INVESTIGATION OF ICE AGE FLOOD GEOMORPHOLOGY AND STRATIGRAPHY IN GINKGO PETRIFIED FOREST STATE PARK, WASHINGTON: IMPLICATIONS FOR PARK INTERPRETATION

A Thesis

Presented To

The Graduate Faculty

Central Washington University

In Partial Fulfillment

of the Requirements for the Degree

Master of Science

Resource Management

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by

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May 2006

CENTRAL WASHINGTON UNIVERSITY

Graduate Studies

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ABSTRACT

INVESTIGATION OF ICE AGE FLOOD GEOMORPHOLOGY AND STRATIGRAPHY IN GINKGO PETRIFIED FOREST STATE PARK, WASHINGTON: IMPLICATIONS FOR PARK INTERPRETATION

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Documentation of Ice Age flood evidence in Ginkgo Petrified Forest State Park, Washington fills a gap in landscape-scale analysis and interpretation of cataclysmic flooding in the Vantage Reach of the Columbia River Valley. High-energy floodwaters exiting Frenchman Gap excavated soil and modified underlying basalt bedrock up to 600 ft above the paleo-Columbia River. Subsequent hydraulic pooling reached maximum depths of at least 783 ft. Eddy bar, rhythmite, and ice-rafted deposits developed within low-energy flood environments. Ice-rafted erratic deposits occupied study area elevations between 641 ft and 1,263 ft. The highest frequency of ice-rafted erratics occurred above 1,100 ft on erosional landforms. High-density erratic cluster and bergmound deposits, resulting from deposition of large icebergs, were limited between 917 ft and 1,218 ft. Public interpretation of research results should occur within a three-level park interpretive network comprised of previsit and on-site orientation, interpretive hubs, and site-specific story points.

ACKNOWLEDGMENTS

The development and completion of this thesis included input from several participants, in particular, my committee members Dr. Karl Lillquist, Dr. Anthony Gabriel, Dr. Allen Sullivan, and Steve Wang. Thank you to Dr. Lillquist who nurtured all phases of this thesis, and served as a mentor during my undergraduate and graduate career at Central Washington University. Dr. Gabriel contributed greatly to my graduate education and was instrumental in the quantitative design of this research. Dr. Sullivan provided valuable feedback during critical phases of this thesis. Steve Wang has served as a mentor throughout my career in Interpretive Services at Washington State Parks. His support of my decision to return to graduate school and the many insights and hours of discussion he contributed to this thesis is greatly appreciated. In addition, I would like to thank Dr. Lubinski for his guidance during the early stages of this work.

Thank you to Jack Powell for his time in the field and valuable insights gained from his previous geologic work in the park, as well as Dr. Bruce Bjornstad who readily shared his research and provided me with helpful feedback regarding research questions. Thank you to Jim Mitchell and the staff of Ginkgo Petrified Forest State Park for their contributions to my understanding of the park. To all my fellow Resource Management students who have contributed to this thesis, your time and energies are appreciated.

Special recognition goes to my parents Helen and Ray, brothers Colby and Marty, and close friends who have supported me throughout my career. Special thanks to my partner Lara Tomlin, who contributed to this work, as well as my sanity throughout this process. I dedicate this work to my son Liam, a constant source of inspiration.

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CHAPTER I

INTRODUCTION

Research Problem

Throughout the Pleistocene, the cyclic advance and recession of the Cordilleran Icesheet developed a series of temporary ice-dammed lakes within the Columbia River Basin. Repetitive ice dam failures of glacial Lake Missoula, derived from damming of the Clark Fork River, produced the largest floods known to the continent. Raging floodwaters released from glacial Lake Missoula carved an extensive drainage network into the basalt plateau of eastern Washington forming a region known as the Channeled Scabland (see Figure 1).

Various scientific efforts have documented evidence of Pleistocene flooding in the Channeled Scabland over the past 80 years (Allison, 1933; Atwater, 1986; Baker, 1973; Bjornstad, Fetch, & Pluhar, 2001; Bretz, 1923, 1927, 1928, 1930; Bretz, Smith, & Neff, 1956; Flint, 1938). However, less attention has been focused on Pleistocene flood features located in the Vantage Reach of the Columbia River Valley (CRV) between the Quincy and Pasco basins. Previous investigations in the western Channeled Scabland by Bretz (1930), Cochran (1978), Dunbar (1998), Fecht and Tallman (1978), and Mullineaux, Wilcox, Ebaugh, Fryxell, and Rubin (1978) identified a need for Pleistocene flood analysis in tributary environments west of the Columbia River. The absence of landscape-scale Pleistocene flood documentation north of Ryegrass Coulee provided this opportunity to conduct primary research.

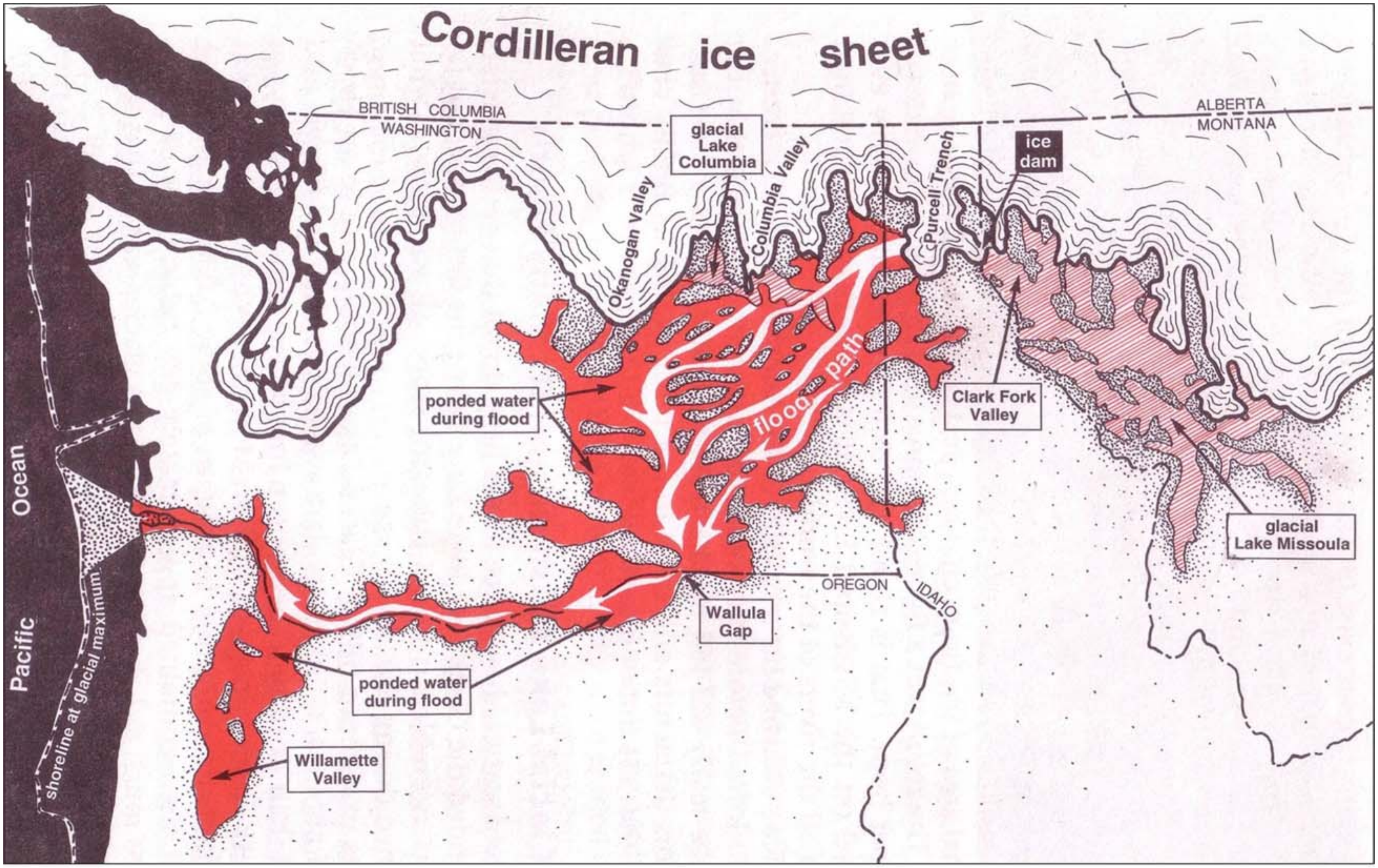


Figure 1. Lake Missoula floodway including glacial Lake Missoula, glacial Lake Columbia, and the Channeled Scabland. Source: Alt and Hyndman (1995).

Recent planning efforts by the National Park Service (2001) identified a need for public interpretation along the route of the Pleistocene flooding. To address this public need, the Washington State Parks and Recreation Commission (WSPRC) is currently developing a statewide Ice Age Floods (IAF) interpretive plan to enhance interpretation of the state's IAF heritage to the general public. Currently, there are no developed WSPRC interpretive sites along the western Channeled Scabland that focus on IAF interpretation. The existing Ginkgo Petrified Forest Interpretive Center and associated self-guided trail system have great potential to serve as sites for IAF interpretation and orientation to regional features of the Channeled Scabland.

Research Objectives

The purpose of this research is to identify and interpret evidence of Pleistocene flooding along tributary drainages in the Vantage Reach of the CRV using a landscape-scale approach. The study area is located on Ginkgo Petrified Forest State Park, as well as Washington Department of Fish and Wildlife lands, and includes the lower reaches and tributary drainages of Rocky, Schnebly, and Ryegrass coulees (see Figure 2).

I hypothesize hydraulic constrictions in the CRV at Frenchman Gap and Sentinel Gap, in concert with hydraulic pooling of floodwaters at Wallula Gap, produced identifiable flood features in the study area. These flood processes resulted in erosional and depositional features determined by topographic variables of the study area. My specific objectives were to (a) identity and map the extent of Pleistocene flooding, (b) identify and map the distribution of Pleistocene flood features, (c) interpret geomorphic relations of flood and landform features, (d) interpret flood processes acting in the study

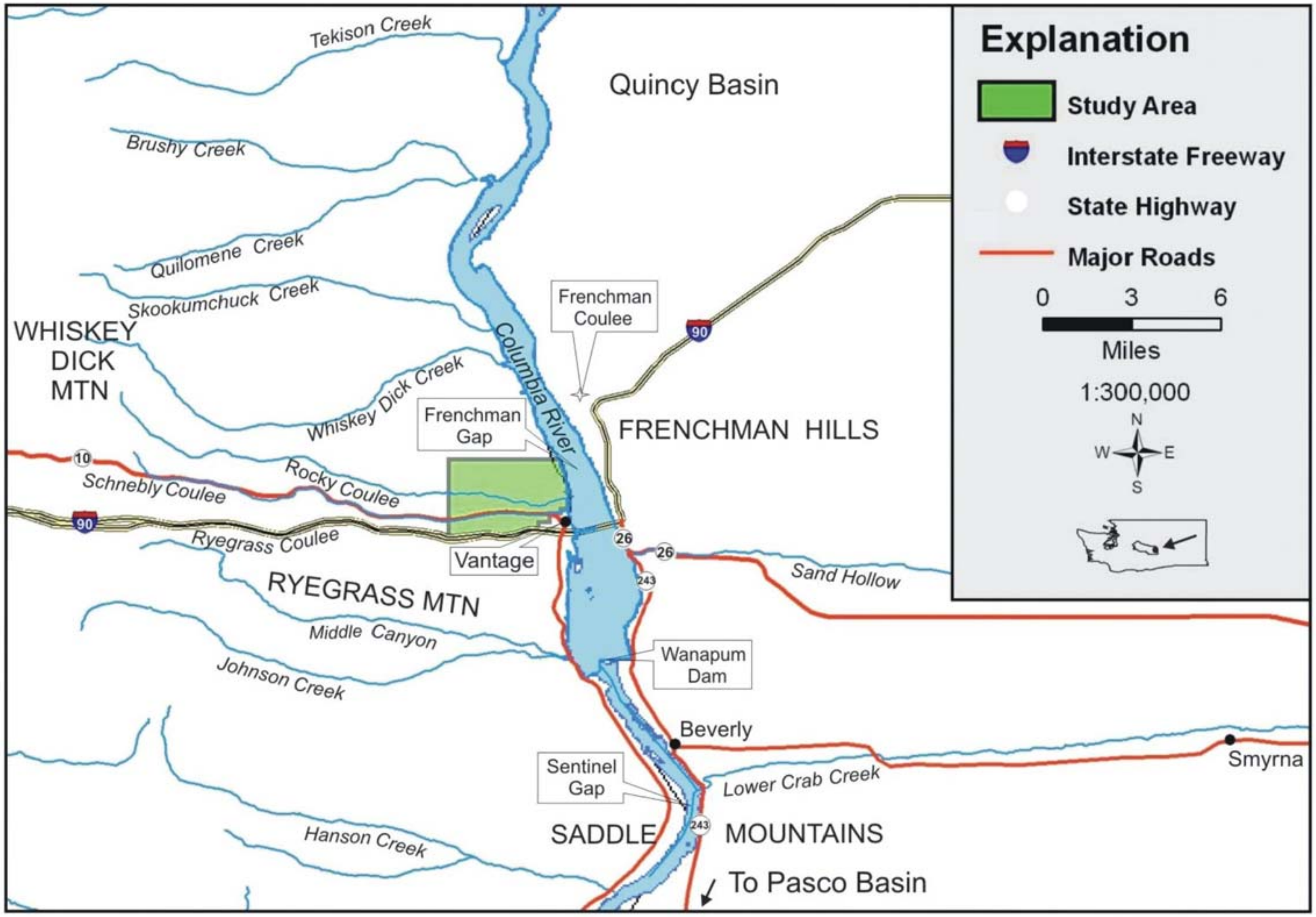


Figure 2. Location of study area in the Vantage Reach of the Columbia River Valley. Study area is located northwest of Vantage, Washington between constrictions in the Columbia River Valley at Frenchman Gap and Sentinel Gap.

area, and (e) develop recommendations for a network of IAF interpretive opportunities to effectively communicate research results to the public.

