) subtracted from the flow to account for the base flow included in the LiDAR data. Likewise, any results produced by the model had 422 cubic m/s (14,900 cubic ft/s) added to them.

To calibrate the model, the elevation of a known flood event was used. On July 20, 2010, (Trosper, 2011) measured a wrackline for a flood that occurred on June 5, 2010. Trosper (2011) measured a 5.3-meter elevation difference between the flood wrackline and the surface of the Snake River on July 20, 2010. Records show that the maximum discharge on June 5, 2010 was 4,900 cubic m/s (173,000 cubic ft/s) and approximately 800 cubic m/s (28,000 cubic ft/s) on July 20, 2010. To fine-tune the model input parameters, different combinations of Manning’s *n* values were used to alter the water surface elevations between the two known flows until they matched the 5.3 meters recorded in the field by Trosper (2011). Once the model was calibrated, discharges for the Snake River were incrementally increased by 150 cubic m/s (5,000 cubic ft/s) until a water surface elevation and discharge were identified that overtopped the Snake River Flood Terrace at Redbird Beach, Dietrich, and Ten Mile Creek. This information provides the minimum discharge required to create a slackwater deposit on the surface of the Snake River Flood Terrace and also reveal the magnitude of the most recent prehistoric floods to occur on the Snake River upstream of Asotin, WA.

CHAPTER III

DATA AND RESULTS

The following sections describe the geomorphic setting, stratigraphy, radiocarbon dates, and flood chronologies of Ten Mile Creek, the Dietrich Property, Redbird Beach, and Bobcat Bar (Figure 1).

Geomorphic Setting

Ten Mile Creek Site Geomorphology

The geomorphology of Ten Mile Creek is composed of four features: 1) the Snake River flood terrace; 2) Snake River gravel point bar\alluvial fan; 3) Ten Mile Creek alluvial fan; and 4) basaltic bedrock that composes the cliff walls and channel of the Snake River Canyon (Figure 2).The Snake River channel is confined within a steep narrow canyon composed of multiple layers of basalt identified as the Grande Ronde Basalt of CRBs. These basalts form the eastern edge of the Columbia Plateau that the Snake River and its tributaries eroded through since their emplacement approximately 15 Ma. Ten Mile Creek is a small intermittent tributary to the Snake River that flows from east to west through the eastern Columbia Plateau that makes up the western edge of central Idaho near Lewiston. Ten Mile Creek is the source for material that accumulated to form the alluvial fan at this site.

At Ten Mile Creek, the Snake River Flood Terrace formed when slackwater deposits accumulated downstream of the point bar on the lee side of the Ten Mile Creek alluvial fan. The Snake River Flood Terrace is ~236 m above sea level and extends approximately 500 m along Idaho bank of the Snake River. The upper surface of the terrace is approximately 7 meters above the surface of the Snake River during average summer flows. Since deposition, the southern end of the Snake River Flood Terrace has been cut through by two individual ephemeral creeks that form dry gullies. This is evident in how the stratigraphic layering truncates at the banks of the gullies.

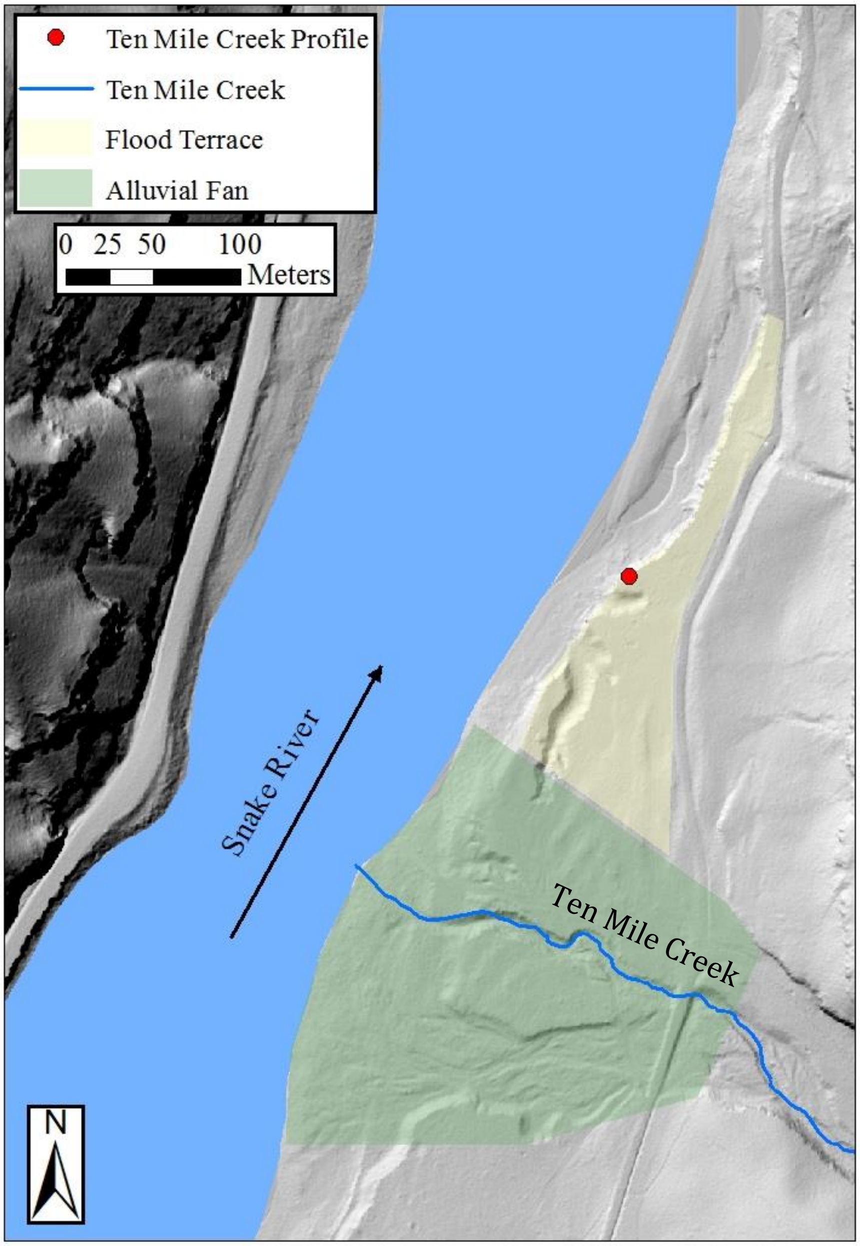

Figure 2. Geomorphic setting of the Ten Mile Creek Site. The red dot represents the location of the Ten Mile Creek stratigraphic column. The area in yellow is the Snake River Flood Terrace downstream of the Ten Mile Creek alluvial fan shown in green. A map of the study reach is shown in Figure 1.

The stratigraphic profile that describes the Ten Mile Creek study site is located at the southern end of the flood terrace where the exposure of slackwater deposits is tallest (GPS coordinates UTM 11T 501200 5126009). The upper units of the flood terrace are composed of fine grained slackwater deposits that alternate between silt and fine sand. The lower units of the flood terrace are relatively coarser-grained fluvial sand deposits interbedded with silt and fine sand.

Dietrich Site Geomorphology

The geomorphic environment of the Dietrich site is made up of three features: 1) the Snake River Flood Terrace; 2) alluvial fans; and 3) the basaltic bedrock canyon. Here, the Snake River Flood Terrace formed along the margin of the narrow basalt canyon (Figure 3). Two alluvial fans located upstream and downstream of the slackwater deposits bracket the Dietrich site. The colluvial material composing these fans is from two ephemeral streams cutting through the basalt walls of the Snake River Canyon. The Dietrich and Redbird Beach sites are related in that they are both parts of a continuous section of the Snake River Flood Terrace that can be traced approximately 3 km downstream from Redbird Beach (the Dietrich site is 1 km downstream from Redbird Beach).

The Snake River Flood Terrace exhibited along the margin of the Snake River Canyon at the Dietrich site extends approximately 350 m north to south between colluvial fans and is on average 240 m above sea level. Here, the top of the terrace is approximately 8 meters above the surface of the Snake River during average summer flows. Like Ten Mile Creek, the stratigraphy at the Dietrich site is composed of slackwater couplets of silt and fine sand underlain by a coarser-grained basal sand. The stratigraphic section described at the Dietrich site is located near the north end of the study area where the exposed slackwater deposits are the tallest. The GPS coordinates for the stratigraphic section at the Dietrich site are UTM 11T 503157 5121409.

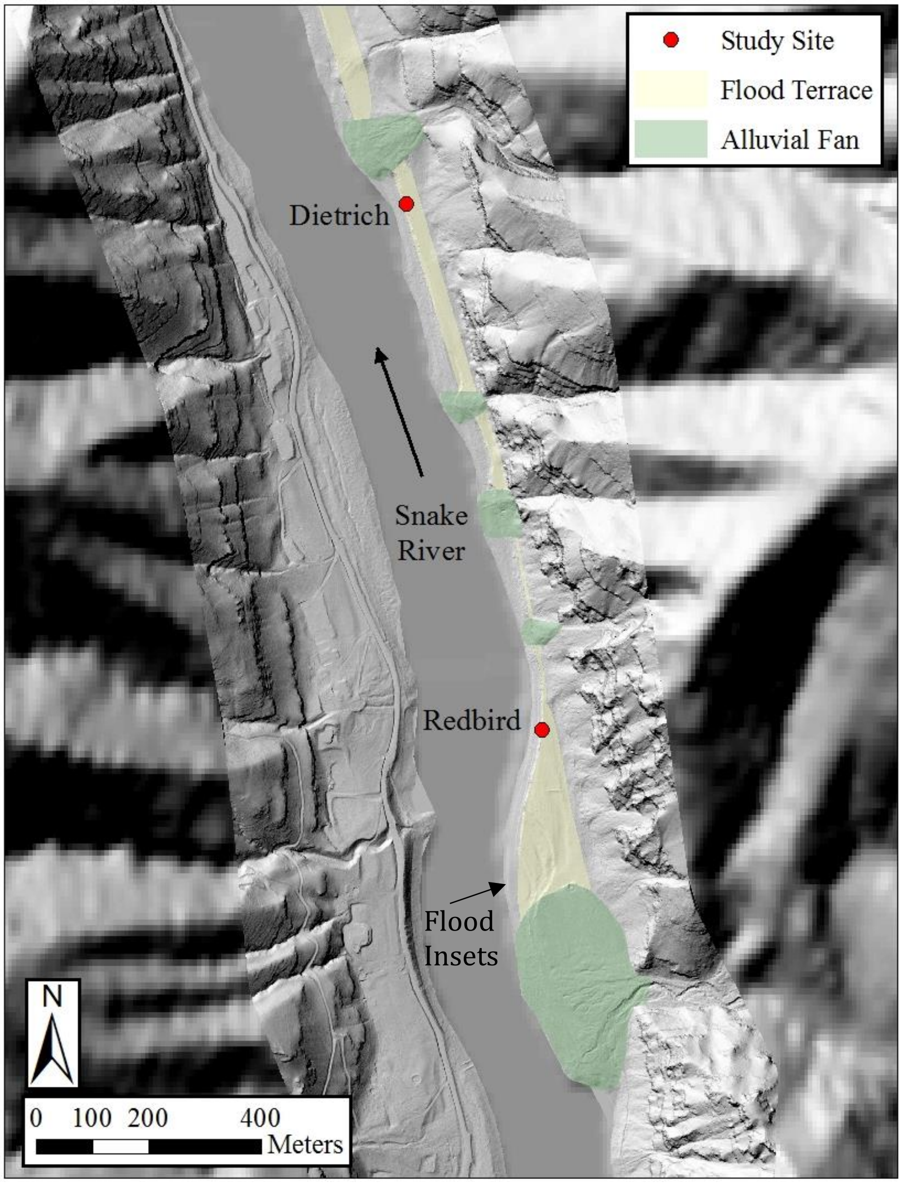

Figure 3. Geomorphic setting of the Dietrich and Redbird Beach sites. The red dots represent the location of the Dietrich and Redbird Beach stratigraphic column. The areas in yellow are the Snake River Flood Terrace and the areas in green are alluvial fans. A map of the study reach is shown in Figure 1.

Redbird Beach Geomorphology

The geomorphic setting at Redbird Beach is composed of three features: 1) the Snake River Flood Terrace; 2) the Redbird Creek alluvial fan; 3) and the bedrock canyon (Figure 3). The channel and canyon walls of the Snake River are composed of the numerous basalt layers of the Grande Ronde formation of the CRBs that make up Columbia Plateau. Redbird Creek is a small perennial tributary of the Snake River that flows east to west as it cuts down through the basalts of the eastern Columbia Plateau in west-central Idaho. This drainage is the source for the debris that accumulated to form the alluvial fan at the outlet of Redbird Creek. The fine silts and sands that compose the Snake River Flood Terrace were deposited and are now preserved and protected on the downstream side of the Redbird Creek alluvial fan (Trosper, 2011). The Snake River Flood Terrace continues downstream from the Redbird Creek site along the margin of the channel approximately 2 km beyond the Dietrich site. The flood terrace is fairly continuous along this reach; however, a number of gullies and their associated alluvial fans have divided it into discrete sections.

The Snake River Flood Terrace at Redbird Beach is approximately 155 meters in length with an elevation of 240.5 m above sea level at the northern end of the terrace, which slowly decreases to 239.5 m at the southern end. The Snake River Flood Terrace is exhibited at the southern end of the Redbird Creek study area. At its highest elevation, the Snake River Flood Terrace is 8 meters above the surface of the river during average summer flows. The northern end of the study area is composed of three benches that contain distinct stratigraphic units that are inset against the Snake River Flood Terrace. These three benches progressively decrease in elevation from north to south at the

Redbird Creek study area (Trosper, 2011). Trosper (2011) originally described three stratigraphic profiles within the Snake River Flood Terrace and one within each of the three southern stratigraphic insets. The stratigraphic profile for this study is from the northernmost end of the Redbird Creek Snake River Flood Terrace. It was originally described by Trosper (2011) and was re-described and reclassified in the field using the methods and criteria defined in this study.

Bobcat Bar Geomorphology

Features that make up the geomorphic setting of Bobcat Bar include: 1) the Snake River Flood Terrace; 2) an alluvial fan; 3) and the basaltic bedrock canyon. The bedrock that composes the channel and canyon walls of the Snake River is basalt derived from the Grande Ronde formation of the CRBs. An unnamed intermittent tributary that cut through the basalts of the Snake River Canyon provides the material for an alluvial fan 200 m upstream of the site. The Snake River Terrace formed along the margin of the canyon downstream of the alluvial fan (Figure 4). The stratigraphy of slackwater deposition includes units of silt, fine sand, and a coarser grained, basal sand. The upper meter at this location is also composed of coarser grained sand that contains evidence of anthropogenic disturbance. Examples of this disturbance include a buried length of metal cable and an access road built on top of the flood terrace which altered the topography as well as the top meter of slackwater deposit stratigraphy.

