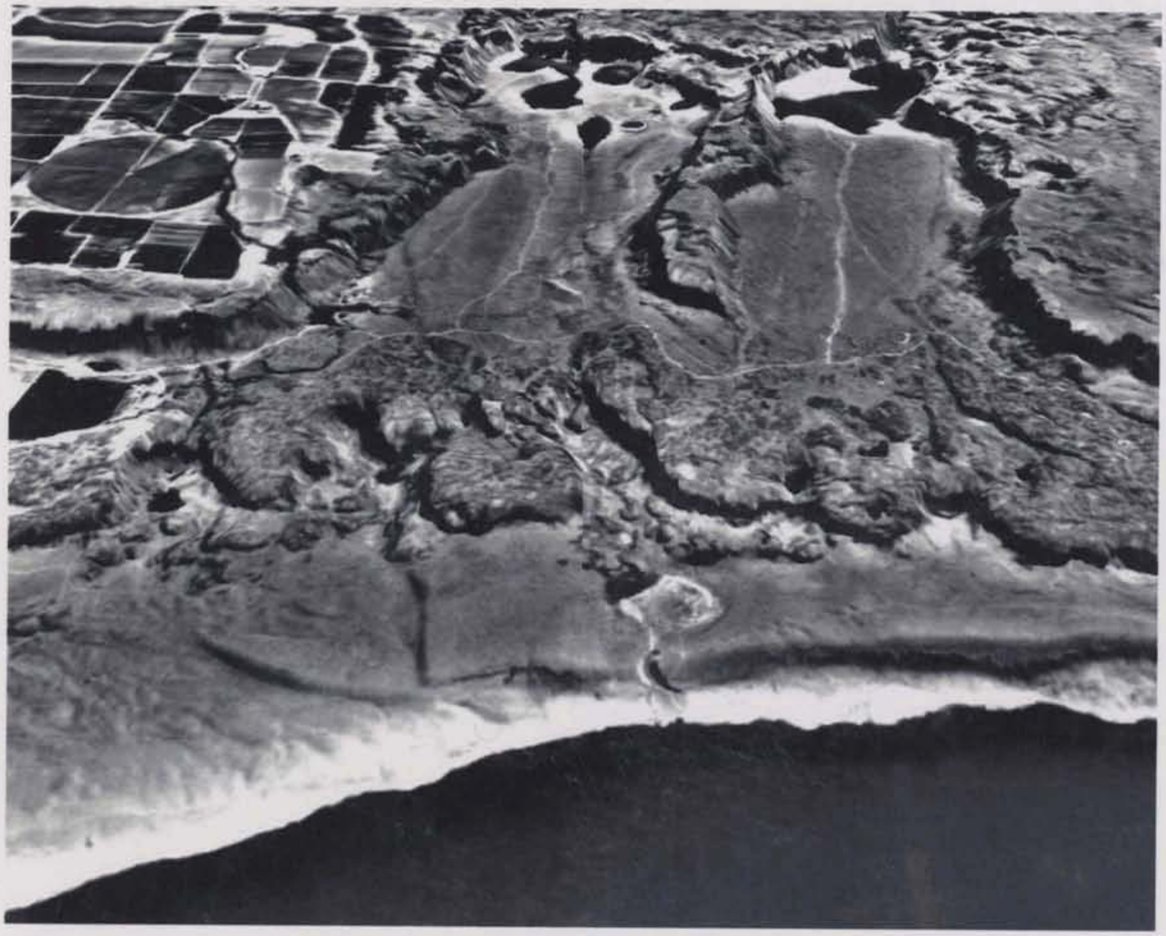
The Geomorphology of Potholes Coulee, Quincy Basin, Washington



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July 21, 2003

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Abstract

The Potholes Coulee is located on the western margin of Quincy Basin, Washington about 15 miles southwest of Quincy. Potholes Coulee has been shaped by various geomorphic processes and agents since the Miocene epoch creating a unique landscape. The bedrock of the basin is Miocene Columbia River flood basalt folded by Pliocene tectonic forces and shaped by catastrophic flooding events of Pleistocene era (Bretz, 1923). Quincy Basin was a depositional (fluvial and eolian) and erosional region of the Missoula floods during the late Pleistocene epoch (Bretz, 1928). Miocene Columbia River Basalts were folded, and then eroded by Pleistocene glacial outburst flood events. The western margin of Quincy Basin has three eroded outlets through Babcock/Evergreen Ridge. The Babcock and Evergreen Ridges are separated by Potholes Coulee. Potholes Coulee is a relict landform characterized as a headwardly eroded cataract. Grolier (1965) describes the coulees as existing prior to the Missoula Floods based on the flood gravels indicating a western source in Quincy Basin. The cataracts contain late Pleistocene Missoula flood crystalline and basalt gravels as various landforms. The flood sediments are capped by a weathering mantle, eolian deposits, and mass wasting debris. The Columbia Basin Irrigation Project during the 1930's enabled increased settlement in the area adding humans as key geomorphic agents. In the early 1950's, Ancient Lake cataract was flooded, filling the cataract with a temporary lake, leaving a rime indicating the past shoreline.

Introduction

Potholes Coulee has been shaped by various geomorphic processes and agents since the Miocene epoch creating a unique landscape. The bedrock of the basin is Miocene Columbia River flood basalt folded by Pliocene tectonic forces and shaped by catastrophic flooding events of Pleistocene era (Bretz, 1923). Quincy Basin was a depositional and erosional region of the Missoula floods during the late Pleistocene epoch (Bretz 1928). After nearly a century of research, many questions remain regarding the geomorphology of the Quincy Basin, and specifically the Potholes Coulee (Figure 1).

The primary focus of this paper is to describe the geomorphology of the Potholes Coulee and adjacent Babcock Bench, as well as to provide geomorphic context to late Pleistocene sloth remains unearthed at Bishop Springs (Figure 2). Secondly, I will describe future research possibilities in the area. The overall intention of this study is to provide further insight to the geomorphology of Quincy Basin and the Channeled Scablands.

Study Area

The Potholes Coulee is located on the western margin of Quincy Basin about 15 miles southwest of Quincy (Figure 1). The Potholes Coulee is situated 134 meters above and 1.5 kilometers east of the Columbia River in sections 7, 8, 9, 18, 17, 16, T. 19 N., R 23 E., W.M., of the Babcock Ridge, Washington United States Geological Survey (U.S.G.S.) 7.5 minute quadrangle. The rim elevation of the coulee varies from 411 to 320 meters elevation with the floor of the cataract varying from 250 to 308 meters elevation. The Potholes Coulee consists of double horseshoe cataracts bisecting Babcock Ridge and

Evergreen Ridge along the western margin of the Quincy Basin (Figure 2). The rim of the cataracts opens to the west onto the Babcock Bench above the Columbia River.

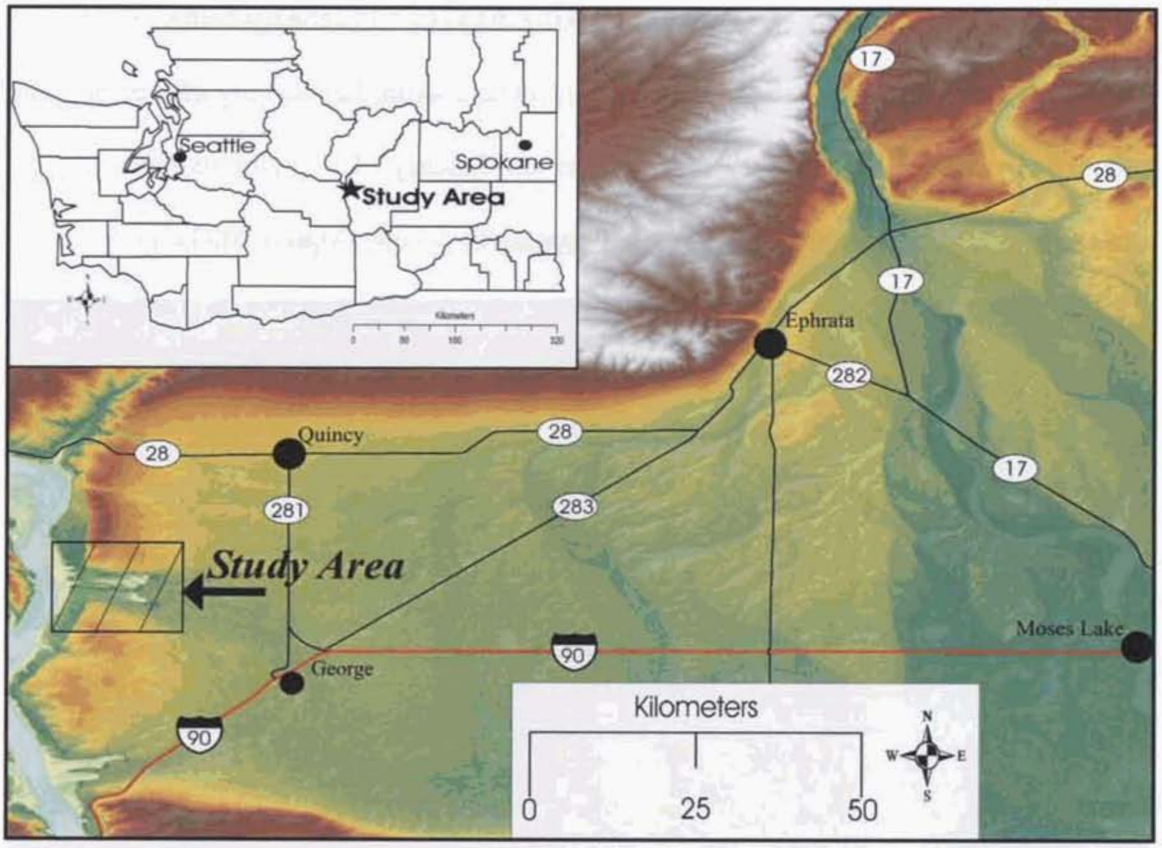


Figure 1. Location map, the study area is located ~15km northwest of George and ~20km southwest of Quincy. (Map derived from U.S.G.S. DEM)

The bedrock consists of the Columbia River Basalt Group (CRBG's) with diatomite and sandstone interbeds. The Rosa flow, Babcock Bench flow and two Ginkgo flows of the Frenchman Spring member of the Wanapum basalt group and Vantage Sandstone are exposed (R.D. Bentley, personal communication, May 2003) to the level of the Babcock Bench. The Babcock Bench consists of the Grande Ronde N2 group of the CRBG's. Loess and cover sand caps glacio-fluvial deposits flooring the cataracts. Brown tuffaceous sand and platy caliche capped by loess cover the Babcock Ridge and Evergreen Ridge (Grolier, 1965).

The region is characterized as a semi-arid, continental setting. At Quincy, from 1941-2002, the maximum average annual temperature was 17° C and the minimum average annual temperature 3° C; with July being 30.1° C, and January being -7° C. The average annual precipitation was 22.3 centimeters, with the majority of precipitation occurring in September, November, December and January. The region receives an annual average of 33 centimeters of snow (www.wrcc.dri.edu, March 2003).

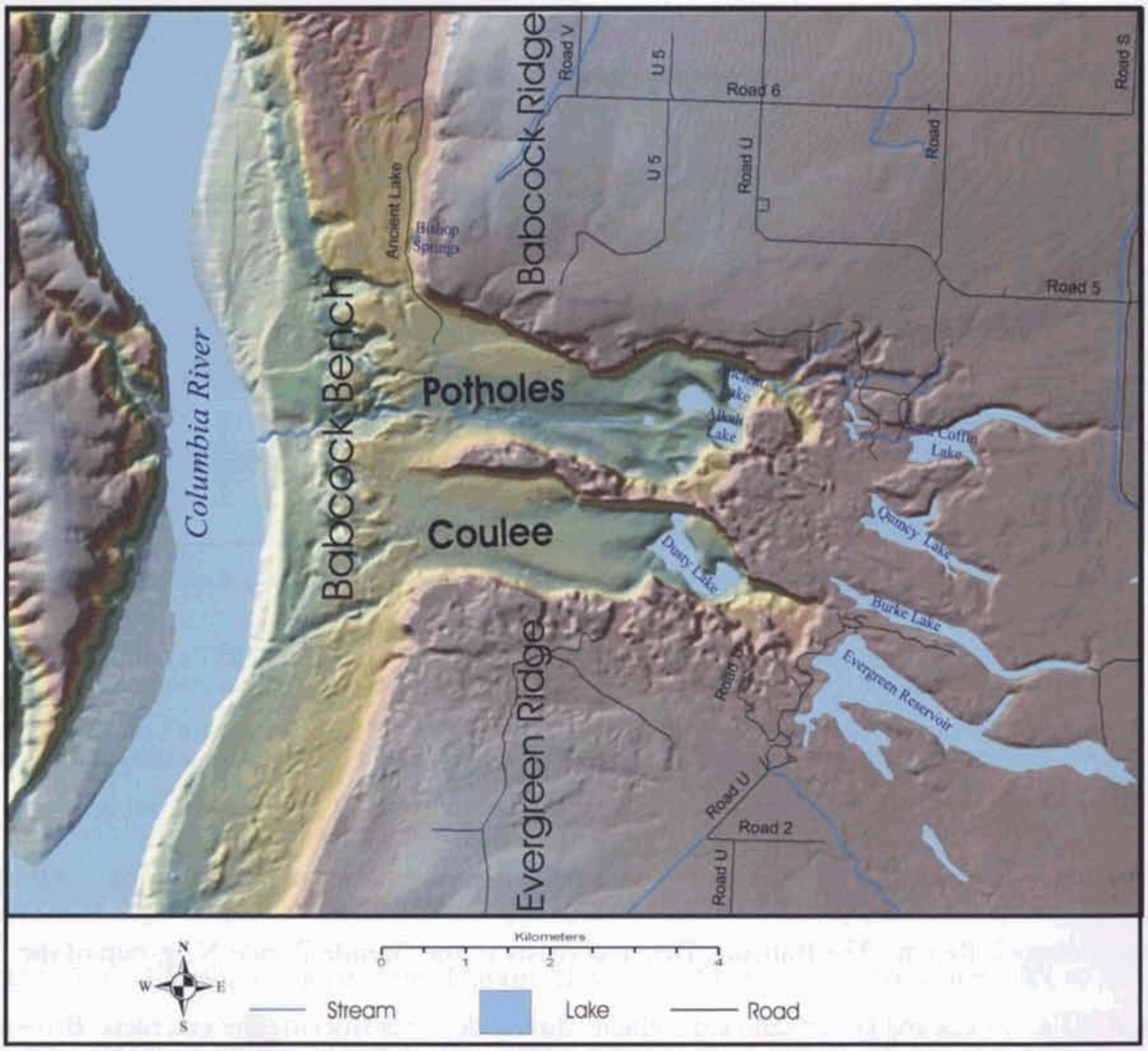


Figure 2. Physiographic map showing Potholes Coulee, located on the western margin of Quincy Basin, east of the Columbia River. Note double horseshoe shape with interfluve separating the two cataracts. (Map derived from U.S.G.S. DEM)

