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Holocene Periods of Aggradation and Incision, Hanson Creek, Washington

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HOLOCENE PERIODS OF AGGRADATION
AND INCISION, HANSON CREEK, WASHINGTON

A Thesis
Presented to
The Graduate Faculty
Central Washington University

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
Geological Sciences

by
Levi Earl Windingstad
November 2019
CENTRAL WASHINGTON UNIVERSITY
Graduate Studies

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Dean of Graduate Studies
ABSTRACT

HOLOCENE PERIODS OF AGGRADATION AND INCISION, HANSON CREEK, WASHINGTON

by

Levi Earl Windingstad

November 2019

The causes and timing of cycles of aggradation and incision in the Hanson Creek drainage in central Washington provide insight into changes in channel morphology and paleoenvironment within the region over the last 8000 years. Stratigraphically and spatially coincident archaeological evidence reveals information related to human occupation during the latter half of the epoch. Using LiDAR imagery and field surveys, recent processes such as degree of modern channel incision, accumulation of valley floor sediment, channel morphology and gradient were evaluated. The spatial distribution of these channel characteristics was assessed in relation to proximal landforms such as colluvial deposits, basalt outcrops, and bedrock anticlinal ridges. Sixteen stratigraphic profiles in the arroyo walls were used to delineate and correlate past depositional episodes based on sediment characteristics. Basal ages of the earliest documented depositional period were constrained using geochemical analysis of tephra beds. Intermediate dates were obtained from $^{14}$C analysis of in situ charcoal. The results reveal an aggrading fluvial system that entrained and transported silt to cobble sized sediment from a
minimum age of 7680-7580 BP prior to the historic arroyo incision event, which most likely occurred between AD 1878 and AD 1954. The cause of the incision is likely a combination of factors, including thick accumulations of easily erodible sediment in reaches of shallow valley gradient and intervening steep gradients. Although the event that triggered the incision is unknown, similar arroyos in the western U.S. have been initiated by high magnitude floods that incised initial knickpoints, subsequently lowering base level.
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CHAPTER I

INTRODUCTION

The research presented here provides stratigraphic and sedimentological evidence of the incision and filling of a currently incised reach of Hanson Creek in central Washington State (Figure 1). The causes and timing of cycles of sediment deposition and erosion in the Hanson Creek drainage provide insight into changes in channel morphology and paleoenvironment within the study area beginning in the mid-Holocene (~8 ka). Stratigraphically and spatially coincident archaeological evidence revealed information related to human occupation during the latter half of the epoch.

Figure 1. Location of study denoted by star. Hanson Creek is labeled in the close-up map. Service Layer Credits: USGS The National Map, August 2019.
The results of this study supplement the limited data currently available related to arroyo formation in the northwestern United States. Arroyos are deeply incised fluvial channels that form in unconsolidated sediment found predominantly in semi-arid and arid climates. The causes and timing of these incision events is a long-debated topic which is discussed in detail in the literature review.

**Research Objectives**

Several primary research objectives are used to evaluate physical environmental changes throughout the Holocene within the incised reach of Hanson Creek:

1. Determine the characteristics and processes involved in the deposition of sedimentary units;

2. Quantify the absolute and relative timing of channel incision and depositional events;

3. Interpret the potential influence of external factors such as sediment influx resulting from axial alluvial fans, groundwater influx and internal feedback mechanisms on deposition and arroyo formation.

The resulting data and interpretations from the research objectives provide context for secondary objectives including:

1. Correlate changes in physical environment with regional paleoclimate and the coincident timing of human occupation;
2. Interpret archaeological site integrity based on geologic evidence.

I hypothesize that Hanson Creek has not always been confined to deeply incised channel banks but was previously a single meandering channel or multiple channels, transporting entrained sediment throughout the valley floor. The aggradation of this fluvial system began during the Mid-Holocene (~8 ka) at minimum, which is prior to the historic arroyo incision event that likely occurred between AD 1878 and AD 1954.

**Regional Setting of Study Area**

Located in central Washington State, the study region exists within the boundaries of the Yakima Training Center (YTC), which is a U.S. Army training base (Figure 1). The semi-arid shrub steppe environment is influenced by the orographic effect of the Cascade Mountains to the west. The mean annual precipitation is approximately 19 cm and a majority of this falls during the winter months as snow in the higher elevations (Tyler, 2006). The streams within the YTC are all recognized as intermittent or ephemeral and none flow perennially throughout the entire stream length (Durkee, 2012).

Between two anticlinal ridges an alluvial valley filled with unconsolidated sediment grades southeasterly towards the Columbia River. The intermittently incised channel of Hanson Creek meanders through this valley. The Saddle Mountains to the north of the valley are an east-trending anticlinal ridge that extend for approximately 70 miles (Reidel, 1988). The northeastern aspect of an unnamed
monoclinal ridge represents the southern valley boundary (Riedel, 1988). These ridges are found throughout the region and are generally composed of Quaternary sediments superimposed on folded Columbia River Basalts (Reidel et al., 1989). This Yakima fold region is composed of deformed flood basalts due to north-south compression forming a series of east-west trending anticlinal ridges (Reidel et al., 1989). The folding and faulting began approximately 15 mya and continues to this day at a reduced rate (Campbell, 1998).

Hanson Creek originates near McDonald Spring on the southeastern aspect of the Saddle Mountains and flows in a southeasterly direction for approximately 20 kilometers before reaching the Columbia River (Figure 1). Hanson Creek is a fourth

Figure 2. Photograph of the Hanson Creek arroyo. The photograph depicts the typical arroyo channel geometry observed within the studied region. The creek flows within the deeply entrenched channel for approximately 1-km. The entire length of the stream is not incised. Person for scale is approximately six feet tall.
order stream with 1st, 2nd and 3rd order tributaries forming the drainage network that originate from slopes north and south of the 4th order stream. The rise in topography near McDonald Springs produces a divide, which results in all water to the east of the divide flowing east and water to the west flowing west. The east-west trending alluvial valleys are common throughout the YTC, as the anticlinal ridges direct flow to the east into the Columbia River or to the west into the Yakima River.

Within the Hanson Creek drainage, a maximum 7-meter deep channel propagates approximately 1 km from west to east. This incised channel (arroyo) reveals the underlying stratigraphic sequence of Holocene sediment packages, which provide sedimentological evidence necessary for the determination of the timing and possible causes of deposition and erosion (Figure 2).

**Alluvial Chronology of the Yakima Training Center**

Previous attempts at interpreting the alluvial chronology of the YTC have been represented in numerous archaeological reports, two master's theses (Durkee, 2012; Sullivan, 1994) and a project funded by the United States Army (Gough, 1998; Galm et al., 2000). The results of previous research present a similar temporal trend of arroyo cut-and-fill cycles that correlate mechanically to the more comprehensively investigated arroyos of the southwestern United States. The most thorough report, *Project Fog Oil*, was funded by the United States Army as a means of dating sediments prior to the initiation of a new smoke screen training, which could potentially obscure further radiocarbon dates within the YTC (Galm et al.,
The results of the area-wide study present four stages of alluviation: 1.) 11,000 B.P to 7,000 B.P.; 2.) 7,000 B.P. to Undefined; 3.) 4,000 B.P. to Undefined; 4.) 1500 B.P. to 130 years ago (Galm et al., 2000). The archaeological reports present many generalizations about the chronology and origin of the alluvial sediments, but most include a call for further geomorphic research. The most concentrated approach at understanding the alluvial history of the YTC focused on determining the chronology of Holocene arroyo cut-and-fill cycles in Selah Creek, in the southern part of the YTC (Durkee, 2012).

**Archaeological Evidence**

Archaeological evidence from site 45KT1975 (Bishop Hollow) was excavated and cataloged by students of Central Washington University (Figure 3). The results of the excavation yielded approximately 4,200 lithic artifacts and 103 faunal remains. The preliminary interpretation of the lithic scatters suggests a temporary camp; however, a chronology of the cultural artifacts is yet to be determined.

Further archaeological excavations occurred during the summer of 2014 (Simmons et al., 2014). Data collected from these excavations was used to correlate the timing constraints of the sedimentary units and associated archaeological evidence. These correlations reveal evidence related to human occupation, climate, and paleoenvironment.
Figure 3. Site map of archaeological site 45KT1975. The Y-shaped confluence is a good reference for map comparison. (Simmons et al., 2014).
Arroyos are deeply incised fluvial channels that have spurred the curiosity of geomorphologists since the beginning of the 20th century (Waters and Haynes, 2001). This type of ephemeral streams were first noted in the middle of the 19th century by military personnel advancing through the southwestern United States. Sections of land, previously described by the military personnel as lush with vegetation and inundated with water, had since, upon their return to the United States, become dry and sparsely vegetated. Furthermore, the advent of deep trenches with steep walls became the foremost path of water flow within the flat valley bottom reaches of the watershed (Bryan, 1925). These rapid rates of incision and resulting consequences, such as the lowering of the water table, were originally attributed to a decline in vegetation caused by overgrazing (Bull, 1997). However, as the understanding of fluvial geomorphology evolved, the focus of research advanced from a simple determination of causes of arroyo incision to multiple fundamental processes involved in the formation of arroyos (Bull, 1997).

Arroyos Defined

Discontinuous ephemeral streams, commonly referred to as arroyos, are typically in the range of 5 to 200 km in length and characterized by flat channel beds with near vertical banks (Bull, 1997). These entrenched channels are commonly found on low-gradient valley floors containing cohesive alluvium. Unlike many
fluvial channels, high discharge flood events typically remain within the boundaries of the channel, which in turn results in rapid down cutting instead of floodplain development (Bull, 1997).

Figure 4. Geographic extent of arroyos in the United States, which are denoted by gray rectangles. Locations with identified arroyos not shown in diagram include eastern Washington, Oregon and western North Dakota (Bull, 1997).

Geographically, the extent of arroyos is generally constrained by climate. Modern arroyos are found in semi-arid to arid environments such as the southwestern U.S. (Waters and Haynes, 2001). However, arroyo research and scope extends beyond the American southwest and includes the arid regions within other states in the interior of North America, including Oregon, Washington, Wyoming, and North Dakota (Figure 4). The climate, as well as other factors that will be discussed in the arroyo formation section below, appear to influence a cycle of
aggradation and degradation in arroyos throughout the Holocene (Schumm and Hadley, 1957; Waters and Haynes, 2001; Harvey et al., 2011).

**Arroyo Formation**

The current hypotheses of arroyo formation are based on an evolutionary collection of research done over the past 80 years. Kirk Bryan wrote a very early and critical article on arroyo formation in 1925. The study used historical records of exploration throughout the American southwest to determine when the multitude of arroyos in the region incised and, postulated about possible causes. The historical records presented a timeline of incision occurring in arroyos in this region between 1860 and 1900 (Bryan, 1925). In 1925, the general cause of incision was thought to be overgrazing, which resulted in rapid run off and increased erosion rates. However, Bryan suggested a few other hypotheses including; slight uplift resulting in incision, a shift in climate towards more arid conditions, and the damming of rivers by previous human populations that resulted in aggradation and ensuing erosion as dams became nonexistent. Neither the uplift nor river damming hypotheses were supported; however, the shift to a drier climate found support from many scientists including Bryan (1925) and Schumm and Hadley (1957).

Additional work addressed the initiation of down-cutting and the idea of cyclical erosion episodes. Schumm and Hadley (1957) proposed that the formation of arroyos was related to a cycle of erosion unique to arid and semi-arid environments. The focus of their research included the observation and quantitative
assessment of longitudinal profiles of arroyos in New Mexico and Wyoming. By determining the gradient along different reaches of discontinuous channels, they hypothesized that initial channel incision occurs along reaches with steeper gradient (Figure 5).

![Figure 5. Longitudinal profile showing possible correlation between channel gradient and incision. Figures are gradient for each section of profile in ft./ft. (Schumm and Hadley, 1957).](image)

Moreover, the idea that erosion and aggradation within arroyos occurs in cyclical patterns began to rise in prominence as an explanation of arroyo formation. The development of these ideas continued to progress through further research, but generally focused on the factors causing arroyo incision until the 1990s (Alford, 1982; VanArsdale, 1982; Waters, 1985).

One exception to the other lines of research related to calcrete as an influence on channel geometry of arroyos. VanArsdale (1982) surveyed and
developed longitudinal profiles and cross sections along different reaches near Buckeye, Arizona containing an impervious calcic soil or calcrete. The first reach, which contained calcrete in the bed and unconsolidated banks, was characterized by a high width to depth ratio and little to no downcutting. The second reach, further downstream, included both bed and banks of calcrete. The development of nickpoints in the calcrete allowed for the initiation of incision. Here the width to depth ratio was low and bed slope was high. Continuing downstream to the third reach, the channel incised through the calcrete bed exposing the underlying alluvial sediment. The presence of an alluvial bed and calcrete banks resulted in an increasing width to depth ratio and an increased cross-sectional area. The final reach, reach four, presented a stage of aggradation as sediment was deposited and the undercutting of the calcrete banks resulted in slumping of the banks, and increased sediment load. These results represent a development in the discussion of arroyo formation, specifically related to the role of the channel boundary sediment type.

The next advance in arroyo formation can be attributed to the understanding of paleoarroyo channels. The idea that the formation of arroyos is solely due to anthropogenic influence was long debated until the understanding of paleoarroyo channels. First reported by Antevs (1952), the stratigraphy in arroyo banks presents evidence for arroyo channels pre-dating human influence. At the time, absolute dating techniques, such as optically stimulated luminescence (OSL) and radiocarbon were unavailable. However, relative age dates were surmised based on
the stratigraphic sequence of the buried channels. It was not until the use of OSL and radiocarbon dating that absolute dates could be determined for stratigraphic layers, making it possible to ascertain the timing of channel fill and cut.

Waters and Haynes (2001) present research with absolute dates given to specific cut and fill events of arroyos using radiocarbon dates taken from paleoarroyo channels in Arizona. Organic material was sampled from the base of each channel to determine the time of channel entrenchment. Once compiled and paired with the stratigraphy, these dates can be used to determine periods of filling and incision (Figure 6). The results of the absolute dates suggest the first arroyos in the study region appeared 8,000 $^{14}$C yr B.P. The channels then began a sequence of cutting and filling starting 4,000 $^{14}$C yr B.P. and continue today. Another attempt to associate arroyo sequences with absolute dates was performed in Utah (Harvey et al., 2011). The dates of paleochannels within Buckskin Wash were determined using dendrochronology to constrain OSL results. The final results reveal a sequence of at least four cut and fill sequences starting 3 ka. Furthermore, observations from another study estimate that the time frame necessary to backfill arroyos ranges from 500-2000 years; whereas, the main period of incision occurs within a scale of a hundred years (Bull, 1997; Durkee, 2012; Hereford, 2002; Waters, 1985).
Figure 6. Correlation of vegetation, climate, and El Niño periodicity to chronology of arroyo cut and fill cycles of Curry Draw and Santa Cruz River in Arizona. Black dots indicate wet periods. Shaded areas indicate time of arroyo cutting (Waters and Haynes, 2001).
Factors Controlling Arroyo Incision

The debate on controlling factors can muddle the discussion of arroyo formation as it often surmounts the underlying pertinent information. Debates over the cause of arroyo incision often include two different camps. The first general viewpoint involves intrinsic geomorphic controls tied to surface topography, vegetation cover and sediment characteristics resulting in cycles of cutting and filling. The opposing viewpoint emphasizes the influence of climate driving the erosion and aggradation. This can be divided into two main causes. The first being a fluctuation of stream base level (wet) rising or (dry) falling, which results in aggradation or erosion (Bryan, 1941; Antevs, 1952; Karlstrom, 1988). The second being erosion occurs during wet conditions, when the stream is capable of transporting the larger fraction of grain sizes (Martin, 1963; Hall, 1977). In the southwestern United States, the increase in rainfall associated with the frequency and magnitude of the El Niño-Southern Oscillation is often attributed. One example of the influence of the El Niño-Southern Oscillation can be found in the results from research done in Arizona by Waters and Haynes (Waters and Haynes, 2001). The authors suggest that the cause of arroyo formation is repeated wet-dry cycles that in turn are linked to El Niño and non El Niño patterns (Figure 6). Moreover, a model of arroyo formation is presented including the lowering of water tables and reduced vegetation during dry periods resulting in increased erosion rates. Therefore, when the increase in precipitation and flooding occurs, arroyo incision ensues as the ground is susceptible to erosion.
An example of the opposing viewpoint can be seen in the semi-arid cycle of erosion presented by Schumm and Hadley (Schumm and Hadley, 1957). The main controlling factor presented within the longitudinal profiles was the direct influence of gradient change due to aggradation. The one problem with this viewpoint as a standalone factor is the cause of initial incision. Although, the debate between the two camps is yet to be settled a common thread can be pulled from all of the research.