Significance

Ginkgo Petrified Forest State Park is an easily accessible, registered National Natural Landmark and home to a diversity of significant natural and cultural resources (Beck, 1945; Carson, Tolan, & Reidel, 1987; Kidd, 1964). Beyond landscape-scale examination of flood features within an undocumented portion of the CRV, an additional intended outcome of this inquiry is to enhance public recognition, understanding, and preservation of Pleistocene flood features. Results of this inquiry benefit the scientific community by closing a research gap in Pleistocene flood documentation while providing a landscape-scale model for flood analysis and interpretation. This effort will contribute to WSPRC interpretive planning efforts to develop interpretive opportunities benefiting regional, state, and national audiences of the park. Significant flood features, lithic resources, and related cultural resources identified within this research will serve future WSPRC land management planning efforts.

CHAPTER II

PREVIOUS RESEARCH

Cordilleran Icesheet

Cyclic advance and recession of the Cordilleran Icesheet occurred throughout the Pleistocene. Interpretation of oxygen isotope records from deep-ocean cores indicates at least 17 complete interglacial-glacial cycles have occurred since the end of the Olduvai normal-polarity subchron, approximately 1.65 million radiocarbon years before present (yr BP). This cyclic pattern suggests several manifestations of the Cordilleran Icesheet have influenced cataclysmic flooding in the Channeled Scabland (Bjornstad et al., 2001).

The extent of Cordilleran Icesheet occupation in the Pacific Northwest likely varied from cycle to cycle (Morrison, 1991). Today, sparse evidence remains of early and middle (pre-late) Pleistocene glacial episode maximums. However, abundant evidence of late-Pleistocene glacial maxima exists in the form of moraines, outwash terraces, and remnant glacial lakes (Carrara, Kiver, & Stradling, 1996; Porter, 1976). Waitt and Thorson (1983) reported that during advances of the Cordilleran Icesheet into the northern Columbia River Basin, several composite lobes occupied south-trending valleys, forming ice-dammed lakes in adjacent valleys. During interglacial episodes the Cordilleran Icesheet receded due to warming climatic conditions (Waitt & Thorson). Each episode of Cordilleran Icesheet recession was marked by increased drainage runoff volumes and lake levels, setting the stage for cataclysmic flooding.

Modern research of Pleistocene Cordilleran Icesheet behavior suggests failure of multiple ice-dammed lakes over time developed flood evidence in the Channeled

Scabland (Baker & Bunker, 1985; Shaw et al., 1999; Spencer & Jaffee, 2002). While scientific debate continues on this topic, it is apparent cyclic behavior of the Cordilleran Icesheet directly influenced the sources of Pleistocene flood events.

Glacial Lake Missoula

The absence of low drainage divides within the Clark Fork Basin, combined with the cyclic occupation of the Clark Fork River mouth by the Purcell Lobe of the Cordilleran Icesheet, provided the site and situation for multiple manifestations of glacial Lake Missoula. This natural reservoir, located in northwestern Montana, was first documented by Pardee (1910) and remains the subject of avid scientific inquiry nearly a century later. Early descriptions of the Lake Missoula Basin by Chamberlain (1886) and Pardee (1910) came from distinct markings of lacustrine shorelines high above existing valley floor elevations. Refined analysis of glacial Lake Missoula sediments by Pardee (1942) and Chambers (1971) estimate the natural reservoir's maximum elevation at 4,150 ft (1,265 m), reaching depths of 2,083 ft (635 m), with a volume > 480 mi^3 (2,000 km^3).

Pardee (1942) used the presence of large 20-ft to 50-ft (6-m to15-m) ripple marks in Montana's Camas Prairie Valley to advance the hypothesis that glacial Lake Missoula drained rapidly due to cataclysmic failure of the Purcell Lobe ice dam. Refined research by Bretz (1959) concluded that more than one, perhaps as many as seven floods from glacial Lake Missoula are documented in the Columbia River Basin. Subsequent research of slackwater and loess deposits by Patton and Baker (1978), Waitt (1980), Atwater (1986), McDonald, Busacca, and Nelstead (1987), Bjornstad et al. (2001), and others have advanced the hypothesis of multiple outburst flood events occurring before and throughout late-Pleistocene stands of glacial Lake Missoula.

Extent of Pleistocene Flooding in the Columbia River Basin

Evidence of cataclysmic flooding along Idaho's Big Lost River and the Snake River Plain, in addition to the glacial Lake Missoula floodway, indicates multiple sources of Pleistocene flooding have impacted the morphology of the Columbia River Basin (Bretz, 1959; Malde, 1968; Rathburn, 1993). The most significant known flood source was ice-dammed glacial Lake Missoula which produced remarkable flood features throughout portions of the western Rocky Mountains, Columbia Plateau, Columbia River Gorge, Willamette Valley, and ultimately the Pacific Ocean floor (Figure 1).

With the exception of flood events believed to have occurred while the CRV was clear of the Cordilleran Icesheet, exiting floodwaters from the Lake Missoula Basin likely encountered neighboring glacial lakes of the Spokane and the main Columbia River valleys (Atwater, 1986; Baker et al., 1991). As floodwaters overtopped neighboring lakes and drainages basins, they formed a series of southwest-trending distributaries across eastern Washington, referred to by Bretz (1923) as the Channeled Scabland (see Figure 3). Eventually, floodwaters converged into a single outlet at Wallula Gap. This major constriction in the CRV, as well as down river in the Columbia River Gorge, and at Kalama Gap, forced surging floodwaters to hydraulically pool. These processes resulted in a succession of temporary lakes from the Channeled Scabland and adjacent valleys to the Willamette Valley (Allison, 1933; Bretz, 1930). Pooled floodwaters reached elevations of over 1,200 ft (366 m) above sea level in the Pasco Basin, 1,000 ft (305 m)

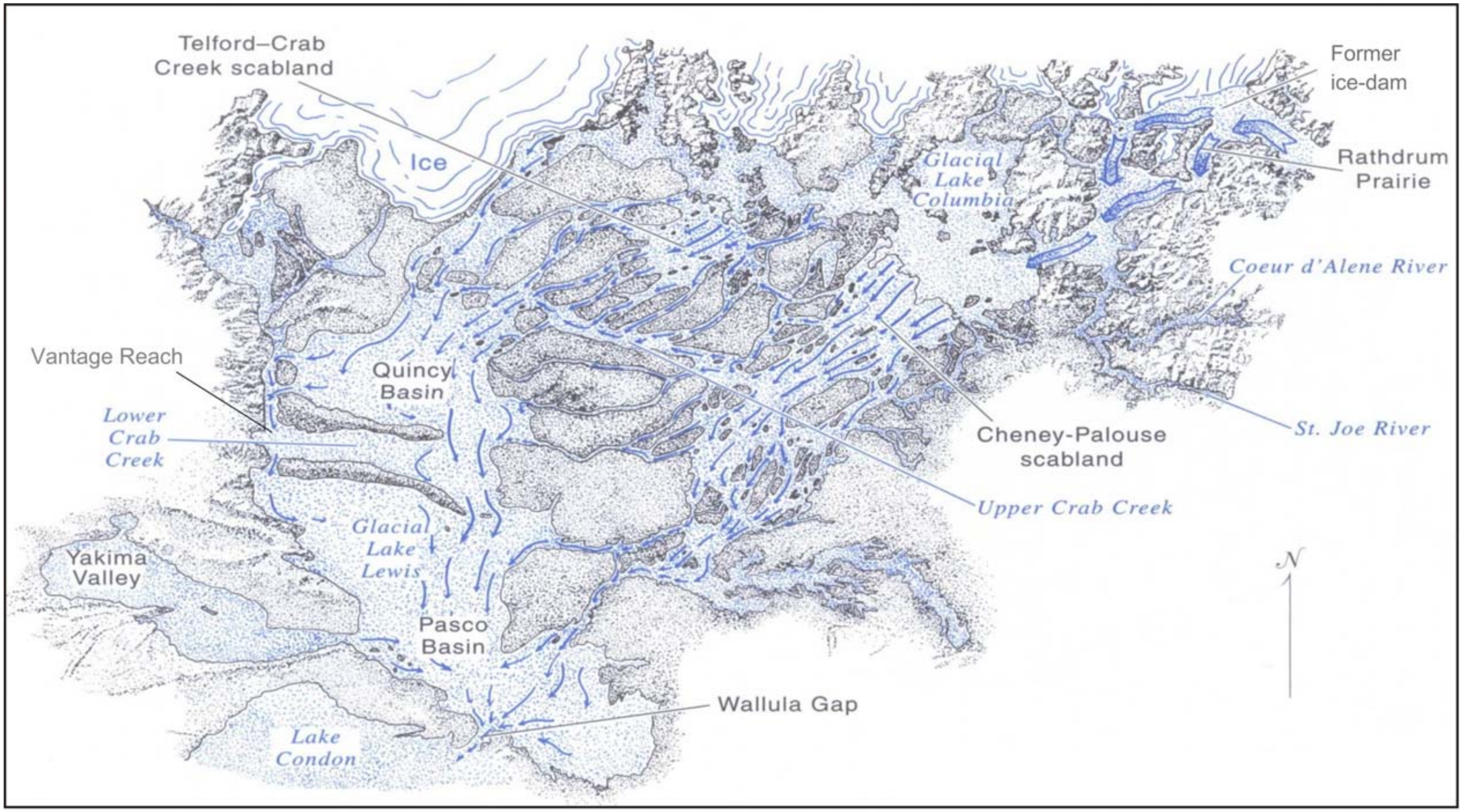


Figure 3. General path of floodwaters in the Channeled Scabland during occupation of the Columbia River Valley by the Okanogan Lobe ice dam. Note the convergence of floodwaters at Wallula Gap. Source: Alt (2001).

at The Dalles in the Columbia Gorge, and 400 ft (122 m) in the Willamette Valley. Ultimately, freshwater stored in, and released from the Lake Missoula Basin returned to the Pacific Ocean, completing a unique and complex hydrologic cycle.

Frequency and Magnitude of Flooding in the Channeled Scabland

Debate over the frequency and magnitude of ice dam failures of glacial Lake Missoula, as well as alternative floodwater sources, continues to stimulate modern research. Extensive research of flood and loess deposits indicates existing features of the Channeled Scabland are the product of multiple flood events of varying magnitudes spanning perhaps the entire Pleistocene (Baker et al., 1991; Bjornstad et al., 2001).

Pre-Late Pleistocene Flood Evidence

Isolated field evidence of pre-late Pleistocene (> 130,000 yr BP) flood events makes it difficult to establish stratigraphic correlations necessary to determine the total sequence of flood events during the Pleistocene (Baker et al., 1991). Evidence from multiple sites in the Channeled Scabland and adjacent Palouse Formations suggests at least two episodes of pre-late Pleistocene flooding occurred (Bjornstad et al., 2001).

Evidence of early Pleistocene flooding (> 780,000 yr BP) was reported by Bjornstad et al. (2001) in the Pasco Basin in a deep gravel bar with reverse magnetic polarity overlain by calcrete-capped deposits of normal magnetic polarity. Radiometric-age dating by Bjornstad et al. of calcrete-capped deposits of normal magnetic polarity indicates they were deposited during mid-Pleistocene flood episodes, between 130,000 and 780,000 yr BP. Therefore, the underlying gravel bar is attributed to an early Pleistocene origin. Additional evidence of early Pleistocene flooding in the Quincy Basin was reported by Patton and Baker (1978) in the form of highly weathered, calcrete-capped flood gravels with basalt cobble weathering rinds up to 3.2 in. thick (8 cm) near the town of George. Furthermore, McDonald et al. (1987) used direct evidence of flood gravels and slackwater deposits interstratified within loess islands, as well as indirect soil and loess deposit stratigraphy, to identify at least one flood episode prior to 780,000 yr BP, and as many as six major episodes in the past 300,000 to 500,000 years.

Late-Pleistocene Flood Evidence

The pre-Holocene oxygen isotope record indicates a 50,000 year interglacial episode separated middle- and late-Pleistocene glacial episodes approximately 130,000 to 80,000 yr BP. This interglacial episode is marked by the accumulation of fine-grained loess within the Palouse Formation resulting from pre-late Pleistocene flood deposition in the adjacent Channeled Scabland (Baker et al., 1991; Morrison, 1991). During the last glacial episode, the Cordilleran Icesheet advanced into the Columbia River Basin reaching glacial maxima between 20,000 and 13,000 yr BP (Waitt & Thorson, 1983).

Based on voluminous field evidence occurring within the Channeled Scabland, three phases of late-Pleistocene flooding are associated with fluctuations in global climatic conditions. Research of loess distribution patterns by Busacca and McDonald (1994) conveys evidence of late-Pleistocene-aged cataclysmic flood events in the eastern Channeled Scabland between 65,000 and 80,000 yr BP. Evidence of subsequent late-Pleistocene flooding came from dating of organic materials retrieved from flood gravels during construction of Wanapum Dam at 32,700 yr BP (Fryxell, 1962). Ensuing stratigraphic research of flood sediments, refined radiocarbon dating techniques, and soil development associated with the Mount St. Helens set C tephra now provides evidence of this second stage of late-Pleistocene flooding between 40,000 and 35,000 calendar years ago (Busacca & McDonald, 1988; Foley, 1976; Moody, 1987).

The most recent phase of flooding occurred approximately 19,000 to 11,250 yr BP (Baker et al., 1991; Benito & O'Conner, 2003). Jökulhlaup (outburst flood) research of glacial Lake Missoula by Waitt (1980, 1985) presented a hypothesis of repetitive failures of the Purcell ice dam occurring during onset of the current interglacial episode between 17,200 and 11,000 yr BP, and that each flood event produced an individual slackwater rhythmite. This hypothesis was challenged by Bjornstad (1980), Baker and Bunker (1985), and Moody (1987) with evidence of unconformities in reworked Mount St. Helens set S tephra found within individual flood rhythmites. While the concept of multiple flood events is now widely accepted, debate continues on their estimated frequency and magnitude.