Five well-drained Aridisols formed on the diverse terrains of Potholes Coulee. Gentry (1984) describes the soils as follows:

1. Ephrata sandy loam: a sandy-skeletal, mixed, mesic, Xerollic Camborthid soil; found on 5-10% slopes, formed on sub-fluvial gravels at the mouth of the Ancient Lakes cataract.

2. Malaga cobbly sandy loam: a sandy-skeletal, mixed, mesic Xerollic Camborthid soil; found on 0-15% slopes, formed on the sub-fluvial bar deposits within the Ancient Lakes cataract.

3. Malaga very stony sandy loam: a sandy-skeletal, mixed, mesic Xerollic Camborthid soil; found on 0-35% slopes, formed on sub-fluvial bar deposits within the Dusty Lake cataract.

4. Starbuck-Bakeoven-Rock outcrop complex: a loamy, mixed, mesic, Lithic Xerollic Camborthid soil; found on 0-45% slopes, formed on basalt bedrock along Babcock bench and Evergreen Ridge.

5. Starbuck-Prosser complex: a loamy, mixed mesic, Lithic Xerollic Camborthid soil; found on 0-25% slopes, formed on basalt along the north/north east rim of Potholes Coulee.

The vegetation is primarily bluebunch wheatgrass, cheat grass, with big sage brush, rabbit brush, knapweed, and herbaceous shrubs.

Historic land uses include human habitation, cattle range, and limited agriculture. After the implementation of the Columbia Basin Irrigation project in the early 1930's, hay farming and subsequently orchards and various crops became a major land use on Babcock Bench. At present, the Potholes Coulee is a Washington State Fish and Wildlife managed area and the majority of land use within the study area is recreational (equestrian, biking, hiking, and fishing).

Background

Miocene-Pliocene Epochs

Between 6 m.a. to 17 m.a. many flows of Columbia River Basalt Group magmas flooded eastern Oregon and southeastern Washington. They originated from fissures in eastern Oregon and southeastern Washington. The flows are characterized as having a blocky entablature cap on colonnade with a pillow structured base. The flows are intermittently bedded with Ellensburg Formation detritus and diatomaceous sediments (Mackin, 1961; Tolan et al, 1989). The CRBGs were then folded from the west then south by Pliocene tectonic forces creating ridges and basins. Subsidence of the plateau, uplift of the Cascade Range, and plunge associated with regional folding are three possible causes of deformation. The Columbia River continued flowing through the region but was diverted at different locations and times. The structural Quincy Basin was formed through these events and is bound to the north by the Beezly Hills, the west by Babcock Ridge and the south by the Frenchman Hills (Mackin, 1961; Watters, 1989).

The Columbia River flowed along the western margin of the Columbia basin in its present course eroding through the CRBGs creating Babcock Bench. Two separate occasions of rising anticlines from the tectonic forces from the south were thought to temporarily dam the Snake River and Columbia River creating Lake Ringold (Newcomb 1958). The impounded Columbia River left fluvio-lacustrine deposits, known as the Ringold Formation, from south in the Pasco Basin to north along the rim of the Babcock/Evergreen Ridge (Grolier and Bingham, 1978).

Pleistocene Epoch (The Channeled Scablands)

The Channeled Scablands of the Columbia Basin are relict landforms of outburst floods from Late Pleistocene glacially dammed Lake Missoula (Bretz, Smith and Neff; 1956). Many huge catastrophic outburst floods (jokulhlaups) from Lake Missoula exceeded the capacity of the existing drainage system of the Columbia River with the flood water flowing up to 2,500,000 m^3 through the Columbia Basin (Waitt, 1985). More then 30 floods occurred between 12,700 and 15,300 years before present (y.b.p) based on tephrichronology and radiocarbon dating (Waitt, 1985). The flood waters flowed across north Idaho into north Washington before encountering the Okanogan lobe of the Cordilleran Ice Sheet which diverted the waters south into the Grand Coulee and into the Quincy Basin.

The water pooled in Quincy Basin before exiting through four outlets. There were three outlets on the western margin of Quincy Basin (Crater Coulee, Potholes Coulee, and Frenchman Coulee) and one to the southeast (Drumheller Channels) at the eastern margin of the Frenchman Hills (Figure 3) (Bretz, 1930). When the Okanogan lobe was not in place, the flood waters flowed down the Columbia River drainage and into Quincy Basin via Crater Coulee and Potholes Coulee (Bretz, Smith and Neff; 1956). During intervals of lower magnitude floods, the waters flowed out the more hydraulically favorable Drumheller Channels to the east (Bretz, 1928).

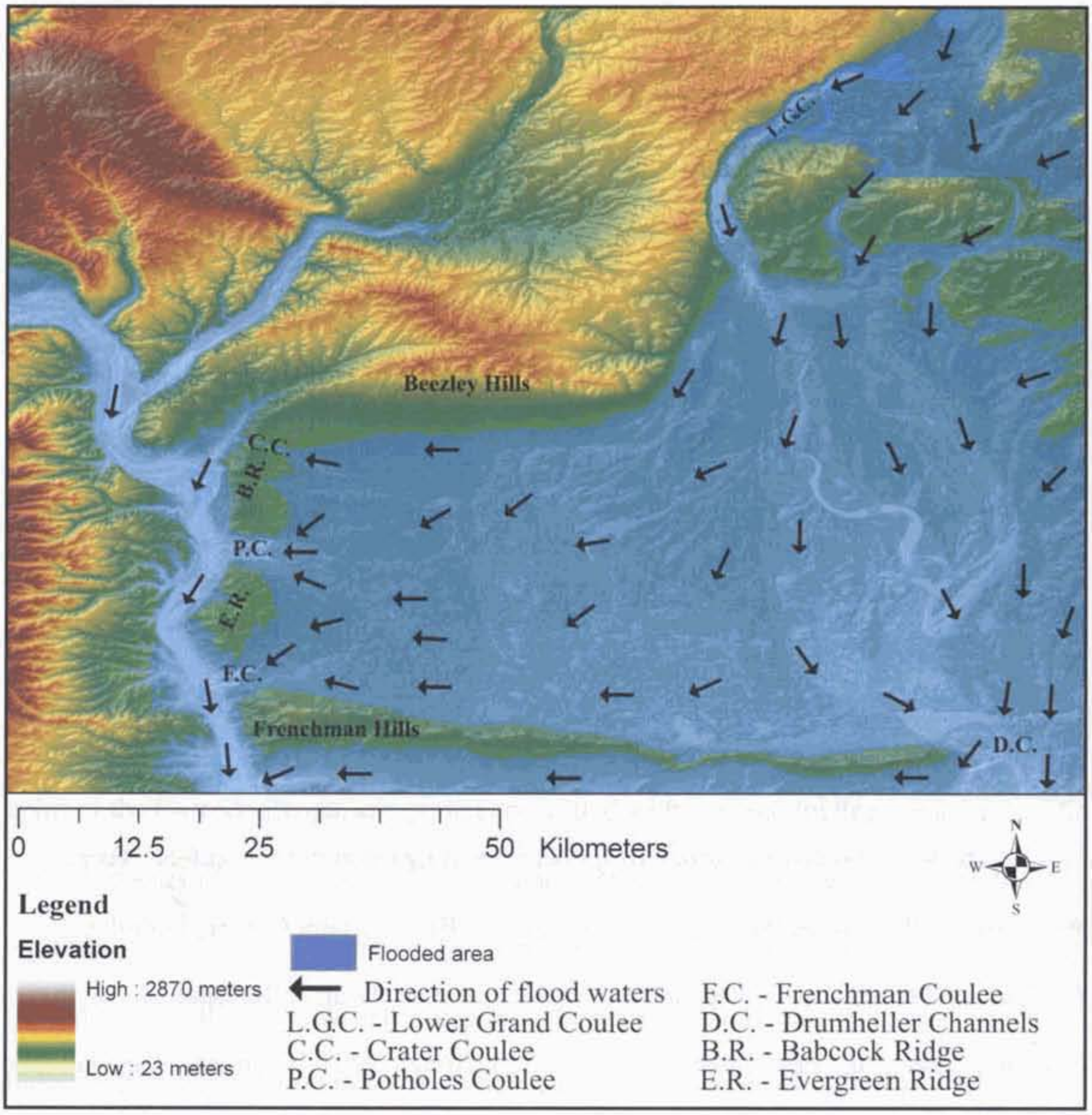


Figure 3. This is an inundation model of Quincy Basin showing the extent of the greatest floods from Lake Missoula. The high-water mark in Quincy Basin was 409 m adapted from Baker (1973). (Map derived from U.S.G.S. DEM)

The catastrophic flooding created an amazing anastomising channel complex in the bedrock (Bretz, 1923). The abandoned cataracts are described as resulting from sub fluvial plucking of the columnar basalt by vortices and transporting the blocks downstream by the extremely competent flow during the largest flood events (Bretz 1930; Baker 1974). The eroded bedrock features are divide crossings, coulees, buttes and mesas of basalt and kolks (i.e. eroded hollows). Loess was eroded creating streamlined "loess islands". The floods are further evidenced by sub-fluvial mega-bed forms, such as various bars and giant current dunes (Bretz, 1927). After flowing through Quincy Basin, the waters ponded behind a hydraulic constriction formed at Wallula Gap in the Horse Heaven Hills forming temporary Lake Lewis with a depth of 350 m. O'Connor and Baker (1992) calculated the flow through Wallula Gap at 10 million m^3/s^{-1}, a discharge greater than any rivers or flooding events previously or since. Waitt (1995) notes smaller flooding events down the Columbia post dating late Pleistocene Lake Missoula Floods.

Methods

This research was accomplished through document review, interviews, Geographic Information System (GIS) techniques, airphoto analysis, and field work. I first reviewed past literature that describes regional and local geomorphic processes and factors, landforms, historic use, and recent occupation to better understand the parameters of the study area. I interviewed a resident of more than 50 years, Dave Bishop, to understand the role of recent human occupation at the site. The spatial and temporal parameters for the project were decided with understanding the past research.

1:12,000 1949 and 1961 U.S. Department of Agriculture and 1996 1:24,000 U.S.G.S. digital orthophoto quads were compared to gauge the rate of environmental change since the Columbia Basin Irrigation Project. I then used U.S.G.S. 1:24,000 topographic maps, airphotos, and ArcGIS by Environmental Systems Research Institute (ESRI) to identify and analyze key landforms and plan field trips for field checking of those features.

Field observations and field checking of observed remotely sensed data was completed from July, 2002 – May, 2003. GPS techniques were used to locate various attributes to better interpret landforms in the field such as chord length on possible sub-fluvial bedforms. Once identified, the various geomorphic agents and resulting land-forms were mapped onto copied airphotos and topographic maps in the field. In the C.W.U. GIS lab the measured observations were entered into the computer by downloading GPS coordinates into ArcGIS and digitizing field observations and attributes as polygons in ArcGIS. The polygons were then used in slope process modeling using ESRI Spatial Analyst to better understand the processes that may have occurred on the slopes since initial deposition. Comparisons between the computer's modeled predictions versus field observations were made. Observed historic and present geomorphic processes and factors were mapped using ESRI ArcGIS.

The various geomorphic processes and factors were categorized in a relative temporal and spatial hierarchy beginning with the formation of the primary landform (Potholes Coulee) of the study area and finishing with the recent advent of humans to the region. This classification is based on the order of landform origins derived from an application of Steno's Principles and observed physical evidence.