The Snake River Flood Terrace extends north to south along the margin of the Snake River for approximately 50 m at the Bobcat Bar study area. Bobcat Bar is the furthest upstream site within the 20-km study reach (Figure 1). Here the Snake River terrace is approximately 250 m above sea level. The stratigraphic section described at

Bobcat Bar is located near the center of the study area where the tallest section of slackwater deposits is exposed (Figure 4). The GPS coordinates for the Bobcat Bar stratigraphic section are UTM 11T 504959 5108994.

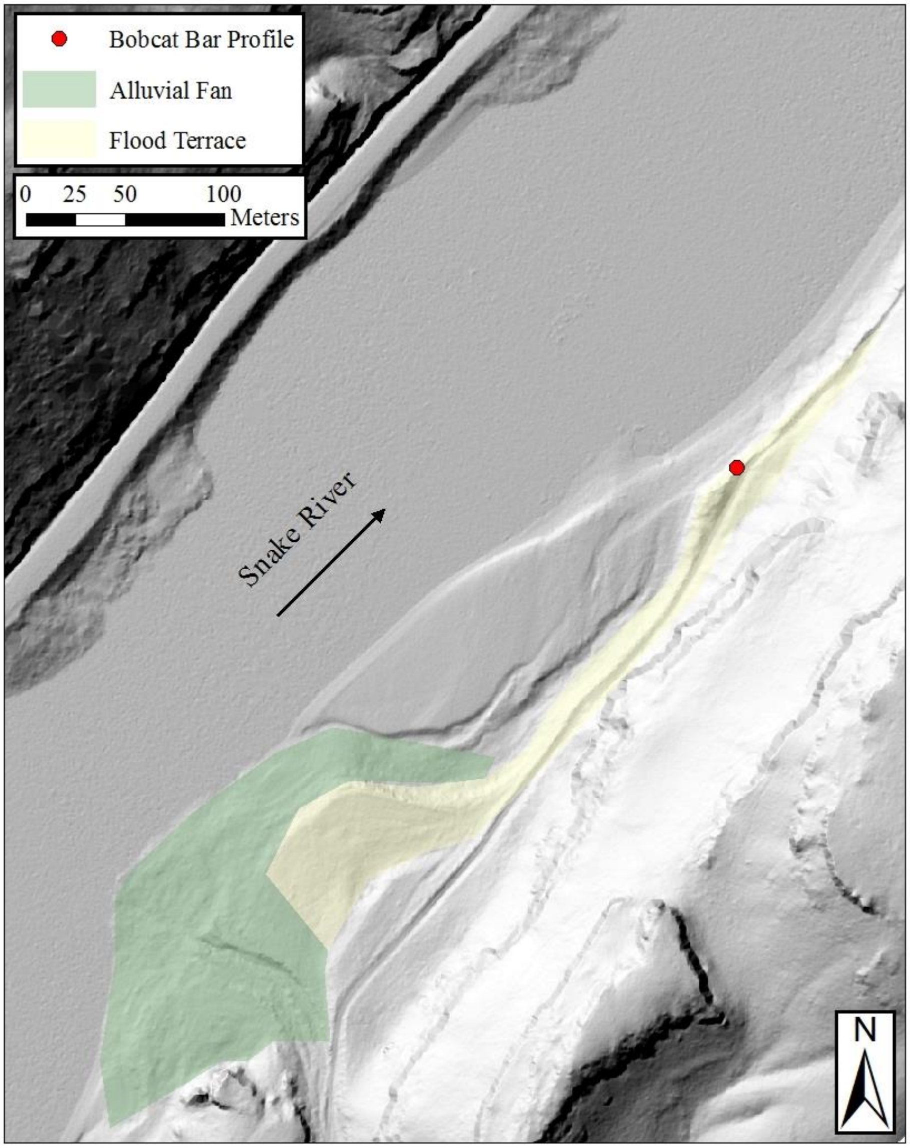

Figure 4. Geomorphic setting of the Bobcat Bar site. The red dot represents the location of the Bobcat Bar stratigraphic column. The area in yellow is the Snake River Flood Terrace downstream of an alluvial fan shown in green.

Flood Terrace Stratigraphy

The stratigraphy of the Snake River Flood Terrace observed at Ten Mile Creek, the Dietrich site, Redbird Beach, and Bobcat Bar is composed of accumulated fine-grained sand and silt slackwater deposits overlying relatively coarser-grained alluvial sand and silt deposits derived from the Snake River. Alluvial materials present at the margins of the study areas were not described in this study. Detailed descriptions of discrete layers recorded within the stratigraphic profile at each of the three study areas is in Tables A1-A3, Appendix A. The stratigraphic profiles recorded at the Ten Mile Creek, Dietrich, Redbird Beach, and Bobcat Bar sites are summarized below (Figure 5).

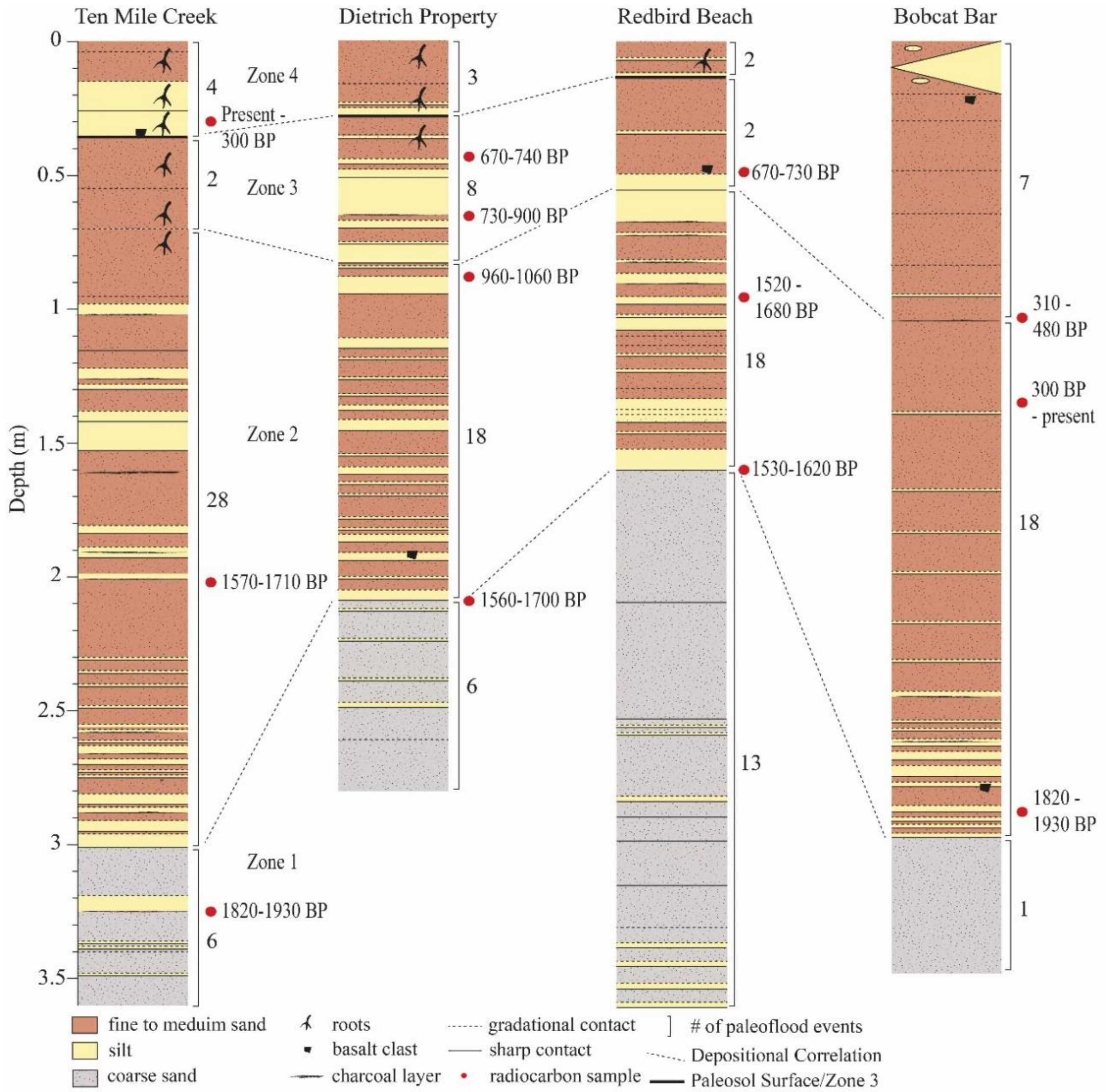

Figure 5. Stratigraphic correlation of Snake River paleoflood deposits. Radiocarbon dates were calibrated with Oxcal v4.2.4 (Bronk Ramsey, 2013); IntCal13 atmospheric curve (Reimer et al. 2013). The thick dark line indicates a paleosol that developed during an ~400-year hiatus in paleoflood deposition from ~730 BP to 300 BP.

Ten Mile Creek Stratigraphy and Ages

The Ten Mile Creek study site is located at the northern end of the 20-km Snake River Flood Terrace study reach downstream of the Dietrich, Redbird Beach, and Bobcat Bar sites (Figure 1; Figure 2). The stratigraphy at Ten Mile Creek exhibited 65 distinguishable units that were described from within a profile 360 cm in depth (Figure 6; Figure 7). The colors of the silt and sand units within the Ten Mile Creek profile are a range of light brown (Munsell 2.5Y 4/2-6/3 and 10YR 4/2-6/3) (Appendix A). The lowest portion of the stratigraphic profile, from 301 cm to the base of the described profile, is composed of coarse sands and silt layers that together form silt/sand couplets. This section of the profile appears to correlate with the basal coarse sand identified by Trosper (2011) at Redbird Beach. From 190 cm to 301 cm, the Ten Mile Creek profile is made up of numerous tightly spaced silt/sand couplets composed of fine sand and silt. The profile from 36 cm to 190 cm is a massive fine sand interbedded with difficult to distinguish silt

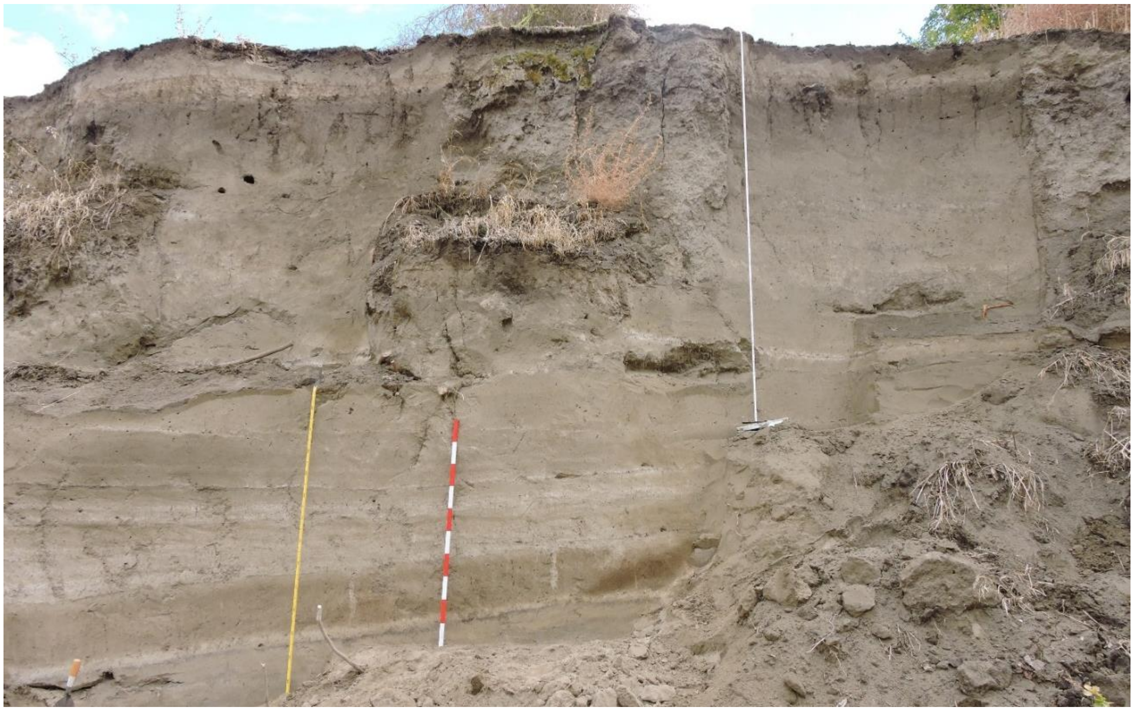

Figure 6. Photograph of stratigraphy at Ten Mile Creek.

layers. The upper portion of the profile, from 36 cm to the surface, is made up of alternating layers of silt and medium-grained sand that form silt/sand couplets. In addition, the profile is a darker brown color (paleosol) from 36 cm to ~80 cm in