Atwater (1986) reported evidence of glacial Lake Missoula flood sediments in glacial Lake Columbia, placing the most recent occurrence of glacial Lake Missoula between 15,550 and 13,350 yr BP (Figure 3). Further research by Waitt and Atwater (1989) adjusted this lifespan of glacial Lake Missoula to 15,500 to 12,700 yr BP. The lower limit date of flooding was determined by widespread evidence of 11,250 yr BP Glacier Peak tephra overlying late-Pleistocene flood deposits (Baker et al., 1991).

Recent research by Waitt, O'Conner, and Burns (2000) and Benito and O'Conner (2003) places the largest failure of the Purcell ice dam before 15,000 yr BP, with successively smaller and more frequent ice dam failures over a period of nearly 3,000 years. This high-magnitude flood event is believed to predate glacial Lake Columbia, thus damming of the CRV by the Okanogan Lobe of Cordilleran Icesheet, with estimated discharges of > 547 x 10^6 ft^3/s (15.5 x 10^6 m^3/s) by Waitt et al., and > 353 x 10^6 ft^3/s (10 x 10^6 m^3/s) by Benito and O'Conner.

Research questions remain concerning the frequency and magnitude of flood events during late-Pleistocene stands of glacial Lake Missoula. Waitt (1994) reported the last floods from glacial Lake Missoula to be confined to the Grand Coulee, exiting the western Channeled Scabland via lower Crab Creek, thus through Sentinel Gap to Wallula Gap. Stratigraphic evidence from glacial Lake Columbia sediments indicates it outlived glacial Lake Missoula (Atwater, 1986). Furthermore, debate continues on the magnitude and origin of the last floods to exit via the CRV < 13,000 yr BP. Potential sources include the collapse of glacial Lake Columbia or some other northern Columbia Basin glacial drainage source. Overall, it can be inferred that no less than seven major cataclysmic flood events, and potentially as many as 100 late-Pleistocene flood events of varying magnitude and frequency are documented in the Channeled Scabland (Atwater, 1986; Baker et al., 1991; Waitt, 1994).

Flood Erosional Features

The unique geomorphology of the western Channeled Scabland is a result of the rapid movement of water through an overfit preflood drainage network (Baker & Nummedal, 1978). During the largest documented flood events, floodwaters surged across this Miocene basalt plain at speeds of nearly 60 mph (97 km/hr; Baker, 1973). As the floodwaters entered constrictions in the CRV, floodwater velocities increased, developing steep-angle scabland escarpments along drainage channels. When floodwaters extended above drainage channels, basalt surfaces were stripped of soil materials, resulting in erosional scabland topography. Perhaps the most fascinating erosional landforms in the western Channeled Scabland are cataracts. These distinctive horseshoe-shaped features formed in localities with steep water-surface gradients and continuous vertically jointed basalt. In the western Quincy Basin, cataract recession was initiated by the presence of escarpments carved by the Columbia River, creating up to 850 ft (249 m) of relief between the river channel and the Quincy Basin floor (Bjornstad, 2006). Cataracts developed subfluvially from plucking erosion along columnar-jointed basalt flows and relentless kolk activity working in concert to undermine the cataract lip. Kolking forces develop from secondary circulation patterns present within deep flood currents. This circulation is characterized by spiral vortexes possessing intense energy displacement which serves to lift bedload or bedrock from the channel bed surface (Baker & Nummedal, 1978). Undermined and excavated blocks of basalt were transported as bedload as cataract head cuts receded upstream (Baker, 1973).

Flood Depositional Features

Depositional features in, and marginal to, the Channeled Scabland provide key evidence used to determine the frequency and magnitude of Pleistocene flooding. As Pleistocene floodwaters submerged the landscape, its preflood topography, acting as a temporary channel bed, directly influenced the deposition of flood sediments (Kochel & Baker, 1988). A variety of depositional features resulted from fluctuations in sediment size and proximity to the thalweg of flood currents (Baker, 1973).

The most notable display of these processes occurred at Wallula Gap (Figure 1). Here, the Columbia River channel width is reduced to less than 2 mi (3.2 km). This constriction hydraulically pooled converging floodwaters from the Channeled Scabland developing a temporary lake, known as glacial Lake Lewis. Backflooding of glacial Lake Lewis inundated the Pasco and portions of the adjacent Yakima, Walla Walla, and Quincy basins (Allison, 1933; Waitt, 1980). This thesis provides focused research of depositional features within the northwestern margins of glacial Lake Lewis.

Flood Channel Deposits of the Lake Lewis Basin

With the exception of initial flood surges, floodwaters racing across the Channeled Scabland eventually encountered the fluctuating margins of glacial Lake Lewis (Baker et al., 1991). This abrupt change in base level and decrease in current velocity induced rapid aggradation of suspended bedload, resulting in subfluvial bars comprised of coarse gravels and boulders (Baker, 1973). The morphology and structure of subfluvial bars can be attributed to the influence of underlying topography on flood channel configurations (Bretz, 1928).

Pendant bars occur as streamlined mounds of flood gravel found parallel to the direction of flow and immediately downstream of channel obstructions (Malde, 1968). Pendant bars are most common in northeastern portions of the Lake Lewis Basin within uniform, steep-gradient flood channels. Pendant bars contain an internal structure of well-sorted foreset beds resulting from downstream surface migrations of giant current ripples, which often cover these distinct bar features (Baker, 1973).

Eddy bars form in low-energy environments of tributary valleys adjacent to high-velocity flood channels. Sediment sizes range from erratic boulders to silts and clays often occurring within intermixing structures of poorly sorted gravel and graded sand-silt layers. Poorly sorted bedding in eddy bars possesses varying orientations indicating fluctuations in the direction and velocity of depositional currents. An abundance of coarse eddy bar material is typically deposited near the mouths of adjacent tributary drainages with finer deposits grading upstream (Baker, 1973; Pardee, 1942).

Expansion bars occur where floodwaters decelerated into an expanding channel, often downstream of major constrictions in the floodway. Sediment size within expansion bars typically decreases in a downstream direction. Expansion bar surfaces are often channeled with boulders lining the margins of the deposit (Baker, 1973).

Waitt (1994) describes delta bars as features formed where floodwaters moving parallel across an upland surface encounter a transverse tributary alcove in which it deposits a flat-topped bar. A similar description is used by Bretz (1928) to describe the Priest Rapids Bar located just downstream of Sentinel Gap.

It is important to note that classification of depositional bars in the field can be complex. Many bar forms represent an evolutionary process developed over multiple flow regimes (Baker & Nummedal, 1978). Therefore, many of the bar types described above can take on composite forms or be morphologically modified by subsequent flooding events with varying current velocities (Waitt, 1994).

Slackwater Deposits of the Lake Lewis Basin

Tributaries located along the margins of the Lake Lewis Basin are ideal locations to investigate evidence of Pleistocene floods (Bretz, 1930; Waitt, 1980). In the Lake Lewis Basin, backflooding of tributary valleys occurred as a result of initial flood surges and hydraulic pooling (Baker et al., 1991). As floodwaters entered marginal tributary valleys, their velocities declined, causing suspended sediments to settle as bedded couplets of laminated sands and silts, known as rhythmites (Kochel & Baker, 1988).

Within a typical rhythmite couplet a distinct horizon of coarse, denser sediments is found underlying a distinct horizon of finer sediments, which is often contrasting in color and texture. This pattern represents the deposition of suspended sediment at two distinct velocities within a flood surge or event (Baker, 1973).

While inundated by pooled floodwaters, adjacent tributaries often contained icebergs which migrated into low-energy environments along prevailing eddy current and wind patterns, influenced by the specific topography of the area. As floodwaters receded, drifting icebergs grounded within tributary environments (Fecht & Tallman, 1978). Melting icebergs deposited erratics comprised of exotic granitic, basaltic, and metamorphic debris (Baker et al., 1991).

Slackwater deposits provide many clues to the frequency of Pleistocene flood events. Backflooded valleys protected from subsequent flood erosion and active slope erosional processes often contain a record of bedded rhythmites (Waitt, 1980). Radiocarbon dating of organic residue and volcanic tephra deposits found between rhythmite sequences has been used to determine the relative timing of flood events (Atwater, 1986; Mullineaux et al., 1978; Waitt, 1980). The stratigraphic marker most common to rhythmite sequences in the Lake Lewis Basin is the Mount St. Helens Set S tephra deposit, dated by Mullineaux et al. at approximately 13,000 yr BP.

Ice-rafted erratics (erratics) can serve as useful indicators of the extent of Pleistocene flooding. Fryxell and Cook (1964) reported erratics up to 150 ft (46 m) higher than nearby loess scarps. These data suggest slackwater deposits can be more reliable than erosional features in the identification of maximum flood elevations. Baker (1973) used high-elevation erratics as paleo-stage indicators in hydraulic analysis of locally pooled floodwaters of the Lake Lewis Basin. Erratics located in the CRV likely originated from ice dam remnants containing Rocky Mountain fold-belt bedrock or glacial ice containing Columbia-Okanogan valley bedrock and alluvium (Bartlett, 1995). Bjornstad, Jennett, Gaston, and Kleinknecht (2003) reported how quantitative analysis of significant relationships between the frequency of surface weathering and roundness of erratics may provide evidence of pre-late Pleistocene flood episodes.

Ice-rafted erratic deposits are typically classified into three broad categories: isolated, clusters, and bergmounds (Allison, 1935; Bjornstad, Jennet, Ryan, & Edwards, 2006; Bretz, 1930). Isolated erratics are individual erratics that range in size from large boulders to cobbles deposited during melting of small or clean icebergs. Isolated erratics are found at nearly all elevations of flooding and often serve as high water indicators. Erratic clusters contain more than one to several individual erratics. They can result from the grounding of medium-sized icebergs or the clustering of small icebergs along a topographic barrier by waning flood currents or wind. Erratic clusters often contain multiple crystalline rock types, including basalt, indicating they originated in ice that had contact with Columbia River Basalts (Fecht & Tallman, 1978). Bergmounds are isolated mounds of till-like debris deposited by a grounded iceberg (Bretz). This form of ice-rafted debris is composed of sediments ranging from boulder to clay in size. Bergmounds form on the downstream side of a stranded iceberg in the lee of receding floodwaters (see Figure 4). The erosive force of waning flood currents developed their topographic relief, which in the Lake Lewis Basin ranges from 3 ft to13 ft (1 m to 4 m) in height and 33 ft to164 ft (10 m to 50 m) in diameter (Bartlett, 1995; Bjornstad et al.; Chamness,

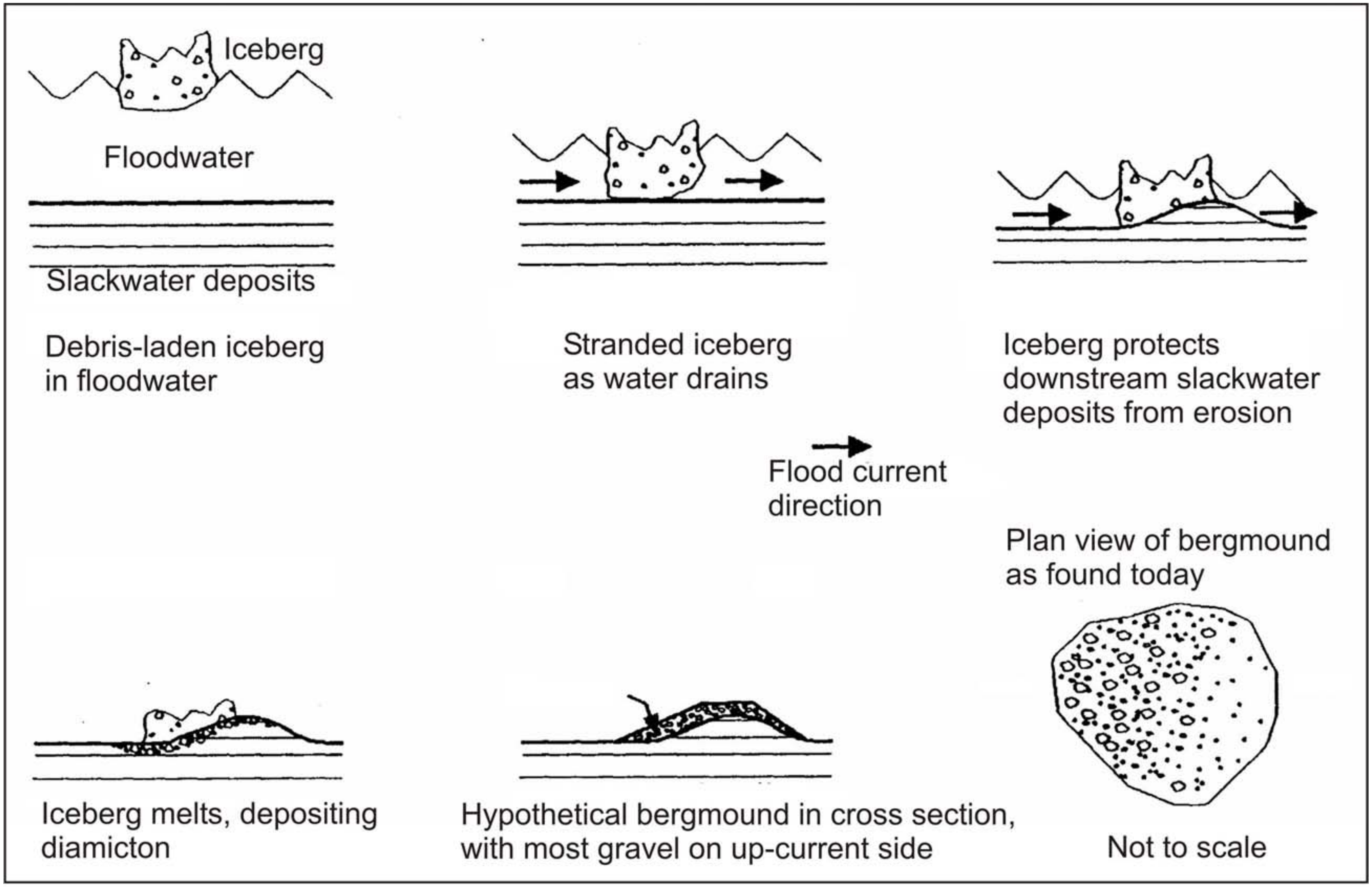


Figure 4. Model of bergmound formation in the Pasco Basin region of glacial Lake Lewis. Source: Chamness (1993).