Geomorphology

Fluvial Features

Potholes Coulee: Grolier (1965) describes Potholes Coulee as a sag in the Babcock/Evergreen anticline that was subsequently modified by Pleistocene flood waters flowing down Grand Coulee into Quincy Basin. These flood waters then flowed out through the sag rejoining the Columbia River. Potholes Coulee, similar to Niagara Falls, formed by head-ward erosion by sub-aqueous undercutting then transport of sediment down flow as waters from the Quincy Basin flowed through the breech to rejoin the

Columbia River (Figure 3) (Bretz, 1930; Grolier, 1965; Baker, 1973). The fluvial event, that formed Potholes Coulee, appears to be ephemeral as there are no visible channels connecting the mouth of lower Grand Coulee (northeast) to Potholes Coulee in the southwest. The events attributed to the formation of the landform are the late Pleistocene Lake Missoula Floods (12,700-15,300 ybp) (Bretz, 1930).

George Gravels and George Channel: Potholes Coulee appears to have an origin much earlier then the late Pleistocene as older, extrabasinal, flood sediments (George Gravels) are found in a channel (George Channel) trending to the southeast from Potholes Coulee into Quincy Basin. Though, it is evident the cataract formed as waters flowed down Grand Coulee into Quincy Basin and out the Potholes Coulee from the northeast, probably occurring as early Pleistocene flood waters. Grolier (1965) describes the coulees as existing prior to the late Pleistocene Missoula Floods based on the flood gravels indicating a western source in Quincy Basin (Bretz, Smith, and Neff, 1956). Bretz (1969) noted the massive capped flood sediments (the George Gravels) flowing up the Crater Coulee and Potholes Coulees as pre-Wisconsin (80,000 ybp) flood deposits (Figure 4).

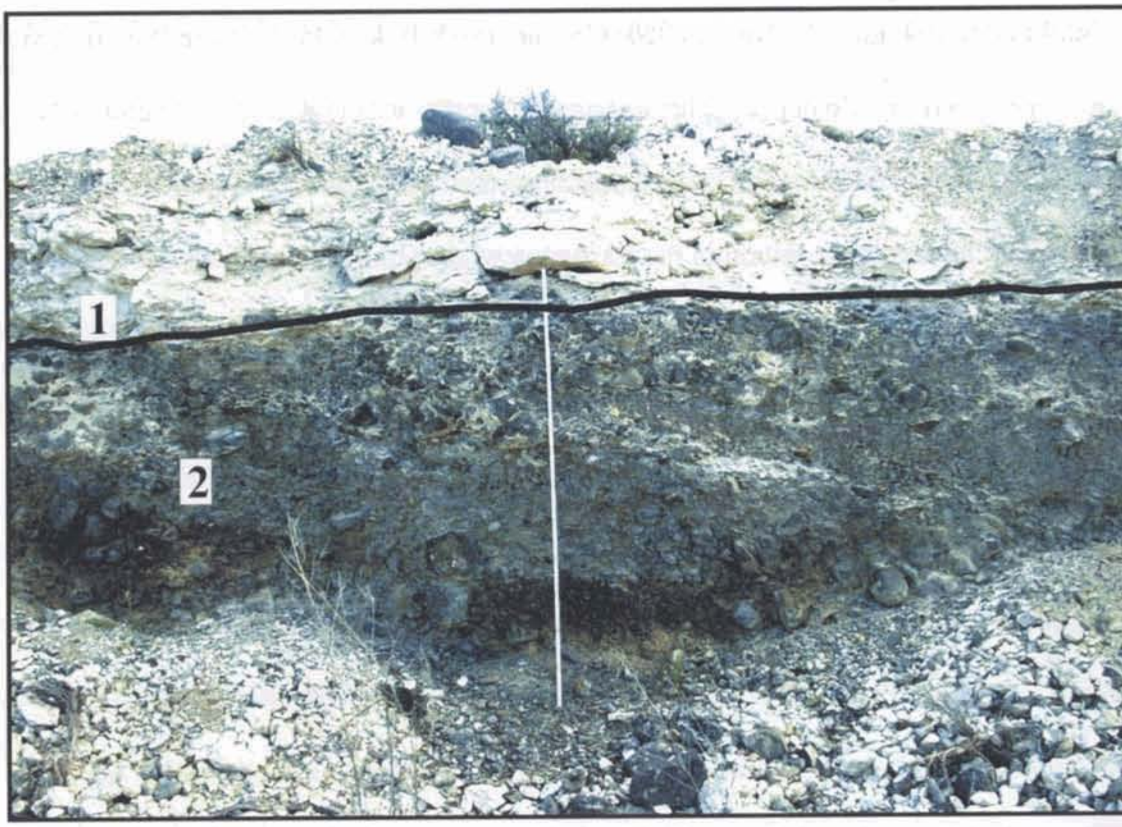


Figure 4. Oblique ground view of George Gravels at gravel pit near George, Washington. Notations: 1) George Gravels are capped by a 1.5m B/K horizon that strongly reacted to the presence of 10% HCl. 2) Clast supported George Gravels

The George Gravels are a conglomerate composed of extremely weathered basalts with palagonite, gneiss, schist, quartzite and granite cobbles with imbrications indicating a western source (Figures 5 & 6). The gravels are capped by a 1.5-m of calcrete (Baker, 1973; Patton and Nummendal, 1978). Bjornstad, Frecht and Pluhar (2001) recognize the George Gravels as similar in age to the Old Maid Coulee gravels, having a reverse magnetic polarity indicating an early Pleistocene (Brunhes-Matuyama, 780,000 ybp) age. Though the George Gravels have imbrications indicating a western source it is evident they post date the cataract's formation by early Pleistocene flood waters issuing from Grand Coulee.

Figure 5. Clast supported George Gravels. The gravels have western source imbrications and are well cemented together. Note the caliche on the bottom of the clasts indicating a prolonged period of stability.

Figure 6. An example of extremely weathered schist removed from matrix in-situ in the George Gravels.

The George Channel has a northwest to southeast trend coming from the head of the Potholes Coulee to the southeast and contains the George Gravels (Figure 7). The cataracts had to be formed by waters flowing from the northeast prior to genesis of the channel and deposition of the George Gravels. The implications are intriguing but are in need of detailed research on the George Gravels and the sediments within the Potholes Coulee. A source for flood waters competent enough to create the landform is in question as it predates the late Pleistocene Glacial Lake Missoula. Alternate water sources could be paleo-glacial lakes since obliterated by subsequent glacial advances, or multiple jokulhlaups (sub-glacial outburst flood) from Okanogan region of British Columbia (Shaw et. al 1999; Lesemann and Shaw 2000a, 2000b; Mate and Levson 2000).

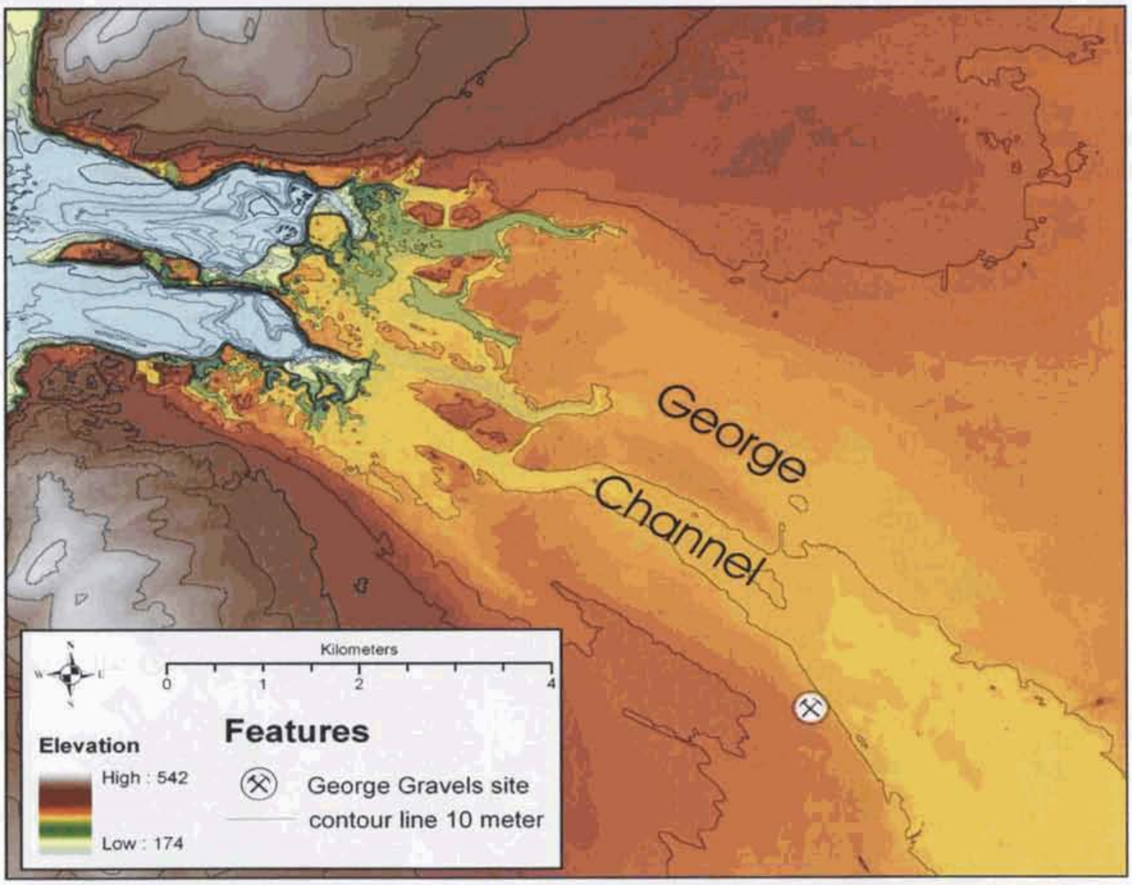


Figure 7. Map view of George Channel showing the George channel and the George Gravels. Note the direction of channel trending northwest to southeast and location of the George Gravels. (Map derived from U.S.G.S. DEM)

Basin and Butte Topography: Basin and butte topography is a term describing generic scabland topography consisting of various scales of eroded landforms resulting from regional catastrophic flood activities. This topography was created by flood waters abrading and plucking less resistant bedrock leaving terrace, channel, kolk, and butte landforms that range in size from <1 meter to hundreds of meters (Figure 8). Buttes are localized areas of sharp relief that culminate in a flat "table" top surface that ranges from a few meters to thousands of meters in volume. Basins are eroded anastomising channels, terraces or kolks.

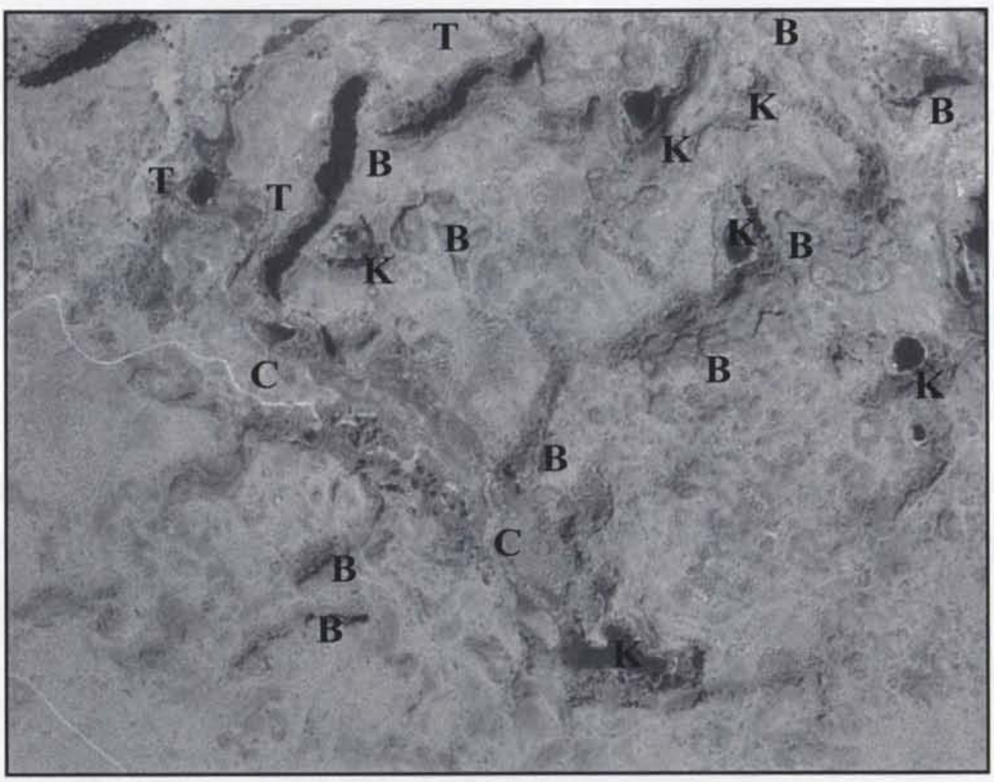


Figure 8: A generic annotated map view of basin and butte topography. Basin (local areas of low elevation): T - terrace, C – channel, K – Kolk. B - Butte (local areas of higher elevation). (1961 U.S.D.A airphoto)

Stripped structural bedrock terraces are formed at the heads and margins of the cataracts by turbulent waters through sub-aqueous undercutting, vortices plucking then transport of the sediment down flow by the extremely competent flow of catastrophic flood waters. The colonnades of the basalt are plucked leaving the more resistant entablature cap of the lower flow to form long, broad, planar terraces (Figures 9 & 10). Striped structural bedrock terraces indicate an extremely high magnitude and competent diluvial origin. The features vary in area from $33{,}150\text{m}^2$ - $529{,}200\text{m}^2$, and are 15 m - 67 m above the cataract floor and are up to 53 m deep. They are capped by a shallow to well developed weathering mantle and loess (5 cm to > 2 meters). Some terraces are well sheltered from wind creating eolian deposition hollows which support a variety of flora and fauna. Some of the terraces do not appear to have been affected dramatically by the late Pleistocene floods, as indicated by the development of the weathering mantle and lichen growth on exposed bedrock.