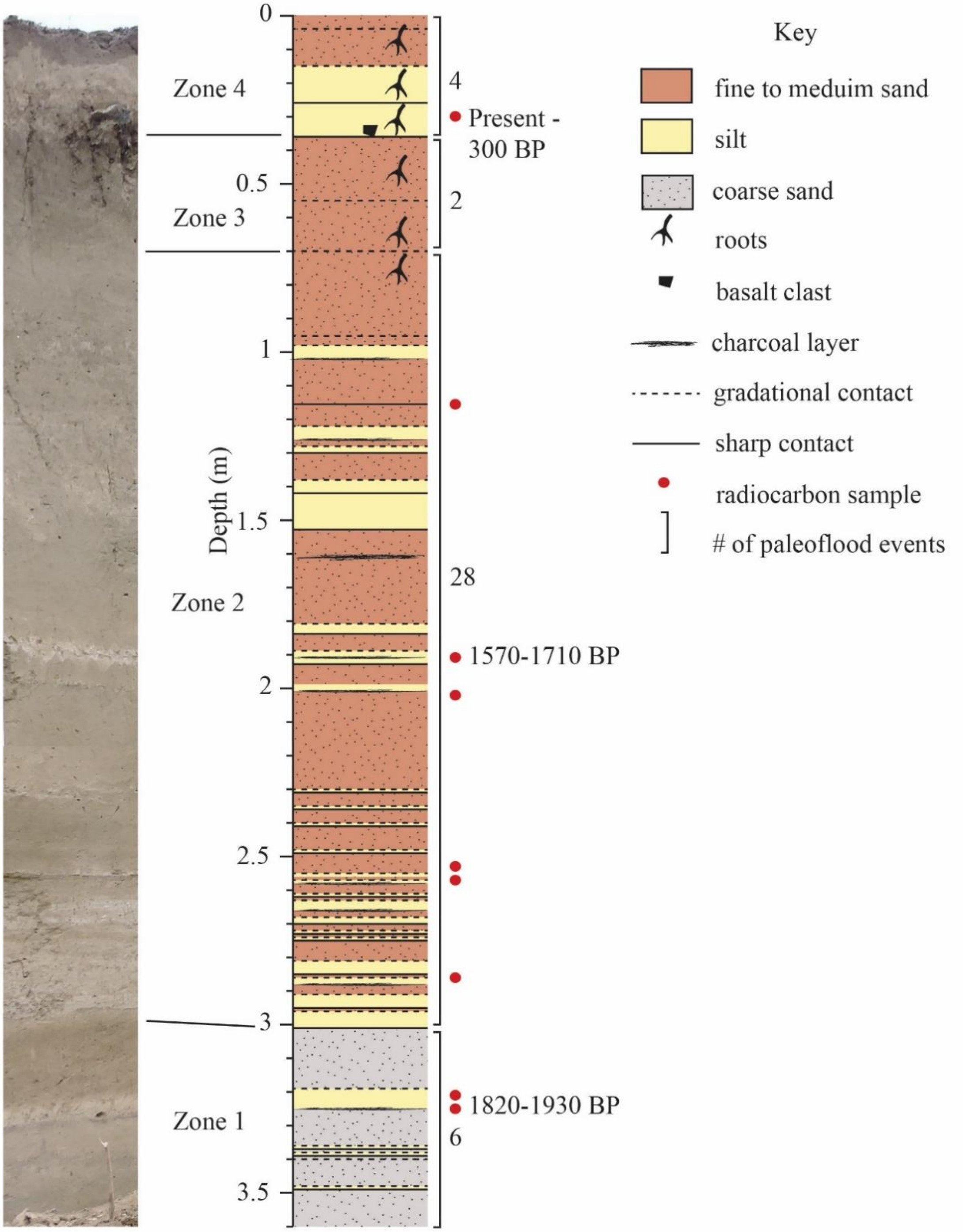

Figure 7. Stratigraphic column and image of stratigraphy at Ten Mile Creek. Description of stratigraphic units and identification of sand-silt flood couplets is in Appendix A.

depth, this section of the profile may correlate with darker colored stratigraphy observed at the Dietrich and Redbird beach sites. Overall, the stratigraphic profile at Ten Mile Creek is made up of 28 silt/sand couplets and 9 individual units. This indicates that the stratigraphic profile at Ten Mile Creek is the result of flood deposition left behind by 40 individual floods, depending on the interpretation of the paleoflood stratigraphy (Figure7).

The pair of silt and sand layers that compose a silt/sand couplet is typically characterized by a thin silt unit overlain by a relatively thicker sand unit. The contact at the top and bottom of a silt/sand couplet is sharp and wavy whereas the boundary between the silt and sand within the couplet is consistently inversely gradational (Appendix A). It is common to observe a very thin continuous layer of carbonized plant material capping silt/sand couplets within the stratigraphic profile (Appendix A) (Figure 8).

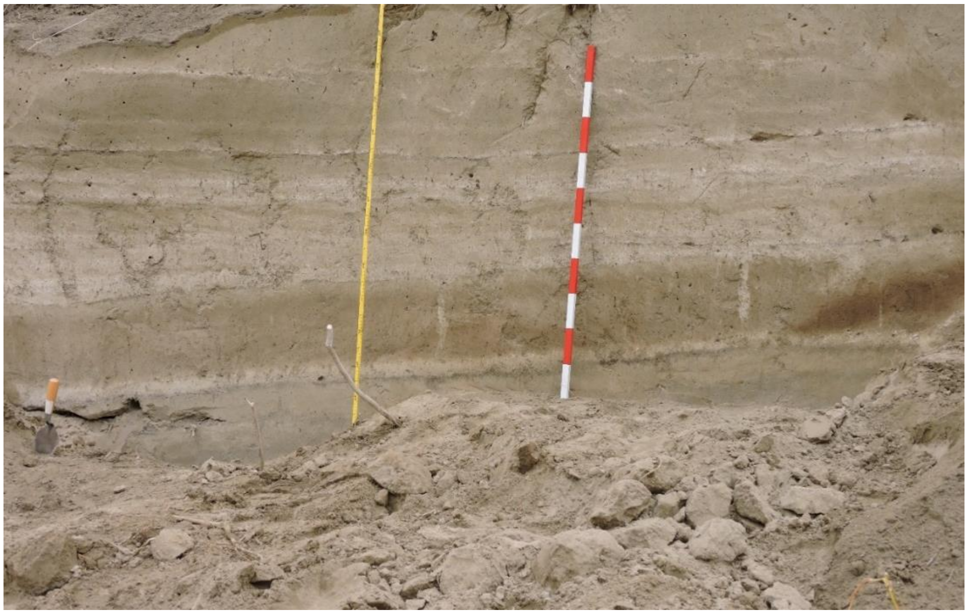

Figure 8. Photograph of charcoal or carbonized plant material layers. Semi continuous layers of carbonized plant material capping sand/silt couplets at the base of the Ten Mile Creek stratigraphic column. These layers are present at 5 cm, 23 cm, and 35 cm from the bottom of the measurement stick.

Nine samples of charcoal were collected from within and between stratigraphic units at Ten Mile Creek (Table 1). Of these, three were dated using radiocarbon analysis to constrain the history of flooding at Ten Mile Creek (Figure 5). A piece of *in situ* charcoal collected from near the base of the profile was dated of 1820-1930 BP (20-130 AD). A second sample of *in situ* charcoal from the middle of the profile provided an age of 1570-1710 BP (240-380 AD). The third sample, a fragment of flood transported detrital charcoal collected 30 cm from the surface of the profile provided an age of present to 300BP (1660-present AD) (Appendix B).

Table 1: Radiocarbon analysis report for Ten Mile, Dietrich, and Bobcat Bar study sites.

Sample #	Lab #	Depth (cm)	Strat Unit[1]	Org. Type[2]	$\delta^{13}C$	^{14}C Age Yrs. BP	Calibrated Age cal BP[3]
Ten Mile Site							
SR2-10-25-15-CH1	014356	30	4	C, T	-19	186 ±25	present-300
SR2-10-25-15-CH5	014357	191	21/22	C, IS	-18.8	1736 ±25	1570-1710
SR2-10-25-15-CH10	014358	325	56/57	C, IS	-18.1	1926 ±27	1820-1930
Dietrich Site							
SRI-10-4-15-CH6	014302	43	8	C, T	-22.7	801 ±22	670-740
SRI-10-4-15-CH1	014299	65	12/13	C, IS	-26.9	873 ±23	730-900
SRI-10-4-15-CH2	014300	88	20/21	C, IS	-15.7	1100 ±26	960-1060
SRI-10-4-15-CH4	014301	209	53/54	C, T	-27.6	1721 ±25	1560-1700
Redbird Beach Site[4]							
RB1-7-21-10-R6	7238	120		C, IS	-7.5	1663 ±25	1520-1690
RB1-7-21-10-R7	7237	120		SH, IS	-22.7	3608 ±26	1046
RB1-2-16-11-R1	8829	65		C, CH	-23.9	764 ±22	670-730
Bobcat Bar Site							
SR3-11-12-15-CH8	014361	102	8/9	C, T	-19.8	343 ±26	310-480
SR3-11-12-15-CH7	014360	135	9	C, T	-15.7	209 ±26	present-300
SR3-11-10-15-CH1	014359	288	37	C, T	-16.8	1920 ±26	1820-1930

Notes: 1. Stratigraphic Unit Description: Number indicates the stratigraphic unit from which the sample was taken; 21/22 = sample is from boundary between units. 2. Type of organic material: C = charcoal, SH = bivalve shell; Subset organic type: T = transported, IS = *in situ*, H = Hearth. 3. Age ranges are in years BP; Calibrated with Oxcal v4.2.4 (Bronk Ramsey, 2013); IntCal13 atmospheric curve (Reimer et al., 2013). Radiocarbon samples from this study were processed at Direct AMS in Bothell, WA. 4. Ages from Trosper (2011).

Dietrich Site Stratigraphy and Ages

The exposure of the Snake River Flood Terrace at the Dietrich site is located 5 km upstream of the Ten Mile Creek site (Figure 1; Figure 9). Observation of the stratigraphic section at the Dietrich site revealed 63 units within a profile 280 cm in depth. The sediments within the stratigraphic profile at the Dietrich site are a grayish brown (Munsell 2.5Y 4/2 to 6/3 or 10YR 5/2 to 6/2) (Appendix A) (Figure 10). The depositional pattern observed at the Dietrich site is similar to that of Ten Mile Creek site (Figure 11).

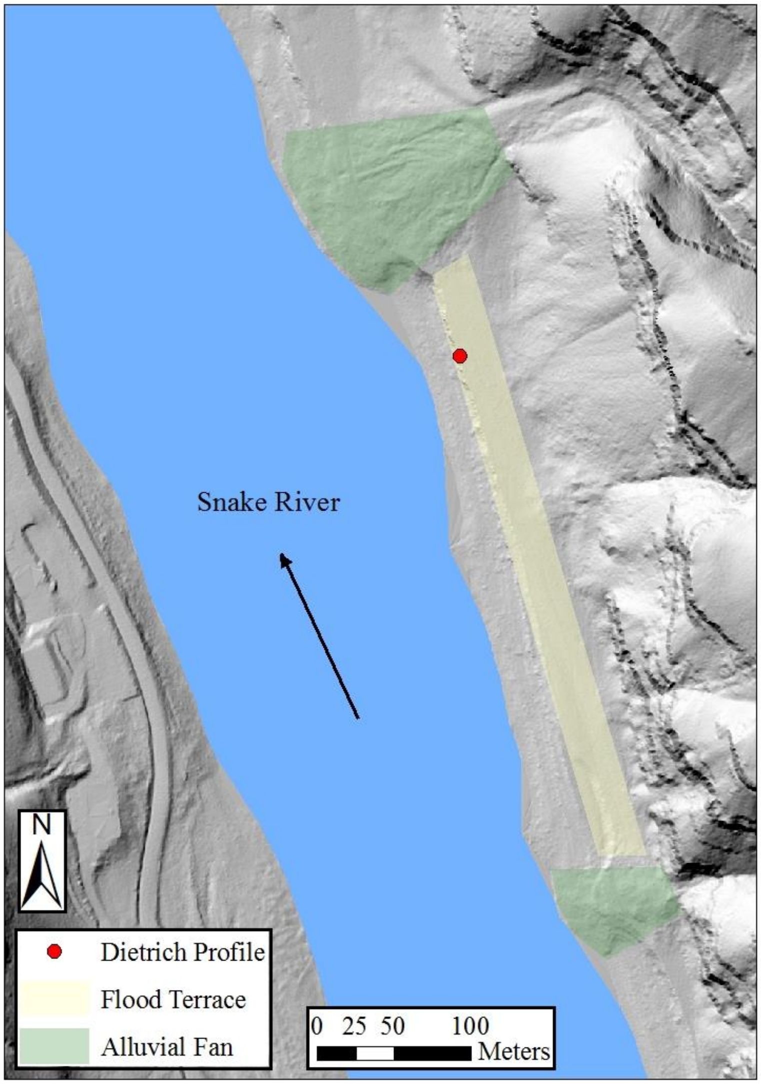

Figure 9. Geomorphic setting of the Dietrich site. The red dot represents the location of the Dietrich stratigraphic column. The area in yellow is the Snake River Flood Terrace situated between two Colluvial fans shown in green.

Figure 10. Photograph of stratigraphy at Dietrich property.

The basal portion of the flood terrace from 209 cm to 280 cm and beyond is composed of alternating units of medium to coarse sand and silt which pair to form silt/sand couplets. The stratigraphic profile from 187 cm to 209 cm is made up of alternating layers of silt and fine sand that also form silt/sand couplets. From 83 cm to 187 are composed of a massive fine sand deposits interbedded with layers of silt that are difficult to distinguish due to gradational boundaries. The profile from 83 cm to 28 cm is darker brown color in outcrop and is made up silt and fine sand couplets. From 28 cm to the surface, the Dietrich profile is composed layers of silt and coarse sand that combine to form silt/sand couplets. Contacts between units and within sand/silt couplets were similar to the Ten Mile Creek site (Appendix A). Stratigraphic evidence in the form of silt and sand deposits indicate that 35 floods have occurred at the Dietrich site each of which left behind a silt/sand couplet (29) or individual sediment layer (5).