One common factor that everyone seems to agree on is the influence of vegetation. Whether the decrease in vegetation can be directly tied to overgrazing or is linked more directly to a shift to a drier climate continues to be a debate. The fact remains that arroyo incision does not occur in heavily vegetated humid regions (Alford, 1982; Bryan, 1925; Huckleberry and Duff, 2008).

The current state of arroyo literature remains at a stalemate involving the debate on the main causes of incision. However, the main controlling factors affecting the formation of arroyos seem to be similar. A common tie in all of the literature provides a general model of arroyo formation (Figure 7).

The necessary factors for arroyo incision appear to be the channelization of sheet flow over lightly vegetated, unconsolidated, valley floor alluvial sediment common in a semi-arid to arid environment. Some factor, likely to vary slightly from arroyo to arroyo, results in the formation of an initial nickpoint. In some cases, several nickpoints may occur downstream of the initial incision, forming
discontinuous channels. The ensuing incision, both headward and downstream, causes the channel to deepen and widen. This process continues to be driven by what are likely large rainfall events until the discontinuous channels are connected. At this point in the process, the flow of water is essentially unobstructed causing undercutting of the banks and slumping.

Figure 7. Hypothesized stages of arroyo formation displayed in longitudinal and cross section profiles (Bull, 1997).
Up to this point the majority of research is dedicated to incision, but as the necessity of arroyo mitigation becomes more prevalent, the fundamentals of arroyo filling will become pertinent. One model developed with a focus on aggradation presents a variation on the model presented by Bull (Bull, 1997). The first stage of the four-stage cycle involves a period of stability and soil genesis occurring on the flood-plain alluvium. Secondly, channel entrenchment and widening of the flood-plain occurs along the middle and upper reaches of the channel. Thirdly, aggradation of the flood-plain and channel occur throughout the lower reaches. Finally, the channel begins to incise in the lower reaches (Gonzalez, 2001). This model is based on the observations of recent arroyos forming in western North Dakota and provides an interesting perspective of the influence of the ongoing aggradation in the incision process. This is important to note, because it is likely that these aggradation and degradation events will be challenging to completely segregate as research on arroyo development continues.

One successful attempt to determine the timing of aggradation revealed a unit of valley fill alluvium, which is bounded by unconformities resulting from arroyo incision. This unit is found in the valleys of the Paria River in Arizona and Utah and coincides with the Little Ice Age A.D. 1400 to 1880 (Hereford, 2002).

This project will supplement the available literature with additional sedimentation, valley profile and channel geometry data related to arroyo
formation. Currently, very few investigations of arroyos in the semi-arid interior of the Pacific Northwest have occurred (Durkee, 2009; Peacock, 1994; Sullivan, 1994).
CHAPTER III

METHODS

To address the research questions; aerial LiDAR imagery, historic air photos, a historic plat image and field surveys provided data for recent processes such as degree of modern channel incision, accumulation of valley floor sediment, channel morphology and gradient. The spatial distribution of these channel characteristics was assessed in relation to proximal landforms such as colluvial deposits, basalt outcrops, the Saddle Mountains and an unnamed monocline. Longitudinal profiles of both the incised channel floor as well as the surrounding valley floor were generated to evaluate the extent and degree of the stepped topography in the longitudinal valley profile that was observed in the field. The locations of steep vs. shallow reaches of the valley profile relative to the characteristics of the underlying sediment were assessed to evaluate potential effects of these topographic steps on the stratigraphy and geomorphology.

The descriptions of eleven detailed stratigraphic profiles from the arroyo walls were used to determine the frequency, magnitude and relative timing of sediment pulses. These profiles were used to delineate, and correlate depositional periods based on sediment characteristics such as layer thickness, grain size, sorting, sedimentary structure and color. Paleocurrent indicators were recorded and analyzed to bolster stratigraphic correlations and divulge chronological deviations in channel morphology or direction. The timing of depositional periods
was constrained using geochemical analysis of tephra layers and radiocarbon dates from charcoal.

**Mapping and Surveying the Arroyo Channel and Valley**

The mapping and evaluation of the modern arroyo channel required several methods. Existing aerial LiDAR imagery was used to determine the extent of the present arroyo incision and morphology of the Hanson Creek watershed within the study area. ArcGIS was used to measure, quantify and classify several channel characteristics including slope, width and incision depth. Field mapping was used to reveal the extent and variation of surficial sediments and geomorphic features. Field surveys supported interpretations of recent geomorphic processes related to the stability of the eroding valley.

**Aerial LiDAR**

I generated Digital elevation models (DEM) from the last returns of an aerial LiDAR flight which occurred in 2009. The resolution of the aerial LiDAR data was 1 m², which provides adequate raster data for measuring channel width, depth, and generating longitudinal profiles and channel cross sections within the ESRI ArcMap software.

The longitudinal profile of the un-incised surface was generated by creating a false surface across the incised reaches, thus allowing for the underlying topography to be represented by a single and continuous line. This surface best represents the most recent topographic analog of the valley prior to incision.
Cross sections were generated from the LiDAR DEM using the Profile Graph Tool in the 3D Analyst Tools of ArcMap. The profile lines were drawn transverse to the channel at sites HC1-HC8 and HC10-HC16. The data collected for each cross section was exported into Microsoft Excel to create scatter plots that represent the channel geometry of the incised channel.

Field Mapping

Field mapping was performed intermittently from June, 2014 to October, 2014. The spatial relationship of geomorphic landforms such as mounds of accumulated unconsolidated sediment, colluvial deposits, basalt outcrops, and anticlinal ridges to the incised reach and associated sediments was catalogued and mapped. These data were used to complement the remote sensing data.

Mapping Historic Arroyo Incision

The mapping and evaluation of historic arroyo incision was completed using a combination of resources including a General Land Office (GLO) survey plat from 1878 AD and a historic air photograph from 1954 AD. The survey plat image from the original 1878 land survey was acquired through the Bureau of Land Management’s General Land Office Records. The survey was observed and interpreted to assess any changes in channel characteristics since that time, primarily evidence of incision as well as variations in the spatial relationship of the channel to the parallel road. A single air photo, originally created by the United States Department of Agriculture in 1954 AD, (NJ-4N-191) was acquired from the
Central Washington University Department of Geography historical aerial photography collection. The photo was observed for identical purposes as the survey plat image previously described; however, the air photo provides greater topographical information and a more recent time frame.

**Sediment Characterization**

The sediment data collected included both field observations of general characteristics and lab analyses that resulted in precise grain size distribution data.

**Field Descriptions of Stratigraphy**

Eleven detailed stratigraphic profiles, measuring 1 meter wide, were described throughout the incised reach of the 1.5-km arroyo. Variability of sediment characteristics was the deciding factor for the location of profiles, as the type and amount of sediment varies spatially upstream and downstream as well as bank to bank. The stratigraphic columns disclose the most concise and accurate representation of the sedimentological variation existing throughout the incised reach. The sediment data collected and utilized in the delineation of sedimentary units included bed thickness, grain size (modified Wentworth scale), sorting, roundness, sedimentary structure, reaction to HCl and color (Munsell Soil Color Chart). Column depth was measured in centimeters from the top of the arroyo wall to the apex of the talus, although in some instances, the talus was excavated by shovel to reveal buried sediment and facilitate the correlation of sedimentary units. The characterization of sediment also included photographs of the entire columns.
for analysis. Samples were collected from each delineated sedimentary unit for lab analysis following the characterization of each stratigraphic profile.

The determination of the number and frequency of sedimentation events and incision events required field observations of the underlying stratigraphy. Individual sedimentation events varied in the stratigraphy, but can be delineated according to specific sediment characteristics and contacts between sedimentary units. An example of this would be upward-fining, stacked alluvial sequences representative of an aggrading stream. Previous arroyo research suggests that channel entrenchment and aggradation within these systems is often episodic; therefore, recurrences of channel incision are commonly represented by abrupt and unconformable basal contacts overlain by fill deposits often exhibiting the arroyo channel geometry. The stratigraphic remnants of these events are often preserved within curved banks of the modern arroyo (Antevs, 1952; Hereford, 2002; Waters and Haynes, 2001).

**Laboratory Analysis of Sediment**

Grain-size distributions of the samples collected in the field were analyzed in the lab at Central Washington University. The analysis was conducted with a Malvern Mastersizer 2000 laser particle-size analyzer and some samples were sieved using a Ro-Tap. The Mastersizer is well suited for this particular project, as many of the fine-fraction sediments were well sorted, silt-size and smaller; therefore, sieving alone would not produce data with the same precision and
accuracy. Prior to analysis, all the samples were reduced to mineral content only. Two separate methods were used to remove any organic material with potential to skew the analysis. A majority of the samples contained very little or no organic matter, so the large material was removed with a tweezers and the following fraction was removed by oversaturating the sample with water in a beaker, stirring vigorously, removing the floating fraction with a pipette and returning the pipette solution to a beaker through a fine mesh. This method proved to be effective as the residual pipetted organic matter was all larger than the mesh. To ensure procedural efficacy samples were observed under the microscope to confirm organic matter had been removed. The samples were then placed in an oven to dry prior to analysis. Once the samples were dry, they were placed in a mortar and pestle and gently broken down to ensure grains were isolated but not defected. Samples were then placed individually in a sonication bath for 90 seconds. Following sonication, the sample was added to the Mastersizer by spoonful to reduce sampling bias until the desired obscuration of approximately 20% was achieved. The Masterizer settings for all of the samples were 750 RPM-stir, 2100 RPM-pump and 80% ultrasound. Prior to measurement each sample was exposed to the ultrasound emitted by the device for 60 seconds. This time was dependent on several test runs that proved the grains were isolated according to a non-fluctuating obscuration level following sixty seconds of ultrasound. Samples containing grain size fractions larger than 2 mm were sieved and separated with the Ro-Tap, as the Mastersizer 2000 can only analyze sediment grains ≤ 2 mm.
Paleocurrent Indicators

Due to a lack of stratigraphic evidence of paleorroyo channel cross-sections, an analysis of paleocurrent indicators was conducted to bolster the correlation of sedimentation events as well as provide further insight into fluctuations in channel morphology throughout the Holocene. The paleocurrent indicators were observed and measured in the field. The data were analyzed in ArcMap.

Field Measurements

In the field, both sides of the entire reach of the arroyo were investigated to locate sedimentological evidence of paleochannels. Criteria for paleochannel occurrence included sedimentary structure and presence of measurable paleocurrent indicators. The data collected from each feature was comprised of paleocurrent direction, depth, location (GPS coordinates), type of paleocurrent indicator (imbrication, ripple marks, etc.) and description of feature (thickness, width, structure and grain size). Lenticular gravel structures and ripple marks were bi-directional indicators. Imbrication represented a single direction of current. These data were then imported into an Excel spreadsheet for GIS analysis.
GIS Analysis

The GIS analysis was performed using ArcMap software to display current direction from each recorded location and depth. To provide a visual reference to the location of each of the paleocurrent indicators, a shapefile was created using the GPS coordinates collected in the field. The buffer tool was used to provide a visual reference to the amount of error associated with each GPS measurement. The buffer generated a circle around each point with a radius equivalent to the amount of error.

Figure 8. Plot of depth (y-axis) in centimeters and longitude (x-axis) in decimal degrees. Each dot represents one paleocurrent measurement. Intervals for analysis based on groups displayed by dashed horizontal lines at 200 and 300 cm.
recorded for each GPS measurement taken. This buffer was utilized as many of the measurements collected in the bottom, near the steep walls of the arroyo, produced large errors, maximum +/- 18 feet. These points were placed on an extrapolated hill shade model of a 1-m resolution raster obtained from aerial LiDAR data acquired in 2009. This model provided a reference to the geographic and geomorphic setting that each location was associated. The directional data for each of the paleocurrent measurements were displayed using the *bearing distance to line* tool, which draws lines based on the x and y data related to the origin of the line, the distance of the line, and the bearing of the line. For this project, distance was set at a standard of 250-m. The bearing was based on the paleocurrent direction derived from the data collected in the field.

The range of depth for each of the current indicators was categorized based on three criteria. First, it was assumed that channel gradient did not change substantially throughout time and spatial extent. This is a bold and likely untrue assumption; however, for the purpose of this study no influential evidence of unconformable surfaces was observed. Also, the gradient of the horizontally bedded sediments as well as the gradient of the current surface emulate the expected topography of steeper gradient (single channel) sections followed by low gradient (braided channel) steps trending to low-gradient, fine-grained, sheet flow deposits. Second, field observations revealed a maximum of four channel aggradation phases noted in one locality. Therefore, it was assumed that the number of breaks assigned in categorizing the range of depths was likely four or less. Third, a plot of depth (y-
axis) and longitude (x-axis) produced a result of three clearly identifiable groups in paleochannel depth observations throughout the entire reach (Figure 8). These groups are observed in the actual stratigraphy at multiple locations and thus reinforce the method. Based on the previously mentioned criteria, the intervals used for this study included 0-200, 200-300, and 300-500 cm below present surface levels. These intervals represent episodic periods of aggradation.

**Geochronology**

**Radiocarbon Dating**

Burned charcoal fragments are preserved throughout the stratigraphic record at Hanson Creek. Two charcoal samples were prepared and sent to DirectAMS in Bothell, Washington for accelerator mass spectrometry to provide age constraint and correlation of units. Preparation involved the mechanical removal of extraneous materials. The lab results were calibrated to calendar years before present using the IntCal13 atmospheric curve in OxCal v4.3.2 (Bronk Ramsey, 2009).

**Tephra Analysis**

Several fine grained, white and laterally extensive laminae exist throughout the stratigraphic record. Several samples were collected to provide age constraints and correlation of stratigraphic units through a geochemical comparison with a database of known volcanic tephras from the region. Samples were submitted to Washington State University School of Earth and Environmental Sciences
GeoAnalytical Laboratory for electron beam analysis following an initial petrographic microscope examination.

The samples were prepared for the microscope by dispersing the sediment in water and using a pipette to apply the solution to a slide. Several characteristics were used to identify the presence of volcanic glass within the tephra samples. The morphology of glass fragments is known to be both angular and vesicular. The size of glass shards is known to be within the range of 1-150 µm when contained within tephra samples deposited greater than 100-km from the source (Kittleman, 1973; Mullineaux, 1996). Also, the shards must appear dark under cross polarization as volcanic glass is known to be isotropic (Enache and Cumming, 2006). The results of the microscopic examination produced three viable samples to be analyzed.

**Correlation**

The correlation of sediment units from any point upstream to any point downstream proved a difficult task. The relative age of the sediments is easily understood when observed at a single location. However, units are frequently found cutting through previously existing sedimentary packages, which results in unconformable surfaces. These unconformities are abundant and make correlation of sediments based only on depth insufficient. Absolute age dates were acquired from locations HC3, HC6 and HC7.
CHAPTER IV

RESULTS AND INTERPRETATIONS

The results and interpretations will begin with the map and image analyses before transitioning to stratigraphic data of the underlying sediments. The map and image analyses provide insight into the modern physical characteristics of Hanson Creek. This includes an AD 1878 survey plat image, AD 1954 Air Photo and an AD 2018 Google Earth image. A longitudinal profile of the valley floor surface, which is adjacent to the incised channel, reveals the slope of the valley. The results of the stream cross sections provide data on the geometry of the incised channel.

The stratigraphic data will be presented per unit, HC1 through HC16. The unit descriptions for HC1 through HC11 include stratigraphic columns, photographs, and site descriptions. Descriptions for HC12 through HC16 include site descriptions, photographs and stratigraphic information that includes the depth and height of two distinct units, which include: 1.) gravel/cobble or 2.) fine grained. The final section includes data on observed paleocurrent indicators.

Maps and Imagery

The maps and imagery were used to assess physical changes in Hanson Creek through historical time and determine the timing of incision of the modern arroyo.
Figure 9. Plat image of original survey approved September, 30 1878. The inset displays text stating “Dry in Summer, Water in Spots” (GLO, 1878).

The plat image (Figure 9) is the result of a survey conducted of Willamette Meridian, Washington, T. 15 N, R. 22 E in June 1878 by I.A. Navarre. A digital copy of the original survey was acquired from the U.S. Department of the Interior, Bureau of Land Management, General Land Office (GLO) Records.

A stream is depicted running parallel to an adjacent road which begins in Section 7 and trends southeasterly continuing through Section 24. A note was made
by the surveyor which states, “Dry in summer, water in spots.” This annotation is adjacent to the stream on the plat that shares the current location of Hanson Creek. The surveyor does not make any mention of incised reaches of the stream. Also, the image shows the road intersecting and crossing the stream in Section 23.