1993; Fecht & Tallman). Erratic research in the Pasco Basin by Bjornstad et al. reports the presence of bergmounds limited to elevations below 1,000 ft (305 m), more than 200 ft (59 m) below the maximum level of glacial Lake Lewis (1,250 ft/380 m). These data suggest large icebergs were required to generate bergmounds (see Figure 5).

Pleistocene Flood Research in the Vantage Reach

Few regional studies conducted in the western Channeled Scabland address the flood dynamics of the Vantage Reach specifically. Previous flood research indicates floodwaters entered the Vantage Reach via the CRV to the north and the lower Crab Creek drainage to the east (Bretz, 1930). Bretz (1928) introduced the hypothesis of high-magnitude floodwaters entering the CRV upriver from the Vantage Reach via the Crater, Potholes, and Frenchman Coulee cataracts of the western Quincy Basin.

Field evidence of flood features in the Vantage Reach was initially recorded by Bretz (1930) in his brief surveys of scabland topography and channel deposits in Schnebly Coulee and lower Crab Creek. Subsequent field research of Vantage area Columbia River Basalts by Alto (1955) and Mackin (1961) identified the presence of gravel deposits and erratics associated with Pleistocene flooding; however, only brief, qualitative descriptions resulted from their work. Fryxell (1962) provided the first relative dating of flood deposits within the Vantage Reach discussed previously in this chapter.

Baker (1973) provided initial hydraulic analysis of flood processes in the Vantage Reach. Based on his water-surface profile model, the maximum elevation of pooled floodwaters behind Sentinel Gap in the Vantage Reach was 1,200 ft (366 m). Late-

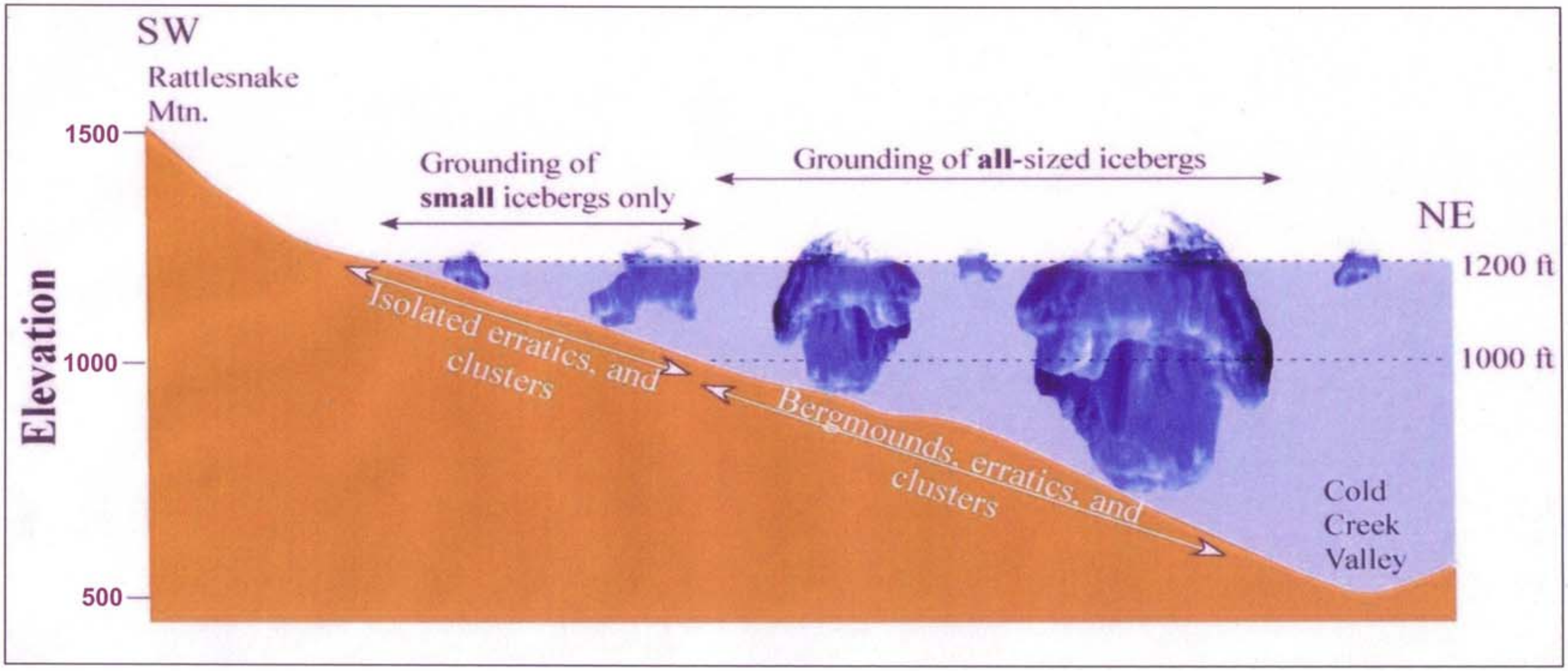


Figure 5. Model explaining limited distribution of bergmounds in the Cold Creek Valley region of glacial Lake Lewis. Large icebergs required to generate bergmounds apparently grounded approximately 200 ft (61 m) below the 1,200 ft (266 m) maximum level of glacial Lake Lewis. Source: Bjornstad et al. (2003).

Quaternary stratigraphic research in the Johnson Creek drainage by Cochran (1978) reported the presence of gravel bar, laminated rhythmite, and ice-rafted erratic deposits.

Cochran (1978) reported evidence that Pleistocene flooding modified and excavated portions the Columbia River Basalts lining the CRV, stripping the loess mantle that once occupied the area below 1,100 ft (355 m). The highest erratic reported by Cochran was found at 1,227 ft (374 m) on the northeast slope of the Saddle Mountains.

Bergmound research in the Vantage Reach by Fecht and Tallman (1978) was limited to the Johnson Creek area. They reported low-relief bergmounds of < 10 ft (1.5 m) in height with diameters up to 50 ft (15 m), at elevations < 1,000 ft (305 m). Fecht and Tallman attributed the low relief and lack of fine-grained debris found in bergmounds of the Vantage Reach to extensive Holocene erosion.

Mullineaux et al. (1978) examined three separate rhythmites in the Vantage Reach containing Mount St. Helens Set S tephra. The top rhythmite containing subset So, and the lower two contain Sg tephra, were all determined to be approximately 13,000 yr BP. Dunbar (1998) reported the presence of remnants of Mount St. Helens Set S and C tephra in slackwater deposits of the Schnebly Coulee drainage determined to be approximately 12,900 and 35,000 yr BP, respectively. In addition, Dunbar conducted a pedestrian survey of high-elevation erratics in portions of the Johnson Creek, Middle Canyon, and Ryegrass Coulee drainages. He also reported the presence of eddy bars at tributary mouths and the extent of flooding within the Vantage Reach at 1,200 ft (366 m), based on the presence of erratics.

Existing Pleistocene Flood Interpretation in the Pacific Northwest

Interpretation of Pleistocene flood processes and features is limited primarily to scientific journals and private outreach publications. The need for public interpretation of Pleistocene flooding within the Columbia River Basin has been identified by a number of private and public entities including the WSPRC and the National Park Service. As a result, the National Park Service (2001) conducted a congressionally authorized study of alternatives and environmental assessment for the establishment of an IAF National Geologic Trail to identify its feasibility and potential implementation partners. The formal designation of the IAF National Geologic Trail currently awaits passage by Congress in 2006.

The WSPRC currently operates the Dry Falls Interpretive Center, located at the head of the lower Grand Coulee near Coulee City, which serves as the primary IAF interpretive facility within the states of Montana, Idaho, Washington, and Oregon. However, several potential IAF interpretive sites within the Pleistocene flood route have been identified by the National Park Service (see Figure 6).

Within the western Channeled Scabland, self-guided interpretive waysides in the Drumheller Channels near Othello and at the Frenchman Gap Wayside along Interstate 90 provide brief IAF interpretation. These developed sites, as well as undeveloped sites such as Frenchman Coulee, Sentinel Gap, and the Cold Creek Valley, possess great potential for future interpretive media development. In response to public need for interpretation of IAF heritage, the WSPRC is planning interpretive improvements at Dry Falls, as well as recommendations for IAF interpretive media at 20 additional WSPRC properties along the IAF route, including Ginkgo Petrified Forest State Park.

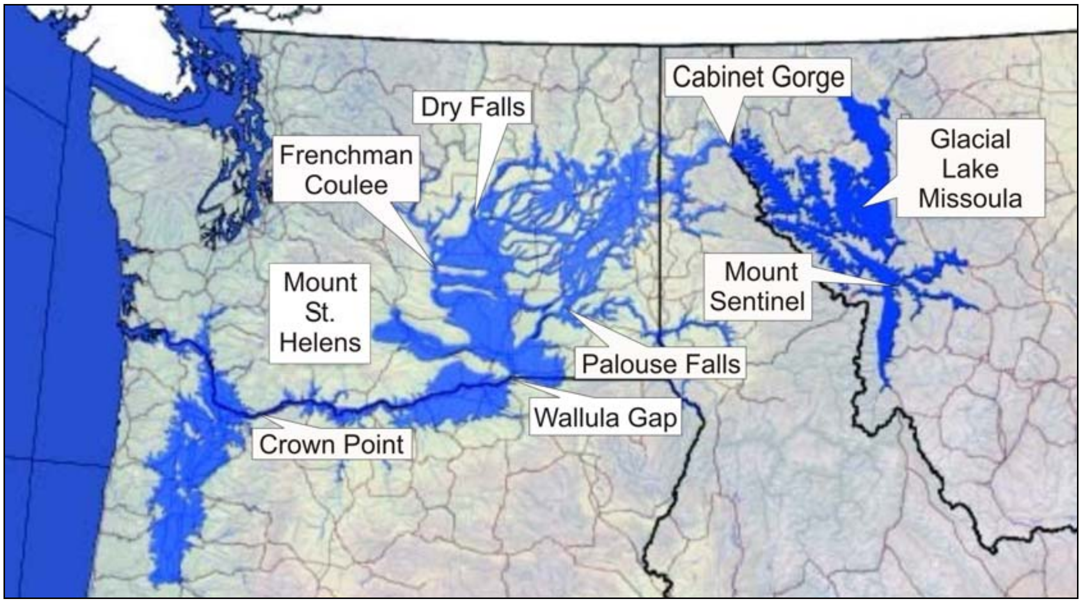


Figure 6. Existing and potential interpretive sites along the proposed Ice Age Floods National Geologic Trail route. Source: National Park Service (2001).

CHAPTER III

STUDY AREA

This inquiry was conducted in the Ginkgo Petrified Forest State Park area which includes WSPRC and Washington Department of Fish and Wildlife lands. The study area lies within the Vantage Reach of the CRV along the western margin of the Channeled Scabland at approximately 47ºN and 120ºW in central Washington (Figure 2). The study occupies approximately 4,000 acres in Section 13, 14, 23, 24, and portions of Sections 10, 11, 12, 15, 22, 25, 26, and 27 of Township 17N, Range 22E, and portions of Section 6, 18, and 19 of Township 17N, Range 23E of the Willamette Meridian. The study area is located near Vantage, 30 mi (48 km) east of Ellensburg, and 12 mi (19 km) west of George. State Route 10 runs through the study area along the floor of Schnebly Coulee and serves as a main access route. Bordered by Interstate 90 to the south, the Columbia River to the east, the Whiskey Dick drainage to the north, and the Hog Ranch anticline to the west, the study area includes the lower reaches and tributaries of Schnebly and Rocky coulees, as well as northern tributaries of Ryegrass Coulee (see Figure 7).