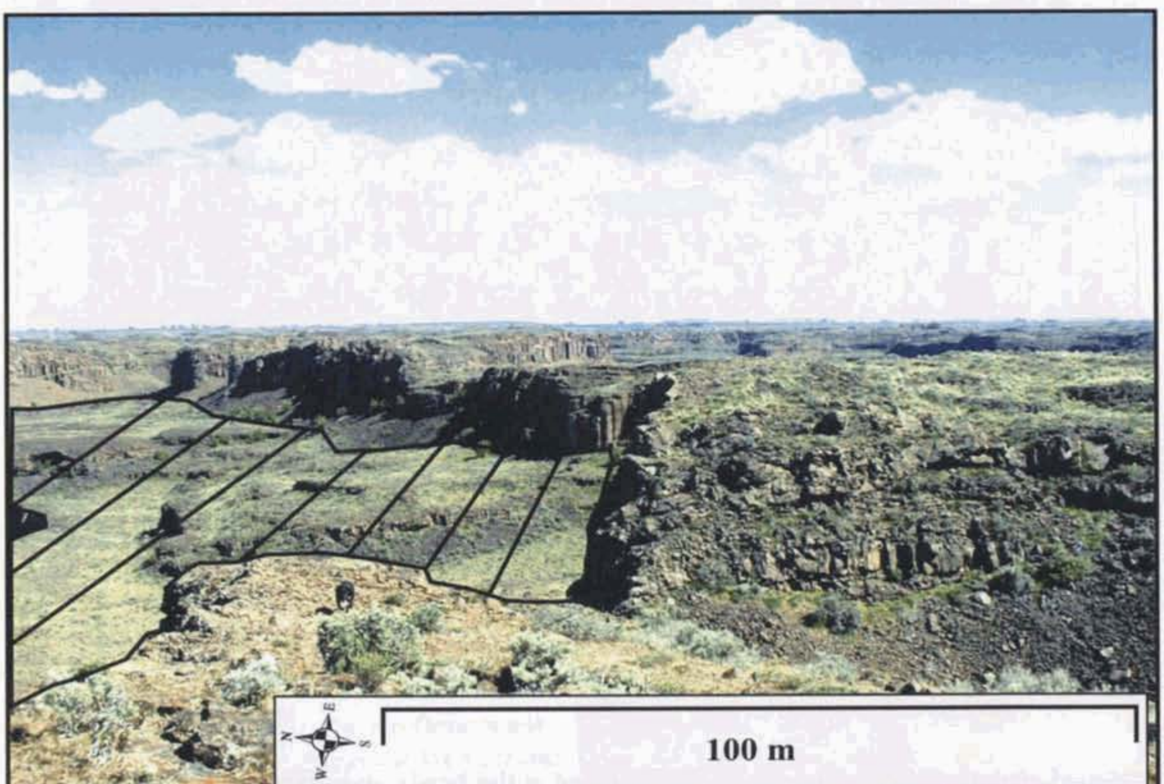


Figure 9: Oblique ground view from west of stripped structural bedrock terrace, identified by cross-hatch, 40 meters above cataract floor at the head of Ancient Lake cataract along the southeast rim of the cataract.

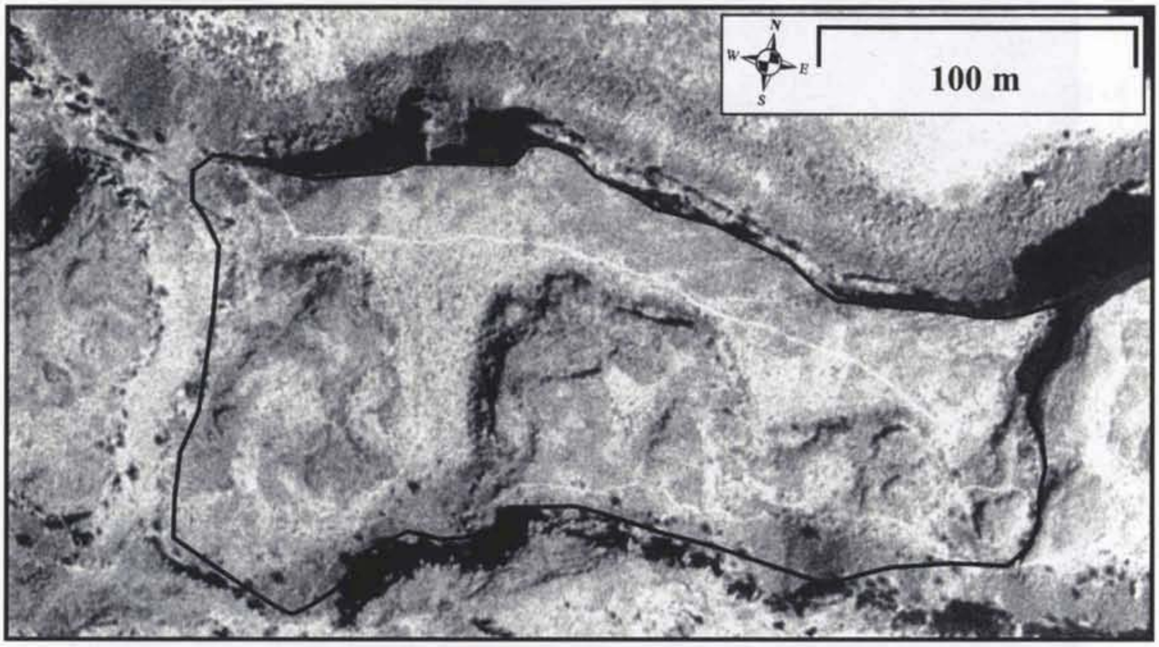


Figure 10: Map view of striped structural bedrock terrace of same terrace in Figure 9, identified by outline, 40 meters above cataract floor at the head of Ancient Lake cataract along the southeast rim of the cataract. (1996 U.S.G.S. digital orthophoto quad)

Kolks: Kolks are formed in turbulent waters by sub-aqueous vortices exploiting localized weaknesses in the entablature cap creating "pits" (Baker, 1973). Kolks are similar in morphology to plunge pools, save in the study site, they are located in areas up and down flow from the cataracts heads. Kolks formed in bedrock indicate an extremely high magnitude and competent flow at time of origin (Baker, 1973). Some of the larger kolks (diameter > 10m, depth > 10m) cut through the entablature cap, then into the colonnade below and have potential to be depositional hollows that can provide datable material in form of tephra, organic material and loess (Figures 11 & 12). The kolks on the interfluve between the cataracts are formed on different surfaces with some being breeched during cataract formation.

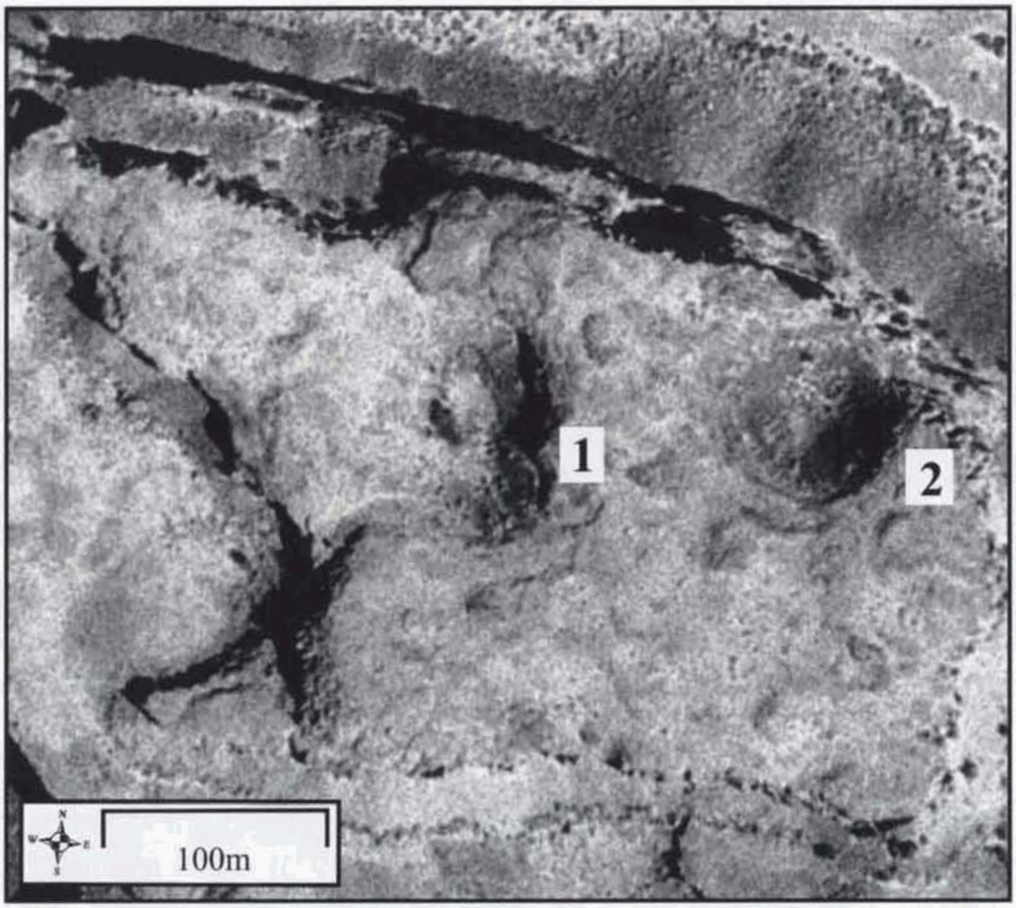


Figure 11. Map view of kolks located on the interfluve between Ancient Lake and Dusty Lake cataracts. Notations: 1) the same kolk as in Figure 12. 2) Breeched kolk on Ancient Lake side of interfluve. (1996 U.S.G.S. digital orthophoto quad)

Figure 12: Oblique ground view of a kolk (1) located on the interfluve between Ancient Lake and Dusty Lake cataracts. This kolk is >40 m in diameter and > 20 m deep.

Plunge Pools: Plunge pools formed down flow at the heads of the cataracts as a result of sub-fluvial erosion and transport of sediment or bedrock at the base of waterfalls (Figures 13 & 14). The plunge pools within the heads of the Ancient Lake and Dusty Lake cataracts are formed in bedrock, though there is a "misplaced" plunge pool near the mouth of the Ancient Lake cataract that formed early in the cataract formation. The plunge pools generally have bars mantle the plunge pool floor, as well as, extending down stream from them. The plunge pools in the heads of the cataract contain water from the Columbia Basin Irrigation Project; having an elongated to circular morphology with the long axis indicating direction of flow, and no distinct volume. Plunge pools illustrate the fluvial origin by which Pleistocene flood waters once flowed through these cataracts before rejoining the Columbia River.

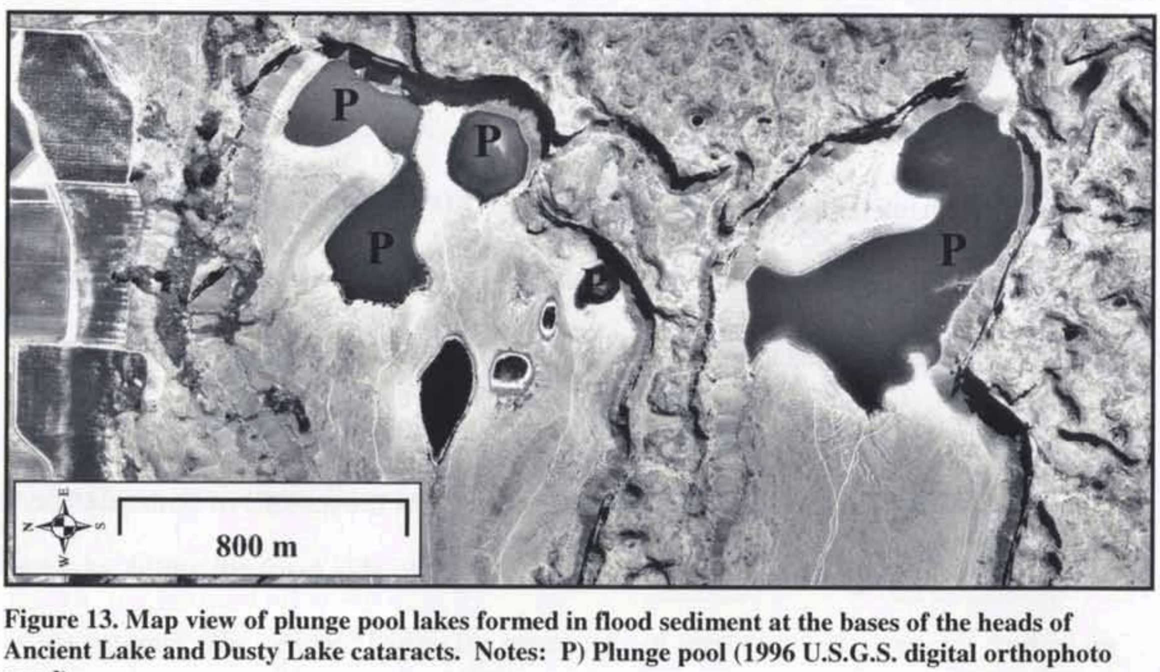


Figure 13. Map view of plunge pool lakes formed in flood sediment at the bases of the heads of Ancient Lake and Dusty Lake cataracts. Notes: P) Plunge pool (1996 U.S.G.S. digital orthophoto quad)

Figure 14. Mosaic oblique ground view of plunge pools located at the heads of Ancient lake and Dusty Lake cataracts. Photos were taken from the interfluve between the two cataracts.