1954 Air Photo

The photo (Figure 10) was acquired from Central Washington University, Department of Geography, Central Washington Historical Aerial Photograph Project. The original photograph (NJ-4N-191) was taken by the United States Department of Agriculture on August 11, 1954. This air photo shows a long reach of Hanson Creek as an incised channel. The depth of incision cannot be measured in the air photo; however, the characteristics of the modern channel including very steep channel banks and a channel bed covered with dense vegetation suggest physical characteristics akin to the modern channel geometry. An interesting observation unique to this air photo is a body of standing water, which is located at the far downstream end of the incised reach. This pond is not visible in any of the modern observations or images.
Figure 10. Air photo from AD 1954. The inset photo is increased in size for visibility (USDA, 1954).
Google Earth (October 14, 2018)

The physical characteristics and geometry have not changed discernably within the time span of Google Earth imagery, which includes June 2000 through October 2018. Therefore, the most recent image will be used for evaluation and comparison of changes in channel shape through time.

Comparisons of the Google Earth image (Figure 11) and the 1954 air photo (Figure 10) reveal very few changes in the channel from an aerial perspective. One notable change is the general increase in sinuosity of the incised channel as seen in the Google Earth images. This increase in sinuosity is evident throughout the entire reach but is most notable at the most upstream sections and beginning of incision.

Figure 11. Google Earth image of studied reach of Hanson Creek. Imagery date October 14, 2018. Acquired November 7, 2018.
Summary of Imagery Comparisons

The channel has been incised since at least 1954. The extent of incision (length and width of channel) appear to have remained unchanged since 1954. The changes in geometry of the incision include an increase in sinuosity from 1954 to 2018. GLO survey information from 1878 does not provide definitive data regarding the incision; however, it may be inferred that the lack of notation of a deep channel propagating through the surveyed region is evidence of a lack of incision in 1878. The surveyor drew a stream on the map and noted, “dry in summer, water in spots.” If the surveyor had climbed down into and out of the present 7-m deep and 50-m wide arroyo, it might have warranted noting on the survey notes.

Valley Profile and Map

The slope of the valley surface, as determined by the difference in height above sea level of location HC1 and HC16, was found to be 0.035 or 3.5%. The longitudinal profile of the valley surface grades downwards in a southeasterly direction (Figures 11 and 12). The slope of the incised channel bed, as determined by the difference in height above sea level of the deepest channel bed measurement at locations HC1 and HC16, was found to be 0.037 or 3.7%.

A straight line from HC1 to HC16 was used to create a longitudinal profile of the valley surface (Figures 12 and 13). A new raster was generated in ArcMap to create elevation points. These points give a measure of the valley floor above the deeply entrenched channel. A linear trend line was added to the plot of the profile.
The $R^2$ value of the linear trend line is 0.995 and the equation of the line is $y=-0.0389x+416.86$.

The points above the best fit line are considered greater than trend and points below are less than trend. A series of sequential values greater than trend represents the flattening of topography and a series of sequential values less than trend represent a steepening.

Figure 12. Longitudinal profile of valley floor. Ellipses represent study site locations. Colors represent corresponding facies.

The plot displays three distinct groupings of values that are greater than the linear trend. These are observed at; 125 to 350 meters, 700 to 825 meters and 975 to 1075 meters. Two distinct groupings of values below the linear trend can be observed from 0 to 60 meters and 370 to 660 meters.
The results of the longitudinal profile analysis reveal a similar pattern that was also noted during field observations. The slope does not change at a constant rate, but rather alternates between flatter and steeper sections. Three oscillations from shallower to steeper gradients occur within the 1075-meter reach, with the furthest upstream oscillations deviating more from trend than the downstream. The maximum y-axis variance from the trend line is ±2 m.

Figure 13. Line representing valley profile of unincised surface. The profile originates at HC1 and ends at HC16. The tick marks are placed at 100-m intervals. The DEM displays the incision, but the raster data collected beneath this line represents the unincised surface.
Modern Channel Characteristics

The following section includes descriptions of the field observations pertaining to the modern channel per site location (Figure 14). These observations will begin at the furthest upstream study location and end at the furthest downstream location. Observations may include; channel width, channel depth, presence of water and amount of vegetation. The channel geometry is presented as channel cross-section plots (Appendix A).

Figure 14. Location of sites and channel x-sections. The dashed lines represent the location of each channel cross section. The dots represent the location and corresponding site number where stratigraphic data was collected.
HC1

The total distance from the top of the incised surface to the channel bed is approximately 5 meters. The width of the incised channel is approximately 40 meters. The first two meters below the surface form a vertical wall of unconsolidated sediment. The lower two and a half meters consist of a talus slope resulting from accumulated sediment eroding from vertical walls.

The channel bed is dry, contains very little vegetation and is blanketed with gravel bars. The southern half of the bed is deeper than the northern half (Appendix A).

HC2

The arroyo incision is approximately 20 meters wide and eight meters deep at the deepest point in this reach. The walls are vertical or near vertical from the surface to a depth of approximately three meters. The accumulated sediment forms talus slopes, which connect the vertical walls to the channel bed. The channel bed is covered in thick vegetation. Water accumulates and flows slowly and intermittently in shallow channels on the bed but does not fill the entire incised channel width.

HC3

The depth of the channel is approximately seven meters on the southern channel bank and five meters on the northern bank. The channel is wider than HC1 and HC2 and measures approximately 50 meters. The first 3.5 meters below the
surface are near vertical banks and the remaining distance to bed is less steep slopes of scree. The channel bed is filled with dense vegetation including willows and other wetland species. Water was observed intermittently along the bed of the channel. The depth of the water was not measured but noted as being knee depth.

HC4

The incised channel is approximately 16 meters wide and 4 meters deep. The banks are vertical from the surface to a depth of approximately two meters. Accumulated loose sediment forms gradual slope from a depth of two meters to the channel bed. The channel bed and the talus are blanketed in dense vegetation. Shallow water flows intermittently on the bed of the incised channel.

HC5

This location is unique, because it is within a side channel and not part of the main incised channel (Figure 14 and Figure 15). This side channel is also incised but not as deep or wide as the main channel. The channel branch parallels and joins the main channel 175 meters downstream of HC5 and begins approximately 400 meters upstream, which is near the beginning of the incision of the main channel. The depth of the channel is approximately 3.5 meters and the width approximately 13 meters. The channel bank at this site is vertical from the surface to 70-cm depth. At 70-cm to 240-cm depth is a step out to vertical bank, which narrows the lower width of the channel. The channel bed is densely vegetated with large and established vegetation. No water was present near HC5.
HC6

The channel is approximately five meters deep and 45 meters wide. The first three meters below the surface are vertical. The vertical banks are connected to the channel bed by slopes of loose sediment accumulated from the eroding banks. The channel bed is approximately one meter deeper on the northern half than the southern half, which creates a gradual downslope gradient from the southern to northern bank. The bed of the channel is filled with dense, mature wetland vegetation. Ankle deep water flows slowly on the deeper, northern half of the channel bed.

HC7

The channel is approximately 5 meters deep and 50 meters wide. The channel bed is densely covered with mature vegetation. Water was found intermittently on the channel bed much like HC6.

HC8

The bank is vertical to a depth of approximately 325 cm, where it transitions to a slope of loose, unconsolidated material. The channel is approximately 5 meters deep and 40 meters wide. Water was found intermittently on the channel bed. The channel bed is densely covered with mature vegetation.
**HC 9 and HC 10**

The characteristics of HC 9 and HC 10 are the same because of the proximity to one another. The channel is approximately 5 meters deep and 35 meters wide. Water was observed intermittently on the channel bed. The channel bed is densely covered with mature vegetation.

**HC 11**

The channel is approximately four meters deep and approximately 25 meters wide. The bank is vertical to a depth of approximately four meters before transitioning to a slope of loose, unconsolidated material. The channel bed and slopes of loose, unconsolidated sediment are densely vegetated. Water was not observed.

**HC 12**

The wall is vertical for approximately 4 meters before transitioning to slopes of accumulated sediment. The channel is approximately 35 meters wide and 5 meters deep. The channel bed is densely vegetated. The flow of water is audible at this location.

**HC 13**

The bank is vertical for approximately three and a half meters before transitioning to a slope of accumulated sediment that extends to the channel bed. The channel is approximately 30 meters wide and 4 meters deep. The channel bed is densely vegetated with flowing water.
HC14

The channel is approximately 25 meters wide and 5 meters deep. The southern bank contains three meters deep vertical banks and the northern approximately five meters vertical banks. The southern bank transitions to a slope of loose material before reaching the channel bed. The channel bed is filled with vegetation and running water.

HC15

The channel is approximately 20 meters wide and 6 meters deep. The bank is vertical to a depth of approximately six meters. The channel bed is densely vegetated with flowing water.

HC16

The channel is approximately 23 meters wide and 5 meters deep. The banks are vertical for approximately three meters depth before transitioning to banks of accumulated sediment. The channel bed is filled with dense vegetation and a quickly flowing stream.

Summary of Incised Channel Geometry

Fifteen channel cross-section plots reveal a square-shaped channel with steep banks that varies in depth and width (Figure 14 and Appendix A). The maximum measured channel width is 51 meters at HC3. The minimum width measured, not including side channel location HC5, is 19 meters at HC4. The
maximum depth measured is seven meters at HC3. The minimum depth measured to the incised channel bed is 2.5 meters.

**Stratigraphy**

The sediment units within the stratigraphy at Hanson Creek can be divided into three categories based solely on grain size. The most commonly found sizes include silt, sand, and cobbles. These three distinct grain sizes are found throughout the studied reach of Hanson Creek and often found in recognizable and repeating patterns within the stratigraphy. These patterns provide information for interpreting the mechanisms and required energy that may have been involved in the deposition of the sediment. A common pattern that is often associated with alluvial chronologies is an upward fining (cobble to silt) in the sediment size. This is evident throughout the stratigraphy in Hanson Creek; however, characteristics such as grain roundness (sub angular), massive bed structure, reverse grading, and redoximorphic features suggest that multiple mechanisms were involved in the deposition of sediment and that they have likely changed through time. Stratigraphic units of similar characteristics were combined into a few general categories to identify and correlate patterns throughout the study site.

The sedimentary units were delineated into four facies and two distinct tephra deposits as seen in (Figure 15). These four facies include; aeolian facies, fluvial channel facies, fluvial over-bank facies and alluvial fan facies. The two tephra deposits are the Mount Saint Helens AD 1980 tephra and the Mazama Climactic
Tephra. The following paragraphs include an archetype of each category and the physical characteristics associated with each category.
Figure 15. Diagram showing the relationship of interpreted lithologic facies for sites HC1 through HC11. The y-axis of each column represents depth (cm) and the x-axis represents d50 grain size, from clay to boulder, according to the modified Wentworth scale. The blue dashed line represents a connecting, laterally extensive unit. Cross cutting relationships (younger unit cuts older unit) are labeled oldest to youngest (I, II, III). Each cutting relationship represents a younger unit (i, ii, iii) cutting the corresponding older unit (I, II, III). Arrows indicate measured paleocurrent direction with north oriented up. All ages are calibrated. Enlarged, detailed versions of each stratigraphic column are included in Appendix B.
Aeolian Facies

The first facies includes well sorted, very fine sands that lack sedimentary structure. The ideal example can be seen in HC1 (Figure 16). The facies is found at the surface in most units and generally extends to approximately 30-cm depth. Sediment disturbance and mixing is common, which is often observed as inclusions.

Figure 16. Photograph of aeolian facies example. Extent is 0 to 35 cm depth at location HC1. The horizontal, white, very thin bed represents the Mount Saint Helens 1980 tephra deposit.
The sediment is not compact and is generally laden with roots and vegetation. The lower half of this unit often exhibits weak granular soil structure.

**Fluvial Facies**

The second category is the dominant facies and will be subdivided into two facies; over-bank facies and channel facies. An ideal example can be seen in HC3 (Figure 17). Fluvial channel facies consist of well-sorted, rounded to sub-rounded clasts that range in size from gravel to cobble. The larger gravel and cobble sized grains are often found in lenticular structures. The thickness of these units can range from a few centimeters to over a meter. Fluvial overbank facies, the finer-grained (silts and sands) end of this category, is generally found in thin (3-10 cm thick), planar-laminated beds. An upward fining, fluvial facies is identified at multiple locations; however, the disparity within the sequence between grain sizes is often very large. For example, a sequence involving an upward fining directly from cobbles to very fine sand.
Figure 17. Photograph of fluvial facies example. Extent is 240 to 413 cm depth from HC3. Represented by the gray gravels (channel facies) and tan fine grained (over-bank facies) sediment cap. The extent of the fluvial facies is depicted by the orange column. The contacts of the fluvial channel facies is outlined with horizontal dashed lines.
Wetland Facies

The third category is massive, often dark gray to almost black, silt. Bioturbation of the upper contact of the wetland facies, which was the result of burrowing animals or roots (~2 cm diameter) was observed at multiple locations. Location HC3 includes examples of this category (Figure 18). These silt units are found at many different depths, but never at the surface; they only appear isolated in two regions throughout the reach in HC2, HC3, HC4, HC 14, HC 15 and HC 16. Redoximorphic features are prevalent including redox concentration and redox depletion (Figure 19). These features were identified in the field based on color relationships. The reduced features are gray in color and less red than adjacent sediments. The concentrations were redder or more black than adjacent matrix. A weak, blocky, subangular soil structure is common but not ubiquitous.

The presence of redoxomorphic features are one of the main characteristics that delineates the fluvial and wetland fine-grained, massive facies. These features are often associated with a wet meadow or ponded environment. Redox concentrations are important, because they indicate saturated soil conditions, which can often be attributed to water table depth. Saturated soils lead to anaerobic conditions, which eventually results in zero oxygen for soil microbes. Microbes within the soil begin to take the electron from the iron molecules instead of the oxygen molecules, which results in a change from \( \text{Fe}^{3+} \) to \( \text{Fe}^{2+} \). Unlike \( \text{Fe}^{3+} \), the \( \text{Fe}^{2+} \) ions are mobile and begin to move throughout the soil and often collect in masses. When the soil becomes unsaturated, the oxygen returns to the pore spaces and interacts with the Fe
molecules, which changes the color to rust red (Mausback and Parker, 2001; Hurt et al., 2003; Grybos et al., 2009; Dorau et al., 2016).

Figure 18. Photograph of a wetland facies example. Extent shown is 219 to 375 cm depth at HC3. The wetland facies displayed above upper dashed line (dry) and below lower dashed line (wet). White colored Mazama Climatic Tephra (Group VI) observed between dashed lines.
Figure 19. Redoxomorphic features at depth 180 to 240 cm at location HC4. The gray colored sediments represent reduced conditions and the orange colored stains represent redox concentrations.
Alluvial Fan Facies

The fourth category includes matrix- or clast-supported angular clast units that include grain sizes ranging from silt to cobble. Some but not all units within the

Figure 20. Example of alluvial fan facies as observed at location HC11. Large dark colored, angular, basalt clasts entrained in the lighter colored fine-grained matrix material.
alluvial fan facies are reversely graded. This category of sediment is found in HC11 (Figure 20).

**Volcanic Tephra Deposits**

The fifth category includes both the stark white, approximately one centimeter thick, Mount Saint Helens 1980 (MSH 1980) tephra layer (Figure 16) and the light gray (dry), approximately 10 to 20- centimeter thick, Mazama Climactic tephra (Figure 21). The MSH 1980 tephra is found throughout the reach a few centimeters below the surface and bounded by aeolian facies. The Mazama Climactic Tephra is found at HC3, HC4 and HC5 at ranges in depth from 374 to 197 centimeters (Figure 21).

![Figure 21. Example of the Mazama Climactic tephra deposit from HC3 at depth 355-375 cm. The horizontal, white colored, medium thickness bed correlates chemically with the Mazama Climactic tephra.](image)
Descriptions of Stratigraphic Sections

The following descriptions of stratigraphic sections and profiles are organized starting at the upstream end of the incised reach and progressing downstream (Figures 14 and 15). The stratigraphy of HC1-HC11 was described in detail in the field (Figure 15, Appendix B and Appendix C). Less detailed, basic stratigraphic zones were described for HC12-HC16 (Figures 14 and 22).