Geology

During the Miocene, several basalt flows flooded the area, burying previous landscapes under tens to hundreds of feet of cooling lava (Carson et al., 1987). Basalt flows residing in the study area are considered part of the larger Columbia River Basalt Group which erupted from fissures located in thinner portions of earth's crust to the southeast. These included the Rocky Coulee member and Museum member of the Grand Ronde Basalts, erupted between 17 and 15.5 yr BP (see Figure 8). The Rocky Coulee

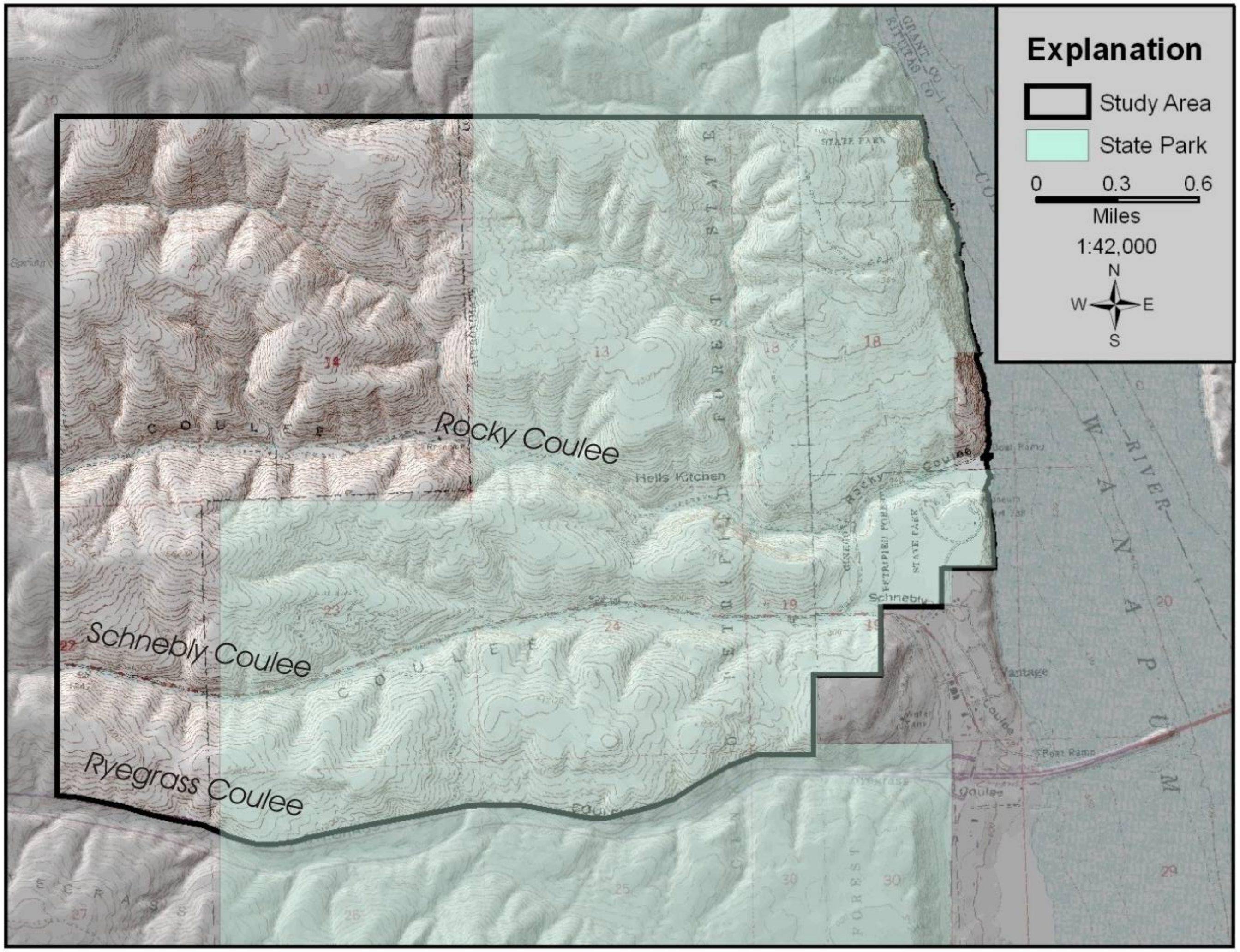


Figure 7. Study area boundaries including the lower reaches of Rocky, Schnebly, and the northern tributaries of Ryegrass coulees. Study area includes the northern portions of Ginkgo Petrified Forest State Park.

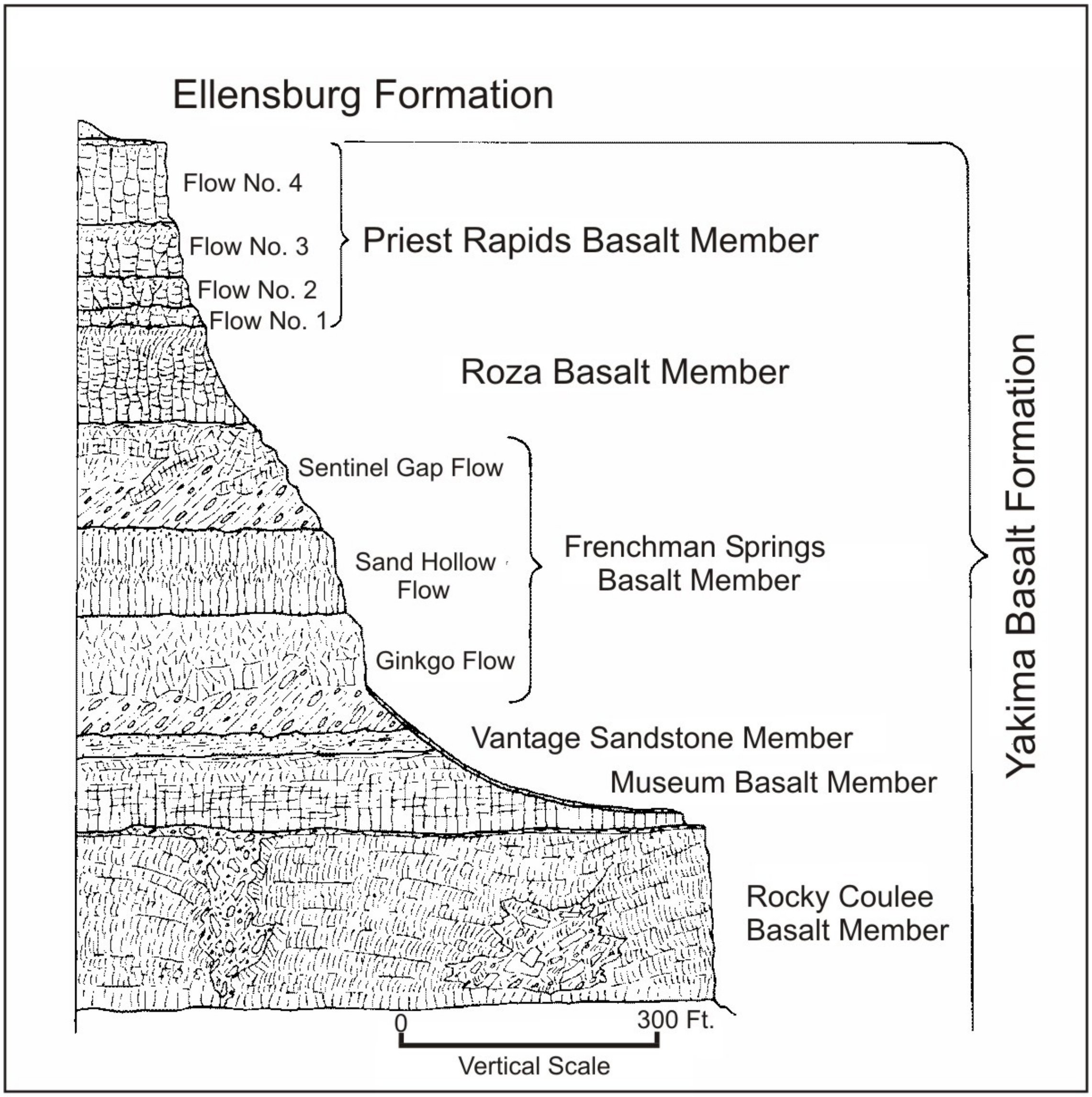


Figure 8. Stratigraphy of the Yakima Basalt Formation within the Vantage-Priest Rapids area. Source: Mackin (1961).

and Museum basalt members are approximately 200 ft and 90 ft (61 m and 27 m) thick in the study area, respectively (Mackin, 1961).

Between episodes of basalt flooding, the landscape incorporated a variety of deposits from temporary lakes, the Columbia River floodplain, and debris flows from the emerging Cascade Volcanic Province to the west (Smith, 1988; Tolan, Reidel, & Fecht, 1991). Approximately 15.5 million yr BP, the voluminous basalt floods of the Grande Ronde volcanic period ceased for perhaps 100,000 to 500,000 years before the onset of the Wanapum Basalt volcanic period (Carson et al., 1987). During this time, the Cascade Volcanic Province developed extensive lahars and debris flows that interrupted the ancestral Columbia River, forcing its drainage channel east into the Vantage area. Tracts of forest in the path of high-magnitude debris flows were likely denuded of trees, and then transported and deposited into the study area landscape (Tolan et al.). Remnants of Columbia River sediments and Cascade volcanic deposits from this period are referred to as the Vantage member of Ellensburg formation (Figure 8). In this region, the Vantage member is approximately 35 ft (11 m) thick outcropping along road cuts and incised tributary arroyos (Mackin, 1961). In addition, saturation of the Vantage member has been linked by geologists to slope instability and landslides in the region (Grolier & Bingham, 1978; J. E. Powell, personal communication, July 13, 2005).

Overlying the Vantage member are the Frenchman Springs and Rosa members of the Wanapum Basalts (Figure 8). In the dawn of the Wanapum Basalt volcanic period, the Columbia River was dammed by basalt flows from the southeast, forming a shallow lake, Vantage Lake, which inundated the study area (Mackin, 1961). As this lake expanded, it incorporated logs from Vantage period deposits, causing them to become waterlogged (Tolan et al., 1991). Eventually, the Ginkgo flow of the Frenchman Springs member flooded the area, burying the landscape in a layer of molten lava (Beck, 1945). The Ginkgo flow buried the study area landscape to depths of 150 ft to 200 ft (46 m to 61 m). As molten lava of the Ginkgo flow advanced into Vantage Lake, it quickly cooled into a sheet of pillow-palagonite basalt. The cooling lava entombed waterlogged and mud-coated logs of the lake bottom. Over time, the silica-based minerals of the pillow-palagonite basalt transformed the entombed logs into a fossil bed of petrified logs found in the base of the Ginkgo flow (Beck).

Overlying the Ginkgo flow are the Sand Hollow and Sentinel Gap flows of Frenchman Springs member basalt, respectively (Figure 8). The Sand Hollow flow contains two subunits of colonnades nearly equal in size ranging from 30 ft to 40 ft (9 m to 12 m). The Sentinel Gap basalt flow thins rapidly to the north of Sentinel Gap and terminates in the vicinity of Ryegrass Coulee. Therefore, it is unlikely to be present within Schnebly and Rocky Coulee drainages to the north (Mackin, 1961). The northern terminus of the flow is comprised of pillow-palagonite basalt indicating another basalt-dam lake occupied the study area prior (< 15.5 million yr BP) to the onset of Rosa member basalt eruptive period (Mackin).

The Squaw Creek member of the Ellensburg formation acts as a stratigraphic marker between the underlying Frenchman Springs Basalt and overlying Rosa Basalt members (Carson et al., 1987). The Squaw Creek member is comprised of diatomite, siltstone, and sandstone sediments remaining from the Sentinel Gap-era lake (Mackin, 1961). The overlying Rosa member is the youngest basalt exposed in the study area (Figure 8). Due to the platy jointing of this basalt, the lower and middle portions of the flow are easily eroded, leaving slopes covered with thin, angular slabs and chips of rock talus (Grolier & Bingham, 1978).

During and after eruption of the Columbia River Basalts, north-south compression along the western margin of the Columbia Basin resulted in a series of east-west-trending anticlinal ridges known as the Yakima Fold Belt (YFB). The topography of east-west-trending anticlines and sediment filled syncline valleys found in the study are the result of deformational and erosional processes acting along the eastern margin of the YFB (Reidel, Campbell, Fecht, & Lindsey, 1994). However, not all anticlines in the western Columbia River Basalt Province resulted in east-west ridges. The Hog Ranch anticline, located just west of the study area, is a broad north-south-trending anticline that intercepts the YFB at a right angle (Reidel et al.). This uplift, which coincided with YFB activity, forms the anticlinal topography of the headwaters for Ryegrass, Schnebly, and Rocky coulees (Smith, 1988).

Climate

Gradual uplift of the Cascade Range profoundly impacted the climate of the Vantage area. The Cascade Range provides an effective barrier to offshore marine air, thus forming a rain-shadow zone that extends nearly 150 mi (240 km) east of the Cascade crest. The study area is located approximately 70 mi (115 km) east of the Cascade crest, in the heart of this zone. Elevations in the study area range from 1,600 ft (488 m) to 570 ft (174 m) at the shoreline of the Columbia River. The Vantage area is semiarid, receiving 8 in. (20 cm) of precipitation annually. The climate is characterized by typically hot, dry summers and cool, moist winters (see Figure 9). Average monthly temperatures range from 75 ºF (24 ºC) in July to 31 ºF (-0.5 ºC) in January, with a mean annual temperature of 53 ºF (11 ºC; Western Regional Climate Center, 2005).