Bars: The cataracts are floored by glacio-fluvial deposition with bar morphology. A bar is a streamlined deposition pointing in the direction of flow. A fosse, an elongate, eroded hollow next to the cataract wall, forms where water depth, channel topography and hydraulics allow for deposition of sediment. . The bars are classified based on morphology and depositional location. The bars of the study site are categorized as: 1) crescent-point bar, 2) pendant bar, and 3) expansion-longitudinal bar (Waitt, 1994).The bars consist of a mixed lithology of sub-rounded to angular sand and cobble sized basalt, quartzite, schist, gneiss, rip-up clasts of calcrete, calcrete coated basalt, petrified wood, palagonite clasts with the mode being basalt. There are also angular basalt boulders with an intermediate diameter >1 m.

Crescent–point bars, similar to point bars in morphology and deposition, form on the lee side of a bend in the channel, with or without an obstruction or a slowing of flow (Waitt 1994). Great crescent bars rising more than 30 meters above the Babcock Bench and more then 720m long formed on the southeast edges of the mouths of both cataracts of Potholes Coulee (Figure 15).

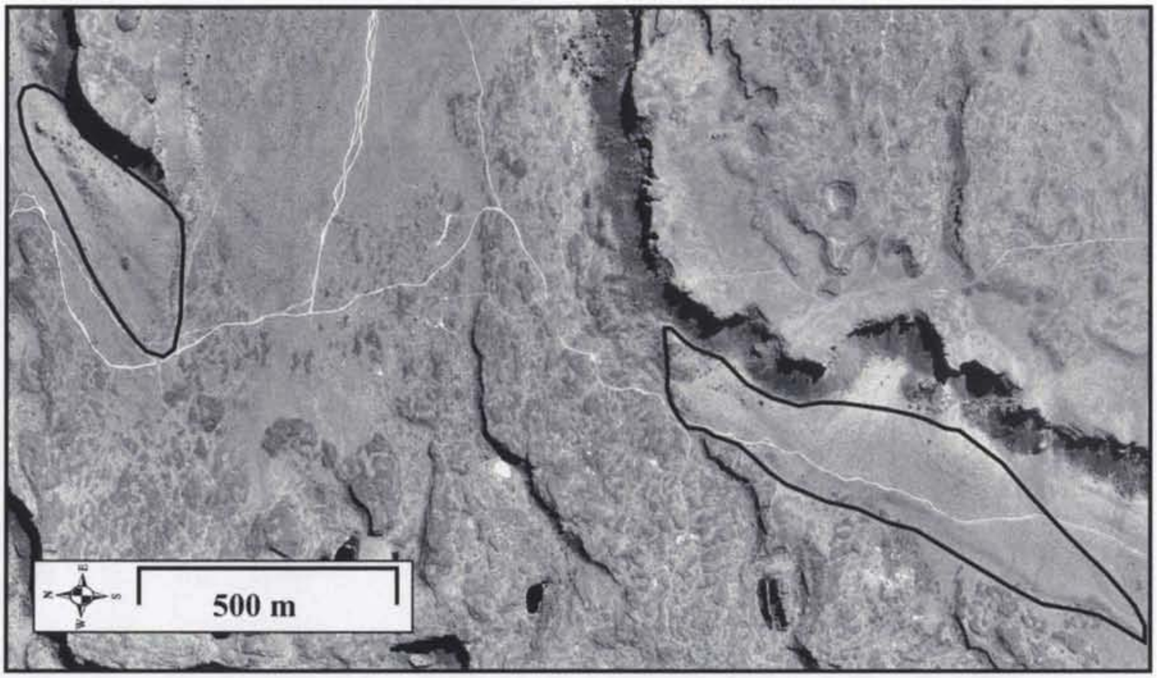


Figure 15. Map view of crescent-point bars on the southwest edge of the mouths of Ancient and Dusty Lake cataracts, indicated by outline. (1996 U.S.G.S. digital orthophoto quad)

Pendant bars form on the lee side of an obstruction or spur on a channel wall extending down current and are named for the way a pendant hangs from one's neck (Waitt 1994). Pendant bars have formed along the north and south in the Ancient Lake Cataract and north side of the Dusty Lake cataract. The bar on the north side of the Ancient Lake cataract rises >30m above the cataract floor and is more then 2.25 km long with talus partially to completely filling the fosse side (Figures 16 & 17). Further, the bar was reworked to form plunge pools at the head of the cataract. The bar along the south wall of the Ancient Lake cataract experienced 3 bar building events evidenced by three pronounced "terrace like" features on the north side of the bar. This bar complex rises >30m above the cataract floor and is more then 1.25 km long with a mass wasting block and talus filling the fosse side of the bar and is reworked to form plunge pools at the head of the cataract. The pendant bar on the north side of the Dusty Lake cataract formed on the down current side of a channel spur and rises >15m above the cataract floor and is more then 1 km long with talus partially filling the fosse side of the bar.

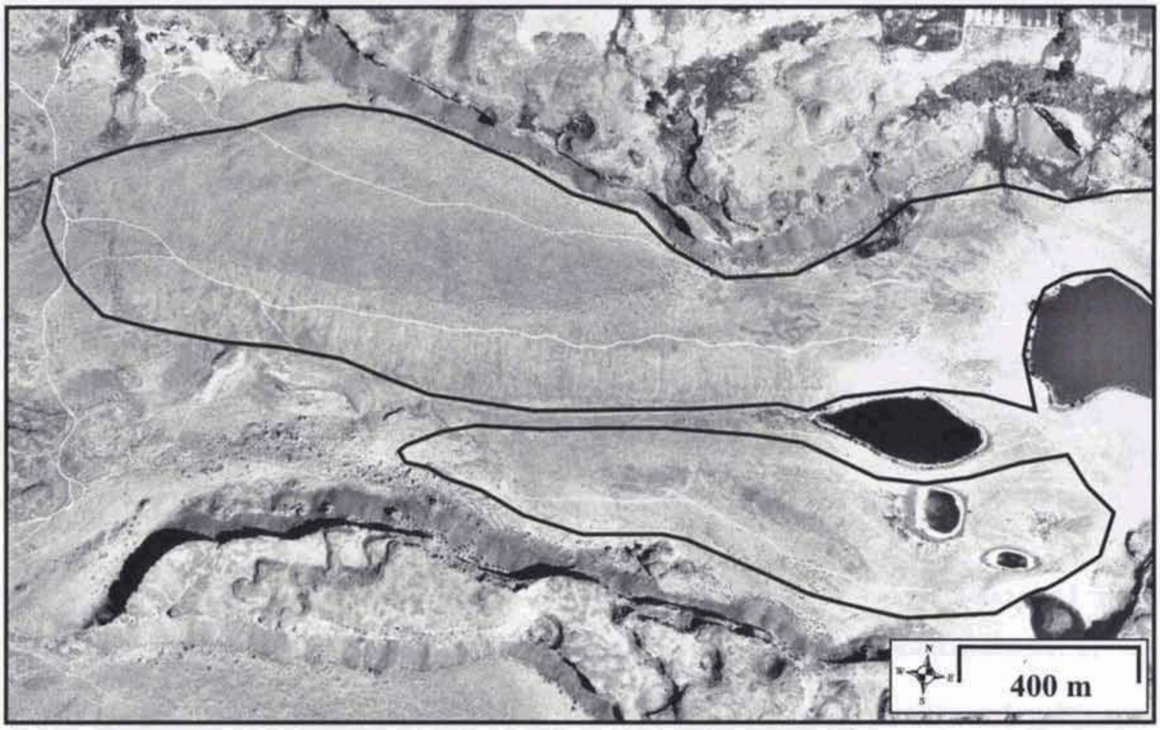


Figure 16. Map view of pendant bars in Ancient Lake cataract, indicated by outline. The pendant bar on the north side of the cataract is 2.25 km long, and the pendant bar on the south side is 1.25 km long. (1996 U.S.G.S. digital orthophoto quad)

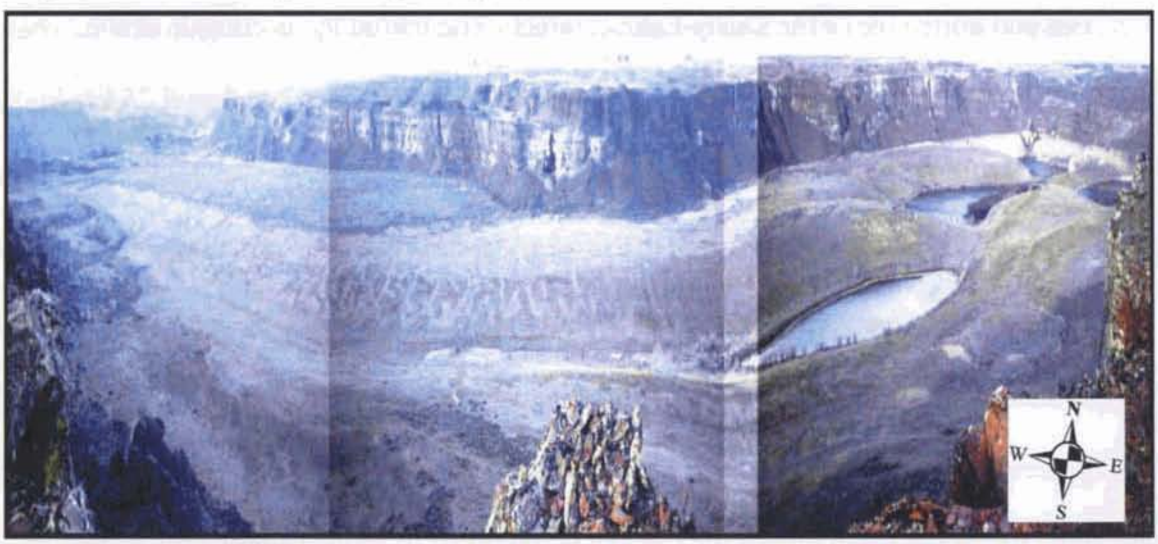


Figure 17. Mosaic oblique ground view of pendant bar along north side of the Ancient Lake cataract taken from interfluve to the south. Note current dune train on the south side of the bar, evaporite "ring", and plunge pools in the head of the cataract to the east.

Expansion/longitudinal bars are formed in side channels or mid-channels with or without obstruction or channel widening (Waitt 1994). The expansion/longitudinal bar in Dusty Lake Cataract formed at a widened section mid-channel. This bar rises >10m above the cataract floor and is more then 2 km long with talus partially filling the fosse sides and a plunge pool carved in to it at the head of the cataract (Figure 18).

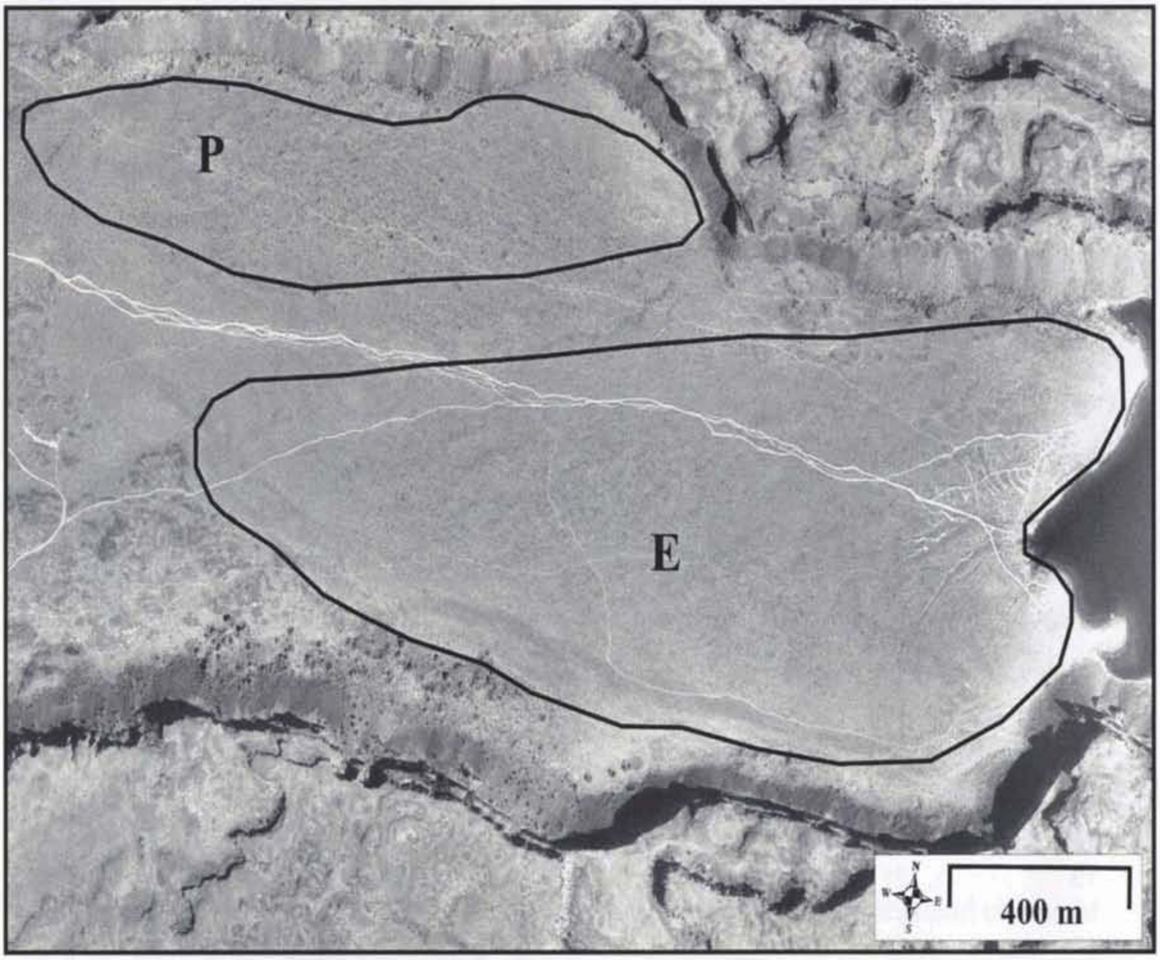
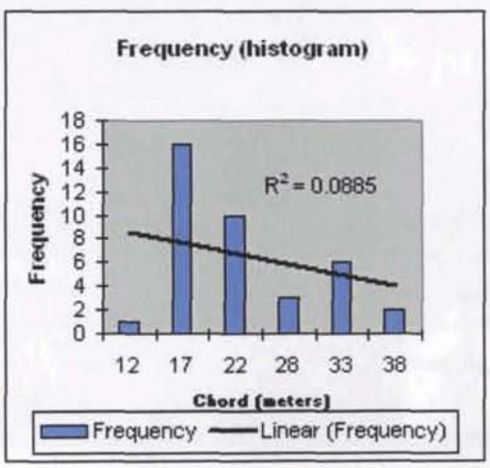