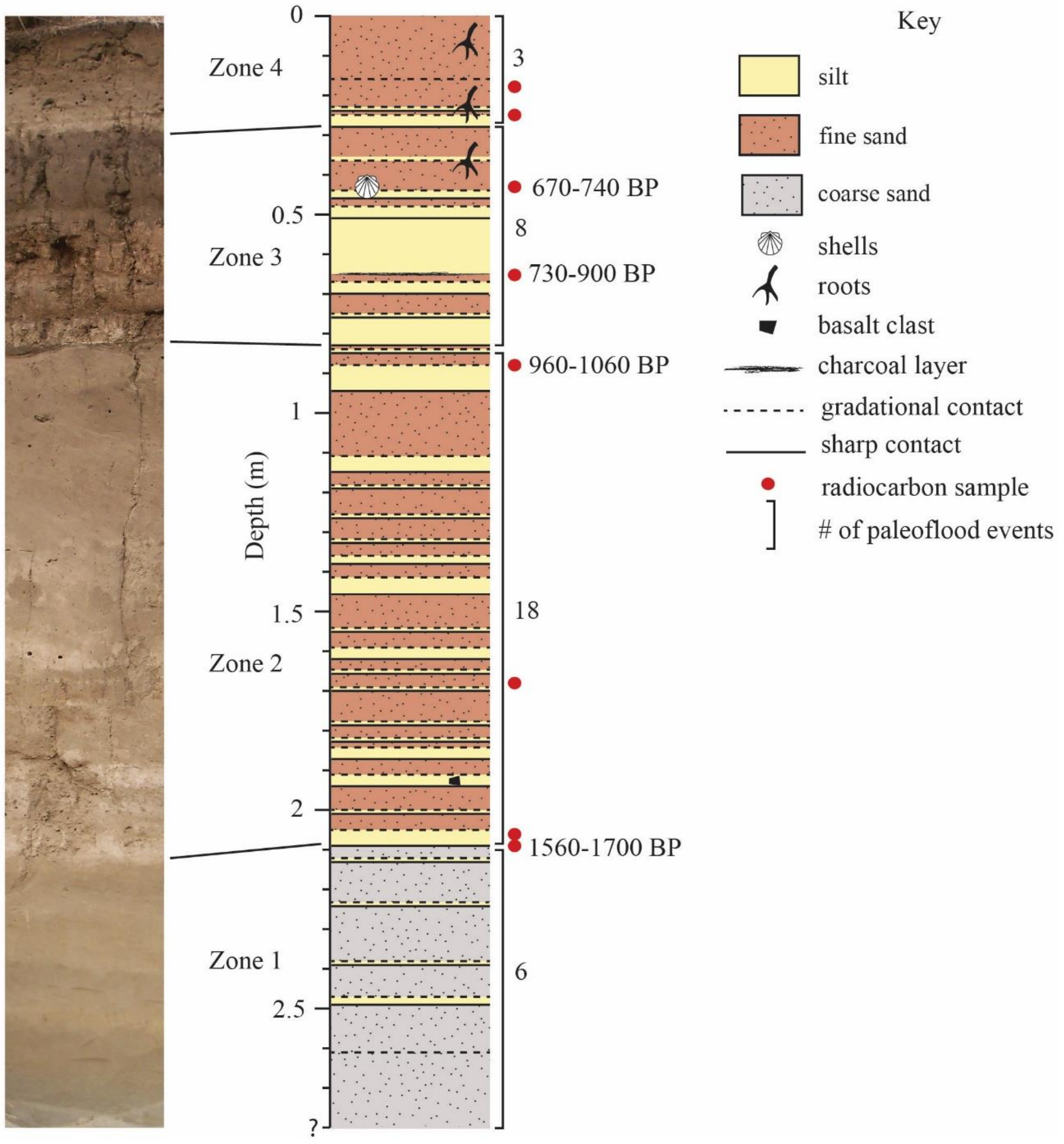

Figure 11. Stratigraphic column and image of the stratigraphy at Dietrich property. Description of stratigraphic units and identification of sand-silt flood couplets is in Appendix A.

Eight samples of charcoal were collected from throughout the stratigraphic profile at the Dietrich property. Radiocarbon analysis was conducted on four samples to constrain the timing of paleoflood deposition at the Dietrich property (Figure 5). A fragment of flood transported charcoal fragment collected from 209 cm at the contact between the upper slackwater deposits and the lower alluvial deposits was dated at 1560-1700 cal BP (250-390 cal AD) (Table 1). Samples of *in situ* charcoal collected from the middle of the profile at 88 cm and 65 cm were dated at 960-1060 cal BP (890-1000 cal AD) and 730-900 cal BP (1050-1220 cal AD). A sample of flood transported charcoal collected from near the top of the profile, at 43 cm of depth, provided at date of 670-740 cal BP (1210-1270 cal AD) (Appendix B).

Redbird Beach Stratigraphy and Ages

The previously studied Redbird Beach site is located one kilometer upstream of the Dietrich Property and six kilometers from the downstream end of the study reach at Ten Mile Creek (Figure 1; Figure 2). The Dietrich and Redbird studies are both located on a semi-continuous section of the Snake River terrace. However, the presence of alluvial material, vegetation, and distance between the Dietrich and Redbird sites makes direct correlation of the stratigraphy difficult.

Using the criteria for delineating stratigraphic flood units set in this study, a stratigraphic analysis was conducted in person on the northernmost stratigraphic profile (RB-1) described by Trosper (2011) (Figure 12). Some layers of silt and sand that were paired in the original study were classified as separate flood deposits based on the methods for this study. The new stratigraphic analysis identified 55 distinct depositional layers within a vertical stratigraphic profile 425 cm in depth at Redbird Beach (Figure 13).

The stratigraphy from 358 to 329 cm is composed of alternating layers of silt and coarse sand that form silt sand couplets. From 329 to 281 cm the stratigraphy reverts to multiple layers of massive coarse sand, and then converts back to couplets of silt and coarse sand from 281 to 251 cm in depth. Two units of massive coarse sand make up the stratigraphic profile from 251 to 159 cm. At 159 cm depth the stratigraphy transitions from the coarse basal sands to couplets of fine sand and silt. These couplets of silt and fine sand begin at 159 cm in depth and continue to the surface of the stratigraphic profile at the Redbird Beach site. This depositional transition from basal coarse sand deposits to silt and fine sand couplets was also observed at the Ten Mile Creek and Dietrich sites. The contacts between stratigraphic units are generally sharp and wavy (Trosper, 2011). The analysis of the profile in the current study revealed that the boundary between the silt and sand layers that compose silt/sand couplets are inversely gradational. Using the methods of this study, an analysis of the stratigraphy within the RB-1 profile at Redbird Beach, previously described by Trosper (2011), identified 21 silt/sand couplets and 13 individual layers of silt or sand.

Figure 12. Photograph of stratigraphy at Redbird Beach.

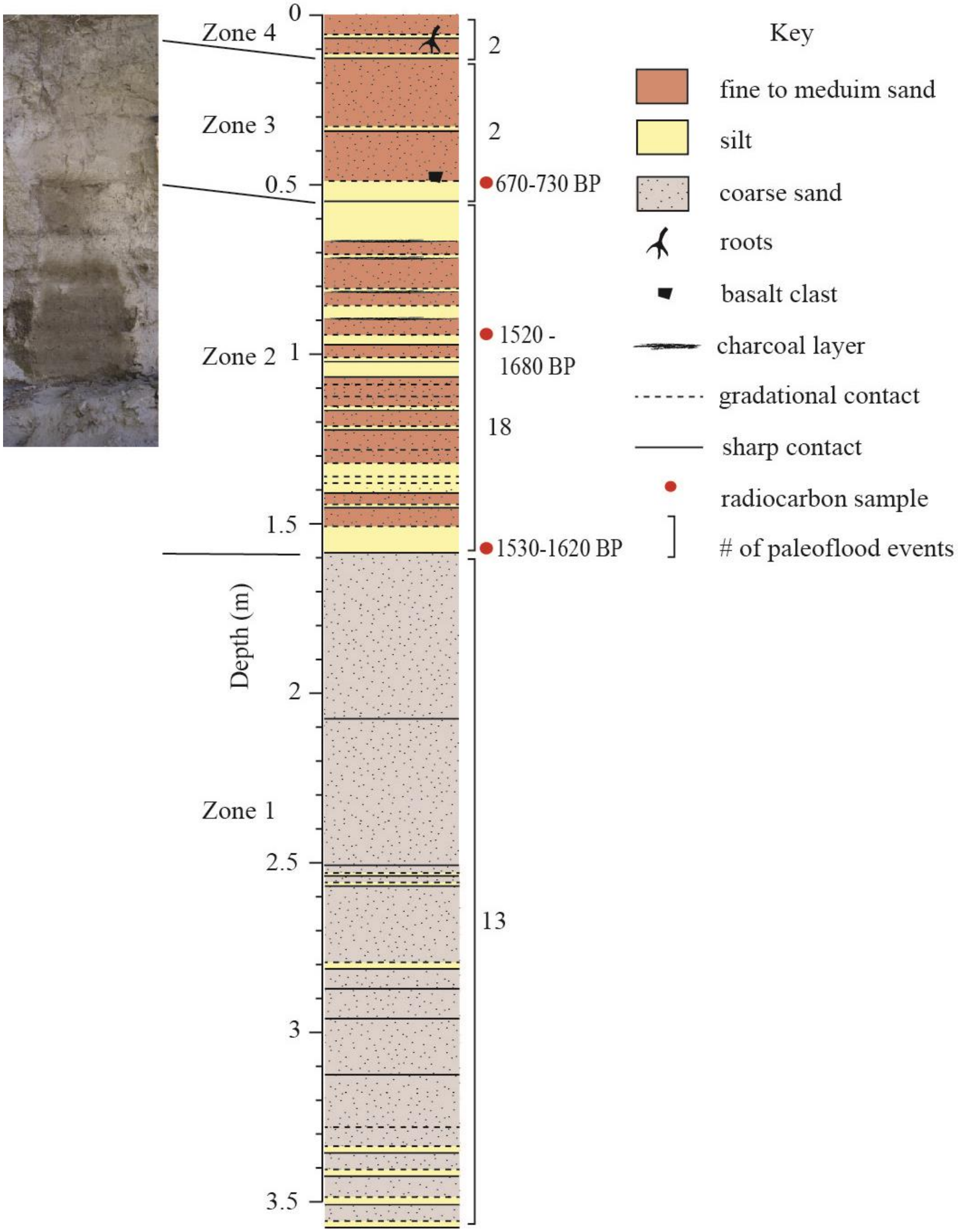

Figure 13. Stratigraphic column and image of stratigraphy at Redbird Beach. Description of stratigraphic units and identification of sand-silt flood couplets is in Appendix A.

Trosper (2011) obtained five radiocarbon ages from 4 charcoal fragments and one bivalve shell to constrain the age of the tallest bench of slackwater deposits at Redbird Beach (Table 1). The age of the shell initially gave an erroneous date but was later corrected by accounting for the carbon reservoir effect (Trosper, 2011, Osterkamp et al. 2014) Fragments of flood-transported charcoal collected near the base of the section within the coarse basal alluvial sand provided the oldest age for the Redbird section at 2010-2300 cal BP (350-60 BCE) . A sample of *in situ* charcoal collected from 120 cm below the surface at the transition between the upper fine-grained deposits and the basal coarse sand deposits provided an age of 1530-1690 cal BP (330-420 cal AD) (Figure 5). An additional sample of *in situ* charcoal collected from 120 cm below the surface provided a radiocarbon date of 1520-1690 cal BP (270-430 cal AD). The youngest age obtained from the tallest section at Redbird Beach was obtained from a piece of *in situ* charcoal collected from a hearth 65 cm below the surface (Trosper, 2011). The date provided by this sample was 660-720 cal BP (1220-1280 cal AD). Additional radiocarbon dates obtained from lower elevation slackwater insets, as well as personal observations made by Trosper in 2010, indicate that slackwater deposition has occurred up to the present day at Redbird Beach.

Bobcat Bar Stratigraphy and Ages

Bobcat Bar is the farthest upstream site in the study, located approximately ten km south of Redbird Beach and 16 km from the downstream most site, Ten Mile Creek (Figure 1; Figure 4). The 380-cm deep stratigraphic profile at Bobcat Bar contains 46 stratigraphic units that are light brown in color (Munsell 2.5Y and 10YR 4/2-6/3) (Figure 14; Figure 15). A layer of silt caps the massive basal layer of coarse sand that comprises the lower portion of the stratigraphic profile at Bobcat Bar. This massive layer of sand extends an unknown distance below the upper contact at 299 cm in depth. Couplets of silt

Figure 14. Photograph of stratigraphy at Bobcat Bar.

and fine sand are present within the outcrop from 299 to 105 cm in depth. The silt layers within this section of the profile are very thin and difficult to distinguish. The contacts at the tops and bottoms of silt/sand couplets are generally sharp and wavy. The boundary between the lower silt and the overlying sand that make up a silt/sand couplet are consistently inversely gradational (Appendix A). Unlike the downstream sites, the upper 105 cm of the profile at Bobcat Bar is composed of 7 layers of coarse sand. The top 20 cm of the profile are intermingled with modern anthropogenic debris that pinches out at the downstream (north) end of the section. Analysis of the stratigraphic profile at Bobcat

Bar reveals that the profile is composed of 8 individual layers of sand or silt and 18 silt/sand couplets.

Ten samples of charcoal were collected from the stratigraphy at Bobcat Bar. Three radiocarbon dates were selected from these to constrain the period over which 44 flood deposition occurred at Bobcat Bar. A flood-transported fragment of detrital charcoal collected from just above the transition between the basal sand and the overlying slackwater deposits, unit 37 at 288cm depth, was dated 1820-1930 BP (20-130 AD) (Figure 10). A flood-transported charcoal sample collected from within unit 9 at 135 cm was dated 300 BP to present (1650-present AD). The third date, 310-480 BP (1470-1640 AD), obtained from a fragment of flood-transported detrital charcoal was collected from the boundary at 102 cm between the slackwater deposits and the overlying anthropogenic sand units (Table 1).

One discrepancy occurred at Bobcat Bar, sample SR3-11-12-15-CH8 returned an older age than sample SR3-11-12-15-CH7 located beneath it. Sample SR3-11-12-15-CH8 collected from 102 cm was dated at 310-480 BP (1470-1640 AD) and sample SR3-11-12-15-CH7 collect from 135 cm was dated present-300 BP (1650-present AD). Notes indicate that both samples were flood transported fragments of charcoal. A third sample located at 288 cm was dated at 1820-1930 BP (20-130 AD). The discrepant age obtained from sample SR3-11-12-15-CH8 can be attributed to its unknown source (see methods section). Subtracting this sample from the temporal analysis of Bobcat Bar indicates that the accumulation of fluvial sediments began as early as 1820-1930 BP (20-130 AD) and continued to the present, which is consistent with the findings from the other locations.