HC1

Section HC1 (46°47.790’ N 120°04.527’ W) is located at the upstream end of incision on the southern wall of the arroyo (Figures 14 and 15). The stratigraphy at HC1 includes two of the facies and one tephra (Aeolian, Fluvial and MSH 1980). The surface to a depth of 57 cm is the aeolian facies. The alternating fine sand and very fine sand layers lack visible structure. The main distinction among these alternating layers is the color and hardness. From 57 to 89 cm below the surface; a dark brown, root-laden, granular soil structure represents minor soil development. Soil formation suggests that this layer was at one time the surface and likely existed in an environment with minimal erosion. Based on the massive structure and fine sand, these upper units are interpreted as aeolian.

Two upward-fining sequences, interpreted as fluvial facies, occur within 89 to 271 cm below surface. These sequences fine vertically from cobble and gravel sized to silt. The larger clast sizes are moderate to well sorted, and the finer grained are well sorted. The minimum depth is 293 cm. From 271 to 293 cm below the
surface is a horizontally bedded medium sand. These upward fining sequences suggest a minimum of two distinct periods of stream aggradation.

HC2

HC2 is located (46°47.765' N 120°04.391' W) approximately 200 meters downstream of HC1 (Figures 14 and 15). The stratigraphic profile is on the southern bank of the incised channel.

The underlying sediment includes three facies and one tephra (Aeolian Facies, Fluvial Facies, Wetland Facies and MSH 1980 tephra). From the surface down to a depth of 67 cm is a layer of massive, very fine sand unit with some minor soil development occurring within the first 30 cm below surface (Aeolian Facies). From a depth of 67 to 116 cm is a massive silt unit that is gray in color, reacts to HCl and is cemented (Wetland Facies). From 125 to 148 cm depth a dark brown, root-laden, granular soil structure represents minor soil development. This buried soil is very similar characteristically to the buried soil found in HC1, but this soil is approximately 70 cm deeper. A fluvial facies of alternating silt and fine sand is found at a depth of 148-290 cm. This sequence sits atop a laterally extensive, moderately sorted, upward fining, cobble- to gravel-size lens at 290-310 cm depth. This lens provides evidence of a fairly high-energy stream channel and indicates that the arroyo was not incised to its present depth at the time of deposition.

Directly below the channel gravels from 310 cm to a minimum depth of 413 cm is a well sorted, massive, silt unit that includes redox concentrations (Wetland Facies).
The amount, depth, and gray coloring of the silt suggests long periods of water ponding, which resulted in the deposition of very fine grained and saturated sediment. The redoxomorphic concentrations found throughout the profile suggest several different stages of ponding and sediment accumulation. This proximity to a spring may be evidence that a wet meadow or pond would form here if a barrier existed and held the water in place.

HC3

HC3 is located (46°47.726' N 120°04.298' W) approximately 150-meters downstream of HC2 on the southern bank of the incised channel (Figures 14 and 15).

The underlying sediment includes three of the facies and both tephras (Aeolian, Fluvial, Wetland, MSH 1980 and Mazama Climactic). The uppermost unit extends to a depth of 36 cm. The unit includes massive, very fine sands with evidence of minor soil development. From a depth of 36-137 cm is a massive silt unit of varying color and hardness. From 137-153 cm the very fine sands are massive and root laden. A granular soil structure suggests minor soil development. Beneath the buried soil to 301 cm is a gray, massive, silt unit. This unit includes redox concentrations. The massive silt unit is interrupted by a massive, very fine sand unit that extends to a depth of 355 cm.

From a depth of 355-375 cm is a mottled, white, very fine sand unit. A sample of this unit was sent to Washington State University's School of Earth and Environmental Sciences GeoAnalytical Laboratory for electron beam analysis. It was
determined, based on the chemical composition of the volcanic glass, that it is a volcanic tephra that correlates with the Mazama Climactic tephra, which provides an absolute age of 7680-7580 BP (Egan, et al., 2015). The lower contact of this unit is undulating and abrupt. Beneath the Mazama tephra to a minimum depth of 569 cm is a saturated, massive silt unit (Wetland Facies).

The absence of sedimentary structure, such as bedding, in the fine-grained units along with the absence of larger gravel and cobble sized lenses suggest that HC3 may represent a different depositional environment than the higher energy stream mentioned in Section HC2. The silt layer just below the tephra was wet, but not saturated, which suggests that somewhere beneath 3.75-meter depth is a confining layer that forces the water to seep from the vertical banks.

The contact between hard, massive silts below 36 cm and the fine sand above is likely the stratigraphic marker that represents the end of a period of ponding and the initiation of the incised channel at this section. This point is significant because the amount of sediment deposited above this point is interpreted as aeolian, floodplain or sheetwash. It is very unlikely that the physical characteristics of these sediments would represent a high energy form of deposition. The low energy involved in deposition suggests minimal or no erosion occurred to the underlying sediments. This underlying, massive, gray, cemented, silt unit could not form if the adjacent channel were already incised during the time of its deposition.
Study location HC4 is located (46°47.715’ N 120°04.224’ W) approximately 100 meters downstream or east of HC3 on the northern bank of the incised channel (Figures 14 and 15).

The underlying sediment includes three of the facies and both tephras (Aeolian, Fluvial, Wetland, MSH 1980 and Mazama Climactic). The aeolian facies extends from the surface to a depth of 16 cm. This unit includes the Mt. St. Helens 1980 tephra on the surface. From a depth of 16-26 cm, thin beds of very fine sand and silt alternate. This sequence might include the finer silt size particles, because they are the most abundant sediment type upstream from this location. This likely represents the same surface (Aeolian Facies) present throughout the reach. Also, the soil development directly beneath may suggest that this area is “protected” from erosion, which may allow the silt particles to remain in place. The sediment from a depth of 26-51 cm is a massive, very fine sand.

Beneath and extending to 64 cm is a massive, gray silt unit. The upper contact of this unit at 51 cm is very abrupt and likely represents an erosional contact. This contact may represent the point in time that incision occurred. The previously mentioned silt unit lacks evidence of soil formation, but the underlying, massive, gray colored, silt unit from 64-151 cm depth exhibits blocky, subangular soil structure. The color change that occurs at 133 cm may indicate horizonation, which suggests an extended period of soil formation at HC4 prior to the incision of the channel. The lower portion includes redox concentrations from 127-151 cm.
depth. From 151-236 cm are massive silt layers of various colors that include redox concentrations.

At a depth of 236-245 cm is a well-sorted, massive, light-colored, very fine sand unit. The characteristics of this unit are similar to the tephra in HC3. The upper contact is very gradual, but the lower contact is abrupt and irregular. The final unit is massive a silt that extends from 245 cm depth to a minimum 264 cm. The upper contact of this unit includes redox concentrations. This layer was wet when described in the field.

The stratigraphy at this location represents at least one extended time period of soil formation, as well as a period of saturated ground or ponding. The depth of the Mazama tephra that correlates with this profile is about a meter less than at HC3 (HC1=236-cm; HC3=355-cm). Therefore, it may be inferred that less sediment was accumulating at a slower pace, or sediment was removed above the Mazama Climactic tephra at HC4.

HC5

This location is unique, because it is within a side channel and not part of the main incised channel (Figure 14 and Figure 15). The site is located on the northern bank of the side channel approximately 80 meters NNW of HC4 (46°47.756’ N 120°04.185’ W).

The underlying stratigraphy includes two of the facies and both tephras (Fluvial Facies, Alluvial Fan Facies, MSH 1980 and Mazama Climactic tephra). The fluvial facies consists of well, sorted, olive brown, very fine sands and extend from
the surface to a depth of 30 cm. The Mount Saint Helens 1980 tephra was not found within the confines of the characterized region; however, it is located directly at the surface ubiquitously as near as 50 cm to the west. The underlying stratigraphy can be traced and correlated to the MSH1980 tephra, so it will be included within the stratigraphy at a depth of zero centimeters.

From 30-36 cm depth is a laterally extensive, moderately sorted, sub-rounded, gravel. Beneath 36 cm to a depth of 104 cm is a sequence of massive, brown colored, cemented silts. At a depth of 104-110 cm is a sub-rounded, moderately sorted gravel. This unit included two potential lithic fragments and traced to the jaw bone of a large sized animal, which is located approximately 30 cm to the east of HC5. From 110-153 cm is a poorly sorted, matrix-supported, cemented silt and gravel unit. The gravels are an estimated five percent of the matrix composition but mixed throughout the entire unit. The lower portion of this unit, from 146-153 cm depth, includes redox concentrations. From 153-160 cm depth is a massive, cemented silt. This silt is characteristically identical to the matrix of the previously mentioned unit. From a depth of 160-178 cm is a laterally extensive, sub-rounded, moderately sorted, gravel unit. Beneath the gravel from 178-190 cm is a well-sorted, massive, coarse sand layer. From 190-197 cm depth is a light colored, mottled, silt, which is characteristically similar to the Mazama tephra found at HC3 and HC4. The upper contact is abrupt and linear but lower contact of this unit is abrupt and irregular. Beneath the tephra from 197-206 cm depth is a massive, gray colored, silt with fine roots. From a depth of 206-223 cm is a well-sorted, massive,
oxidized, medium sand. From 223-287cm depth is a brown colored, massive, very fine sand. A hand auger determined that a gravel unit begins at 287 cm depth.

The silt sized units within HC5 are massive in structure like silt units within HC2, HC3 and HC4; however, the silts in HC5 are brown in color, lack soil structure and often interrupted by an abrupt increase in size from silt to gravel. Furthermore, the poorly sorted and matrix-supported unit from 110-153 cm depth is suggestive of a very high energy event, such as a debris flow. The Mazama tephra at HC5 is shallower than at HC3 and HC4, which is the result of less sediment accumulating or sediment being removed. The debris flow sediment suggests an erosion event after the deposition of the Mazama tephra.

HC6

Location HC6 is on the northern bank of the main incised channel approximately 250 meters downstream of HC4 (46°47.685’ N 120°04.046’ W) (Figures 14 and 15). The underlying stratigraphy includes two facies and one tephra (Aeolian Facies, Fluvial Facies and MSH 1980 tephra). The aeolian facies includes the massive, well-sorted, very fine sand unit that exists throughout the reach at the surface. The MSH 1980 tephra is found within this unit at a depth of 10 cm.

The surface unit extends to a depth of 13 cm where it is interrupted by a moderately sorted, sub-rounded, clast supported, medium gravel layer. The gravel layer is approximately one and a half meters in width and extends to a depth of 33 cm. From 33 to 64-cm depth is a well-sorted, massive, very fine sand unit. However, this unit is dissimilar to the surface unit when hardness is evaluated. The top unit
allowed for easy penetration of a nail, but the lower unit resisted penetration. Attempts to penetrate the lower sediment from 33-64 cm resulted in “blocks” falling from the wall. From 64-84 cm depth a moderately sorted, sub-rounded, very coarse gravel extends laterally for approximately three meters. From 84-122 cm depth well sorted, planar-laminated, medium-thick beds range from silt to fine sand. Beneath the medium-thick beds to a depth of 147 cm are well sorted, planar-laminated, laterally extensive, thin beds that range in size from silt to coarse sand. From 147-174 cm depth is a massive, cemented, laterally extensive, silt unit containing carbonate concretions. From 174-243 cm depth is alternating, laterally extensive, well sorted, silts and very fine to coarse sand beds of varying thickness. From 243-277-cm depth is a moderately sorted, well-rounded to sub-angular, clast supported, coarse sand to cobble size, ten meters wide lens. This unit does not show evidence of grading. From 277 cm to a minimum depth of 310 cm depth are thin beds of very fine sand delineated by hardness. A bed of massive, cemented, silt interrupts the fine sand unit at a depth of 294-298 cm.

The interpretation of this stratigraphy reveals a post-incision unit that extends from the surface to a depth of 13 cm. The massive, very fine sand to a depth of 13 cm is prevalent throughout the surface but is thinner at HC6 than other locations. The MSH 1980 tephra extends laterally at 10-11 cm depth. The fine-grained units beneath the pre-incision contact at 13 cm depth are all interpreted as fluvial deposits. The contact at 13 cm depth is not sharp, but the AD 1980 Mount St. Helens tephra caps a two cm thick silt unit (Aeolian Facies), which sits directly on top of a gravel lens (Fluvial Over-bank Facies). This abrupt change in grain size is
interpreted as representing a non-conformable surface. The non-conformable surface explains the shallow depth of the aeolian facies at HC6.

The bedded structure represents pulses of fine-grained sediment deposition. It could be interpreted as either a channel or a flood plain deposit. The fine-grained, bedded sands might be the result of the translational shift of the aggrading stream. Further evidence of a fluvial environment is the lens of rounded gravel from 243-277 cm depth, which probably represents a channel bar in a fluvial system. The truncated nature of the gravel suggests that the channel was oblique to the current incision. Furthermore, this suggests the directional flow of the stream was similar to today. Beneath the gravel layer is another alternating, fine layer, which is similar to the overlying deposits. Within these deposits a piece of charcoal was removed at a depth of 302 cm. Charcoal sample 070914-2, was determined to have a calibrated age of 2489-2731 BP. This absolute age represents the maximum age constraint for HC6.

HC7

HC7 is located (46°47.677’ N 120°04.031’ W) approximately 30 meters downstream and to the east-southeast of HC6 on the northern incised bank (Figures 14 and 15).

The underlying stratigraphy was evaluated for grain size in the field, but unlike HC6 the sediment was not analyzed to establish d50 grain size values in the lab because of the proximity to HC6. Therefore, minor discrepancies in grain size
might be noted when comparing units that correlate between the two stratigraphic columns.

The underlying stratigraphy includes two facies and one tephra (Aeolian Facies, Fluvial Facies and the MSH 1980 tephra). The sediment located at the surface of HC7 is the same as found throughout Hanson Creek (Aeolian Facies). This massive, well sorted, very fine sand extends to a depth of 22 cm and contains the MSH 1980 tephra from 8.0-8.4 cm depth. A non-laterally extensive gravel lens extends from 22-32 cm depth. The lens composition includes a moderately sorted, sub-rounded, clast supported, medium gravel. This gravel does not trace laterally to HC6, but a correlative gravel unit is found at a similar depth within both units HC7 and HC6. These units are included in the post-incision sedimentation phase. Beneath the gravel is a massive, well sorted, very fine sand that is yellowish brown in color. This unit shares a gradational contact with the overlying gravel. Units HC7.4 and HC7.5 may be interpreted as separate or combined, but both are interpreted as being part of the post-incision phase. The basal contact of HC7.5 at a depth of 50 cm is very abrupt. Each of the fine-grained sediments beneath HC7.5 are cemented to some degree. From a depth of 50-70 cm, HC7.6 a well sorted, massive, very dark grayish brown colored, very fine sand truncates the underlying well sorted, massive, brown colored, very fine sand of HC7.7 that extends from a depth of 70 to 84 cm. Both units HC7.6 and HC7.7 are adjacent to evidence of a swale that does not extend into the approximately meter wide stratigraphic column (Figure 22 and Appendix C).
From 84-127 cm depth is a sequence of well sorted, massive, very fine sands, that vary only in color. From 127 to 227 cm depth is a sequence of alternating very fine sand beds and silt laminae. Within this sequence is a laterally extensive, silt couplet that traces to HC6 and HC8. From 227 to 244 cm depth is a well sorted, very hard, cemented, silt unit. The fine-grained units are interrupted by a moderately sorted, sub rounded, clast supported, coarse gravel lens that extends to a depth of 264 cm. This lens does not trace directly but was noted to be located at similar depth to a gravel lens in HC6 at depth 243-277 cm. Beneath the gravel from 264 to 340 cm depth are alternating beds of well sorted, very fine sand and silt. The upper and basal contacts of the entire unit are bound by matrix-supported, very coarse sand and silt units that are laterally extensive. At depth 340 to 360 cm is a laterally extensive, planar laminated, sub rounded, clast supported, medium gravel. From 360 to 399 are beds of massive, silts and very fine sands with prevalent redox concentrations. A laterally extensive, dark grayish brown, very thin, silt bed exists at a depth of 380 cm. From 399 to a minimum 410 cm depth is a well sorted, sub-rounded, planar laminated, coarse gravel.

Charcoal sample 070814-4 was collected within a unit that directly traces to HC7.7 that was located approximately 0.5 meters to the southeast (Figure 22 and Appendix C). The absolute age of the charcoal sample was found to be 10 to 270 cal BP, which represents a time prior to incision, but more importantly a maximum age of incision.
Unit HC7.7 contained evidence of sediment mixing and an abundance of charcoal at the contact with HC7.6 approximately one to two centimeters in diameter. The combination of the charcoal and sediment mixing near the edge of a previously active channel may be evidence of human occupation or disturbance. An alternative interpretation is over-bank flows from the swale deposited the charcoal and caused the mixing of the sediments.