Figure 18. Map view of expansion/ longitudinal bar (E) and pendant bar (P) in the Dusty Lake cataract. (1996 U.S.G.S. digital orthophoto quad)

Current dunes: Current dune features have ripple morphology and are formed by water flowing over workable sediment at a specific depth and velocity. The current dune features are located on the south side of the pendant bar along the north wall of the Ancient Lakes cataract (Figure 19). The dune train is >1.5 km long forming on slopes < 15° trending east-west with the dunes trending north- south 100m long and have an average chord of 23 m and a mode of 17 m with surface amplitude < 1 m (Table 1). The morphology, acruate shape and sub-critically climbing dunes of the feature indicate direction of flow from the east. The coarse sediments on the surface and in the current dunes indicate a fluvial origin.

Table 1. Current dune chord length and statistical analysis completed for current dunes in Ancient Lake cataract.

Giant Current Dunes		Giant Current Dunes			
Dune	Chord (m)	Dune	Chord (m)	Statistics	
1	35	22	20	Sum	948
2	41	23	27	Average	23
3	41	24	12	Mode	17
4	41	25	28	Median	19
5	43	26	30	Minimum	12
6	30	27	17	Maximum	43
7	19	28	17	Std. Dev.	8.647974
8	19	29	19		
9	18	30	15		
10	17	31	13		
11	13	32	17		
12	17	33	15		
13	21	34	21		
14	20	35	33		
15	24	36	17		
16	17	37	16		
17	22	38	14		
18	23	39	30		
19	16	40	18		
20	13	41	31		
21	17	42	31		



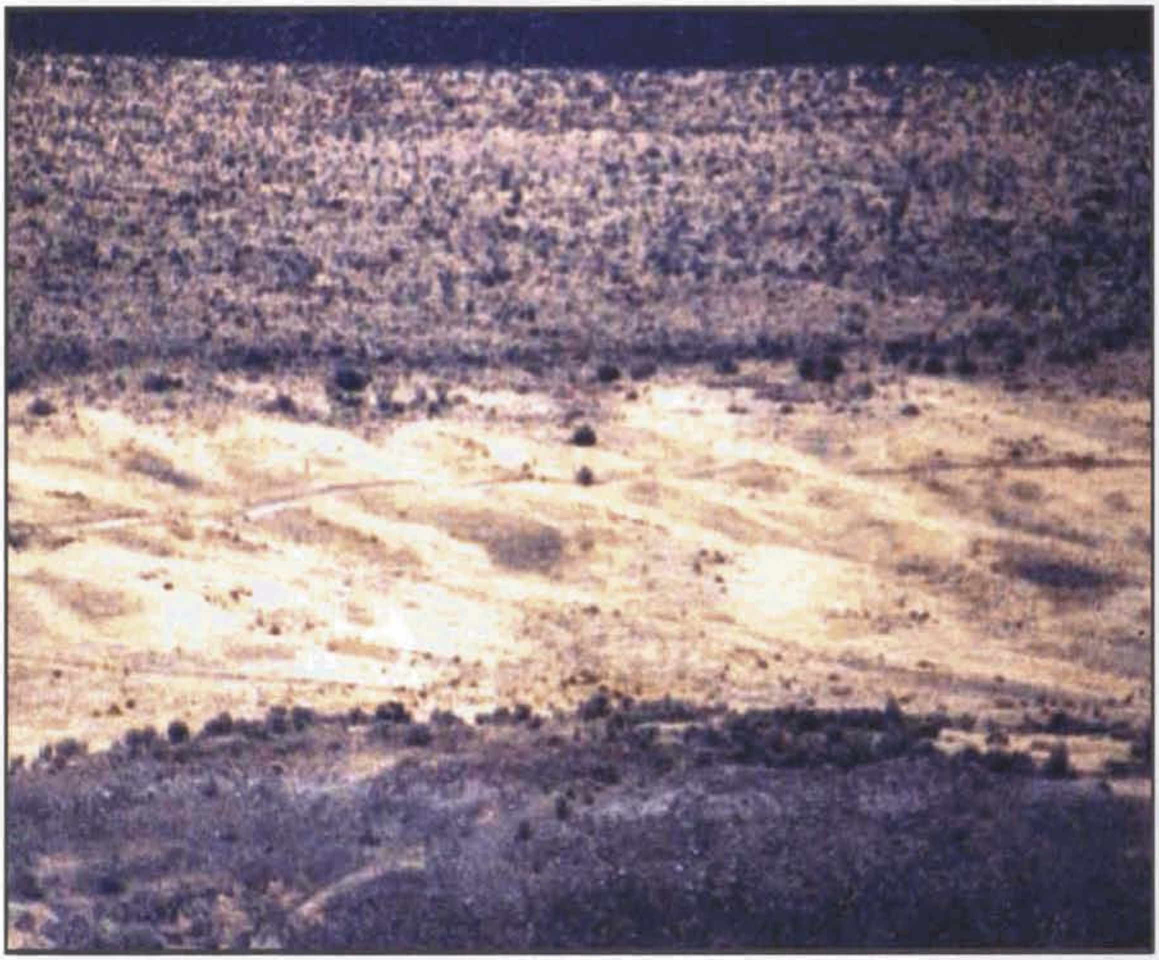


Figure 19: Oblique ground view of current dunes from southwest. Note the undulating topography of the current dune train. Also note the break in shrubs resulting from a biotic barrier created by the 1950s ephemeral human made lake.

Weathering Features

Chemical and physical weathering both occurs within the study site and, despite being discretely categorized, they often occur simultaneously. Physical and chemical weathering enable each other: for example, physical weathering creates more surface area, thereby enabling chemical weathering to occur. Further, chemical weathering weakens the substrate enabling physical weathering to occur. Both forms of weathering occur at present.

Physical Weathering: Physical weathering is the degradation of rock via mechanical means, often with more then one mechanism occurring at once. The dominant form of physical weathering at the site is a composite of thermal expansion-contraction (freeze-thaw) and frost wedging. This weathering occurs at locations of bedrock exposed by floodwaters and on cliffs and horizontal surfaces with maximum surface area exposed to the environment. Freeze-thaw shattering and wedging enables rockfall and talus collection at the base of the cliffs as talus slopes. Freeze-thaw shattering occurs at an abandoned plunge pool/kolk inside the eastern margin of the mouth, more than 250 m away from cliffs of the Ancient Lake cataract. The exposed bedrock is discontinuously mantled by a layer angular to sub-angular rock fragments, 5 to 25 cm (intermediate diameter) resembling colluvium and talus. The rock fragments have a weak, < 1mm weathering rind, little lichen growth with some having an evaporite coating from the flooding of the cataract in the early 1950s. Similar weathering has formed a well developed weathering mantle on the long plateau surface of the interfluve. A less common form of physical weathering in the area is root wedging, the wedging apart of rock by shrubs growing the joints of rock. Though this is not common in the study site, it does occur on cliff faces. Spalling occurs with isolated boulders creating a round corestone. An example of spalling is found on the fosse side of the pendant bar along the south wall of the Ancient Lake cataract measuring 0.75 m (Figure 20).

Figure 20. Oblique ground view of spalling, basalt corestone resting in fosse of pendant bar located on the south side of the Ancient lake cataract. Note the jointing parallel to the surface on the rock creating a round corestone. Also note the red-brown weathering rind and white evaporite coating. (Seth Mattos for scale)

Chemical weathering: Chemical weathering is the in situ decomposition of rock via chemical reactions resulting in the formation of new minerals. The dominant chemical weathering in this area is oxidation; the process leads to the collapse of the crystal structure of the iron in the basalt enabling weathering by other means. Oxidation of iron minerals is shown as a red weathering rind on exposed basalt be it a cliff or rock fragment. The development of the oxidation weathering rind varies with the amount of time the rock is exposed to the environment; thus a freshly broken piece of basalt will show little or no weathering rind in contrast to a fragment of basalt with long exposure to the environment will show a deeper weathering rind. The basalt rock fragments on the interfluve have resulting from a combination of oxidation and chelation (chemical weathering resulting from the production of organic acids by biota such as lichen). The basalts are subject to hydrolysis, replacement of Potassium cation (K^+) with Hydrogen ion (H^+) with the presence of water to break down the mineral to clay.

Composite Weathering: As mentioned previously physical and chemical weathering rarely occur independent of each other, so the two will also be addressed simultaneously. The long interfluve and cataract rim surfaces exhibit signs of composite chemical and physical weathering occurring together in a feedback system. During the formation of the Potholes Coulee and subsequent floods, the surface was stripped of available sediment, leaving the bedrock bare. After this time physical and chemical weathering occurred creating a shallow weathering mantle. A combination of frost action, freeze-thaw and oxidation fragmented rock on the surface creating more surface area enabling chemical weathering. The rock fragment were then subjected to further physical and chemical weathering decomposing and degrading the rock fragment into angular to sub-angular very coarse oxidized basalt sand and pebbles (figure 21). The composite weathering regime on the interfluve has culminated in forming a shallow, well-developed weathering profile capped by loess. The stability and location of the sediment has enabled various biota and landforms to form such as patterned ground resulting from shrink-swell and lichen.

Figure 21. Physical and chemical weathering on the interfluve surface. Note the basalt weathered to angular to sub-angular coarse sand, granules, and pebbles, the weathering rind, and lichen growth.

Eolian Deposition

Eolian processes in past and present affected the landscape with loess and cover sand blanketing the fluvial depositions and weathering mantles. The loess forms as very fine sediments transported as suspended load then settles from the air in areas of decreased velocity and is the dominate land cover within the Columbia Basin. The depth of loess ranges from 20 cm at the mouths and rims of the cataracts to more then 1.5 m on striped bedrock terraces, cataract floors, and along the cliff bases of Babcock Bench. The loess consists of buff colored silt-sized particles and varies in compaction throughout the year based on available moisture and bioturbation. A thin, discontinuous cover-sand/lag resulting from deflation is found through out the study site, mostly occurring at the mouth of the cataracts along Babcock Bench or areas of consistent bioturbation. Eolian processes still occur, deflating disturbed surfaces as well as depositing loess.

Mass Wasting Features

Mass wasting is the downslope movement of sediment and/or bedrock as a result of gravity and is affected by fluvial undercutting, weathering, slope, aspect, climate, and vegetation. Mass wasting occurs in the study site as rockfall, rotational slides, undifferentiated slides and solifluction ranging in magnitude of events from small rockfall (<10 cm) to composite undifferentiated landslides more than 500 m wide.

Rockfall: Rockfall occurs when a rock is pulled from a vertical or nearly vertical surface by gravity enabled by frost wedging and freeze-thaw action. Rockfall in the area occurs at all aspects of exposure with the most occurring along cliffs with a northern aspect and ranges from 3cm to >5 m in diameter. For this report, rockfall is classified as two categories based on size: talus and discrete large block.

Talus is classified in this report as coarse angular rock fragments, less than 1 m intermediate diameter, that collects at the base of the cliff it fell from. The majority of the rockfall is classified as talus and forms 20°-30° slopes, more than 25 m tall. The majority of the clasts, in talus, range from 5 - 50 cm diameter with some clasts up to 1 m in diameter. The talus cones coalesce into one continuous apron at the bases of the cliffs in the study area, partially to completely filling the fosse side of the bars. The talus slopes show no pressure ridges or a pronounced berm at the toe of the slope (Figure 22).