West-to-southwest winds prevail in the Vantage area. The most persistent winds occur in the spring and summer months due to a strong temperature gradient between

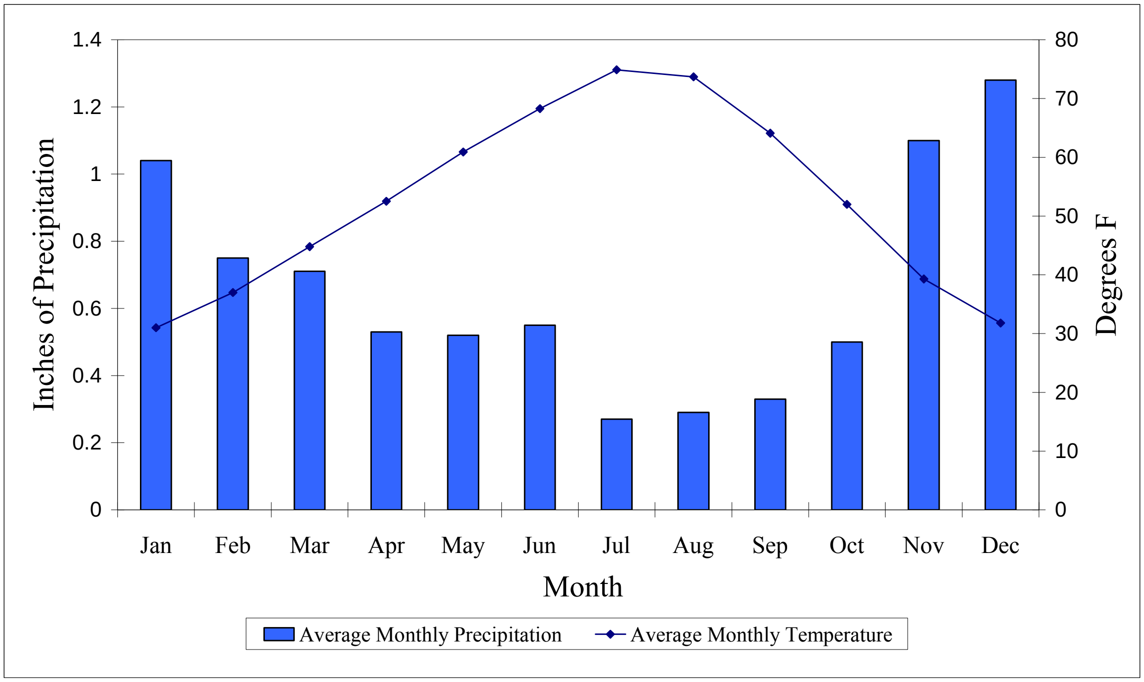
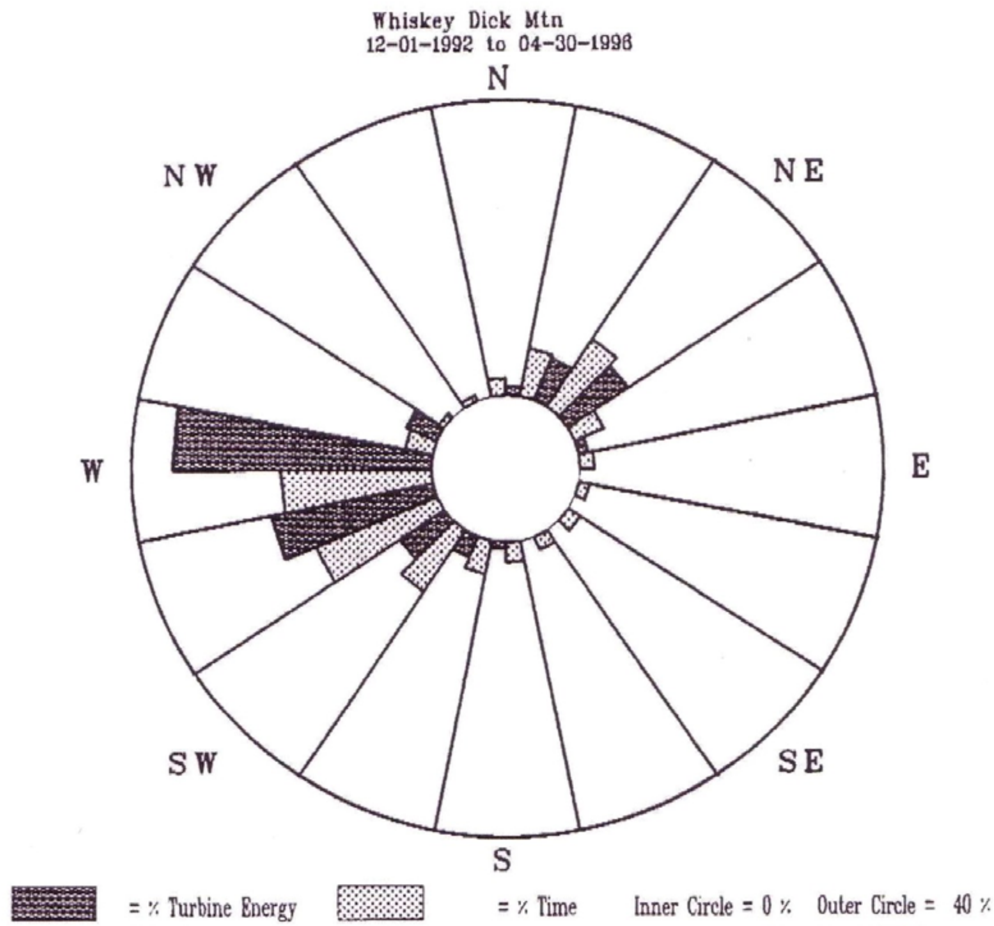


Figure 9. Climograph of Smyrna, Washington. Climograph based on precipitation and temperature data collected from 1951-2005. Smyrna lies 15 mi (24 km) southeast of Vantage in the lower Crab Creek valley. Source: Smyrna, Washington Weather Station, Western Regional Climate Center (2005).

cool Puget Maritime and hot Columbia Plateau air masses (Jones & Stokes, 2004). Local wind patterns generally result in loess deposition along north- and east-facing slopes (see Figure 10; Pavish, 1973). However, within protected tributary drainage slopes significant loess deposition can be found on south- and west-facing slopes.

Hydrology

The hydrology of the Vantage area is largely influenced by the Columbia River Valley and the north-south-trending Hog Ranch anticline. Drainage networks in the study area are dominated by west-east-trending anticline ridges and minor syncline valleys resulting in several parallel west- to east-draining tributaries including the Rocky,



Compass Direction	% Time	Mean Speed (MPH)
N 349 – 11	2.5	12.0
NNE 11 – 34	7.1	16.3
NE 34 – 56	11.9	16.4
ENE 56 – 79	4.6	10.7
E 79 – 101	2.1	7.7
ESE 101 – 124	1.5	7.9
SE 124 – 146	2.1	8.6
SSE 146 – 169	2.1	8.9
S 169 – 191	2.9	10.7
SSW 191 – 214	5.1	13.8
SW 214 – 236	11.1	14.4
WSW 236 – 259	19.2	18.9
W 259 – 281	21.9	22.6
WNW 281 – 304	4.2	18.3
NW 304 – 326	0.9	7.8
NNW 326 – 349	0.9	7.6

Source: Wind Ridge Power Partners, LLC 2004.

Figure 10. Wind direction patterns of the Whiskey Dick Mountain area. Wind data collected from 1992 through 1996 near Whiskey Dick Mountain, located 10 mi (16 km) west of the study area. Source: Jones and Stokes (2004).

Schnebly, and Ryegrass drainages (Figure 7). These small-scale intermittent streams are subject to subsurface flow regimes expressing the current semiarid character of the region. During strong cyclonic- and convection-induced storm events, high-surface flows do occur within the Vantage area. Evidence of high-flow events are documented by alluvial fans which dominate synclinal valley topography, suggesting major fluctuations in weather and climate over time (Pavish, 1973).

The climate prior to uplift of the Cascade Province likely resulted in perennial drainages that produced higher water table levels, lakes, and wetlands that provided for growth of lush broadleaf and coniferous forests (Beck, 1945). Climate research by Whitlock, Sarna-Wojcicki, Bartlein, and Nickerman (2000) indicates during the past 125,000 years the region has experienced continuous changes in climate, marked by few short-lived periods of stability. During the recent maximum of the Cordilleran Icesheet, between 20,000 and 13,000 yr BP, advancement of the Okanogan Lobe forced the Columbia River to drain south along the lower Crab Creek drainage entering the CRV in the Vantage Reach. During this time, the region began to transition from cold, dry steppe-like climatic conditions to more moderate cool, humid conditions (Whitlock et al.). This climatic transition triggered Cordilleran Icesheet ablation, resulting in rapid transfer of water from the Columbia River Basin to the Pacific Ocean via high-magnitude floods.

Substrate, Vegetation, and Wildlife

Semiarid climatic conditions caused by Cascade Range uplift had a profound impact on soil development, and resulting vegetation and wildlife. Daubenmire (1970) and Franklin and Dyrness (1973) classify the shrub-steppe vegetation of this region as part of the *Artemisia tridentata-Pseudoroegneria spicatum* (tall-sage/bluebunch wheatgrass) assocation, forming known as the *Artemisia tridentata-Agropyron spicatum* association. However, landscape-scale vegetation mapping of the park by Easterly and Salstrom (2003) identified a diverse mosaic of shrub-steppe vegetation based on substrate distribution of basalt lithosols, loess deposits, outcropping Vantage member interbeds, Pleistocene alluvial deposits, and colluvium.

Lithosols formed on Miocene basalts are the most widespread substrate. Lithosols are typically nutrient poor, shallow soils dominated by weathering basalt fragments. They are common to basalt flow tops, moderate slopes, and alluvial fan deposits. Basalt lithosols are dominated by *A. rigida-Poa secunda* (stiff-sage/Sandberg bluegrass) associations (Easterly & Salstrom, 2003).

Loess deposits are typically found on north- and east-facing slopes with occasional pockets within protected tributary valleys. They are most commonly observed as isolated islands or linear belts recognizable by variations in surface vegetation. Loess deposits are typically dominated by *A. tridentata* associations and have been found to host significant populations of microbiotic soil crusts (Easterly & Salstrom, 2003).

Outcropping Vantage member interbeds provide a sharp contrast to adjacent basalt-derived soils and are easily recognized in the field by their silty-to-sandy surface texture and banded outcrop pattern. Vantage interbeds provide ecotonal habitat by supporting a diversity of habitat structures. Interbed soils are often deep, and contain fine-grained sediments which efficiently absorb and maintain soil moisture, favoring the growth of *A. tridentata* and associated grasses and forbs. Vantage interbeds are often the source of springs which provide for growth of critical riparian vegetation such as *Populus trichocarpa* (black cottonwood) and various species of *Salix spp*. (willow; Alto, 1955).

Slackwater sediments are the principal Pleistocene alluvial deposits found in the area. These coarse- to fine-grained deposits support a mixture of species. On southern aspects *A. tridentata, Salvia dorrii* (purple sage), and *Eriogonum microthecum* (slender buckwheat) are common. Along northern aspects, *A. tridentata* and *P. spicatum* are present (Easterly & Salstrom, 2003). This pattern is also common to loess deposits on northern aspects, making their classification difficult without field observation.

Large- and small-scale colluvial (landslide) deposits are located in the study area. Colluvial sediments encompass the spectrum of substrates previously described. Vegetation associations found on colluvial deposits are variable. Colluvial substrates are commonly found adjacent to tributary stream channels and road cuts. Large-scale translational landslides in the study area exhibit deranged topography, creating a unique mosaic of irregular hydrologic and vegetation patterns.

The combination of a distinct environmental gradient between the Columbia River shoreline and basalt ridge tops and a unique mosaic of substrates provides a wide diversity of semiarid habitat for residential and migratory fauna. Low-elevation valleys and the presence of forage grasses make the area a primary food source for large ungulates. During winter months, herds of *Cervus canadensis* (elk) are found in the area, as well as *Odocoileus hemionus hemionus* (mule deer) and occasionally *Ovis canadensis* (big-horn sheep). Other notable species inhabiting the area include *Sylvilagus nuttallii* (Nuttall's cottontail), *Marmota flaviventris* (yellow-bellied marmot), and *Lepus townsendii* (white-tailed jack rabbit). Ground burrowing micro-fauna, such as the

Spermophilus townsendii (Townsend's ground squirrel) and *Peromyscus maniculatus* (deer mouse) are common to Vantage interbed and loess substrates (Kidd, 1964).

Aboriginal and Historic Land Use

The Vantage area contains evidence of human land use dating back at least 6,600 years (Munsell, 1968). Aboriginal land use of the region ranges from intense occupation of the Columbia River shoreline to seasonal use of tributary coulees and springs for travel, plant harvesting, and game hunting (Dancey, 1973).

Prior to inundation of the floodplain by Wanapum Dam, this landscape was characterized by the Vantage Bar, an extensive linear gravel bar extending 7.5 mi (12 km) in length along the western shoreline of the river. The Vantage Bar, and adjacent tributary alluvial fans, served as a strategic seasonal fishing and river crossing location until the installation of Wanapum Dam at its southern terminus was completed in 1963 (Greengo, 1982).

Salvage archaeology in the park area prior to and during construction of Wanapum Dam by Kidd (1964) and Swanson (1962) resulted in the investigation of 30 aboriginal sites along the Columbia River. Artifacts recovered from two aboriginal village sites, as well as several rockshelters and pit house structures were examined and found to indicate intermittent to intense aboriginal occupation up to the period of Euro-American contact (Kidd). In addition, an extensive petroglyph series was documented along the river shoreline north of Vantage.

Additional pedestrian surveys of Hell’s Kitchen, Hole-in-the-Wall Canyon, and Whiskey Dick Canyon were conducted by Kidd (1964) to determine associated land-use patterns of adjacent tributary drainages. Evidence of intense utilization in the Whiskey Dick Canyon area was found with a lesser degree of occupation and use evident in Hell's Kitchen and Hole-in-the-Wall Canyon (Kidd). Aboriginal sites located near Vantage and Swauk member interbeds provide evidence of stone tool production in the area, making the location desirable to resident and traveling Native Peoples (Munsell, 1968).

Aboriginal residents of the region were referred to as the *Sokulks* in the maps and journals of the 1803-1806 Lewis and Clark Expedition (Moulton, 1988). Emerson (1982) refers to the *Sokulks* as the Wanapum band residing in the greater Priest Rapids-Wanapum region. The Vantage area is situated near the historic boundary between Sahaptin and Columbia Salish territories, and is known to Wanapum and related Sahaptin speaking cultures as *pank'ú*, after a highly desired forb species, *Tauschia hooveri* (Hoover's tauschia), endemic to the Vantage region (Hunn, 2000).

Oral history of high-magnitude flooding exists within Sahaptin speaking cultures of the Columbia Plateau. The Sahaptin name for the eastern prominence of Rattlesnake Ridge, a 3,000-ft (914-m) anticline in the western Pasco Basin, is *Lalíik*, meaning "standing above the water" (Hunn, 2000, p. 17). Therefore, Sahaptin oral histories may record a late-Pleistocene flood in the Pasco Basin of the CRV.

Historic contact in the Vantage area came in July of 1811, when David Thompson of the Canadian North West Company camped along this reach of the Columbia River near the mouth of Crab Creek en route to Fort Astoria (Emerson, 1982). Within 44 years, as a result of the 1855 Yakama Treaty, Wanapum territory became part of the United States providing for the migration of miners and eventually settlers into the region.