![Diagram of correlated units in HC6 through HC10](image)

**Figure 22. Relationship of correlated units in HC6 through HC10. Not to scale. For detailed descriptions of sites (Appendix B and C and Figure 15).**

**HC8**

HC8 is located (46° 47.672’ N 120° 04.030 W) approximately five meters to the south of HC7 on the northern bank of the incised channel (Figures 14 and 15).

The underlying stratigraphy includes two of the facies and one tephra deposit (Aeolian Facies, Fluvial Facies and the MSH 1980 tephra). The surface to a depth of 23 cm is categorized as the fluvial facies. The massive, very fine sand layers vary
only in hardness. Weak granular soil structure is observed between 4.5 and 9 cm. The MSH 1980 tephra is located from 2 to 4.5 cm depth. The sediment from 23-110 cm depth is the fluvial facies. The well sorted, cemented, planar laminated, silt to very fine sand unit abruptly becomes a non-cemented, massive, well sorted silt unit at 110 cm depth. This unit is also part of the fluvial facies and extends to a depth of 122 cm. From 122-153 cm depth the massive, well sorted, silt units begin to exhibit a slight dip to northeast. The dip becomes apparent due to the darker colored interbeds that often include visible pieces of charcoal. From 153-162 cm the sediment is identical to the previous 122-153 cm but coarsened to a very fine sand. The sediment from 162-192 cm depth includes a well sorted, massive, dark grayish brown, fine sand. From 192-303 cm is a moderately sorted, sub-rounded to rounded, clast supported gravel and cobble unit. This unit includes three distinct cross cutting relationships. The deepest lenticular unit cuts into a pre-existing, horizontal, laterally extensive, planar laminated unit. Both of which are cut by the youngest lenticular shaped unit. The grading is either ungraded or normal. From 303 cm to a minimum of 368 cm depth are alternating very fine sand and silt beds with darker colored charcoal laden interbeds. The beds mimic the contour of the overlying gravel and cobble lens. The beds follow a concave shape that dips to the northeast before flattening.

The fluvial facies are the majority facies within the stratigraphy at HC8. The interpretation of fluvial deposits is supported due to the prevalence of sedimentary structures, such as planar lamination, along with the presence of lenticular gravel.
and cobble units. The cross-cutting relationships observed from 192-303 cm depth present data to support a sinuous channel that changes direction frequently.

The dark colored charcoal rich beds represent over-bank flow deposits at the edge of the lenticular channel.

Units that may correlate to HC7 are the human influenced soil, which is observed in HC8 just above the gravel cobble lens from 162-192 cm depth. The two units do not physically trace but are characteristically identical (Figure 22).

**HC9**

HC9 is located approximately five meters to the southwest of HC8. This location is on the edge of the corner on the south-southwest facing bank on the rounded corner between HC8 and HC10 (Figures 14 and 15).

The sediment was not characterized from the surface, but instead from 160 cm to a minimum depth of 456 cm. The focus of characterization was to correlate locations HC6 through HC10. This was done by tracing a laterally extensive unit between HC1 and HC9. The sediments from surface to 160 cm were noted as characteristically like HC8, but without characterization the direct correlation of this depth is avoided.

The stratigraphy of HC9 contains only fluvial facies. The sediment from 160-200 cm depth includes a moderately sorted, clast supported, pebble to gravel lens. From 200-207 cm depth is ungraded, matrix supported, very fine sand unit with gravel sized clasts. From 207-218 cm is a well sorted, massive, cemented, silt. From
218-231 cm depth is a laterally extensive, well sorted, medium sand. From 231-237 cm depth is a massive, laterally extensive, well sorted, cemented silt. This unit laterally traces to HC7. From 237-246 cm depth is a laterally extensive, well sorted, medium sand. From 246-252 depth is a laterally extensive, well sorted, light gray colored silt. The unit laterally traces to HC7. From 252-258 cm is a cemented, dark colored, laterally extensive, well sorted, very fine sand. This unit laterally traces to HC7. From 258-268 cm depth is a massive, well sorted, very fine sand. From 268-296 cm depth is a well sorted, massive, cemented silt. From 296-405 cm is ungraded, matrix supported, very fine sand, with fine gravel sized clasts. The composition percentage of clasts is less than 5%. From 405 to a minimum depth of 456 cm is a lenticular, moderately sorted, sub rounded, clast supported very fine to very coarse gravel unit.

**HC10**

HC10 is located on the southeast facing vertical bank around the corner from HC9. The unit was characterized to fill in missing gaps necessary to correlate HC6 through HC9. However, only the gravel and cobble units were characterized in detail. The d50 size of the fine-grained units is based on field characterization. After determining that the surface elevation was the same for both HC9 and HC10, a depth datum was established at 316 cm. The datum was used to correlate sedimentary units of HC9 and HC10. The stratigraphy was not assessed from the surface to the depth of the datum at 316 cm.
The stratigraphy of HC10 only includes the fluvial facies. From 316-405 cm depth is planar laminated, laterally extensive, very fine sand and silt unit. This fine-grained unit contains a light gray colored couplet. Sample number 070814-9 is a sediment sample of this couplet that was analyzed for tephra correlation. The results of the tephra analysis were negative for tephra correlation. The sample was found to contain trace amount of glass that was too small for reliable microprobe analysis. The unit from 405-418 cm is ungraded, laterally extensive, moderately sorted, sub rounded, clast supported very fine gravel and large cobble. From 418-506 cm depth is a massive, well sorted, very fine sand unit. From 506 to a minimum of 558 cm depth is an approximately 2.5-meter wide, lenticular, moderately sorted, sub-rounded, fine gravel to large cobble unit.

The results of the tephra analysis were negative for tephra correlation. The sample was found to contain a trace amount of volcanic glass that was too small for reliable microprobe analysis. The composition of the sample was determined to be primarily biogenic silica (diatoms) with minor amounts of silicate minerals. 

**HC11**

HC11 is located (46°47.619’ N 120°03.963’ W) approximately 125 meters downstream of HC8 on the southern bank of the incised reach (Figures 14 and 15).

The underlying stratigraphy includes two facies and one tephra deposit (Fluvial Facies, Alluvial Fan Facies and the MSH 1980 tephra). The surface to a depth of 33 cm is the alluvial fan facies. The silt supported matrix includes coarse gravel to small cobble clasts. The grading of the clasts is reverse or downwards fining.
33-46 cm depth is categorized as the fluvial facies. The laterally extensive, massive, well-sorted, medium sand and silt beds are bounded by poorly sorted, matrix supported sediments. From 46-72 cm depth is categorized as the alluvial fan facies. The silt supported matrix includes reverse graded, angular, pebble to cobble sized clasts. From 72-79 cm depth contains moderately sorted, fine sand supported matrix with angular, pebble sized clasts. From 79-83 cm depth a massive, well sorted, fine sand unit is categorized as the fluvial facies. The very dark color of the unit is attributed to charcoal contained within the sediment. The fluvial facies is also observed from 83-147 cm depth. The massive, well sorted, very fine sands are cemented. A change in color was noted at a depth of 122 cm. Also, the very fine sands above 122 cm react to HCl and those below do not. From 147 cm to a minimum of 437 cm depth is categorized as alluvial fan facies. The ungraded, silt supported matrix contains angular, cobble size clasts.

The stratigraphy at HC11 is dissimilar to the other locations selected for characterization. Most notably, the prevalence of the alluvial fan facies, which is likely attributed to the proximity to the nearby, steep and eroding hill slope. The angular nature of the large clasts indicates low transport distance. The poorly sorted, matrix fabrics are likely interpreted in this instance as hill slope colluvium. This provides context for understanding how the larger sized clasts are being introduced into the stream system. Just like the clasts found within HC11, the clasts found throughout the study area are almost exclusively basalt. The dark colored, charcoal-rich, fine sand unit is interpreted as the result of a previous fire.
The remaining stratigraphic descriptions (HC12-HC16) were described in less detail in the field. The units were delineated as fine grained and coarse grained. The fine-grained units include grain sizes less than gravel and the coarse grain is gravel and larger (Figures 14 and 23).

HC12 is located (46°47.610' N 120°03.868' W) on the opposite bank facing the point depicted on the maps (Figures 14 and 23).

From the surface to 20 cm depth laterally extensive, fine-grained unit. From 20-220 cm is laterally extensive, clast supported, gravel and cobble size that traces to HC13.

Figure 23. Diagram of unit grain size and depth from locations HC12 through HC16. The vertical axis of each column represents depth in centimeters with 100-centimeter intervals. The black units are gravel and larger and the light gray indicate less than gravel size. HC14 and HC16 include information from both banks of the incised channel, which is indicated by “N”-north or “S”-south of channel. All black units were clast supported and rounded (Fluvial Channel Facies). Gray units include both fluvial overbank facies and wetland facies.
From 220-240 cm depth is laterally extensive fine-grained unit. From 240-290 is a laterally extensive, clast supported, gravel and cobble unit. Fine-grained sediment extends from 290 cm to a minimum depth of 400 cm.

**HC13**

HC13 is located (46°47.616' N 120°03.839' W) on the opposite bank facing the point depicted on the maps (Figures 14 and 23).

The surface to a 30 cm depth is fine grained. From 30-180 cm depth is a lenticular, clast supported, cobble unit. From 180 cm to a minimum of 310 cm is a laterally extensive, fine-grained unit.

**HC14**

HC14 includes data from the north and south banks of the incised channel. The location of the north bank point is 46°47.612' N 120°03.818' W (Figures 14 and 23).

The surface to a depth of 20 cm on the south bank is fine grained. From 20-30 cm depth is gravel. From 30-150 cm depth tan colored fines with laterally extensive, dark gray interbed at approximately 90 cm depth. From 150-260 cm is a lenticular, clast supported, cobble unit. From 260 to a minimum of 310 cm depth is a unit of fine-grained sediment.

The surface to depth 40 cm on the northern bank is non-cemented, fine grain unit. This unit is characteristically the same as the aeolian facies. From 40-70 cm depth is cemented, white colored, fine grained unit. From 70-260 cm depth is a
cemented, tan colored, fine grain unit. From 260 cm to a minimum of 460 cm depth is cemented, light gray colored, fine grained unit. All the units beneath 40 cm were very hard and laterally extensive.

**HC15**

HC15 is located (46°47.606’ N 120°03.800’ W) on the northern bank of the incised channel (Figures 14 and 23).

The surface to 20 cm depth is non-cemented, fine-grain unit analogous to the aeolian facies. From 20 cm-40 cm depth is a white colored, cemented, fine-grain unit. From 40-270 cm depth is a cemented, tan fine-grained unit. From 270 cm to a minimum of 570 cm depth is cemented, light gray colored, fine grain unit. A laterally extensive, very thin bed of white colored, fine-grained sediment at an approximate depth 550 cm was collected for tephra correlation analysis, Sample 081314-1. The results of the correlation analysis were negative, but the composition of the sample was determined to be primarily biogenic silica (diatoms) with minor amounts of silicate minerals.

**HC16**

HC16 is located on the southern bank opposite the point on the map 46°47.587’ N 120°03.736’ W (Figures 14 and 23).

The surface to a depth of 30 cm includes a tan, wavy laminated, fine grained unit. From 30-150 cm depth is a cemented, tan color fine-grain sediment. These sediments were noted as being characteristically similar to the tan colored
sediments in HC 14 and HC15. From 150 cm to a minimum depth of 280 cm is a unit of laterally extensive, clast-supported, well rounded, gravel and cobbles, forming an approximately five-meter wide, light gray colored, fine grained lens.

**Paleo Current**

Results from the analysis of 39 measurements of paleocurrent indicators show a minimum of three separate aggradational periods resulting in the deposition of gravel conglomerates and associated fine-grained deposits throughout the incised reach of Hanson Creek. These groupings were established based on field evidence and a graph that displayed the relationship between the longitudinal coordinates of each paleocurrent measurement and the depth of the measurement (Figure 8). Of the 39 total measured paleocurrent directional indicators, 18 were within the range of 0-200 cm, 16 within 200-300 cm, and 5 within 300-500 cm below the surface. The direction of flow for all 39 indicators is dominantly to the southeast and northwest. This bipolar distribution is due to the abundance of bi-directional indicators, which include lenticular structures and ripple marks. However, based on the gradient of the present channel and valley, the present direction of flow, and the gradient of correlated buried deposits all of these bi-directional indicators were assumed to indicated flow toward the southeast. When the measurements are displayed independently based on depth, no discernable directional change is observed (Figure 24).
Figure 24. Bearing of each paleocurrent indicator and associated depth interval; a.) 0-200 cm; b.) 200-300 cm; c.) 300-500 cm.
The spatial distribution of paleochannels observed within the incised reach is not equally distributed upstream to downstream (Figure 25). In fact, a distinction can be made between the three separate groupings of paleochannels within the study reach. These groupings are interesting as they imply non-deposition of the gravel-cobble conglomerates, erosional surfaces unidentified in field observation or

Figure 25. Digital Elevation Model (DEM) with all paleocurrent measurement locations and bearing. Depth is indicated by color (yellow=0-200 cm, red=200-300 cm and blue=300-500 cm). Bearing is relative to North as displayed on map.
within the current incised reach, or channel migration to the north of the incised reach.

Analysis and Interpretation

The paleocurrent results confirm a minimum of three periods when the main channel bed flowed through the portion of the valley that is exposed in the present walls of Hanson Creek. These periods can be defined by the presence of up to cobble-size gravel conglomerates bound by fine-grained deposits. In some sections the gravel units occupy paleochannels that were partially incised into the underlying fine-grained sediment by a few meters, but none of them incised to the depth of the present incised channel. A schematic based on the spatial distribution between paleochannels illustrates the relationship of aggradation rate, lateral channel migration, and avulsion to channel preservation supporting an overall trend for an aggrading system (Figure 26).

A comparison of the morphology of Hanson Creek sediments to those on the schematic reveals a trend that includes high rates of aggradation, low amount of migration and frequent channel abandonment (Best and Bristow, 1993). This may be partially explained by the gaps in the groupings of gravel-cobble conglomerates. Alternatively, the gaps may simply infer that the main channel of the stream that deposited the conglomerates migrated laterally across the valley over time and the main channel was north of the incised reach during the periods of fine-grained sedimentation within the exposed arroyo walls.
Figure 26. Diagram illustrating preservation of braided river depositional morphology as a function of aggradation rate, lateral channel migration and channel-belt avulsion (Best and Bristow, 1993).
Summary of Stratigraphic Results

The sediment units within the stratigraphy at Hanson Creek are divided into four facies. The aeolian facies is interpreted as alluvium deposited by wind or sheet wash. The sediments are only found at the surface, often contain Mount St. Helens 1980 tephra and cap underlying cemented units. The aeolian facies is associated with post-incision deposition on the top of the banks of the present incised channel. The fluvial facies is interpreted as alluvium deposited in a fluvial environment, which includes sheet wash and aeolian deposition. The gravel and cobble units (Fluvial Channel Facies) are interpreted as deposited in a fluvial environment with greater energy than what is presently observed at Hanson Creek. These coarser-grained units are in three distinct depth ranges and represent periods of higher-energy stream channels or a main channel occupying different locations laterally across the valley at different times. The laterally extensive, planar-laminated, fine-grained sediments of the fluvial over-bank facies in proximity to fluvial gravel and cobble deposits of fluvial channel facies are interpreted as fluvial flood plain deposits. The wetland facies is interpreted as being deposited in ponded or wet meadow environments. Unlike the aeolian and fluvial facies, the massive, gray colored, silt units are not found throughout the extent of the incised reach, but instead appear to be confined to two distinct concentrated regions as seen in HC2, HC3 and HC4 and HC14, 15, and 16. They are often truncated by an abrupt contact with overlying fluvial facies. The alluvial fan facies is interpreted as hillslope colluvium/alluvium. The rounded to sub rounded, cobble sized sediment of the
fluvial facies may be interpreted as entrained, angular sediment from the alluvial fan facies.

HC3 contains a confirmed sample of Mazama Climactic tephra. HC4 and HC5 contain a characteristically similar unit to the confirmed Mazama tephra, which establishes an age constraint of 7680-7580 cal BP (Egan et al., 2015). The AD 1980 Mount St. Helens tephra is found just beneath the surface in nine of the stratigraphic columns, within the post-incision sediment of the aeolian facies.
CHAPTER V

DISCUSSION

Extent and Timing of Incision

The Hanson Creek stratigraphy reveals a transition from an aggrading system filling the valley to what is currently a low gradient valley floor (3.5% slope) that contains a deeply incised channel. The extent of incision within the surveyed region is approximately 1.3 km in length and the maximum depth measured is 7 meters. Stratigraphic evidence of previous incision events was observed at two locations, HC9 and HC16, but these small fine-grained swales and gravel lenses were not as deep and wide as the modern channel incision. Therefore, the data supports a single arroyo incision event. There is no evidence of any events of similar magnitude within the stratigraphic record of Hanson Creek at the study site, which extends back before 7680-7580 cal BP (Egan et al., 2015). This date is the oldest age constraint on the stratigraphic record at this site, derived from the Mazama Climactic tephra sample collected in HC3. The Mazama Climactic tephra was found at depths ranging from three and a half to two meters below the surface.