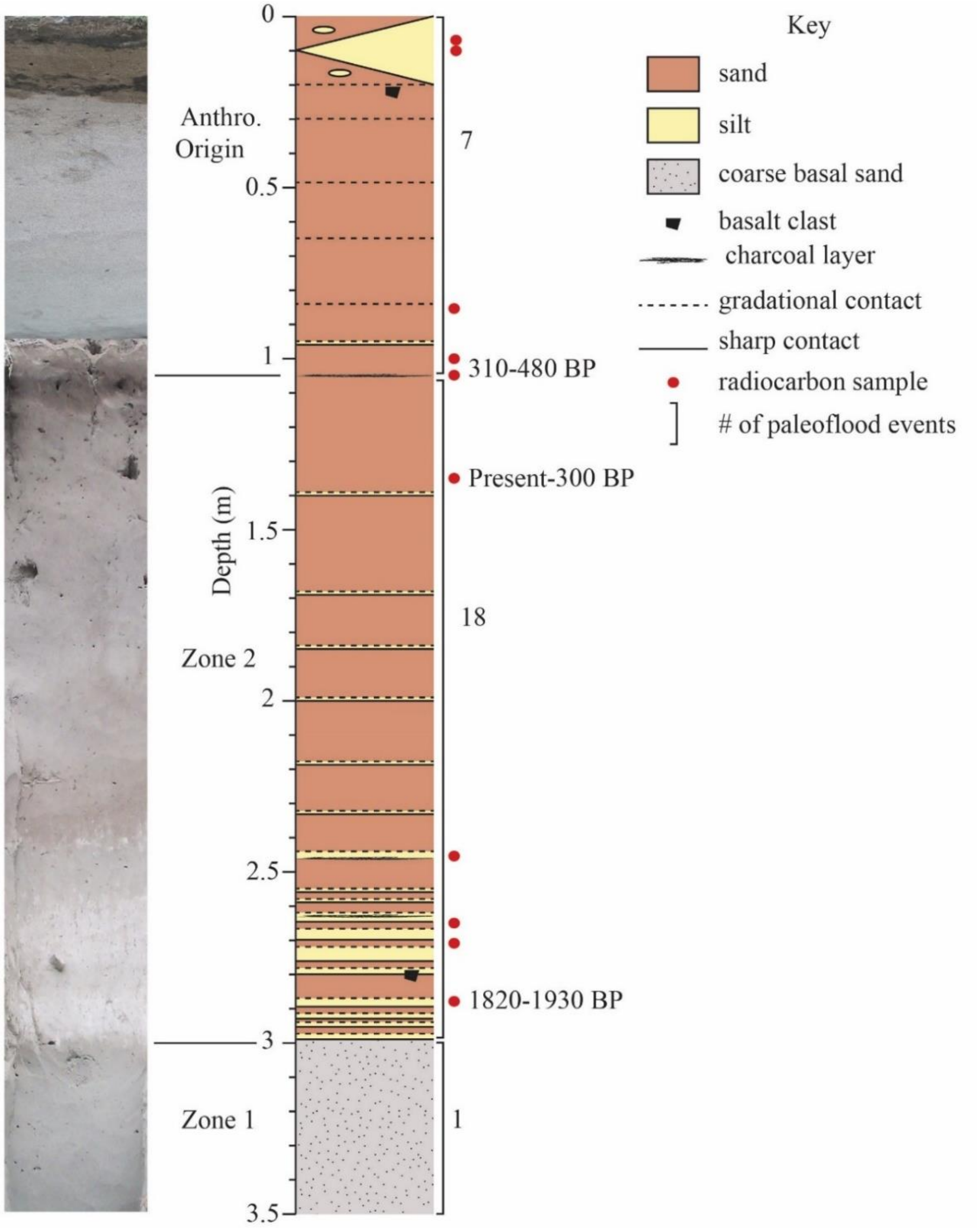

Figure 15. Stratigraphic column and image of stratigraphy at Bobcat Bar. The upper 20 cm of profile was wet when photo was taken. This gives the upper 20 cm of the profile a darker brown color. The line in the photo at 95 cm is the transition between the photo of the upper part of the profile and the lower section of the profile. Description of stratigraphic units and identification of sand-silt flood couplets is in Appendix A.

Hydraulic Modeling

Calibrating HEC-RAS to match the 5.3-meter difference between the water surface elevations for the flood on June 5, 2010 (4,900 cubic m/s (173,000 cubic ft/s)) and the base flow on July 20, 2010 (800 cubic m/s (28,000 cubic ft/s)) required multiple iterations. Multiple runs with different values for Manning's *n* in the channel and over bank areas eventually resulted in a fit. The best fit for the 5.3-meter difference between the June 5, 2010 surface water elevation 4,900 cubic m/s (173,000 cubic ft/s) and the July 20, 2010 surface water elevation was obtained using a discharge of 800 cubic m/s (28,000 cubic ft/s) for the July 20, 2010 water surface and a Manning's *n* value of 0.02 for the channel and 0.03 for the overbank areas (Figure 18; Table 2). With the model calibrated, the minimum discharge required to overtop the Snake River Flood Terrace was determine by incrementally increasing the discharge in the Snake River by approximately 150 cubic m/s (5,000 cubic ft/s). Hydraulic modeling of the Snake River using HEC-RAS and Lidar data revealed that the flood magnitude necessary to overtop the highest point on the slackwater deposits that compose the Snake River Flood Terrace is approximately 6,500 cubic m/s (230,000 cubic ft/s)(Figure 18; Figure 19; Figure 20). Additionally, the minimum discharge required to reach the contact between the top of the coarse basal sands and the first silt/sand couplets is approximately 3,000 cubic m/s (106,000 cubic ft/s) (Figure 21). This reveals a 3,500 cubic m/s (123,600 cubic ft/s) difference in the minimum discharge required to deposit the older lower elevation and younger higher elevation slackwater deposits at the Ten Mile Creek site. The elevation of the contact between the basal sand and silt/sand couplets at the Dietrich and Redbird Beach sites is approximately 0.5 meter higher in elevation relative to the river channel. This indicates that the minimum discharge difference between the surface of the terrace and the top of the base sand is less at these site locations.

The following is a comparison of the modeled results with that of historic gage records. The Anatone gauge located upstream of the study reach near Anatone, WA began recording in 1958. The largest flood recorded by the Anatone gage occurred in 1974 with a discharge of 5,520 cubic m/s (195,000 cubic ft/s). This shows that largest flood recorded by the gage was insufficient to overtop the Snake River Flood Terrace. A second stream gage located in Weiser, Idaho has a record that begins in 1910 (Figure 16). The largest flood recorded at the Weiser gage is 3398 cubic m/s (120,000 cubic ft/s). A statistical correlation between the two gauges provided a slope equation that indicates that the 1910 flood could have been as large as 8778 cubic m/s (310,000 cubic ft/s) at the Anatone gage site (Figure 16; Figure 17). The next two highest peak flows recorded at the Weiser gaging station occurred in 1921 and 1952, before the installation of the gage at Anatone in 1958. It is possible that one of these floods exceeded the discharge of the 1974 flood recorded by the Anatone gage, however it is unlikely. The 1921 and 1952 floods recorded by the Weiser gage were less than one percent greater than the top four floods recorded by the Anatone gauge after 1958, while the discharge of 6,500 cubic m/s (230,000 cubic ft/s necessary to overtop the highest paleoflood deposit of the Snake River Flood Terrace is 18 percent greater than the 1974 flood at Anatone (Figure 16).

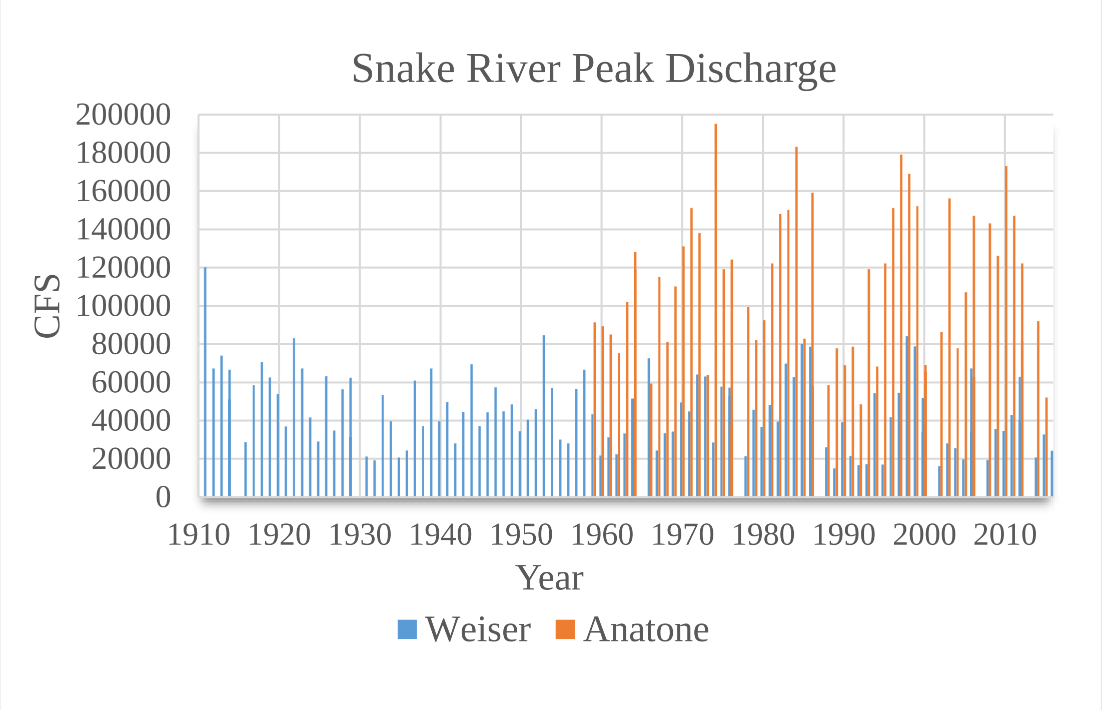

Figure 16. Snake River peak annual discharge gage record. Yearly Snake River peak discharge records at the Weiser, ID and Anatone, WA gage stations located upstream of the Snake River Terrace study reach (U.S Geological Survey, 2015).

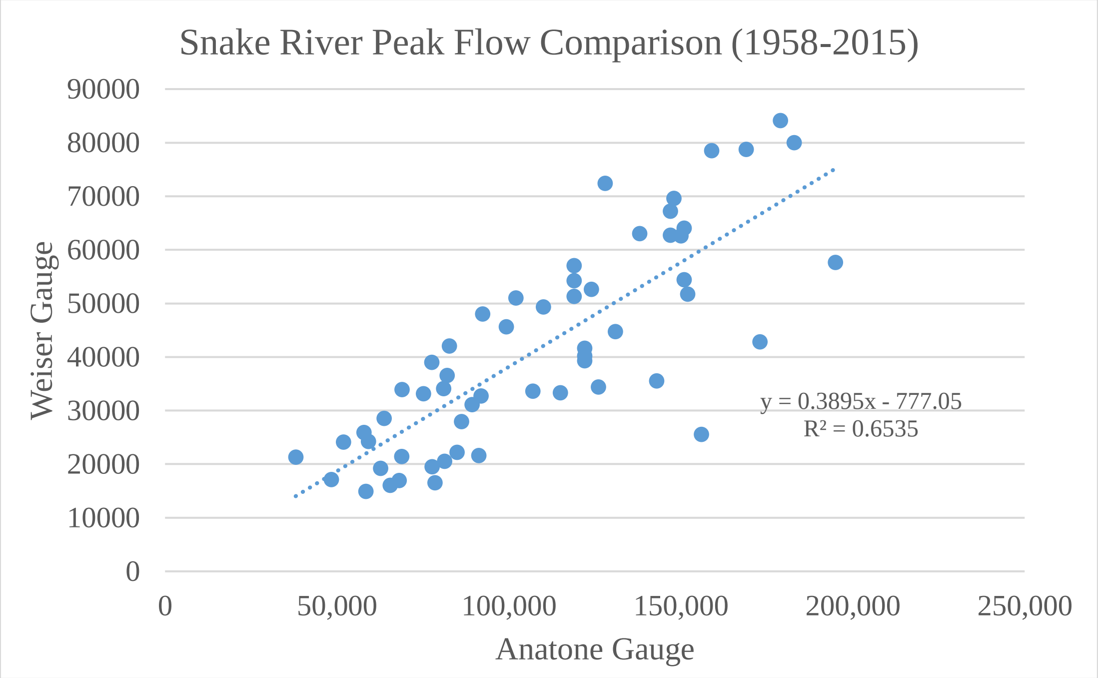

Figure 17. Snake River gage record statistical correlation. Statistical correlation between the overlapping portions of the gaged records at Anatone, WA and Weiser, ID (U.S Geological Survey, 2015).

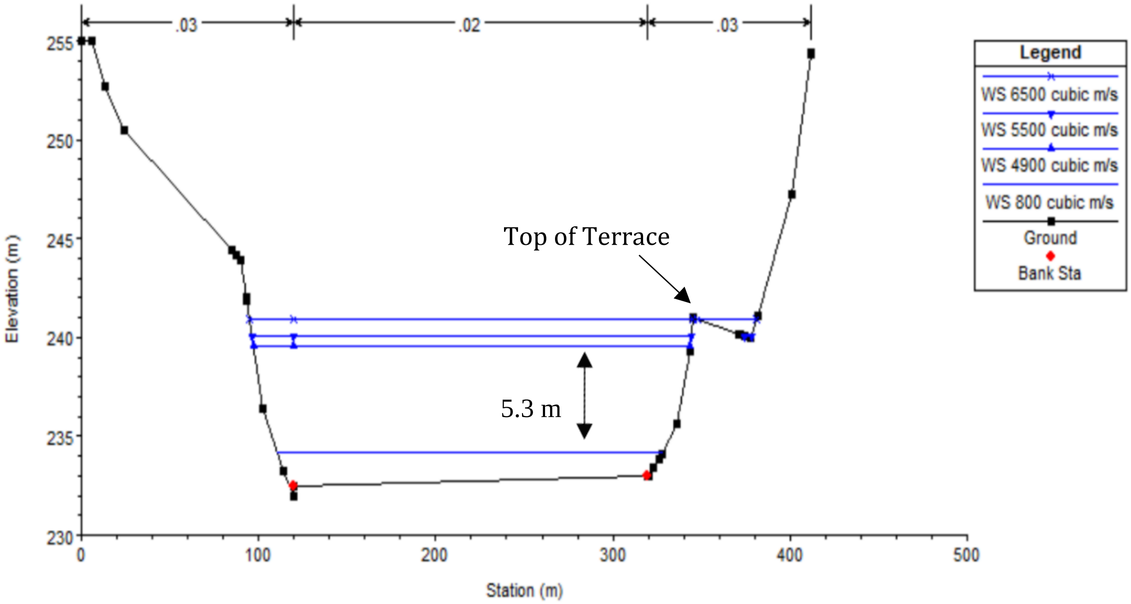

Figure 18. Cross Section #8877 at Redbird Beach. The ground represents the surface of the Snake River at 422 cubic m/s (14,900 cubic ft/s) when the LiDAR data was collected on November 21, 2010. The first water surface (WS) is the level of the Snake River on July 20, 2010, 800 cubic m/s (28,000 cubic ft/s). The second water surface is for a flood of 4,900 cubic m/s (173,000 cubic ft/s) that occurred on June 5, 2010. The third water surface represents a flood that occurred in 1974 with a discharge of 5,500 cubic m/s (195,000 cubic ft/s). The final water surface models the flow required, 6,500 cubic m/s (230,000 cubic ft/s) to overtop the Snake River Terrace at the Redbird Beach, Dietrich, and Ten Mile Creek sites.