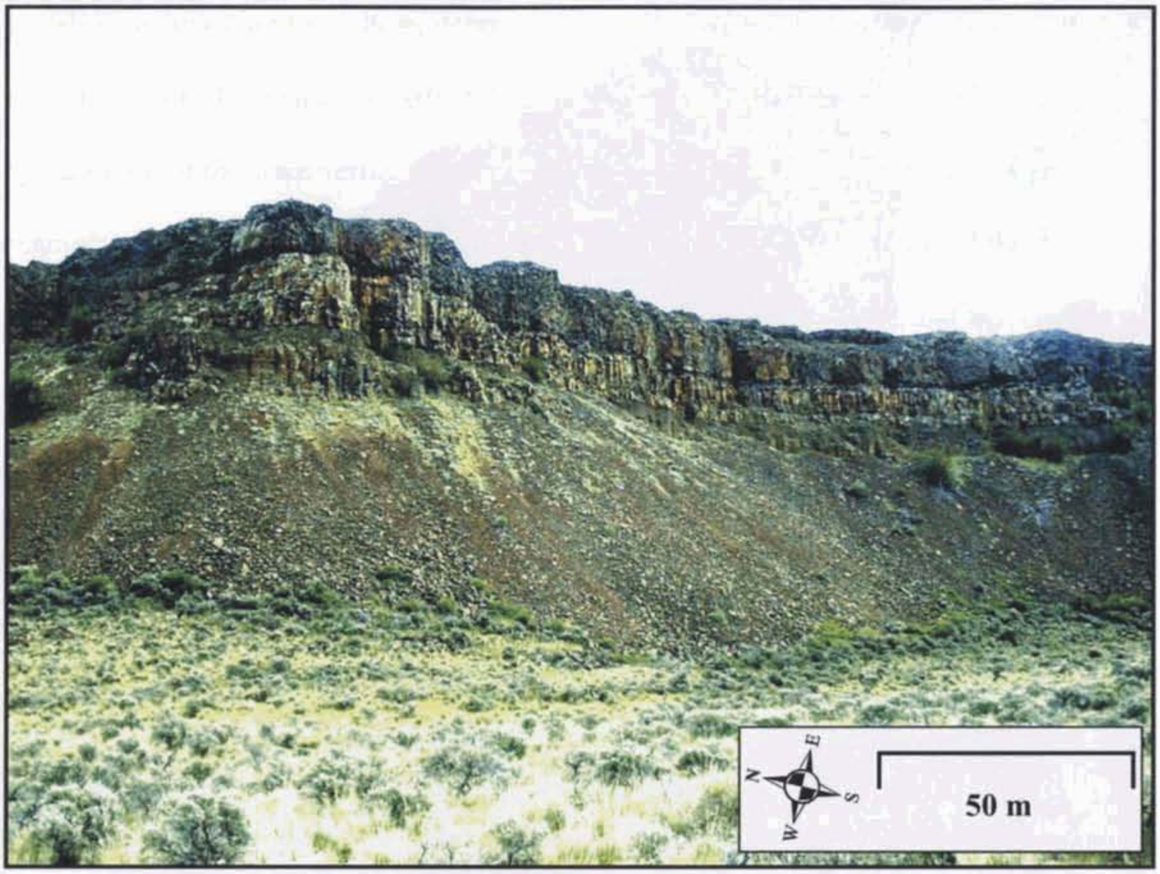


Figure 22. Oblique ground view of talus slopes mantling fosse side of crescent/point bar south of Potholes Coulee on Babcock Bench.

Discrete large block rockfall is classified as angular blocks of rock that collects at the base of the cliff it fell from occurring as large blocks greater than 1 meter intermediate diameter and as large as 10 meters intermediate diameter. It consists of entablature or colonnades that succumb to the forces of gravity enabled by the jointed nature of the basalt bedrock, physical weathering, seismic events and sometimes extreme weather. In the study site, rockfall commonly occurs from cliffs with a northern aspect in both the Ancient Lake cataract and the Dusty Lake cataract as well as the along the Babcock Bench (Figure 23). Much of the large block rockfall, after rolling, comes to rest mantling the fosse side of bars and the cataract floors.

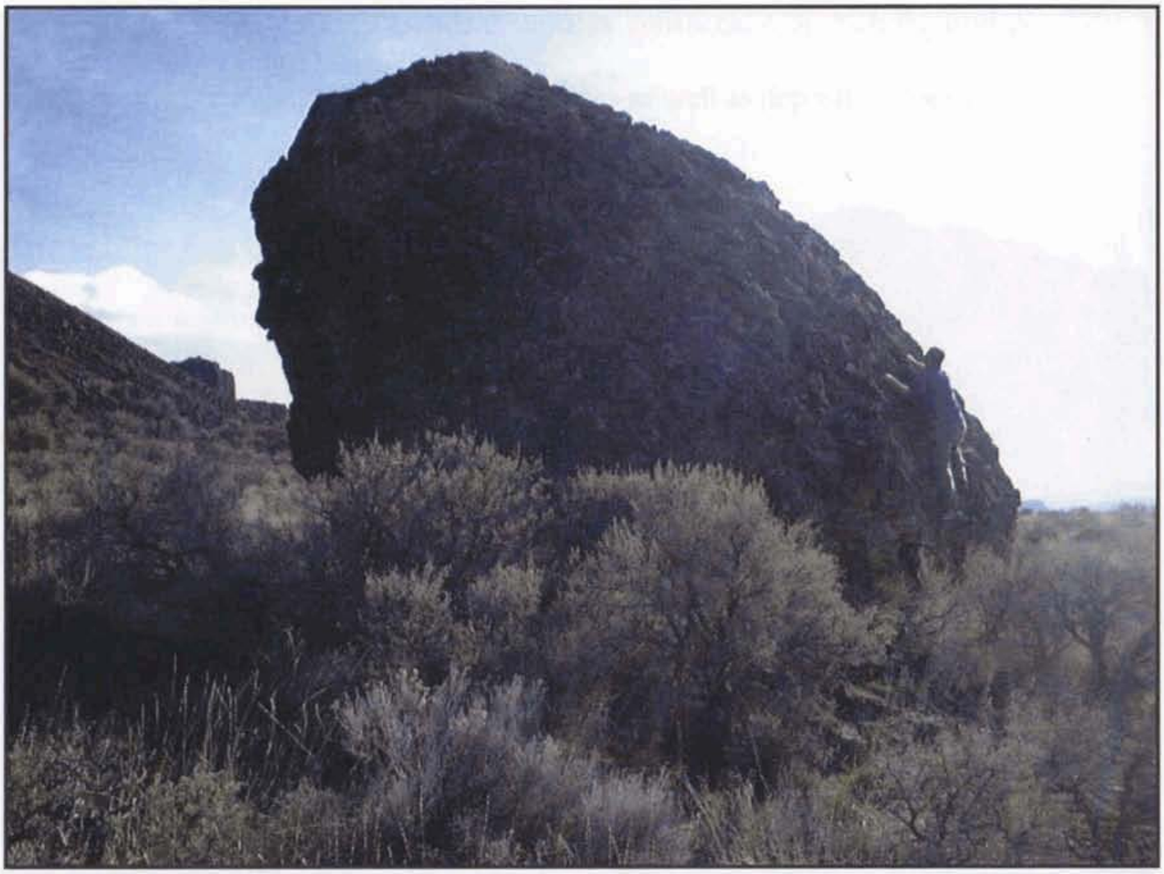


Figure 23. Oblique ground view of large block rock fall on Babcock Bench. This rock is more than 5 meters in intermediate diameter.

Landslides: Landslides result from the downslope sliding of an area or the slope pulled by gravity enabled by bedrock structure, fluvial undercutting, weathering, seismic events, or extreme weather. Landslides occurring at the study site include rotational slides and undifferentiated slides and range in width from 50 m to greater than 300 m. The landslides occur on slopes with northern aspects in Ancient Lake and Dusty Lake cataracts; and western aspects along the slope between the Babcock-Evergreen Ridge and Babcock Bench.

Rotational landslides are mass movements in which the bottom of the slope is cantilevered away from the slope allowing the top of the slope rotated downslope leaving a scallop-shaped scarp in the cliff above the slide. The morphology of a rotational landslide includes: a sag, hollow, depression like feature, behind the main body with a toe at the terminus of the slide. Rotational slides in the study site are often easily identified by the offset of the once vertical colonnade after the slide has come to rest. A textbook example of a bedrock rotational slide occurred in middle of the south side of the Ancient Lake cataract (Figure 24). The slide occurred after bar deposition as it and associated debris rest on the fosse side of a pendant bar.

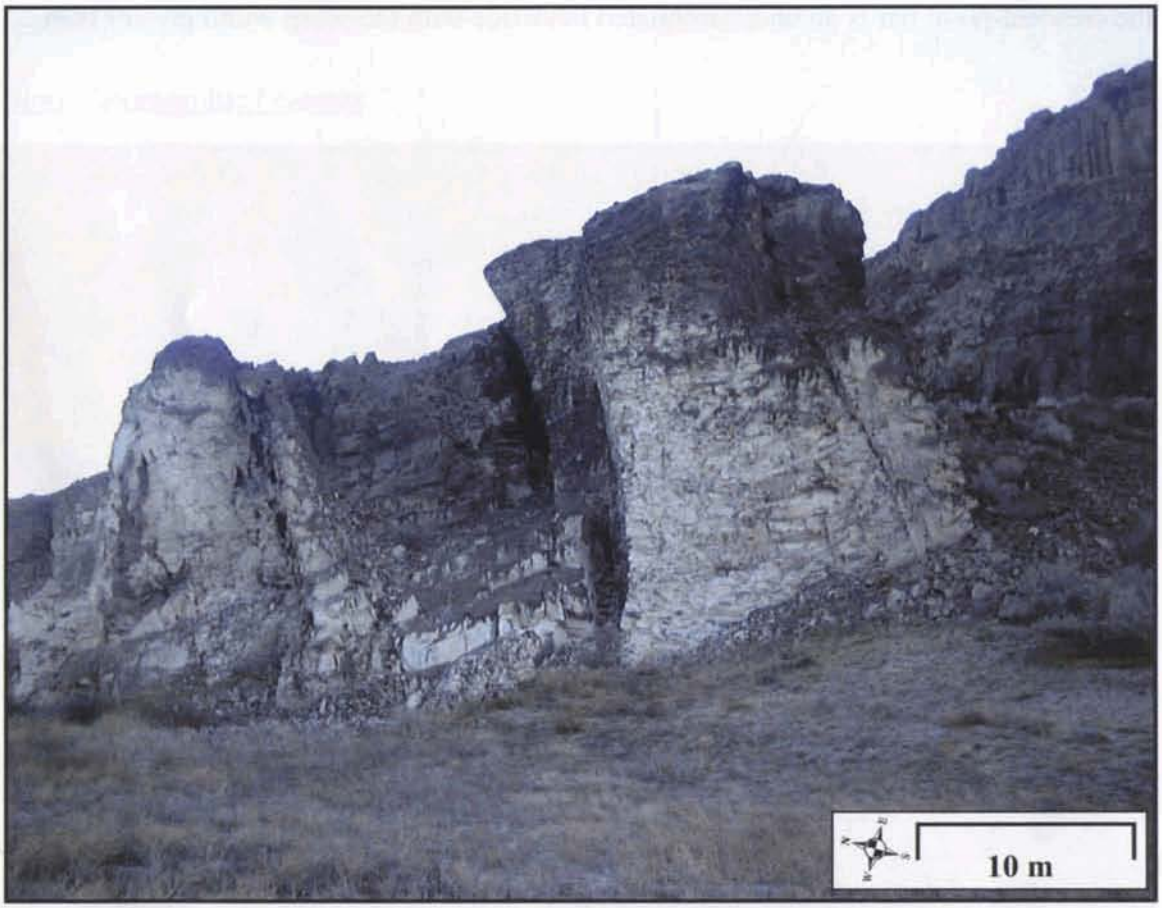


Figure 24 – Oblique ground view of a rotational landslide block in the middle of the south side of Ancient Lake cataract. This slide was determined to be rotational by the horizontal colonnade in the middle of the main body of the slide. The main body of the slide rises more than 15 m above the bar where it came to rest.

Undifferentiated landslides are landslides that the mechanics of the slide cannot be determined by visual observations either due to the nature of the slide or post event modification. These landslides occur in the southwest extent of the study site on the

Babcock Bench along the Evergreen Ridge south of the mouth of the Dusty Lake cataract. The slides are recognized by the scallop-shaped scarp left in the Evergreen ridge above the slide. The difficulty in determining the mechanism of the slide is that the main body of the slide has been reworked by late Pleistocene flooding down the Columbia River coupled with bar building. Two of the scarps have channels leading to them indicating fluvial flow prior or subsequent to the mass wasting event. Two km south of the crescent-point bar is an undifferentiated landslide with the scarp width greater than 300 m.