The timing of the modern day incision event has been established using the calibrated radiocarbon age of AD 1680-1940 from Sample 070814-4 (Appendix E and Figure 21), AD 1878 GLO survey (Figure 9) and the AD 1954 air photo (Figure 10). The stratigraphic location of Sample 070814-4 correlates to the unit interpreted as the final surface deposited prior to incision. This unit, interpreted as fluvial overbank facies, is often cemented, fine grained, massive or laminated and
observed at multiple locations throughout the studied reach. The contact between the fluvial facies and overlying aeolian facies is often very abrupt. The sample was collected near HC7 at a depth of 64 cm (Figure 22).

The charcoal of Sample 070814-4 is located within sediments that are interpreted to be deposited at the edge of a stream. It is not possible for a stream to exist at the location and deposit sediment directly onto the vertical banks if the channel is incised. Therefore, it is interpreted as being pre-incision deposition. The resulting calibrated age of AD 1680-1940, represents the most recent age prior to channel incision.

The AD 1954 air photo reveals that the channel was incised. The AD 1878 GLO survey depicts a drawn stream with the label “dry in summer, water in spots,” but omits any mention of an incised channel. The report does not explicitly state whether the channel was incised or not incised at the time. However, it seems more likely than not that an incision of this magnitude would be mentioned, especially due to the difficulties the incision would impinge on the survey process. Therefore, it is likely that incision occurred between AD 1878 and AD 1954. If the 1878 GLO report is omitted, the incision occurred between AD 1680 and AD 1954.

**Holocene Period of Aggradation**

The physical environment of the modern Hanson Creek includes a deeply incised and moderately sinuous channel that propagates along a low gradient, 3.5% slope, valley floor of unconsolidated sediment. The stratigraphy included four facies and two distinct volcanic tephra deposits (Aeolian Facies, Fluvial Facies, Wetland
Facies, Alluvial Fan Facies, MSH 1980 tephra and Mazama Climactic tephra). The aeolian facies have been previously discussed as a post-incision correlative group. Because the channel is now incised, fluvial facies do not occur on the modern surface of the valley floor. All evidence of modern stream flow was observed within the confines of the incised channel banks. The fluvial facies are associated with both large and small grain sizes, but all exhibit evidence of being transported by water or wind.

The gravel and cobble units occur at multiple depths within the same stratigraphic profiles, which can be interpreted as either a single fluvial channel or multiple fluvial channels. These channels (Fluvial Channel Facies) were the result of higher energy flows than what is currently observed at Hanson Creek. Paleocurrent indicators reveal a single sinuous channel or multiple channels of various orientations. The finer grained sediment (Fluvial Overbank Facies) is interpreted in two ways. Firstly, the laterally extensive and laminated units are most likely deposited by fluvial mechanisms such as over-bank flow (Miall, 1977; Picard and High Jr., 1973). Secondly, the massive units of the fluvial overbank facies most likely represent fluvial or aeolian deposition (Miall, 1977; Picard and High Jr., 1973). A second interpretation of the fluvial overbank facies is that laminated sediments were deposited near the main channel and massive units further away from the main channel (Picard and High Jr., 1973). Much of the landscape surrounding the study area is blanketed in aeolian silt, which could be transported into the Hanson Creek valley by either water or wind, making it difficult to distinguish between fluvial and aeolian silt deposits in the stratigraphy.
These interpretations are not entirely dissimilar to the modern channel. Cobble-sized gravel was observed on the bed of the incised channel in gravel bar formations. However, these gravels may have been originally deposited in the past and been uncovered during the incision event. The geometry of the channel bed of HC1 (Appendix A) shows this gravel channel bed forming a bench with a deeper incision on the southern end of the channel. Furthermore, abundant gravel was observed in the surrounding channel banks.

These gravels in lenticular form represent incision, but evidence of large, incising channels that result in the deposition of lenticular gravel were not observed. Therefore, a change in the fluvial system within this valley has occurred in the past and the incised channel is likely both the result of and a contributor to this change.

The wetland facies are massive, often dark gray-colored, silt, often containing redoximorphic features. The upper contact of the wetland facies often contains evidence of bioturbation (Figure 18). They are interpreted as deposited in a wet meadow environment or ponded water. These sediments are only located in two distinct concentrated regions: 1.) HC3, HC4 and HC5; and 2.) HC12-HC16 (Figures 11 and 13). Wetland facies were never found stratigraphically above aeolian facies, which is logical when considering that the aeolian facies was deposited after the channel incised. Saturated conditions were not observed, but wet sediment at depths greater than 3.5 meters was common in stratigraphic columns that include the wetland facies.
A pond is observed in the AD 1954 air photo approximately 200 meters downstream of HC16 (Figure 10). The pond was located on the valley surface south of the channel. This location was also observed in the field, but in 2014 it was a dry depression of fine grained, white sediment with desiccation cracks. This white sediment is interpreted as an evaporative mineral accumulation that formed from the intermittent holding of water within the depression. When the water evaporates the dissolved minerals are left as an accumulation on the surface. The evidence of standing water in the AD 1954 air photo supports this interpretation.

A very similar unit was observed in HC16. The white-colored, thick bed extends laterally beneath the aeolian facies. Beneath are fluvial overbank facies which overlie wetland facies. If the white-colored unit is interpreted as an evaporative mineral accumulation, the instance of intermittently ponded water at section HC16 was temporally singular.

No evidence was observed to suggest the wetland facies are being deposited within the modern system. The white evaporative minerals are indicative of standing water but represent frequent changes in water holding capacity. The wetland facies are indicative of long periods of saturation.

These extended durations of saturation occur either during or after deposition. However, deposition in a wet meadow environment is favored based on the spatial concentration, depth and height of the wetland facies. Furthermore, redox concentrations are found at multiple depths, three distinct zones in HC3 and
HC4, in the same stratigraphic columns, which is interpreted as evidence of a change in the depth of the water table, base-level or both.

The alternative, post depositional reduction, can occur if a perched water table saturates previously deposited sediment. The vertical extent of the reduced features, extensive bioturbation and localized occurrence of the wetland facies make this less likely. However, this can not be disqualified as a contributing factor, because wet but not saturated zones were observed above the incised bed, which is the current base level of the stream. The determination of when and how the saturation occurred is not as pertinent as the recognition that saturation occurred, which was likely attributed to a wetter climate.

The alluvial fan facies consist of coarse, angular gravel, and are largely interpreted as being hillslope alluvium and colluvium. These angular cobbles represent an influx of sediment from the surrounding valley slopes.

**Chronology of Fluvial Aggradation**

One valuable data point that is useful when interpreting the change in the physical environment through time is the gradient of the stratigraphic units found beneath the surface. This would be accomplished with the correlation of the upstream and downstream fluvial facies; however, the attempt to trace individual units along the length of the study reach was proven unsuccessful. This is a common issue with the correlation of fluvial sedimentation events as the sinuous and erosive nature removes physical correlation data. One method to fill in these missing gaps is to acquire absolute age data to constrain stratigraphic units. The
absolute ages that were used in this project turned out to be insufficient for
correlation due to the lack of quantity.

The oldest age constraint found for the fluvial facies is a calibrated age of
2490-2730 BP. This sample was collected from HC6 at a depth of 302 cm, which
coincides with a fluvial facies, which suggests that the dated sample was most likely
transported prior to deposition. Therefore, this date is a maximum age constraint on
the timing of deposition.

When considering the relative ages of the sediment units in HC6-HC10, many
cross-cutting relationships were observed (Figures 14 and 21). The entire depth of
HC9 is younger than HC10. The laterally extensive couplet traces directly from HC6
to HC7 but is cut by the younger gravel units of HC8, which contained at minimum
two cross-cutting relationships. The laterally extensive couplet is observed in HC9
stratigraphically beneath the youngest inset, which cuts the fine-grained sediments
of HC8. Therefore, it can be posited that this region of the valley has contained an
actively aggrading and eroding stream since a minimum calibrated age of 2490-
2730 BP. This stream has flowed with sufficient energy to erode and transport
cobble-sized sediment in the past.

The paleocurrent analysis reveals further information about the channel
characteristics prior to incision (AD 1900 ± 50) and after a minimum calibrated age
of 2490-2730 BP. The multiple directions of paleocurrent represent a single,
laterally migrating channel or multiple channels that flowed in several directions
simultaneously. The channel(s) that deposited the fluvial facies during this time
period was not confined to the deeply entrenched arroyo banks that are observed at the modern Hanson Creek.

**Relationship of Valley Geometry and Sedimentology**

The relationship of the fluvial facies, wetland facies and the longitudinal profile of the valley floor provides insight into the influence of valley morphology on the sedimentology of Hanson Creek (Figure 12).

One pattern that emerges is the correlation of fluvial sand and cobbles with steeper sections of the longitudinal valley profile. The reaches that contain predominately fluvial facies correspond to locations on the profile that are below the linear trend line (Figure 12). The inverse of this relationship is true where wetland facies indicative of ponded-water environments are observed (Figure 12). These sediments are associated with shallow valley gradients.

The oscillations from steep to shallow gradient are similar to a fluvial step-pool sequence, but the gradient of the entire reach is less than typically observed. Also, the length of the intervening, steep, cobble reaches is much longer than expected.

Observations of modern ground-water seeps from the incised banks above base level, proximity to inflowing higher order streams, dense vegetation cover of the valley floor on the flatter sections, low gradient conditions and saturated sediment conditions reveal what during a wetter environment, without an incised channel, could have been a wet meadow or ponded reach. The intervening steeper
reaches represent an aggrading main channel that connected the low gradient ponded sections.

**Archaeology**

The locations of HC5-HC10 are within the boundaries of archaeological site KT1975 (Figure 3), also called Bishop's Hollow (Simmons et al., 2014). This site was first recorded in 2001 as a prehistoric field camp as evidenced in part by the presence of lithic tools and debitage, fire modified rock (FMR) scatter, and faunal bone (DeBoer, 2001). The site has since been revisited between 2005 and 2006 as well as in 2014 (Simmons et al., 2014).

Results from the archaeological site report reveal that a temporally diagnostic point was recorded on the surface north of the incised channel approximately 125 meters to the southeast of HC5 (Figures 6 and 13; Simmons et al., 2014). The Columbia Corner Notched B projectile point (Figure 27) dates to approximately 2,000 to 150 B.P. based on the style of the projectile point (Simmons et al., 2014). Cultural deposits were found to extend to a depth of 2 meters (Simmons et al., 2014).

**Interpretation of Cultural Artifacts Found in HC5**

Location HC5 from this study corresponds with Stratigraphic Exposure 3 (Simmons et al., 2014) from the archaeological excavation (Figure 3), which is described to include bone, lithics and cobble sized fire modified rock (Simmons et al., 2014). Two units containing archaeological artifacts were also excavated north
of the incised bank, which included lithics, bone fragments and charcoal (Simmons et al., 2014).

The bone and lithics in HC5 are located at the base of a sub-rounded, clast-supported, gravel unit with no grading. Both the upper and basal contacts are gradual, which can be interpreted as representing continuous deposition without unconformity. The sedimentary characteristics of the matrix-supported fine-grained unit beneath the culturally significant unit are indicative of a very brief, water-influenced depositional period, which in this instance is most likely attributed to a debris flow or flood event. If interpreted as such the cultural material would be interpreted as being entrained and transported. This interpretation is supported by the excavation units dug to the north, as artifacts were observed continuously throughout the depth (Simmons et al., 2014). This would require the occupation of the same 1x1 meter square for the duration of time that is required to accumulate sediments to a depth of one meter.
Figure 27. Projectile point found on the surface north of the incised side channel. Location denoted as T1 (Figure 3). Diagnostically similar to Columbia Corner Notched B projectile points (Simmons et al., 2014).
**Environment During Occupation**

A chronology of occupation has not been established for site KT1975, but the temporally diagnostic tool may represent occupation between 150 and 2000 B.P. (Simmons et al., 2014). This time period is before the incision of the present arroyo in this reach of Hanson Creek.

Prior to the arroyo incision event, when people were previously occupying the site, the channel is interpreted as a shallow, meandering or multi-channel stream. This stream consisted of a series of ponds or wet meadows that were separated by steeper fluvial reaches. The wet meadows or ponded sections are supported by the bioturbated wetland facies that are found in the shallow gradient sections of the stream system. These saturated, wet sections were likely very biologically active and supported a rich diversity of both flora and fauna.

The location of the archaeological evidence suggests people were using much of the surrounding area. However, most of the evidence was found to the north of the modern arroyo channel. These locations are higher in elevation and provide an excellent vantage point, which is near a water source that likely attracted many living beings.

**Climate**

Climate has been suggested to have an integral role in the formation of arroyos (Bryan, 1941; Antevs, 1952; Martin, 1963; Hall, 1977; Karlstrom, 1988). The cycles of aggradation and incision match well with many known climatic periods (Waters and Haynes, 2001). The single incision event observed at Hanson Creek
does not represent a recurring cyclical phenomenon. However, the influence of climate should not be discounted.

The single incision event at Hanson Creek is dated as the late 19th to -early 20th century, which is contemporaneous with multiple locations of arroyo incision throughout the world (Cooke and Reeves, 1976; Perroy, et al., 2012). The contemporaneous global extent of dry land incision is fascinating, but the role of such patterns is beyond the scope of this research.

The regional climate during the Holocene has been variable (Chatters and Hoover, 1992). The oldest age in the stratigraphic record at Hanson Creek is the Mazama tephra at 7680-7580 BP (Egan et al., 2015), which coincides with a climate that includes warm winters, hot summers and winter-dominant precipitation (Chatters and Hoover, 1992). An intermediate age of 2490-2730 BP coincides with the transition from a period of cold winters, cool summers and high amounts of winter precipitation to warmer winters, warmer summers and declining precipitation (Chatters and Hoover, 1992).

The timing of the Medieval Warm Period, AD 1000 to 1300 (Crowley and Thomas, 2000), coincides with aggradation at Hanson Creek. This time period has been documented as producing drought-like conditions throughout the western United States (Cook, et al., 2004). This climatic period was not isolated in the stratigraphic record at Hanson Creek, but the presence of large-gravel-sized, fluvial sediments does decline higher in the stratigraphic sequences, that could represent a transition to lower discharges.
Potential Causes of Incision

The deep incision of Hanson Creek is fascinating because it has only occurred one time, and that time was geologically very recent. The incision at Hanson Creek could involve many potential factors, including 1.) Influx of sediment from adjacent alluvial fans, 2.) change in base level due to faulting, 3.) groundwater flux, 4.) extreme climatic events and 5.) human disturbance.

Influx of alluvium from the surrounding valley slopes is a factor because the valley is bound by steep slopes to the north and south. Evidence of both colluvium and hill-slope alluvium was found in the stratigraphy of HC5 and HC11. Several alluvial fans, four from the southern slope, are directly tied to active tributary channels. On the northern slope, three fans, two connected and one not connected to an active channel, were identified (Figure 14). This evidence leads to the conclusion that major contributors to the sediment influx have been local and possibly brief events. It can be posited that large masses moving as debris flows or colluvium would decrease the gradient of the main Hanson Creek valley. However, when observing the gradient patterns within the longitudinal profile and corresponding zones of alluvial fan influx, no correlation was confirmed between the two. Some fans correspond to flatter sections and others correspond with steeper sections. Interestingly, one of the steepest sections 400 to 500 meters downstream of HC1 corresponds with the most well developed and inflowing drainage network (Figure 14). Therefore, influx of sediment from alluvial fans is not considered significant for initiating incision.
Faulting can change the base level of a stream and therefore initiate incision. Faulting has been occurring in the region for 15 mya (Campbell, 1998). However, evidence of faulting, such as lineations or offsets of the surface or geological units, was not observed in the imagery or stratigraphy at Hanson Creek.

The third factor for channel incision is changes in groundwater flux. Several springs were observed adjacent to Hanson Creek on maps and in the field. A pattern was observed that involves the presence of wetland facies, evidence of springs and flattened topography. The steps that are formed as a result of the flattened topography and intervening steeper reaches establish an easily erodible environment. The threshold for a knickpoint to be established is much lower if sediments are accumulating upstream of a steeper downstream reach. If a knickpoint was established in the tall, fine-grained, easily erodible and flatter sections, the stream could continue to cut headward and initiate incision. This process could continue to form discontinuous, incised reaches that eventually connect. The incision could also begin at the furthest downstream section, HC16, and continue headward toward HC1 (Figure 14).