In 1877, General Land Office surveys of the Vantage region opened the area to homesteading. Land use transitioned from aboriginal uses to sedentary livestock grazing with cultivation along the Columbia River floodplain. Livestock grazing dominated land use for nearly half a century until the area's potential as an automobile bridge crossing was realized. Construction of the Vantage Highway through Schnebly Coulee and Columbia River bridge crossing at the mouth of Rocky Coulee was completed in 1927, paving the way for existing commerce and recreational land-use patterns.

Existing Park Facilities

In 1927, Dr. George Beck of Central Washington College discovered a significant collection of petrified logs exposed during construction of the Vantage Highway. The presence of the rare Ginkgo specimen and exceptional diversity of fossil log specimens in the area prompted the state of Washington to purchase an initial 10 acres of fossil bed in 1931. After an unsuccessful attempt to develop the site as a National Monument, the land preserve became a state park in 1935.

Federal Civilian Conservation Corps enrollees stationed at Camp Ginkgo developed the park's interpretive facilities. The enrollees constructed the northern portion of the existing interpretive center, as well as the Petrified Forest Interpretive Trail and Vista House (roadside museum) located 2 mi (3.2 km) west from the Columbia River via the Vantage Highway (State Route 10). The park opened to the public in 1938, and through subsequent land acquisitions in 1948, 1959, 1963, and 1971, the park expanded to a contiguous 7,027 acres.

In 1953, the interpretive center was renovated to include more exhibit space and parking. A second renovation of the interpretive center in the early 1960s included replacement of exhibits, the addition of the exterior Wanapum petroglyph exhibit, and expansion of day use facilities. The park was dedicated as a registered National Natural Landmark in October of 1965. During the mid-1980s the interpretive center received its third renovation, which produced the majority of existing interpretive themes and exhibits.

CHAPTER IV

METHODS

Research methodologies were established through literature review of regional and landscape-scale documentation of Pleistocene flooding. To carry out the objectives of this thesis, the following methods were employed from January 2005 through March 2006: (a) topographic map, aerial photography, and field reconnaissance; (b) field survey of high water indicators and flood feature distributions; (c) field measurement of ice-rafted erratics; (d) quantitative analysis of ice-rafted erratic variables; (e) geomorphic mapping of study area landforms; (f) interpretation of flood and landform feature relations; and (g) identification of IAF interpretive opportunities and recommendations.

Topographic Map, Aerial Photography, and Field Reconnaissance

The initial phase of this inquiry involved 1:24,000 scale topographic map and aerial photography analysis of study area landforms. Aerial photography was analyzed using a pocket stereoscope. Two flights of aerial photography were used: (a) Kittitas County, Washington, 1942 black and white, 1:20,000 scale; and (b) Washington Department of Natural Resources 1984-85 natural color, 1:12,000 scale (Kittitas County, 1942; Washington State Department of Natural Resources, 1984, 1985). The study area was examined for the presence of Pleistocene flood landforms and features. Evidence of high water indicators, such as ice-rafted erratics, was not visible due to limits of image scales. Therefore, pedestrian field reconnaissance was conducted to investigate landforms and flood features not identifiable during aerial photography analysis. The presence of channel and slackwater deposits were noted and field sampling objectives established.

Field Survey of High Water Indicators and Flood Feature Distribution

The second phase of this inquiry involved the systematic field survey of high water indicators and distribution of Pleistocene flood features. United States Coast and Geodetic Survey benchmarks were used to verify Global Position System (GPS) coordinates and elevation accuracy.

High Water Indicators

A preliminary pedestrian field survey was conducted between 1,500 ft (457 m) and 1,000 ft (305 m) to identify potential shorelines and ice-rafted erratic high water indicators (Baker, 1973). The absence of erosional and depositional shorelines prevented their use as high water indicators. Therefore, erratics were used as high water indicators. Due to abundant indigenous basalt, erratics were identified by the surface presence of crystalline and other nonbasalt rock types.

Following methods employed by Dunbar (1998), a systematic survey of erratics was conducted below 1,300 ft (396 m) to determine the extent of flooded terrain (see Figure 11). Erratics smaller than 4 in. (10 cm) in length and width were not documented due to their potential anthropologic transport (hand-held size) and to maintain field survey efficiency. To determine the maximum elevation of flooding, a detailed elevation survey of the two highest erratics identified was conducted using Topcon® Geodetic Total Station (GTS) survey equipment and a benchmark datum point of 894 ft (272.5 m).

Flood Feature Distribution

Based on results from initial topographic map, aerial photography, and field reconnaissance, a landscape-scale pedestrian survey of study area landforms was

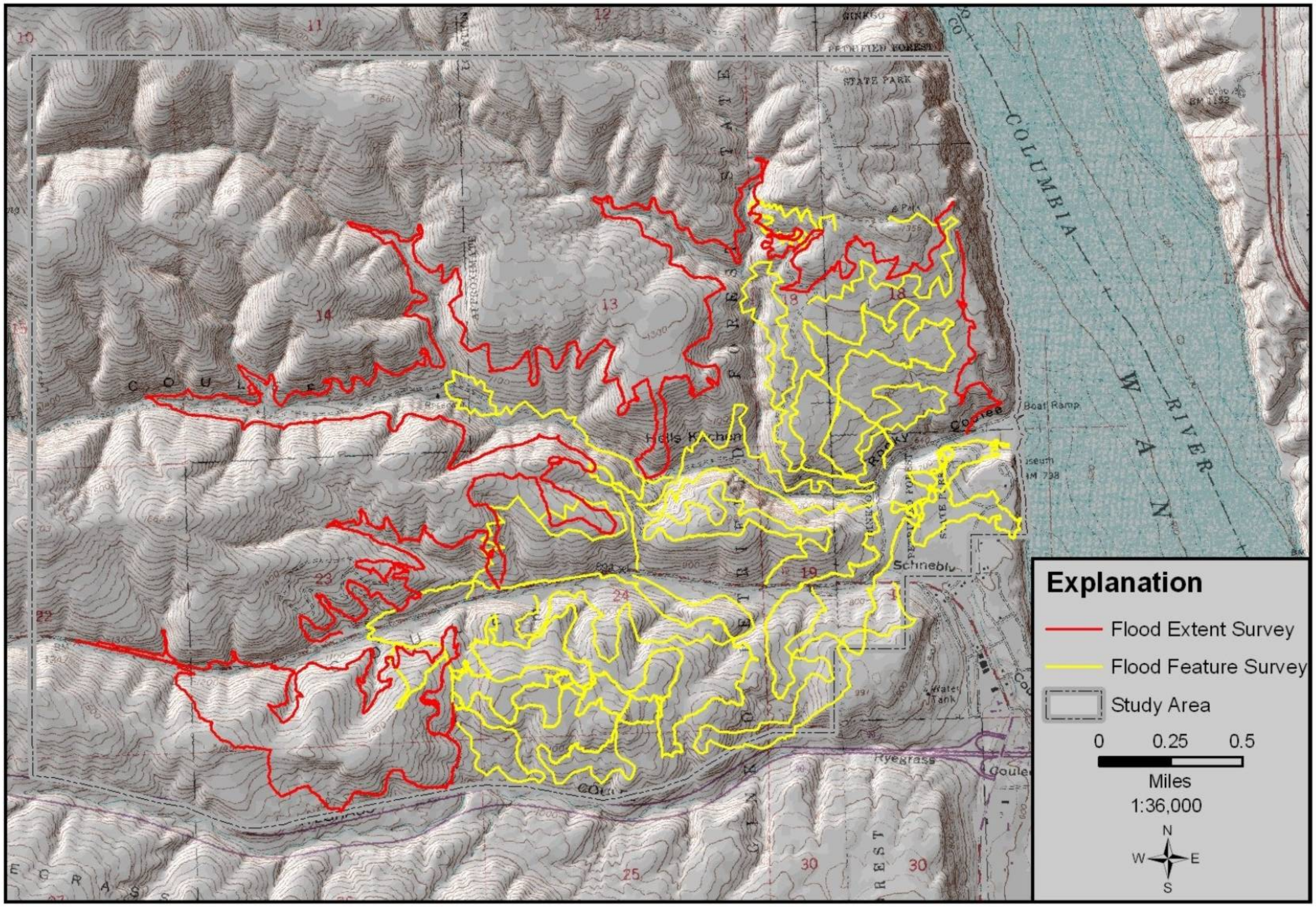


Figure 11. Pedestrian survey routes developed to identify the extent of Pleistocene flooding and distribution of flood features.

conducted outside known Holocene alluvial deposits mapped by Bentley, Campbell, and Powell (1993) to determine the spatial distribution of Pleistocene flood deposits. The sampling design incorporated a stratified approach based on study area landform elevation, aspect, and slope angle (Figure 11). Depositional features were classified as flood channel or slackwater deposits based on criteria developed by Bretz (1928, 1930), Baker (1973), Waitt (1980), and Bjornstad et al. (2003).

Flood Channel Deposits

Exposures of study area landforms were surveyed for presence of floodbar deposits. Identification of floodbar deposits was based on deposit composition, morphology, and orientation to the Columbia River channel. The location, elevation, stratigraphy, and extent of floodbar deposits were documented using topographic maps, 1:12,000 scale natural color aerial photographs, and digital photographs. The topographic site, situation, and extent of floodbar deposits were used to identify potential upvalley slackwater deposits (Baker, 1973; Fryxell & Cook, 1964).

Slackwater Deposits

Study area landforms were surveyed for the presence of fine-grained sediments associated with upvalley tributary flooding, as well as erratics stranded during recession of pooled floodwaters. Identification of slackwater sediments was based on the presence of bedded sand- and silt-grained rhythmites and crystalline sands, gravels, and boulders. Universal Transverse Mercator (UTM) coordinates and elevation of slackwater deposit exposures were determined using a Trimble® GPS receiver and Terra Server® software (Microsoft, 2004).

Field Measurement of Ice-Rafted Erratics

The third phase of this inquiry involved detailed measurement of ice-rafted erratics encountered during field surveys. This research focused on spatial distribution of erratics for two primary reasons: (a) ice-rafted erratics were the most abundant flood deposit available for analysis; and (b) analysis of their frequency, density, size, and topographic orientation can be used to evaluate behavior of channel and slackwater flood processes (Bjornstad et al., 2003).

UTM coordinates and elevation of erratics were determined using a Trimble® GPS receiver and Terra Server® software (Microsoft, 2004). Following erratic documentation methods developed by Bjornstad et al. (2003), erratic length, width, and lithology measurements and observations were recorded. Erratic length and width were determined using a measuring tape. Lithology was determined using personal observation and the *National Audubon Society Field Guide to North American Rocks and Minerals* (Chesterman, 1978). Slope aspect was determined using a Brunton Pocket Transit. The surface exposure of each erratic was determined by field observation of the surrounding soil/surface. Erratics were classified as partially buried if soil or any depositional material prevented observation of the erratic atop the ground surface.

Classification of erratics was determined using a field key developed for this project (see Figure 12). Field key variables were modified from methods employed by Bjornstad et al. (2003). Line-intercept transects were established at the perimeter of each identified erratic. Deposits with a line-intercept frequency of two or more erratics within a 3-ft (0.3-m) radius were further classified by cluster density and presence of topographic (bergmound) relief.

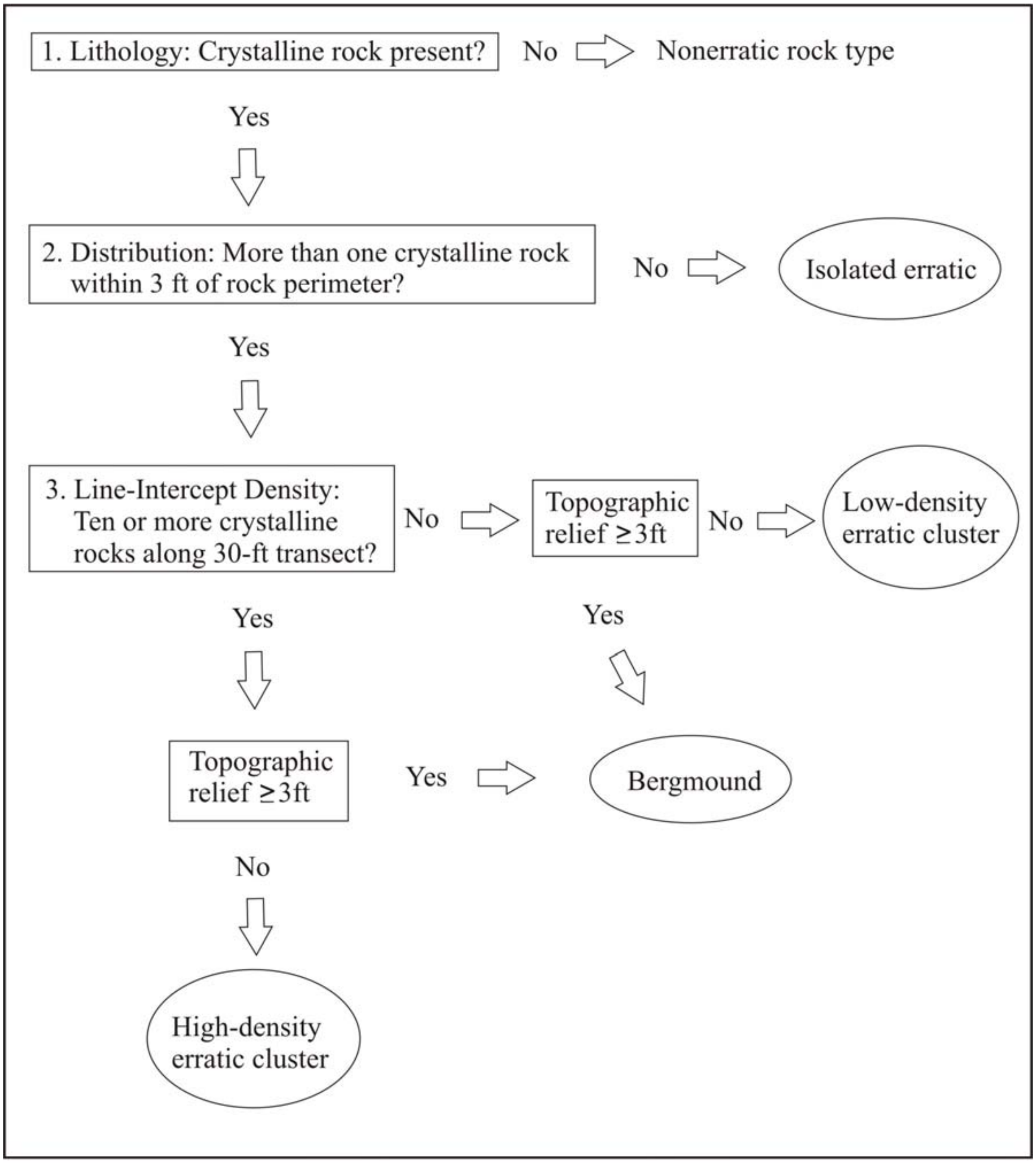


Figure 12. Field key to ice-rafted erratic classification in Ginkgo Petrified Forest State Park. Transect intervals of 3 ft (0.9 m) used in the delineation of low- and high-denisty erratic deposits.