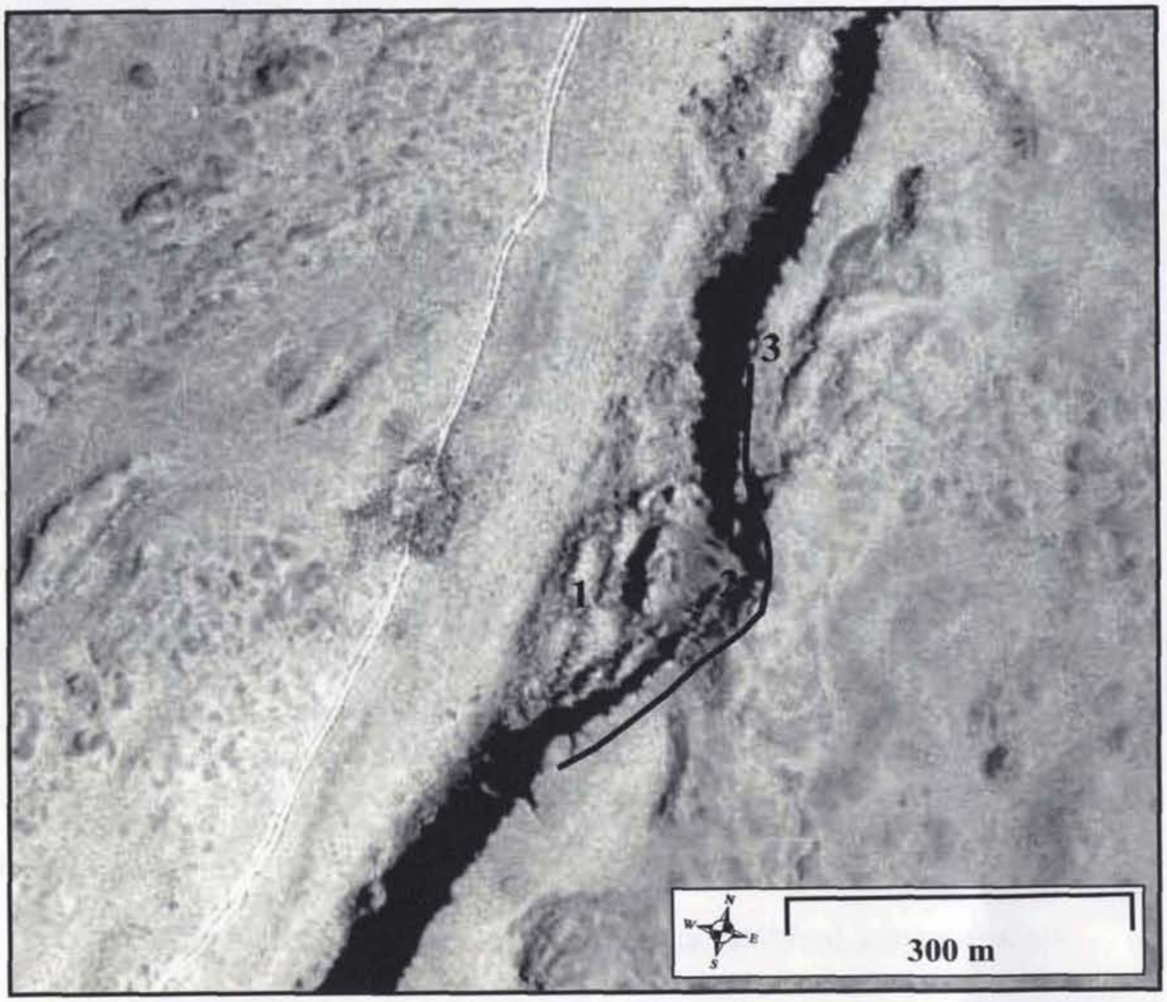


Figure 25. Map view of undifferentiated landslide scarp along Evergreen Ridge 2 km south of the mouth of Potholes Coulee. Notation: 1) landslide foot; 2) main body; 3) landslide scarp. (1996 U.S.G.S. digital orthophoto quad)

Solifluction: Solifluction is the down slope movement of a substrate, in this case flood gravels on a bar, by gravity enabled by saturation of the substrate. Solifluction occurred on the channel side of the pendant bar along the north wall in the head of the Ancient Lake cataract. The movement occurred on a slope greater than 20 degrees providing the energy necessary to compensate for the well draining substrate of the bar. The feature is 10 m wide 20 m long and 0.5 m deep with a small toe on the down slope side of the feature.

Biotic Geomorphic Features

Biota (flora, fauna, and humans) can be competent geomorphic agents. The study site has undergone change by flora, fauna, and humans discreetly and in composite, bringing various forms of change. Biota can act as either a surface stabilizer or a source of surface disruption.

Flora: A well developed flora regime indicates a stable surface. Grasses and shrubs stabilize the surface by covering the surface making it resistant to eolian and slope erosion. Lichen acts as a chemical weathering geomorphic agent by secreting organic acids that decompose the minerals of the rock it's growing on, thereby enabling other forms of weathering and erosion. Lichen grows at a slow rate and the presence of well developed lichen indicates a long duration of surface stability.

Fauna: Coyotes, badgers, mice and other small mammals cause bioturbation of the surface and subsurface mixing the stratum of the soil profile by burrowing and foraging. Worms churn the soil as they work their way through creating a homogenous soil profile as well as adding humus to the soil. Horses and deer create trails and disrupt the surface as they walk, enable and prepare the substrate for eolian processes (transport/deflation) and slope erosion. This is especially noticeable during transition from winter to spring when surface degrades from a compact surface to an unconsolidated loose dust that billows around ones feet.

Humans – Humans, though in the area for a short time, have been very effective geomorphic agents. Humans have occupied the area for several thousand years prior to modern occupation which began in early 1920s with homesteading. The land use included range land taking advantage of the natural corrals created by the cataracts (personal communication, Dave Bishop, June 2002). The area was without irrigation save one perennial spring on Babcock Bench outside of the Potholes Coulee. In the 1950s the Columbia Basin Irrigation Project brought water to the region for agriculture. In the early 1950's, the Ancient Lake Cataract was flooded intentionally to create a lake, however, due to a fault in the cataract the water slowly leaked out (Grolier 1965). There were several attempts to maintain the lake's level, however, this was abandoned in subsequent years. Despite the ephemeral nature of this lake, it had an impact on the cataract creating artificial biotic barriers and creating new landforms. Salts precipitated from the ponded lake water, leaving an evaporite. The shoreline created a barrier blocking the native flora that once occupied the area from re-inhabiting the area (Figure 26). Bacteria and more alkali tolerate plants could process the salts in the soil enabling re-colonization by the local shrubs. At present, more than 40 years since the lake was abandoned, a few sagebrush shrubs are beginning to occupy the area. The dominant flora is cheat grass and Russian thistle.

The lake did not only impact the local biota, it also created unique landforms. The lake left terracettes and a "bath tub" ring of evaporite indicating the past shoreline (Figures 17, 20, & 26). The terracettes are continuous parallel small terrace features similar to shorelines that can be found along reservoirs shores at present. It is unlikely that they are of a faunal origin (cattle trail terracettes), as they do not braid into one another. Also, the phenomenon can be observed at modern reservoirs.

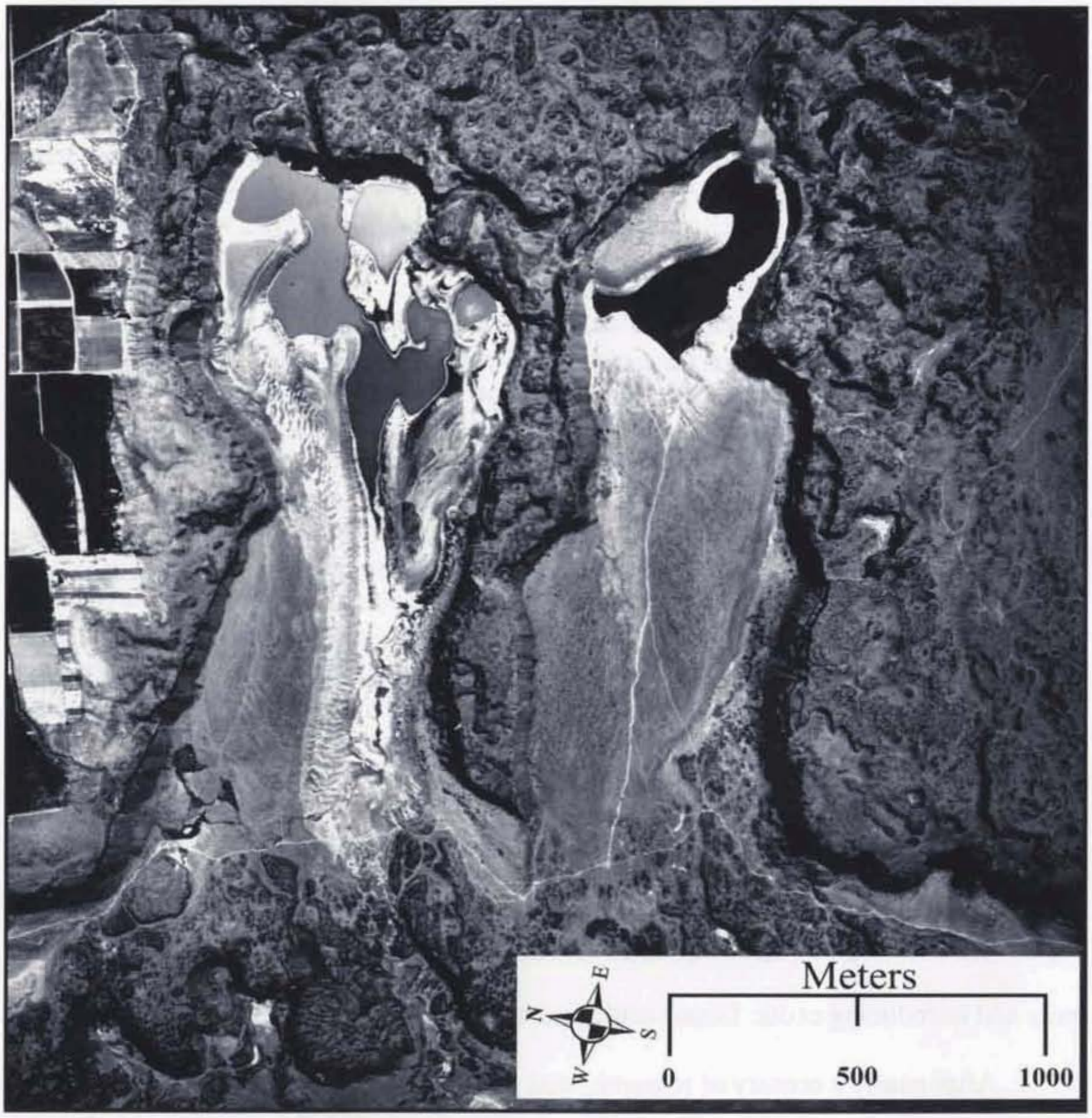


Figure 26: 1962 U.S.D.A. airphoto of the Potholes Coulees showing waning lake waters in the Ancient Lake cataract. Note the white evaporite deposition showing maximum lake level.

Conclusions

The Potholes Coulee has been affected by volcanism, tectonism, fluvial, eolian, weathering, mass wasting, humans, and biotic geomorphic factors from the Miocene epoch to present creating the Potholes Coulee, an amazing landform The Miocene-Pliocene CRBGs created unique bedrock that was folded by Pliocene tectonic forces, setting the stage for future modification by Pleistocene catastrophic flooding events. Though the events setting the stage for future modification occurred over millions of years, they culminate in a crescendo of glacio-fluvial processes which sculpted amazing landforms in the stark CRBGs. Throughout the Pleistocene, episodic catastrophic flooding events operated as competent erosional forces, plucking basalt along structural weaknesses creating the Potholes Coulee, and then deposited fluvial mega-bedforms flooring the excavated cataracts. Eolian deposition blanketed the bedforms, weathering mantles, and mass wasting deposits. Rockfall detritus mantles the base of the cataract's walls. The combined geomorphic processes create a unique landscape. Potholes Coulee is a steep walled double horseshoe cataract with sinuous elongate kolk lakes above the heads of the cataracts. Lakes fill concentric elongate plunge pools at the base of the cataract's heads. Mega-bars and bedforms of flood sediment discontinuously floor the cataracts. Talus and landslides mantle the steep cataract walls. Varied depths of loess blanket the flood sediments and flora has stabilized the surface. Anthropogenic agents exploited the setting through irrigation and lake building events, as well as constructing trails and introducing exotic fauna (cattle and modern horses) to the area.

After nearly a century of research, many questions remain regarding the geomorphology of the Quincy Basin, and specifically the Potholes Coulee: 1) The

George Gravels in the George Channel connected to Potholes Coulee imply it was formed hundreds of thousands of years prior to the late Pleistocene catastrophic floods. Direct research addressing the age of the gravels and linking them to the Potholes Coulee would be a valuable project in explaining the genesis of the Channeled Scabland; 2) Exploring the kolks on the interfluve in the Potholes Coulee would yield further understanding in the temporal origin of the glacio-fluvial activity that flowed through the study site as well as reconcile the dramatic difference in weathering between the elevated interfluve surface and lower cataract surfaces; and 3) Quantifying the current dunes by understanding the sub-loess topography would allow description of the current dunes and calculation of flow through the cataract at time of origin.

Acknowledgements

This research was made possible by the financial support of the Evolving Earth Foundation. I acknowledge David Bishop for excavating the sloth remains, historic site description, use of his personal library, allowing access to the site, and bring his discovery to the scientific community. I acknowledge Steven Hackenberger for incorporating this work into his final report, access to his personal study site photos, and permitting access to the sloth site. I acknowledge Karl Lillquist for his guidance through out the project, assistance in the field, and proof-reading earlier versions of this manuscript. I appreciate Robert Hickey, for guidance with GIS technologies and for proof-reading earlier versions, and Seth Mattos, for assistance in the field

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