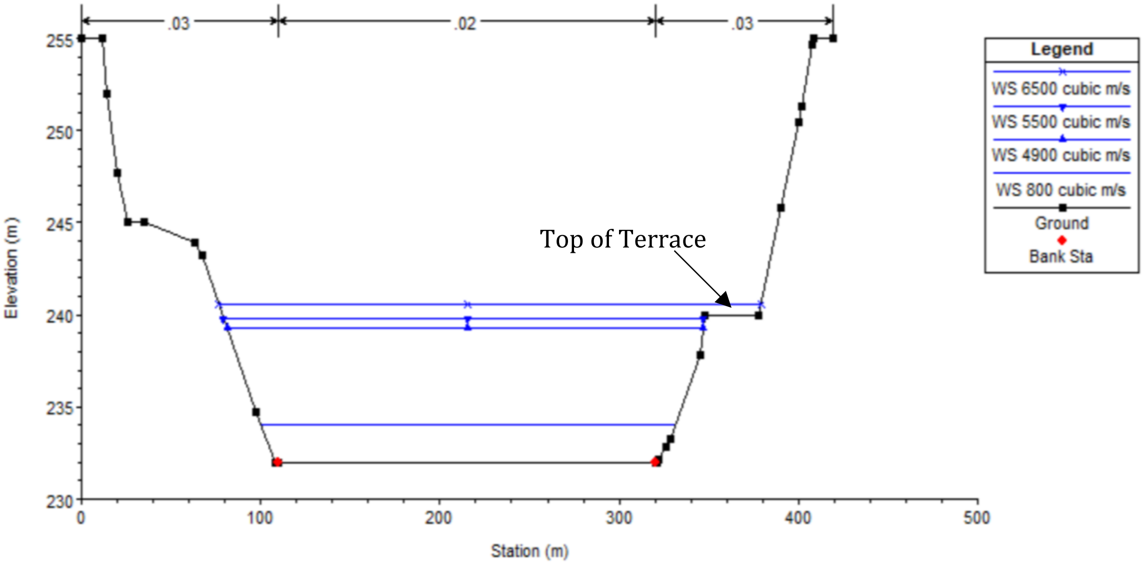

Figure 19. Cross Section #7973 at Dietrich site.

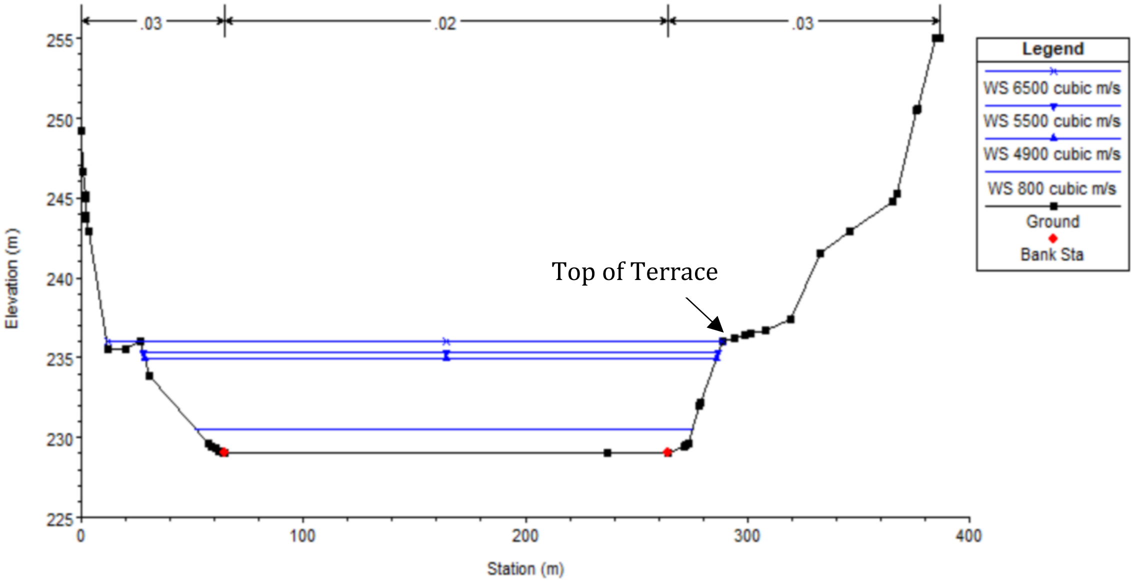

Figure 20. Cross Section #2258 at Ten Mile Creek.

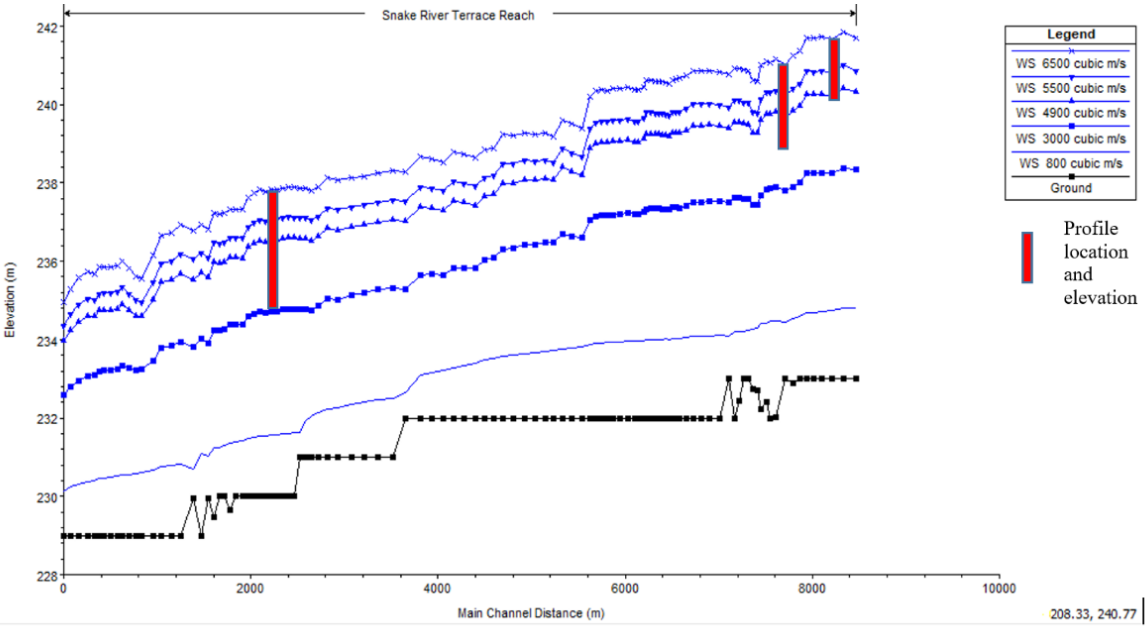

Figure 21. Longitudinal profile of modeled flood/flow events. The modeled water surface for the discharge of 6500 cubic m/s corresponds closely with the elevation of the Snake River Flood Terrace at each of the study sites. Red boxes indicate the location of the Ten Mile Creek, Dietrich, and Redbird Beach Stratigraphic columns from left to right. The height of these boxes corresponds with the elevation of the stratigraphic columns from upper contact of the basal coarse sand to the top of the slackwater deposits at the surface of the Snake River Flood Terrace. Main channel distance is the distance in meters from the upstream most cross section (right) to the downstream most cross section (left) used in the HEC-RAS model.

Table 2. Hydraulic modeling flow elevation table. Elevation above sea level for modeled and observed surfaces and number of flood deposits above defined elevation thresholds.

Redbird Beach	**Elevation (m)**	**Dietrich**	**Elevation (m)**	**Ten Mile Creek**	**Elevation (m)**
Flood Terrace	241.0	Flood Terrace	240.0	Flood Terrace	235.9
6500 cubic m/s	240.9	6500 cubic m/s	240.6	6500 cubic m/s	236
Basal Sand	239.4	Basal Sand	237.9	Basal Sand	232.9
4900 cubic m/s	237.6	4000 cubic m/s	237.3	3000 cubic m/s	233.3
6/5/2010 peak/wrackline	239.5				
7/20/2020 water surface	234.2				
Number of flood deposits above basal sand = 22		Number of flood deposits above basal sand = 29		Number of flood deposits above basal sand = 34	
Flood deposits in last ~300 years = 2		Flood deposits in last ~300 years = 3		Flood deposits in last ~300 years = 4	

CHAPTER IV

DISCUSSION

Analysis of the paleoflood stratigraphy at Ten Mile Creek, Dietrich, and Bobcat Bar sites located along the Snake River Flood Terrace provides evidence for a robust paleoflood record that extends back to at least 1820-1930 cal BP (20-130 cal AD). The 20-km long Snake River Flood Terrace exhibits a relatively consistent geomorphological setting characterized by the uniformity of the stratigraphic, spatial, and chronologic patterns of paleoflood deposition identified at each of the study locations.

Discrete sedimentary layers were used to interpret the flood history preserved in the sediments of the Snake River Flood Terrace. These layers were identified as individual layers of silt or sand and couplets of silt and sand. Paleoflood deposits composed of individual layers of silt and sand were distinguished by sharp upper and lower contacts that indicate a period of subaerial exposure between single flood events. Other evidence of subaerial exposure includes deposits of organic material and or charcoal that cap the sand layers of a silt/sand couplets. Examples of these include multiple discrete layers of fine semi-continuous carbonize plant material and charcoal observed at Ten Mile Creek. These layers are likely derived from buried vegetation and charcoal from brush fires that occurred during periods of subaerial exposer between flood events. Hearths and other evidence of human activity observed at Redbird Beach by Trosper (2011) are indicative of periods of subaerial exposer between flood events where humans occupied the Snake River Flood Terrace.

Silt/sand couplets were also identified to have sharp upper and lower contacts but with the addition of a gradational boundary between the silt and sand that indicate a shift in the depositional energy during a single flood event. This gradational shift from silt to fine sand suggests that floods large enough to top the Snake River Flood Terrace have an initial lower energy depositional environment that allows for the deposition of silt. As the water surface of the flood increases, so increases the depositional energy water column. This increase in depositional energy leads to an inversely gradational paleoflood deposit that coarsen upward from a silt to a fine sand. The sharp contact at the top of silt/sand couplets could indicate that floods on the lower Snake River recede relatively quickly based on the lack of silt observed on the top silt/sand couplets.

Paleoflood deposits that compose the Snake River Flood Terrace were deposited sequentially with the oldest deposits on the bottom and the youngest at the top. As the flood terrace progressively accreted, the terrace became taller and taller as floods left behind deposits. For each subsequent flood to leave behind a deposit, the water surface of the flood must be slightly higher than the top of the deposit left by the previous flood event. This process does not suggest a progressive increase in flood magnitude over time, because there is no way to know the maximum water surface elevation for discrete flood events. It is likely that the water surface for each subsequent flood event varied in elevation, with some rising centimeters to more than a meter above the top of the flood terrace deposits. This could explain the observation of individual slackwater deposits composed of single layers of silt or fine sand. The elevation of each discrete flood deposit represents the minimum water surface required to leave the deposit. As the Snake River Flood Terrace surface increases in elevation, a decreasing number of flood events have the necessary magnitude to leave behind a new deposit. The minimum discharge required to reach the elevation of the oldest fine-grained paleoflood deposits (Zone 2, above the basal sand) is approximately 3,000 cubic m/s (106,000 cubic ft/s). The minimum discharge required to create the youngest deposits at the top of the terrace is approximately 6,500 cubic m/s (230,000 cubic ft/s). This difference in discharge represents a three-meter rise in the water column and a two-fold (216%) increase in flood magnitude. Floods that do not reach current elevation threshold Snake River Flood Terrace are not recorded due to a lack of accommodation space. However, they may be deposited on a younger, lower elevation paleoflood inset adjacent to the taller deposits (Figure 3). These lower elevation flood deposit insets are often closer to the river and more likely to be eroded and replaced with younger deposits, as was found at the Redbird site (Trosper, 2011).

The stratigraphy of the Snake River Flood Terrace is fairly consistent between sites and can be divided into four zones; Zone 1 = the basal coarse sands, Zone 2 = the lower light brown massive fine-grained sands and silt/sand couplets, Zone 3 = the upper dark brown silt/sand couplets, and Zone 4 = upper most unconsolidated light gray silt/sand couplets. Radiocarbon dating indicates that the basal sand (Zone 1) at all four study sites was emplaced before 1560-1700 years B.P. The bottom of basal coarse sand package was not observed at any of the study sites. Analysis of the middle two zones (Zones 2 and 3) of paleoflood deposits composed of individual layers of silt, fine sand, and silt/sand couplets identified approximately 20 to 30 paleoflood events that occurred between 1560-670 years B.P. These units show an obvious extensive paleosol development indicating a long hiatus between floods. The uppermost units of unconsolidated silt/sand couplets (Zone 4) record 2 to 4 paleoflood events that occurred within the last 300 years. There is a hiatus of at least 400 years between Zones 3 and 4, possible longer. As many as 4 flood events were large enough to over top the Snake River Flood Terrace in the last 300 years. At least one of these could be a flood recorded by the Weiser gage that occurred in 1910.

The coarse sands that make up the base of the Snake River Flood Terrace were formed by a slightly higher energy depositional environment than the overlying slackwater deposits. The depositional environment of the basal sands is likely analogous to the present-day sand bars present along the banks of the lower Snake River. At approximately 1560-1700 years B.P., a shift occurred in the depositional environment which led to the formation of slackwater deposits of fine sand and silt instead of the previously deposited coarse beach sands. For this change to occur, there must have been a structural alteration to the river that caused the shift from higher energy beach deposition to lower energy slackwater deposition. Alluvial fans are present across the length of the terrace where intermittent tributaries meet river. For the past 1700 years paleoflood deposits have accumulate in protected backwater zones downstream of the present-day alluvial fans. If these fans were smaller in the past, due to erosion by the Snake River or differences in the tributary sediment supply, then the slackwater zones would have been smaller or non-existent. Another possibility is that river was in different position laterally within the canyon. Within the canyon, the river may be able to change position through meander erosional and accretions processes. Slow meander movement within the channel could cause the depositional environment downstream of alluvial fans to shift from moderate energy coarse sands to the lower energy silt and fine sand slackwater deposits over time and depending on the lateral position of the river with the channel. Additionally, landslide activity located downstream of the study area could raise the base-level of the channel thus causing a shift in depositional environment along the Snake River Flood Terrace from coarse sands to silt and fine sand. A large slow-moving landslide is currently affecting the Snake River channel 5 km downstream near Lewiston, Idaho.

A paleosol with an A and possible B horizon formed on the upper contact of Zone 3, below the loose friable sands of Zone 4 that cap the terraces at Ten Mile Creek, Dietrich, and Redbird Beach. This paleosol may indicate a hiatus in flood deposition at these sites that was long enough to allow soil to develop within the paleoflood deposits that compose the Snake River Flood Terrace. Radiocarbon ages of 730 BP below the contact and 300 BP in the units above the contact indicate a hiatus of at least 400 years. This break in flood deposition could have a couple causes. One, there were no flood large enough to create a flood deposit during that period. Second, a change in base-level are a lateral shift in the river could have made it impossible for large floods to reach the top of the terrace and deposit sediments during that time.