The fourth factor is human disturbance. The timing of incision has been determined to be around AD 1900 ± 50. During this time period ranchers were known to be in the region with grazing cattle (Simmons et al., 2014; Sullivan, 1994). Furthermore, the Yakima Training Center (YTC), which includes the studied area, was established as a military training and munitions testing area in AD 1950.
(Sullivan, 1994). Therefore, the idea that a human presence cannot be ruled out as a contributing factor.

Hanson Creek is not the only stream in the region that arroyo channel geometry is observed. Three other streams, Selah Creek, Cold Creek (Durkee, 2012) and Johnson Creek (Sullivan, 1994), contain reaches that have been deeply incised. Johnson Creek, north of Hanson Creek, flows east into the Columbia River. Selah Creek, south of Hanson Creek, flows west into the Yakima River. Cold Creek, south of Hanson Creek flows east into the Columbia River. Each of these streams are confined by the east-west trending, uplifted folds that dominate the region.

Johnson Creek, as evidenced by historical archives, was observed as exhibiting very little or no channel entrenchment prior to AD 1878 (Sullivan, 1994). The advancement of incision was observed at Johnson Creek in a series of aerial photographs taken in 1942, 1954, 1962 and 1972 (Sullivan, 1994).

Incision of Selah Creek was determined to occur as the result of a dam failure, which occurred AD 1909 (Durkee, 2012). The timing of the Cold Creek incision was estimated to occur around AD 1930 as a result of regional flooding (Durkee, 2012).

The data from this research supports the timing of the incision event at Hanson Creek as AD 1900 ± 50. Subsequently, the cause of the incision is interpreted as being the result of a regional event, such as human occupation, climate, or an extreme weather event. This interpretation is bolstered by the synchronous, local, arroyo incision events previously mentioned (Durkee, 2012;
Sullivan, 1994). The most likely scenario is that an extreme precipitation event occurred within the region causing an increase in erosion and the formation of at least one knickpoint. The freshly eroded surface was then more susceptible to headward erosion and subsequent incision, which resulted in a positive feedback mechanism within the fluvial system. Once the channel became incised it continued to incise.

**Conclusions**

Hanson Creek has undergone several pulses of aggradation dating back at least as far as 7700 BP, based on correlation with the Mazama tephra, and likely since the early Holocene. The spatial correlation of thick wet-meadow sediment to alluvial fan deposits, spring seeps, and flatter reaches of the longitudinal valley profile suggests that the channel formed an alluvial step-pool sequence prior to the current incision. The concentration of paleocurrent data and variability in orientation lends further evidence to an aggrading channel pattern prior to incision.

Several phases of minor channel incision related to the higher-energy channel deposits have occurred throughout the reach during the latter half of the Holocene. The incision of the present arroyo occurred in the late 19th-early 20th century and lowered the stream base level, creating a stark contrast between the basin surface and channel bed as evidenced by vegetation. There is no evidence of any earlier episodes of channel incision to this depth in the Holocene stratigraphic record. The cause of the incision is likely a combination of factors, including thick accumulations of easily erodible sediment in reaches of shallow valley gradient and
intervening steep gradients. Although the event that triggered the incision is unknown, similar arroyos in the western U.S. have been initiated by high magnitude floods that incised initial knickpoints, subsequently lowering base level.

The physical environment prior to incision likely included a series of lush ponded or wet-meadow sections and an intervening channel with a wide flood plain, which was unconstrained due to the absence of arroyo incision. This is the most likely environment to coincide with human occupation prior to AD 1900.

The timing and physical environmental conditions associated with the deposition and erosion of Holocene sediment in the Hanson Creek watershed will supplement the minimal data available on arroyo formation in the northwestern United States and previous alluvial chronologies from the region.
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APPENDIXES

Appendix A

Channel Cross Sections
South

HC7

North

Depth (m)

HC8

395
390
385

0 5 10 15 20 25 30 35 40 45 50 55 60

Width (m)

HC10

395
390
385

0 5 10 15 20 25 30 35 40 45 45
Appendix B

Stratigraphic Columns

Stratigraphy of HC1

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- \(^{14}C\) Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Grain Size represents d50 value. Modified Wentworth scale. X-axis values include; clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters. Arrows represent paleocurrent indicator.
Stratigraphy of HC3

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- C Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- □ 14C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include; clay(cl), silt, very fine sand (vfs), fine sand, medium sand(ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Stratigraphy of HC4

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- $^{14}$C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Stratigraphy of HC5

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- C Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- 14C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters. Arrows represent paleocurrent indicator and orientation.
Stratigraphy of HC6

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- C: Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- ¹⁴C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Stratigraphy of HC9

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- C Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- 14C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Stratigraphy of HC10

Legend

- Massive
- Planar Laminated
- Clast Supported
- Matrix Supported
- C Cemented
- Roots
- Redox Concentrations
- Gradual Contact
- MSH 1980 Tephra
- ¹⁴C Sample Location
- Lithic or Bone
- Erosional Unconformity

Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay(cl), silt, very fine sand (vfs), fine sand, medium sand(ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
Grain Size represents d50 value. Modified Wentworth scale. X-axis values include: clay (cl), silt, very fine sand (vfs), fine sand, medium sand (ms), coarse sand, pebbles to very coarse gravel (gr), cobble and boulder (bld). Y-axis is depth in centimeters.
## Appendix C