Similarities in the number of paleoflood deposits, depositional patterns, and timing of deposition indicate that the Redbird Beach site is but a part of the greater Snake River Flood Terrace. A comparison of the sites shows that each of the sites are similar in the overall pattern of deposition and number of paleoflood deposits. Each of the sites has a consistent pattern of deposition that can be broken into four zones: the basal coarse sand, the light-colored, massive fine sand and silt/sand couplets, the dark brown couplets and the uppermost, friable sand and silt layers. Bobcat Bar does not exhibit the uppermost section, this is likely due to anthropogenic disturbance. The lower three sites, Ten Mile, Dietrich and Redbird, contain a paleoflood record that consists of approximately 22-34 flood events. However, Bobcat Bar has a record of about 18-25 flood events. Differences in the number of floods between sites is caused by variation in the elevation of the basal sand units which accommodated or prevented the deposition of smaller flood that make of the base of the deposits. This explains why Ten Mile Creek has up to 12 more flood records than the other study locations. Additionally, Redbird Beach, because of its geomorphic setting downstream of the Redbird Creek alluvial fan, has lateral accommodation space that has allowed for deposition of three inset sequences of smaller floods directly adjacent to the taller Snake River Flood Terrace. These lower elevation paleoflood insets were not observed at the other sites of study. These variations in individual site geomorphology in addition to anthropogenic disturbance can lead to differences in the flood record between sites (Trosper, 2011). Overall, similarities in paleoflood chronology and depositional patterns across all four sites indicates that a series of flood events that occurred over the last 2000 years emplaced the paleoflood deposits that compose the 20-km long Snake River Flood Terrace that resides above the eastern bank of the Snake River, downstream of Hells Canyon.

The elevation of the contact between the basal sands (Zone 1) and the overlying fine-grained flood units is not as uniform among the sites as the top of the flood terrace at each site. The modeling results indicate a wide range in the discharge values required to overtop and basal sands in Zone 1 and deposit the oldest set of fine-grained slackwater flood deposits (Zone 2). The modeled discharge at the elevation of this contact ranges from 3,000 cubic m/s (106,000 cubic ft/s) at Ten Mile Creek to almost 4900 cubic m/s (173,000 cubic ft/s) at Redbird (Figure 21). The discharge required to overtop the top of the highest portion of the flood terrace at all three sites is close to 6,500 cubic m/s

(230,000 cubic ft/s). The lower elevation of the basal sand at Ten Mile Creek could have allowed more smaller floods to be recorded in the earlier part of the record at that site that are not present at the other sites. This difference could account for the greater number of flood deposits above the basal sand at Ten Mile Creek (34 deposits) vs. 22-29 flood deposits at the other sites (Table 2). The elevations of the three flood terraces above the river evened out later in the record, as the accommodation space at the Ten Mile Creek site filled in, so they are more likely to be recording the same floods in the latter part of the record. By the time of the most recent deposition in the last 300 years, the discharge required to overtop these three sites is very similar.

Hydraulic modeling using HEC-RAS and Lidar data determined that a discharge of approximately 6,500 cubic m/s (230,000 cubic ft/s) is required to overtop the Snake River Flood Terrace at the Ten Mile Creek, Dietrich, and Redbird study sites. This indicates that the last two to four flood events recorded within the uppermost paleoflood sediments of the Snake River Flood Terrace at the Ten Mile Creek, Dietrich, and Redbird study sites had a minimum discharge of close to 6,500 cubic m/s (230,000 cubic ft/s). However, the water surface of these floods could have been centimeters to a meter or more above the upper surface of the highest elevation paleoflood deposits (Ely, 1997). This would indicate that the magnitude of these flood events could have been significantly higher than the minimum estimate of 6,500 cubic m/s (230,000 cubic ft/s) produced by the model. A flood this size could potentially adversely affect flood mitigation and hydroelectric infrastructure located downstream in the communities of Asotin, Lewiston, Clarkston and the four lower Snake River Dams.

A review of the historic record from river gage locations located near Weiser, ID and Anatone, WA was conducted to identify any possible historic (recorded) flood events that could have been large enough to leave a deposit on the Snake River flood Terrace. A flood record by the Anatone gage in 1974 had a discharge measured at 5,500 cubic m/s (195,000 cubic ft/s). This discharge was run through the calibrated HEC- RAS hydraulic model. It indicated that the 1974 flood recorded by the Anatone gage was not quite large enough to overtop the Snake River Flood Terrace at any of the lower three study sites. However, a flood recorded near Weiser, Idaho had a discharge of 3398 cubic m/s (120,000 cubic f/s) in March of 1910. A statistical correlation between the Anatone and Weiser gage station indicates that the 1910 flood could have been approximately 8778 cubic m/s (310,000 cubic ft/s) within the Snake River Flood Terrace study reach. The R^2 of the statistical correlation between the Anatone and Weiser gage equaled 0.65 (Figure 17). This indicates that at least one historic flood might have been large enough to overtop the Snake River Flood Terrace and deposit slackwater sediments. Therefore, the uppermost slackwater sediments observed at the Ten Mile Creek, Dietrich, and Redbird Beach sites may have been deposited by the 1910 flood recorded by the Weiser gage.

Rhodes, 2001 identified large winter precipitation events such as rain on snow events or rain on frozen ground events that result in large amounts of surface water discharge as the primary source of the largest floods on the Snake River. The storms are source from low pressure systems derived from the norther Pacific Ocean that track to the north east as they pass over the Pacific Northwest. Gage records on March 3, 1910 at the Weiser, Idaho gage support this observation and suggest that a large winter storm event that occurred across the Snake River watershed caused the large flood event on the Snake River in 1910.

Over the last 300 years, two to four paleofloods reached the discharge threshold of 6,500 cubic m/s (230,000 cubic ft/s) or more to leave behind slackwater sediments upon the Snake River Flood Terrace, the youngest of which may have occurred in 1910. In a simple model, these results may indicate that a minimum discharge of 6,500 cubic m/s (230,000 cubic ft/s) probably occurs slightly more frequently than an average of once every 100 years on the Snake River upstream of Lewiston, ID and Clarkston, WA. The probability of a flood of this magnitude could be refined by statistically combining the paleoflood data with the systematic gaged record, which was not part of the current study.

The implications of these findings may help communities and hydroelectric agencies identify infrastructure that is insufficient to withstand a flood in the future that is over 6,500 cubic m/s (230,000 cubic ft/s) in magnitude. The construction of the Hells Canyon dam in addition to other upstream dams on the Snake River can likely mitigate the threat of large floods in the future. However, the 5,500 cubic m/s (195,000 cubic ft/s) discharge for the flood that occurred in 1974, after construction of the Hells Canyon Dam, shows that floods derived from the undammed Salmon and Grande Ronde watersheds combined with the controlled flows from Snake River can produce floods nearly as large as the 6,500 cubic m/s (230,000 cubic ft/s) prehistoric floods identified in the study. This is new information is something that would not have been known without a paleoflood analysis of the Snake River Terrace.

The results of this study show that the lower Hells Canyon reach of the Snake River experience 22-34 large flood events over that last 1700 years as observed within the paleoflood record of the Snake River Flood Terrace. The paleoflood record also shows a 400-year hiatus in flood events that occurred from approximately 700 BP to 300 years BP. Other paleoflood studies conducted on the Snake River share similar results. Rhodes (2001) identified a 5000-yr flood record of more than 22 paleofloods exhibited by the slackwater deposits at the Tin Shed and China Rapids sites located 90-km upstream. The paleoflood record at Tin Shed and China Rapids sites also showed a hiatus in paleoflood activity from 1319 BP- 510 BP similar to that identified by this study. Trosper (2011) identified a 2300-year record that contained evidence of as many as 30 large paleofloods. A field reevaluation of the Redbird site conducted by this study found evidence of 22 flood events with the upper fine grained slackwater deposits and evidence of 13 within the basal coarse sand units. Similarities in the paleoflood records across 110 km of the Snake River identified by multiple studies on may indicate that these sites record many of the same flood events as well as record a period when large flood events were scarce. The addition of this study to the paleoflood catalog of the Pacific Northwest along with a future comprehensive review of paleoflood studies from across region may allow future studies to identify long-term links between changes in climate and large floods within the region.

CHAPTER V

CONCLUSIONS

The deposition and preservation of the Snake River Flood Terrace is due to a regionally consistent geomorphic setting present within the Lower Hells Canyon downstream of the Grande Ronde River. Consistencies in the spatial, temporal, and stratigraphic characteristics of the four paleoflood study locations indicates that the 20-km long Snake River flood Terrace was primarily formed by slackwater deposition that began approximately 1560-1700 years B.P. Two primary patterns of sedimentation were observed within the stratigraphy at each of the study locations. The first is a friable coarse fluvial sand that was emplaced by a depositional environment with moderate flow velocities prior to 1560-1700 years B.P. (Zone 1). This environment has a modern analog in the form of coarse sand bars and banks that are observable along the banks of the Snake River today. Fine grained slackwater sediments of silt, sand, as well as couplets of silt and sand make up the upper three zones of the Snake River Flood Terrace. These sediments were deposited in a relatively low energy depositional environment when the Snake River overtopped the Snake River Flood Terrace and formed overbank conditions where slackwater deposits could form. These fine-grained slackwater deposits began accumulating approximately 1560-1700 years B.P. and have continued to the present, with a possible gap in deposition between 670 and 300 years B.P. The depositional shift from the coarser basal sands to the overlying silt and fine sand slackwater deposits indicates a change in the depositional environment approximately 1560-1700 years B.P. This depositional shift could have been caused by a lateral shift in the position of the river (Trosper, 2011) or by a structural change within the canyon which resulted in a lower energy depositional environment above the flood terrace.

18-25

Analysis of the paleoflood sediment indicate that as many as 22-34 distinct flood events are recorded in the deposits at the Ten Mile Creek, Dietrich, and Redbird Beach sites in the last 1700 years and approximately 18-25 floods at Bobcat Bar. These events are recorded within the fine-grained flood deposits (Zones 2-4), above the contact with the basal sand units, that most closely resemble overbank slackwater flood deposits. These fine-grained deposits accumulated within the last 1560-1700 years. Variations in the geomorphic setting along with human disturbance account for the difference in the flood record among the sites. In particular, the lower elevation of the contact between the basal sands and the fine-grained slackwater deposits at the Ten Mile Creek site allowed more, smaller floods to leave deposits at that site early in the record. The upper units at Bobcat Bar might have been altered by human activities.

Hydraulic modeling using HEC-RAS and Lidar data determined that a discharge of approximately 6,500 cubic m/s (230,000 cubic ft/s) is required to overtop the Snake River Flood Terrace at the Ten Mile Creek, Dietrich, and Redbird study sites. This indicates that the last five prehistoric flood events dated within the last 300 years had discharge of at least 6,500 cubic m/s (230,000 cubic ft/s). One of these flood deposits may have been emplaced by a historic flood that occurred in 1910. The number prehistoric flood events over the last 300 years may indicate that the frequency of floods larger than 6,500 cubic m/s (230,000 cubic ft/s) is less than 100 years for the Snake River upstream of Lewiston, ID and Clarkston, WA.

Paleoflood deposits preserved across the length of the Snake River Flood Terrace record the prehistoric flood history of up to 34 events within the Lower Hells Canyon over the last 1700 years. The Snake River Flood Terrace is the physical manifestation of these floods, revealing that the last four pale floods within the last 300 years had flow rates greater than 6,500 cubic m/s (230,000 cubic ft/s) in magnitude. The results of this study appended to historic flood records will help provide a better understanding of the true paleohydrologic regime the river that will in turn improve estimates for the frequency and magnitude of future large flood events within the Lower Hells Canyon of the Snake River.

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APPENDIXES

Appendix A

Stratigraphic Profile Descriptions

Table A1: Description of stratigraphic profile at Ten Mile Creek. The units that compose a discrete flood are indicated by the alternating shade pattern from white to gray.

Unit	**Flood**	**Depth(cm)**	**Description**
1	I	0-4	Color: 10YR 5/3 brown. Texture: medium sand. Lower contact: gradational to indistinguishable. Unit is organic rich containing both live and decaying plant material. The upper 1-2 cm is covered by duff.
2		4-15	Color: 2.5Y 5/3 light olive brown. Texture: medium sand. Lower contact: gradational. Unit is bioturbated by plant roots and krotovina.
3	II	15-26	Color: 2.5Y 5/3 light olive brown. Texture: silt to fine sand. Lower contact: sharp, varying from straight to wavy. Unit normally grades into overlying unit 2. Convoluted lower contact could indicate paleosurface.
4	III +3?	26-36	Color: 2.5Y 5/3 light olive brown. Texture: silt to sand, possibly alternating. Lower contact: sharp, convoluted, and discontinuous. Angular basaltic cobble present at lower contact. Unit alternates between thin, discontinuous layers of silt and sand, possibly four couplets.
5	IV	36-55	Color: 10YR 4/2 dark grayish brown. Texture: very fine sand to silt. Lower contact: gradational, convoluted.
6	V	55-70	Color: 2.5Y 5/2 grayish brown. Texture: fine sand. Lower contact: sediment color change with wavy boundary.
7	VI	70-95	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: sediment color change that is very wavy and discontinuous. Dark gray mottling at 85 cm may indicate presence of charcoal.
8		95-98	Color: 2.5Y 5/2 grayish brown. Texture: fine sand. Lower contact: gradational, convoluted and discontinuous.
9	VII	98-102	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp, convoluted, and discontinuous. Unit overlies thin, discontinuous layer of charcoal.
10	VIII	102-115	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: indistinct, wavy, and discontinuous, mixed with mottled charcoal. Possible thin silt present at lower contact. Krotovina were observed throughout the unit.