### Detailed Descriptions of Sediment Units

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Unit</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0-0.13</td>
<td>HC1.1</td>
<td>Well Sorted, Laminated, Alternating Very Fine Sand and Fine Sand, Thin Beds, 10 YR 4/3 (wet), Brown, Inclusions and Sediment Mixing, Roots Present, Weak Granular Soil Structure</td>
</tr>
<tr>
<td>0.13-0.14</td>
<td>HC1.2</td>
<td>Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit, MSH 1980</td>
</tr>
<tr>
<td>0.14-0.57</td>
<td>HC1.3</td>
<td>Well Sorted, Laminated, Alternating Very Fine Sand and Fine Sand, Thin Beds, 10 YR 4/3 (wet), Brown, Inclusions and sediment mixing, Abrupt Basal Contact</td>
</tr>
<tr>
<td>0.57-0.89</td>
<td>HC1.4</td>
<td>Well Sorted, Massive, Very Fine Sand, 10 YR 4/3 (wet), Brown, Roots, Granular Soil Structure</td>
</tr>
<tr>
<td>0.89-1.17</td>
<td>HC1.5</td>
<td>Well Sorted, Planar Laminated, Silt, 2.5 Y 6/3 (dry), Light Yellowish Brown; 2.5 Y 5/3 (dry), Light Olive Brown, Cemented</td>
</tr>
<tr>
<td>1.17-1.30</td>
<td>HC1.6</td>
<td>Well Sorted, Planar Laminated, Thin Beds, Very Fine Sand, 2.5 Y 5/3 (dry), Light Olive Brown</td>
</tr>
<tr>
<td>1.30-1.69</td>
<td>HC1.7</td>
<td>Well Sorted, Planar Laminated, Silt, Thin Beds, 2.5 Y 5/3 (dry), Light Olive Brown, Cemented</td>
</tr>
<tr>
<td>1.69-1.78</td>
<td>HC1.8</td>
<td>Moderately Sorted, Laterally Extensive, Fine Gravel to Medium Sand, Normal Grade, Abrupt Basal Contact</td>
</tr>
<tr>
<td>1.78-1.88</td>
<td>HC1.9</td>
<td>Well Sorted, Laminated, Silt, Very Thin Beds, 2.5 Y 6/3 (dry), Light Yellowish Brown; 2.5 Y 5/3 (dry), Light Olive Brown, Cemented</td>
</tr>
<tr>
<td>1.88-2.03</td>
<td>HC1.10</td>
<td>Moderately Sorted, Massive, Fine Sand</td>
</tr>
<tr>
<td>2.03-2.71</td>
<td>HC1.11</td>
<td>Moderately Sorted, Cobble to Fine Gravel, Normal Grade, Clast Supported, Sub-Rounded</td>
</tr>
<tr>
<td>2.71-2.93</td>
<td>HC1.12</td>
<td>Well Sorted, Planar Laminated, Medium Sand, Thin Laminae</td>
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<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
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<tr>
<td>0.0 - 0.04</td>
<td>HC2.1</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown, Many Small Roots</td>
</tr>
<tr>
<td>0.04 - 0.06</td>
<td>HC2.2</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit, Mount Saint Helens AD 1980</td>
</tr>
<tr>
<td>0.06 - 0.10</td>
<td>HC2.1</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.10 - 0.36</td>
<td>HC2.3</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/2 Dark Grayish Brown</td>
</tr>
<tr>
<td>0.36 - 0.67</td>
<td>HC2.4</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 5/3, Light Olive Brown, Mild Reaction to HCl</td>
</tr>
<tr>
<td>0.67 - 0.77</td>
<td>HC2.5</td>
<td>Massive, Silt, 2.5 Y 5/3, Light Olive Brown, Mild Reaction to HCl</td>
</tr>
<tr>
<td>0.77 - 0.98</td>
<td>HC2.6</td>
<td>Massive, Silt, 2.5 Y 7/3, Pale Yellow, Very Hard, Reacts to HCl, Inclusions of Very Fine Sand Colored 2.5 Y 5/3 Light Olive Brown</td>
</tr>
<tr>
<td>0.98 - 1.16</td>
<td>HC2.7</td>
<td>Massive, Silt, 2.5 Y 5/2, Grayish Brown, Cemented, Reacts to HCl</td>
</tr>
<tr>
<td>1.16 - 1.25</td>
<td>HC2.8</td>
<td>Massive, Very Fine Sand, 2.5 Y 5/3, Light Olive Brown, Cemented, Does Not React to Acid</td>
</tr>
<tr>
<td>1.25 - 1.37</td>
<td>HC2.9</td>
<td>Massive, Very Fine Sand, 2.5 Y 4/2, Dark Grayish Brown, Soil Peds Present, Roots Present, Carbonate Nodules Present, Only Carbonate Nodules React to HCl, Possible Buried A Horizon, Gradual Contact with HC2.10</td>
</tr>
<tr>
<td>1.37 - 1.48</td>
<td>HC2.10</td>
<td>Massive, Very Fine Sand, 2.5 Y 5/3, Light Olive Brown, Soil Peds Present, No Reaction to HCl, Basal Contact Abrupt</td>
</tr>
<tr>
<td>1.48 - 2.73</td>
<td>HC2.11</td>
<td>Planar Laminated, Alternating Silt and Fine Sand, Medium Beds and Very Thin Beds Respectively, 5 Y 5/4, Light Olive Brown</td>
</tr>
<tr>
<td>2.73 - 2.90</td>
<td>HC2.12</td>
<td>Massive, Well Sorted, Very Fine Sand, 5 Y 6/3, Pale Olive, Redox Concentrations</td>
</tr>
<tr>
<td>2.90 - 3.10</td>
<td>HC2.13</td>
<td>Subrounded, Clast Supported, Small Cobbles to Very Fine Gravel, Normal Grading, Basalt, Lenticular Gravel, Basal Contact Abrupt</td>
</tr>
<tr>
<td>3.10 - 3.51</td>
<td>HC2.14</td>
<td>Massive, Silt, 2.5 Y 5/6 (wet), Light Olive Brown, Redox Concentrations</td>
</tr>
<tr>
<td>3.51 - 3.73</td>
<td>HC2.15</td>
<td>Massive, Silt, 2.5 Y 3/3 (wet), Dark Olive Brown, Redox Concentrations</td>
</tr>
<tr>
<td>3.73 - 4.13</td>
<td>HC2.16</td>
<td>Massive, Silt, 5 Y 5/4 (wet), Dark Olive Brown, Redox Concentrations</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
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<td>------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0.0-0.02</td>
<td>HC3.1</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.02-0.04</td>
<td>HC3.2</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit, Mount Saint Helens AD 1980</td>
</tr>
<tr>
<td>0.04-0.36</td>
<td>HC3.3</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown, Roots, Granular Soil Structure, Abrupt Basal Contact</td>
</tr>
<tr>
<td>0.36-0.54</td>
<td>HC3.4</td>
<td>Massive, Silt, 2.5 Y 5/2, Grayish Brown</td>
</tr>
<tr>
<td>0.54-0.79</td>
<td>HC3.5</td>
<td>Massive, Silt, 2.5 Y 4/2, Dark Grayish Brown</td>
</tr>
<tr>
<td>0.79-1.09</td>
<td>HC3.6</td>
<td>Massive, Silt, 2.5 Y 6/3, Light Yellowish Brown</td>
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<tr>
<td>1.09-1.43</td>
<td>HC3.7</td>
<td>Massive, Silt, 2.5 Y 5/2, Grayish Brown</td>
</tr>
<tr>
<td>1.43-1.52</td>
<td>HC3.8</td>
<td>Planar Laminated, Very Fine Sand</td>
</tr>
<tr>
<td>1.52-2.19</td>
<td>HC3.9</td>
<td>Massive, Silt, 2.5 Y 6/3, Light Yellowish Brown</td>
</tr>
<tr>
<td>2.19-3.01</td>
<td>HC3.10</td>
<td>Massive, Silt, 2.5 Y 5/2, Grayish Brown (Dry), No Reaction to HCl, Redox Concentrations 2.86 to 2.95-Meters Depth</td>
</tr>
<tr>
<td>3.01-3.55</td>
<td>HC3.11</td>
<td>Massive Very Fine Sand, 2.5 Y 4/2, Dark Grayish Brown</td>
</tr>
<tr>
<td>3.55-3.74</td>
<td>HC3.12</td>
<td>Massive, Very Fine Sand, 2.5 Y 7/2 (Dry), Light Gray, Basal Contact Irregular, Redox Concentrations, Confirmed as Mazama Climactic Tephra</td>
</tr>
<tr>
<td>3.74-??</td>
<td>HC3.13</td>
<td>Massive, Silt, 2.5 Y 3/3 (wet), Dark Olive Brown</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
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<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0.0-0.01</td>
<td>HC4.1</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit, Mount Saint Helens AD 1980</td>
</tr>
<tr>
<td>0.01-0.16</td>
<td>HC4.2</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.16-0.26</td>
<td>HC4.3</td>
<td>Well Sorted, Planar Laminated, Very Fine Sand and Silt, Very Thin Beds, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.26-0.52</td>
<td>HC4.4</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown, Abrupt Basal Contact</td>
</tr>
<tr>
<td>0.52-0.64</td>
<td>HC4.5</td>
<td>Massive, Silt, 5 Y 3/1, Very Dark Gray</td>
</tr>
<tr>
<td>0.64-1.13</td>
<td>HC4.6</td>
<td>Silt, 5 Y 4/1, Dark Gray, Blocky Subangular Soil Structure</td>
</tr>
<tr>
<td>1.13-1.51</td>
<td>HC4.7</td>
<td>Massive, Silt, 5 Y 6/3, Pale Olive, Redox Concentrations 1.27 to 1.51- meters depth,</td>
</tr>
<tr>
<td>1.51-2.36</td>
<td>HC4.8</td>
<td>Massive, Silt, 5 Y 5/2, Olive Gray, Redox Concentrations</td>
</tr>
<tr>
<td>2.36-2.45</td>
<td>HC4.9</td>
<td>Massive, Very Fine Sand, 5 Y 7/3 (wet), Irregular Basal Contact, Redox Concentrations</td>
</tr>
<tr>
<td>2.45-2.64</td>
<td>HC4.10</td>
<td>Massive, Silt, 2.5 Y 5/6, Light Olive Brown, Redox Concentrations</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0.0-0.01</td>
<td>HC5.1</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit, Mount Saint Helens AD 1980</td>
</tr>
<tr>
<td>0.01-0.30</td>
<td>HC5.2</td>
<td>Massive, Well Sorted, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.30-0.36</td>
<td>HC5.3</td>
<td>Laterally Extensive, Well Sorted, Clast Supported, Rounded, Coarse Gravel</td>
</tr>
<tr>
<td>0.36-1.04</td>
<td>HC5.4</td>
<td>Planar Laminated, Silt, Medium Bed Thickness, 10 YR 5/3 (dry), Brown, Laminations Delineated By Hardness</td>
</tr>
<tr>
<td>1.04-1.10</td>
<td>HC5.5</td>
<td>Matrix Supported, Coarse Gravel, Rounded Clasts, Silt Matrix, 50 % Clast Composition, Lithic and Bone</td>
</tr>
<tr>
<td>1.10-1.60</td>
<td>HC5.6</td>
<td>Matrix Supported, Medium Gravel, Rounded Clasts, Silt Matrix, &lt;5% Clast Composition</td>
</tr>
<tr>
<td>1.60-1.78</td>
<td>HC5.7</td>
<td>Clast Supported, Medium Gravel, Sub-Rounded, Oxidized</td>
</tr>
<tr>
<td>1.78-1.90</td>
<td>HC5.8</td>
<td>Massive, Clast Supported, Very Coarse Sand, Oxidized, Abrupt Basal Contact</td>
</tr>
<tr>
<td>1.90-1.97</td>
<td>HC5.9</td>
<td>Massive, Silt, 2.5 Y 7/2, Light Gray, Basal Contact Irregular, Redox Concentrations</td>
</tr>
<tr>
<td>1.97-2.06</td>
<td>HC5.10</td>
<td>Massive, Silt, 10 YR 4/2, Dark Grayish Brown</td>
</tr>
<tr>
<td>2.06-2.23</td>
<td>HC5.11</td>
<td>Massive, Medium Sand, Oxidized</td>
</tr>
<tr>
<td>2.23-2.87</td>
<td>HC5.12</td>
<td>Massive, Very Fine Sand, 10 YR 5/3 (wet), Brown, Redox Concentrations</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
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<tr>
<td>0.0-0.10</td>
<td>HC6.1</td>
<td>Well Sorted, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.10-0.11</td>
<td>HC6.2</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit</td>
</tr>
<tr>
<td>0.11-0.13</td>
<td>HC6.3</td>
<td>Well Sorted, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.13-0.33</td>
<td>HC6.4</td>
<td>Moderately Sorted, Medium Gravel, Sub-Rounded, Clast Supported</td>
</tr>
<tr>
<td>0.33-0.64</td>
<td>HC6.5</td>
<td>Well Sorted, Very Fine Sand, 2.5 Y 4/3, Olive Brown, Signs of Bioturbation</td>
</tr>
<tr>
<td>0.64-0.84</td>
<td>HC6.6</td>
<td>Moderately Sorted, Very Coarse Gravel, Sub-Rounded, Clast Supported</td>
</tr>
<tr>
<td>0.84-1.222</td>
<td>HC6.7</td>
<td>Alternating Silt to Fine Sand, 2.5Y 5/3, Light Olive Brown, Medium Bed Thickness, Wavy Beds, Reacts to HCl</td>
</tr>
<tr>
<td>1.222-1.47</td>
<td>HC6.8</td>
<td>Well Sorted, Very Fine to Fine Sand, 2.5Y 5/3, Light Olive Brown, Thin Bed Thickness, Planar Beds, Reacts to HCl</td>
</tr>
<tr>
<td>1.47-1.74</td>
<td>HC6.9</td>
<td>Well Sorted, Silt, 2.5Y 5/3, Light Olive Brown, Cemented, Carbonate Concretions, Reacts to HCl</td>
</tr>
<tr>
<td>1.74-1.76</td>
<td>HC6.10</td>
<td>Well Sorted, Fine Sand, 2.5Y 5/3, Light Olive Brown, Massive, Reacts to HCl</td>
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<tr>
<td>1.76-1.85</td>
<td>HC6.11</td>
<td>Well Sorted, Silt, 2.5Y 5/3, Light Olive Brown, Reacts to HCl</td>
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<tr>
<td>1.85-1.875</td>
<td>HC6.12</td>
<td>Well Sorted, Coarse Sand, Massive, Reacts to HCl</td>
</tr>
<tr>
<td>1.875-2.025</td>
<td>HC6.13</td>
<td>Well Sorted, Very Fine to Fine Sand, Thin to Medium Bed Thickness, Planar Beds, 2.5Y 5/3, Light Olive Brown, Reacts to HCl</td>
</tr>
<tr>
<td>2.025-2.08</td>
<td>HC6.14</td>
<td>Well Sorted, Silt, Cemented, Reacts to HCl</td>
</tr>
<tr>
<td>2.08-2.30</td>
<td>HC6.15</td>
<td>Well Sorted, Very Fine Sand, 2.5Y 5/3, Light Olive Brown, Planar Beds, Thin to Medium Bed Thickness, Does Not React to Acid</td>
</tr>
<tr>
<td>2.30-2.43</td>
<td>HC6.16</td>
<td>Massive, Thin Beds, Silt</td>
</tr>
<tr>
<td>2.43-2.77</td>
<td>HC6.17</td>
<td>Moderately Sorted, Coarse Sand to Cobble Sized, Well-Rounded to Sub-Angular, Clast Supported, Laterally Extensive</td>
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<td>2.77-3.10</td>
<td>HC6.18</td>
<td>Well Sorted, Very Fine Sand, Thin, Planar Beds</td>
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<tr>
<td>0-0.08</td>
<td>HC7.1</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.08-0.084</td>
<td>HC7.2</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit</td>
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<td>0.084-0.22</td>
<td>HC7.3</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
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<tr>
<td>0.22-0.32</td>
<td>HC7.4</td>
<td>Moderately Sorted, Medium Gravel, Sub-Rounded</td>
</tr>
<tr>
<td>0.32-0.50</td>
<td>HC7.5</td>
<td>Well Sorted, Massive, Very Fine Sand, 10 YR 5/6, Yellowish Brown</td>
</tr>
<tr>
<td>0.50-0.70</td>
<td>HC7.6</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 3/2, Very Dark Grayish Brown</td>
</tr>
<tr>
<td>0.70-0.84</td>
<td>HC7.7</td>
<td>Well Sorted, Massive, Fine Sand, 2.5Y 4/2, Dark Grayish Brown, Evidence of Mixing</td>
</tr>
<tr>
<td>0.84-0.86</td>
<td>HC7.8</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 5/3, Light Olive Brown</td>
</tr>
<tr>
<td>0.86-1.10</td>
<td>HC7.9</td>
<td>Well Sorted, Massive, Very Fine Sand, 10 YR 4/3, Olive Brown</td>
</tr>
<tr>
<td>1.10-1.27</td>
<td>HC7.10</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 3/2, Very Dark Grayish Brown</td>
</tr>
<tr>
<td>1.27-2.27</td>
<td>HC7.11</td>
<td>Well Sorted, Planar Laminated, Very Fine Sand Beds, Silt Laminae, 2.5 Y 5/3, Light Olive Brown, Silt Couplet Traces to HC3</td>
</tr>
<tr>
<td>2.27-2.44</td>
<td>HC7.12</td>
<td>Well Sorted, Massive, Silt, 2.5 Y 6/3, Light Yellowish Brown, Cemented</td>
</tr>
<tr>
<td>2.44-2.64</td>
<td>HC7.13</td>
<td>Well Sorted, Planar Laminated, Coarse Gravel, Sub-Rounded, Clast Supported, Mafic Composition</td>
</tr>
<tr>
<td>3.40-3.60</td>
<td>HC7.15</td>
<td>Well Sorted, Planar Laminated, Medium Gravel, Sub-Rounded, Clast Supported, Mafic Composition</td>
</tr>
<tr>
<td>3.60-3.80</td>
<td>HC7.16</td>
<td>Well Sorted, Massive, Silt, 2.5 Y 6/3, Light Yellowish Brown, Redox Concentrations at contact with HC1.17</td>
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<tr>
<td>3.80-3.82</td>
<td>HC7.17</td>
<td>Well Sorted, Massive, Silt, 2.5 Y 4/2, Dark Grayish Brown, Redox Concentrations at lower and upper contact</td>
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<td>3.82-3.90</td>
<td>HC7.18</td>
<td>Well Sorted, Massive, Fine Sand, 2.5 Y 6/4, Light Yellowish Brown, Redox Concentrations</td>
</tr>
<tr>
<td>3.90-3.99</td>
<td>HC7.19</td>
<td>Well Sorted, Massive, Silt, Cemented, 2.5 Y 6/3, Light Yellowish Brown, Redox Concentrations</td>
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<tr>
<td>3.99-4.10</td>
<td>HC7.20</td>
<td>Well Sorted, Planar Laminated, Coarse Gravel, Sub-Rounded, Clast Supported, Mafic Composition</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
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</tr>
<tr>
<td>0.0-0.02</td>
<td>HC8.1</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.02-0.05</td>
<td>HC8.2</td>
<td>Well Sorted, Fine Sand, 2.5 Y 7/1, Light Gray, Volcanic Tephra Deposit</td>
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<tr>
<td>0.05-0.23</td>
<td>HC8.3</td>
<td>Well Sorted, Massive, Very Fine Sand, 2.5 Y 4/3, Olive Brown</td>
</tr>
<tr>
<td>0.23-1.53</td>
<td>HC8.4</td>
<td>Laminated, Silt, Thin to Medium Beds, 2.5 Y 4/4; Olive Brown, Dark Charcoal Rich, Very Thin Beds at Depths of 1.22, 1.33, 1.45 and 1.52 meters</td>
</tr>
<tr>
<td>1.53-1.62</td>
<td>HC8.5</td>
<td>Laminated, Very Fine Sand, Very Thin Beds</td>
</tr>
<tr>
<td>1.62-1.92</td>
<td>HC8.6</td>
<td>Massive, Fine Sand, 2.5 Y 4/2, Dark Grayish Brown</td>
</tr>
<tr>
<td>1.92-2.10</td>
<td>HC8.7</td>
<td>Clast Supported, Sub-Rounded, Coarse Gravel, Abrupt Basal Contact, Normal Grade</td>
</tr>
<tr>
<td>2.10-2.55</td>
<td>HC8.8</td>
<td>Clast Supported, Sub-Rounded, Cobble, Abrupt Basal Contact, Normal Grade</td>
</tr>
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<td>2.55-3.03</td>
<td>HC8.9</td>
<td>Clast Supported, Sub-Rounded, Coarse Gravel, Abrupt Basal Contact, Normal Grade</td>
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<td>3.03-3.47</td>
<td>HC8.10</td>
<td>Planar Laminated, Silt and Very Fine Sand, Thin Beds</td>
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<tr>
<td>3.47-3.51</td>
<td>HC8.11</td>
<td>Planar Laminated, Medium Sand</td>
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<tr>
<td>3.51-3.68</td>
<td>HC8.12</td>
<td>Planar Laminated, Very Fine Sand</td>
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<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
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</tr>
<tr>
<td>1.60-2.02</td>
<td>HC9.1</td>
<td>Lenticular, Clast Supported, Coarse Gravel, Abrupt Basal Contact</td>
</tr>
<tr>
<td>2.02-2.52</td>
<td>HC9.2</td>
<td>Laminated, Alternating Thin Beds of Silt and Medium Sand, Cemented</td>
</tr>
<tr>
<td>2.52-2.66</td>
<td>HC9.3</td>
<td>Laminated, Very Fine Sand</td>
</tr>
<tr>
<td>2.66-2.96</td>
<td>HC9.4</td>
<td>Laminated, Silt, Cemented</td>
</tr>
<tr>
<td>2.96-4.05</td>
<td>HC9.5</td>
<td>Matrix Supported, Very Fine Sand, Pebble Clasts, Clast Composition &lt;5%</td>
</tr>
<tr>
<td>4.05-4.56</td>
<td>HC9.6</td>
<td>Moderately Sorted, Very Fine to Very Coarse Gravel, Clast Supported</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
<td>-----------------------------------------------------------------------------</td>
</tr>
<tr>
<td>3.16-4.05</td>
<td>HC10.1</td>
<td>Planar Laminated, Laterally Extensive, Silt and Very Fine Sand</td>
</tr>
<tr>
<td>4.05-4.18</td>
<td>HC10.2</td>
<td>Laterally Extensive, Moderately Sorted, Sub-Rounded, Clast Supported, Very Fine Gravel and Large Cobble</td>
</tr>
<tr>
<td>4.18-5.06</td>
<td>HC10.3</td>
<td>Massive, Well Sorted, Very Fine Sand</td>
</tr>
<tr>
<td>5.06-5.58</td>
<td>HC10.4</td>
<td>Lenticular, Moderately Sorted, Sub-Rounded, Clast Supported Fine Gravel to Large Cobble</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>Unit</td>
<td>Description</td>
</tr>
<tr>
<td>----------</td>
<td>-------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>0.0-0.33</td>
<td>HC1.1</td>
<td>Poorly Sorted, Silt Supported Matrix, Angular Coarse Gravel to Small Cobble Clasts, Reverse Grade, 2.5 Y 5/3, Light Olive Brown,</td>
</tr>
<tr>
<td>0.33-0.38</td>
<td>HC1.2</td>
<td>Massive, Well Sorted, Medium Sand, 2.5 Y 4/3 Olive Brown, Laterally Extensive</td>
</tr>
<tr>
<td>0.38-0.46</td>
<td>HC1.3</td>
<td>Massive, Well Sorted, Silt, 2.5 Y 5/3, Light Olive Brown, Strong Reaction to HCl, Cemented, Laterally Extensive</td>
</tr>
<tr>
<td>0.46-0.72</td>
<td>HC1.4</td>
<td>Poorly Sorted, Silt Supported Matrix, Angular Cobble to Pebble Basalt Clasts, Reverse Grade, 2.5 Y 4/3, Strong Reaction to HCl</td>
</tr>
<tr>
<td>0.72-0.79</td>
<td>HC1.5</td>
<td>Moderately Sorted, Fine Sand Supported Matrix, Angular Pebble Clasts, 2.5 Y 4/3, Stronger reaction to HCl than HC 9.3 and 9.4</td>
</tr>
<tr>
<td>0.79-0.825</td>
<td>HC1.6</td>
<td>Massive, Well Sorted, Fine Sand, 2.5 Y 3/3 (wet), Stronger reaction to HCl than HC 9.3 and 9.4, Dark Color From Very Fine Charcoal</td>
</tr>
<tr>
<td>0.825-1.22</td>
<td>HC1.7</td>
<td>Massive, Well Sorted, Very Fine Sand, 2.5 Y 6/2, Cemented, Reacts to HCl</td>
</tr>
<tr>
<td>1.22-1.47</td>
<td>HC1.8</td>
<td>Massive, Well Sorted, Very Fine Sand, 2.5 Y 5/3, Cemented, Does Not React to HCl,</td>
</tr>
<tr>
<td>1.47-4.37</td>
<td>HC1.9</td>
<td>Silt Supported Matrix, Angular Basalt Cobble Clasts, 2.5 Y 5/4, Light Olive Brown, Ungraded</td>
</tr>
</tbody>
</table>
Appendix D

Geochronologic Laboratory Data
Dr. Ugo Zotti  
Director, Accelerator Mass Spectrometry Lab  

13 May 2015  

Lori,  
Central Washington University  
400 East University Way  
Ellensburg, WA 98926  

Dear Lori,  

Your samples submitted for radiocarbon dating have been processed and measured by AMS. Following results were obtained:  

| DirectAMS code | Submitter ID | Δ14C (per mil) | Fraction of modern | Radiocarbon age BP | 1σ error BP | 1σ error  
|----------------|--------------|----------------|-------------------|------------------|-------------|----------  
| D-AMS 0191107 | 07/00414  | -17.1          | 98.36             | 1334             | 22               |           
| D-AMS 0191086 | 07/00414  | -17.9          | 73.21             | 2502             | 22               |           

All results have been corrected for isotopic fractionation with δ13C values measured on the prepared graphite using the AMS spectrometer. These δ13C values provide the most accurate radiocarbon ages but cannot be used to investigate environmental conditions.  

Best regards,  

Ugo Zotti


**TABLE 1. GLASS COMPOSITION OF THE HANSON CREEK TEPHRA**

<table>
<thead>
<tr>
<th>Oxide</th>
<th>Windingstad 071414-8</th>
<th>Windingstad 081314-1</th>
<th>Windingstad 070814-9</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>73.13(0.30)$^1$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>14.63(0.15)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>2.13(0.04)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.42(0.04)</td>
<td>biogenic</td>
<td>biogenic</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>4.69(0.24)</td>
<td>silica</td>
<td>silica</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>2.76(0.09)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>MgO</td>
<td>0.44(0.04)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CaO</td>
<td>1.61(0.06)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cl</td>
<td>0.20(0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total$^2$</td>
<td>100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of shards analyzed</td>
<td>17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Probable Source/Age</td>
<td>Mazama Climactic</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Date</td>
<td>6845 ± 50 BP</td>
<td></td>
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</tr>
<tr>
<td>Similarity Coefficient$^3$</td>
<td>0.99</td>
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<td></td>
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</tbody>
</table>

$^1$ Standard deviations in parentheses
$^2$ Analyses normalized to 100 weight percent
$^3$ Borchardt et al. (1972) J. Sed. Petrol., 42, 301-306