Table A1 Continued

Unit	Flood	Depth(cm)	Description
11		115-122	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: indistinct and discontinuous, mixed with mottled charcoal.
12	IX	122-126	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: wavy and discontinuous. Gray mottling at contact may indicate charcoal. Contacts difficult to distinguish due to bioturbation throughout units 11-14.
13	X	126-128	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact. indistinct, wavy, and discontinuous.
14		128-130	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact. sharp, wavy, and discontinuous.
15	XI	130-138	Color: 2.5Y 6/2 light brownish gray. Texture: very fine sand. Lower contact: sharp, wavy, and discontinuous.
16		138-142	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp, wavy, and discontinuous.
17	XII +2?	142-153	Color: 2.5Y 6/2 light brownish gray. Texture: alternating silt and fine sand. Lower contact: sharp, convoluted, and discontinuous. Bioturbation made the silt and sand layers difficult to distinguish. This unit is possibly composed of three sand layers and three silt layers; this could indicate that unit is composed of up to three silt/sand couplets.
18		153-181	Color: 2.5Y 6/2 light brownish gray. Texture: medium sand. Lower contact: gradational, wavy, and discontinuous. Unit is less consolidated/cemented than overlying units. Charcoal present at 162 cm.
19	XIII +1	181-184	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp, wavy, and discontinuous. Mixing due to bioturbation made contacts and layering difficult to distinguish. This unit is possibly two silt layers with a very thin sand between.
20		184-189	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational and very wavy.
21	XIV	189-191	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp. Lower contact overlies continuous, very thin charcoal layer.
22	XV	191-193	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp and very wavy. Top of unit exhibits a very thin, continuous charcoal layer possibly mixed with sand. Possible silt/sand couplet.
23		193-199	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
24	XVI	199-201	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp, wavy, and discontinuous. Unit overlies a thin, continuous charcoal layer.

Table A1 Continued

Unit	**Flood**	**Depth(cm)**	**Description**
25	XVII	201-230	Color: 2.5Y 5/3 light olive brown. Texture: fine to medium sand. Lower contact: gradational. Charcoal present through the upper two cm of unit.
26		230-231	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp.
27	XVIII	231-235	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
28		235-236	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
29	XXIX	236-240	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
30		240-241	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
31	XX	241-248	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
32		248-249	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
33	XXI	249-255	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
34		255-256	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp, overlying continuous, thin charcoal layer.
35	XXII	256-257	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational, overlying interspersed, thin charcoal layer.
36		257-258	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
37	XXIII	258-261	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
38		261-262	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
39	XXIV	262-263	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
40		263-265	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp, overlying continuous, thin charcoal layer. Bioturbation mixed silt, charcoal, and underlying sand at contact.
41	XXV	265-268	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
42		268-270	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
43	XXVI	270-272	Color: 2.5Y 5/3 light olive brown. Texture: fine sand. Lower contact: gradational.
44		272-273	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp.
45	XXVII	273-274	Color: 2.5Y 5/3 light olive brown. Texture: fine sand. Lower contact: gradational.
46		274-275	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp.

Table A1 Continued

Unit	Flood	Depth(cm)	Description
47	XXVIII +1?	275-281	Color: 2.5Y 5/3 light olive brown. Texture: fine sand. Lower contact: gradational.
48		281-285	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp. Possible additional thin silt/sand couplet pinching out at left side of outcrop.
49	XXIX	285-286	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
50		286-288	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: Sharp, overlying continuous thin charcoal layer. Bioturbation mixed silt, charcoal, and underlying sand at contact.
51	XXX +1?	288-291	Color: 2.5Y 6/3 light yellowish brown. Texture: very fine sand. Lower contact: gradational.
52		291-295	Color: 10YR 6/3 pale brown. Texture: silt. Lower contact: sharp. Subtle fine sand and charcoal layers pinch out on left side of outcrop.
53	XXXI	295-296	Color: 2.5Y 5/3 light olive brown. Texture: medium sand. Lower contact. gradational.
54		296-301	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: indistinct, observed bioturbation could cause it to appear gradational when actually sharp. Possible soft sediment deformation (sand fountaining) observed.
55	XXXII	301-319	Color: 10YR 4/3 brown. Texture: Sand. Lower contact: gradational. Unit appears massive but possible color change and fining observed at 306 cm. Beginning of relatively coarser basal sand package first observed at Redbird Beach as well as other locations within the study reach.
56		319-325	Color: 2.5Y 6/3 light yellowish brown. Texture: silt: Lower contact: sharp, overlying continuous thin charcoal layer.
57	XXXIII	325-335	Color: 2.5Y 5/3 light olive brown. Texture: fine to coarse sand. Lower contact. gradational.
58		335-336	Color: 2.5Y 5/3 light olive brown. Texture: silt to fine sand, inversely graded. Lower contact: gradational.
59	XXXIV	336-337	Color: 2.5Y 5/3 light olive brown. Texture: coarse sand. Lower contact. gradational.
60		337-338	Color: 2.5Y 5/3 light olive brown. Texture: silt to fine sand, inversely graded. Lower contact: gradational.
61	XXXV	338-339	Color: 2.5Y 5/3 light olive brown. Texture: coarse sand. Lower contact. gradational.
62		339-340	Color: 2.5Y 5/3 light olive brown. Texture: silt to fine sand, inversely graded. Lower contact: gradational.
63	XXXVI	340-348	Color: 2.5Y 5/3 light olive brown. Texture: fine sand. Lower contact: gradational, wavy.
64		348-349	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp, wavy.
65	XXXVII	349-360	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: not observed.

Table A2: Description of stratigraphic profile at Dietrich Property.

Unit	Flood	Depth(cm)	Description
1	I	0-16	Color: 2.5Y 5/2 grayish brown. Texture: coarse sand that fines upward. Nodules or possible layer composed of silt observed in upper 6 cm of unit. Lower contact: sharp and wavy. Top of unit is covered with vegetation and duff. Unit is bioturbated and contains live and decaying plant matter.
2	II	16-23	Color: 2.5Y 6/2 light brownish gray. Texture: coarse sand. Lower contact: gradational. Units 2 and 3 are bioturbated.
3		23-24	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp, straight, and discontinuous.
4	III	24-25	Color: 2.5Y 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
5		25-28	Color: 2.5Y 6/2 light brownish gray. Texture: silt. Lower contact: sharp, convoluted. Units 4 and 5 are bioturbated.
6	IV	28-35	Color: 2.5Y 4/2 dark grayish brown. Texture: fine sand. Lower contact: gradational.
7		35-36	Color: 2.5Y 4/2 dark grayish brown. Texture: silt. Lower contact: indistinct. Unit is indistinct and discontinuous due to bioturbation throughout units 6-8.
8	V	36-44	Color: 2.5Y 4/2 dark grayish brown. Texture: fine sand. Lower contact: gradational.
9		44-46	Color: 2.5Y 4/2 dark grayish brown. Texture: silt. Lower contact: sharp, wavy, and discontinuous.
10	VI	46-48	Color: 2.5Y 5/2 grayish brown. Texture: fine to coarse sand, inversely graded. Lower contact: gradational.
11		48-51	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp and wavy.
12	VII	51-65	Color: 10YR 5/3 brown. Texture: silt. Lower contact: sharp and straight. Unit is massive, bioturbated and overlies a very thin semi-continuous charcoal layer.
13	VIII	65-67	Color: 10YR 5/2 grayish brown. Texture: medium sand. Lower contact: gradational.
14		67-70	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: indistinct, sharp.
15	IX	70-75	Color: 10YR 5/2 grayish brown. Texture: sand. Lower contact: gradational. Charcoal observed at ~75 cm, most noticeable on right side of profile.
16		75-76	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp.
17	X	76-83	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, slightly wavy
18	XI	83-85	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational. Dark gray coloring near top of unit may indicate presence of charcoal.
19		85-86	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous.

Table A2 Continued

Unit	Flood	Depth (cm)	Description
20	XII	86-88	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
21		88-94	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous. Random dark gray swirls may indicate presence of charcoal at lower contact.
22	XIII	94-111	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational. Charcoal possibly present at 105 cm.
23		111-115	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous.
24	XIV	115-118	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
25		118-119	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous.
26	XV	119-126	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
27		126-127	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous.
28	XVI	127-132	Color: 10YR 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
29		132-133	Color: 10YR 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous, and very wavy. Dark gray coloring at lower contact may indicate presence of charcoal.
30	XVII	133-136	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
31		136-138	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp, discontinuous.
32	XVIII	138-141	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
33		141-146	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp and discontinuous.
34	XIX	146-154	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
35		154-155	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp and discontinuous.
36	XX	155-159	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
37		159-162	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp and discontinuous.
38	XXI	162-165	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
39		165-166	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp, wavy, and discontinuous.
40	XXII	166-169	Color: 2.5Y 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
41		169-170	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp.

Table A2 Continued

Unit	Flood	Depth(cm)	Description
42	XXIII	170-178	Color: 2.5Y 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
43		178-179	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp.
44	XXIV	179-182	Color: 2.5Y 5/2 grayish brown. Texture: fine sand. Lower contact: gradational.
45		182-183	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp, straight, and discontinuous.
46	XXV	183-185	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
47		185-187	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp and discontinuous.
48	XXVI	187-191	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
49		191-193	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp. Angular basalt cobble observed at lower contact.
50	XXVII	193-200	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
51		200-201	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp and discontinuous.
52	XXVIII	201-205	Color: 10YR 6/2 light brownish gray. Texture: fine sand. Lower contact: gradational.
53		205-209	Color: 10YR 6/2 light brownish gray. Texture: silt. Lower contact: sharp, wavy, and convoluted.
54	XXIX	209-211	Color: 2.5Y 5/2 grayish brown. Texture: med. sand. Lower contact: gradational. Top of coarse basal sand observed at other locations within the study reach. Layers below this depth are soft or less consolidated than overlying units.
55		211-212	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp, discontinuous.
56	XXX	212-223	Color: 2.5Y 5/2 grayish brown. Texture: medium sand. Lower contact: gradational.
57		223-224	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp.
58	XXXI	224-238	Color: 2.5Y 5/2 grayish brown. Texture: medium sand. Lower contact: gradational.
59		238-239	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp and straight.
60	XXXII	239-247	Color: 2.5Y 5/2 grayish brown. Texture: medium sand. Lower contact: gradational.
61		237-249	Color: 2.5Y 5/2 grayish brown. Texture: silt. Lower contact: sharp and straight.
62	XXXIII	249-261	Color 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational and or color change.
63	XXXIV	261-280	Color: 2.5Y 5/2 grayish brown. Texture: medium to coarse sand. Lower contact: not observed. Unit is loose and easily erodible, likely cause of cliff formation at site.

Table A3: Description of stratigraphic profile at Bobcat Bar.

Unit	**Flood**	**Depth (cm)**	**Description**
1	I	0-20	Color: 10YR 4/3 brown. Texture: silt pinching out to medium to coarse sand. Lower contact: gradational, color change. Unit is completely silt on the south end of outcrop which pinches out into coarse sand to the north. Contact between sand and silt layer and silt nodules are sharp. Unit pinches out to surface at north end of outcrop.
2	II	20-30	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational, color change. Angular basalt cobble observed at upper contact. Unit pinches out to surface at north end of outcrop.
3	III	30-49	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational, color change.
4	IV	49-65	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational, color change.
5	V	65-84	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational, color change.
6	VI	84-95	Color: 2.5Y 5/3 light olive brown. Texture: medium to coarse sand. Lower contact: gradational.
7		95-96	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp and wavy.
8	VII	96-105	Color: 2.5Y 4/2 dark grayish brown. Texture: fine sand. Lower contact: sharp, overlying continuous thin charcoal layer.
9	VIII	105-139	Color: 2.5Y 5/2 grayish brown. Texture: fine to medium sand. Lower contact: gradational.
10		139-140	Color: 2.5Y 5/2 grayish brown. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.
11	IX	140-168	Color: 2.5Y 5/2 grayish brown. Texture: fine to medium sand. Lower contact: gradational.
12		168-169	Color: 2.5Y 5/2 grayish brown. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.
13	X	169-184	Color: 2.5Y 5/2 grayish brown. Texture: fine to medium sand. Lower contact: gradational.
14		184-185	Color: 2.5Y 5/2 grayish brown. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.
15	XI	185-199	Color: 2.5Y 5/2 grayish brown. Texture: fine to medium sand. Lower contact: gradational.
16		199-200	Color: 2.5Y 5/2 grayish brown. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.
17	XII	200-218	Color: 10YR 4/3 brown, wet. Texture: fine to medium sand. Lower contact: gradational.
18		218-219	Color: 10YR 4/3 brown, wet. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.
19	XIII	219-232	Color: 10YR 4/3 brown, wet. Texture: fine to medium sand. Lower contact: gradational.
20		232-233	Color: 10YR 4/3 brown, wet. Texture: silt to fine sand. Lower contact: sharp. Unit is thin and discontinuous.

Table A3 Continued

Unit	Flood	Depth (cm)	Description
21	XIV	233-244	Color: 10YR 4/3 brown, wet. Texture: fine to medium sand. Lower contact: gradational and convoluted.
22		244-246	Color: 10YR 4/3 brown, wet. Texture: silt. Lower contact: sharp, straight, and discontinuous. Unit overlies a continuous, very thin charcoal layer.
23	XV	246-255	Color: 2.5Y 5/3 light olive brown. Texture: fine to medium sand. Lower contact: gradational.
24		255-256	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp, straight, and discontinuous.
25	XVI	256-258	Color: 2.5Y 5/3 light olive brown. Texture: fine to medium sand. Lower contact: gradational.
26		258-259	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp.
27	XVII	259-262	Color: 2.5Y 5/3 light olive brown. Texture: fine sand. Lower contact: gradational.
28		262-263	Color: 2.5Y 5/3 light olive brown. Texture: silt. Lower contact: sharp. Unit overlies a continuous, very thin charcoal layer.
29	XVIII	263-265	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
30	XXIX	265-267	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
31		267-270	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
32	XX	270-272	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
33		272-276	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
34	XXI	276-278	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
35		278-280	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp. Angular basalt cobble observed at 280 cm.
36	XXII	280-287	Color: 2.5Y 6/3 light yellowish brown. Texture: silty fine sand. Lower contact: gradational.
37		287-289	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
38	XXIII	289-291	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
39		291-292	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
40	XXIV	292-296	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
41		296-297	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp.
42	XXV	297-298	Color: 2.5Y 6/3 light yellowish brown. Texture: fine sand. Lower contact: gradational.
43		298-299	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp and wavy.

Table A3 Continued

Unit	**Flood**	**Depth (cm)**	**Description**
44	XXVI	299-364	Color: 2.5Y 5/2 grayish brown. Texture: coarse sand. Lower contact: gradational. Unit is softer than overlying silt/sand couplets. Top of coarse basal sand package observed at other locations within the study reach.
45		364-372	Color: 2.5Y 6/3 light yellowish brown. Texture: silt. Lower contact: sharp and wavy. Unit is mottled with patches of sand; bioturbation likely mix silt and underlying sand.
46	XXVII	372-380	Color: 2.5Y 5/2 grayish brown. Texture: coarse sand. Lower contact: not observed.