Maximum diameter and surface area calculations of high-density erratic cluster and bergmound deposits were determined using line-intercept transects. For each high-density erratic cluster and bergmound deposit 12 transects, at 30º intervals, were conducted from a random midpoint. Deposit boundaries were delineated based on the absence of a line-intercept frequency of at least two erratics per 3-ft (0.3-m) interval. Boundary and midpoint coordinates were recorded using a Trimble® GPS receiver.

Geographic Information Systems (GIS) methods were used to determine the slope angle of each erratic deposit. A slope identification map, using slope degree mapping units, was developed using a 10-m digital elevation model (DEM). The slope angle of each erratic deposit was determined using ArcGIS 9.1® software (ESRI, 2004).

Quantitative Analysis of Ice-Rafted Erratic Variables

The fourth phase of this inquiry involved statistical analysis of nominal datasets collected during high water indicator and flood feature distribution field surveys of ice-rafted erratics. Survey datasets were used to evaluate the probability of random relations of each variable sample, as well as between individual erratic variables. Datasets were further classified into elevation, aspect, slope angle, size, and erratic type classes to conduct chi-square analysis. One sample and two sample chi-square tests were used to identify significant relations between erratic elevation, aspect, slope angle, classification type, size, and surface exposure variables. A significance level of 0.05 and corresponding confidence level of 95% was established as the basis for null hypothesis rejection and alternative hypothesis acceptance. The null hypotheses established all possible variable relations as random. In addition, Cramer's *V* relationship strength tests were conducted to evaluate variables found to be significantly related (nonrandom) during chi-square analysis. A Cramer's *V* test interpretation scale was established, with weak relationship strengths ranging from 0.0 and 0.20, moderate ranging from 0.21 to 0.50, and strong ranging from 0.51 to 1.0.

Geomorphic Mapping

The fifth phase of this inquiry involved development of a geomorphic map to exhibit landform distribution and to interpret landform relations to Pleistocene flood deposits. Study area landform delineation was conducted using field, aerial photography, and GIS datasets. Study area landforms were identified and classified using a 10-m DEM, aerial photography interpretation, and field survey documentation (Lillquist, 2001). Geomorphic mapping units were developed based on landscape position, slope angle, dominant geomorphic processes, and the relative surface age of study area landforms. The relative ages of surfaces were determined based on the initiation of dominant geomorphic processes acting on the landform in relation to Pleistocene flooding. Therefore, pre-Pleistocene, Pleistocene, and post-Pleistocene relative age classes were developed. Pre-Pleistocene surfaces were determined based on their elevation outside known Pleistocene flood terrain. Pleistocene surfaces were determined based on their known elevation within Pleistocene flood terrain and evidence of flood features. Post-Pleistocene surfaces were determined based on evidence of active Holocene erosion or deposition such as physical weathering, eolian or fluvial processes.

Interpretation of Flood and Landform Feature Relations

The sixth phase of this inquiry involved interpretation and summary of relations between flood and landform topographic features. Observation and documentation of the extent and spatial distribution of flood and study area topographic features provided a basis for interpretation of Pleistocene flood processes within the study area.

Maximum Extent of Flooding Terrain

A GIS map conveying the maximum extent of Pleistocene flooding within the study area was developed based on flood extent survey data and GTS elevation survey data of the two highest ice-rafted erratic UTM coordinates. All erratic deposit UTM coordinates obtained during surveys were projected into 1927 North America Datum using GPS Pathfinder Office 3.0® (Trimble Navigation Limited, 2005).

Flood Feature Spatial Distribution Mapping

The distribution of flood channel and slackwater features was documented using UTM coordinates projected into 1927 North American Datum (Trimble Navigation Limited, 2005). These data were used to develop three thematic GIS maps. First, a map conveying spatial distribution of flood channel and slackwater rhythmite deposits was developed based on survey GPS data. Deposits were plotted by channel (polygon) and slackwater (single-data point) mapping units. Second, a map conveying the spatial distribution of ice-rafted erratic deposits by classification type was developed using point mapping units. Third, a map conveying the spatial orientation of high-density erratic cluster and bergmound deposits was developed.

Interpretation of Flood Processes

Relations between Pleistocene flood deposit and topographic features found to be statistically significant were identified and summarized. Maximum flood extent, flood deposit distribution, and geomorphic map unit GIS data layers, as well as field evidence were used to interpret and summarize the nature of flood processes within the study area.

Ice Age Floods Interpretive Opportunities and Recommendations

The final phase of this inquiry involved the identification of interpretive goals, themes, and opportunities to convey findings of this research to the public. A hierarchy of interpretive goals and objectives was established based on the identification of known and potential parameters influencing park interpretation. Potential IAF thematic messages conveying the results of this inquiry were developed based on desired outcomes from visitor exposure to interpretive media (Ham, 2003).

Interpretive Opportunity Development

Visitor (audience) analysis was conducted using park visitation records and park staff interviews to assess user groups, seasonal frequency of park attendance, and potential for regional increases in visitor use. Based on the location and demand for existing park services, interpretive media and facilities, and accessibility of viewsheds, a network of interpretive opportunities comprised of orientation, interpretive hub, and story point sites was established to effectively communicate IAF interpretive messages. WSPRC resource preservation policies were reviewed to assure compliance and assess resource vulnerability to development recommendations.

Interpretive Media Recommendations

Recommendations for interpretive media were developed based on the goals and desired outcomes of IAF interpretation. Interpretive media prescriptions were developed for the primary components of the proposed interpretive network. Design, fabrication, installation, and maintenance variables were identified and recommendations made based on known interpretive parameters. Steps toward implementation of the IAF interpretive network were developed including prioritization and cost estimates for proposed projects.

CHAPTER V

RESULTS AND DISCUSSION

Maximum Extent of Pleistocene Flooding

The highest ice-rafted erratic identified during this inquiry was surveyed at an elevation of 1,263 ft (385 m). Using this erratic as a high water indicator, it can now be inferred that during at least one high-magnitude flood event, floodwaters containing icebergs reached an elevation of at least 1,263 ft (385 m). The elevation of the paleo-Columbia River in the Vantage Reach was approximately 480 ft (146 m). Using this elevation as an approximate baseline, it can be inferred that during the Pleistocene the study area was inundated to a maximum water depth of at least 783 ft (238 m), approximately 690 ft (210 m) above the existing Wanapum Dam reservoir level (see Figure 13). In addition, erratics were observed 3.5 mi (5.6 km) up the Schnebly Coulee drainage, indicating icebergs drifted at least this distance from the Columbia River.

This research extends the known maximum extent of Pleistocene flooding in the Vantage Reach by 36 ft (11 m), based on Cochran's (1978) estimate of 1,227 ft (374 m). Moreover, this research updates previous research by Baker (1973) and Dunbar (1998), who estimated the maximum extent of flooding in the Vantage Reach at 1,200 ft (365 m). This adjustment in maximum extent of flooding will be most useful in the employment of future Pleistocene flood hydraulic analysis involving the Vantage Reach and the CRV.

The maximum extent of flooding determined by this research indicates hydraulic pooling behind Sentinel Gap produced slightly higher pool elevations than the 1,250 ft (380 m) maximum extent of Pleistocene flooding reported by Baker et al. (1991) and

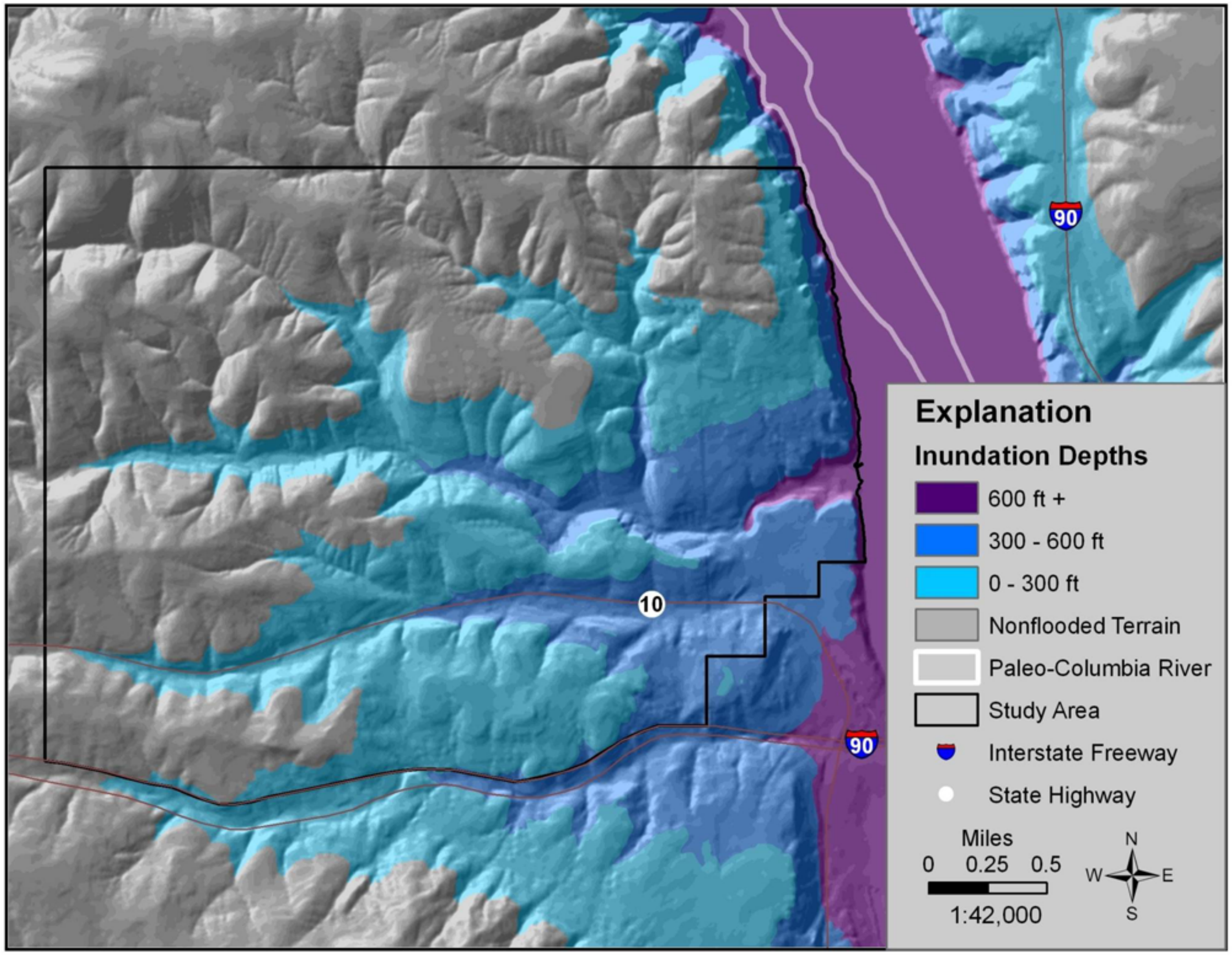


Figure 13. Map of maximum Pleistocene flood inundation levels in a portion of Ginkgo Petrified Forest State Park. Note the paleo-channel of the Columbia River at 480 ft (146 m). The 783 ft (239 m) maximum height of floodwater is based on an ice-rafted erratic surveyed at 1,263 ft (385 m).

Bjornstad et al. (2006) in the Pasco Basin. This research contributes to the hypothesis that hydraulic pooling behind constrictions in the CRV produced a series of inundated basins as floodwaters descended to the primary constriction in the CRV at Wallula Gap (Bjornstad et al.). However, the approximate 13-ft (4-m) variation in maximum elevations of pooled floodwaters behind Sentinel Gap and Wallula Gap is not sufficient to indicate a distinct, temporary glacial lake occupied the Vantage Reach. Therefore, it is likely that glacial Lake Lewis, derived from pooled floodwaters behind Wallula Gap, extended spatially into the study area. Furthermore, it is plausible the constriction at Sentinel Gap enhanced development of low-energy currents within the study area while producing high-energy currents entering the adjacent Pasco Basin.

Spatial Distribution of Pleistocene Flood Deposits

Pedestrian surveys of the topographic variables of elevation, aspect, and slope angle resulted in the landscape-scale documentation of flood channel and slackwater flood deposits. It should be noted that, due to inundation from the Wanapum Dam, the lower 90 ft (27 m) of the CRV in the study area is now submerged. Investigations in the Vantage Reach prior to construction of Wanapum Dam by Bretz (1930) and Fryxell (1962) reported Pleistocene flood evidence that could not be addressed in this inquiry.

Flood Channel Deposits

Flood channel deposits accessible in the study area were limited to elevations < 800 ft (244 m). These data indicate the extent of identifiable subfluvial bar deposition in the study area occurred within the lower 300 ft (91 m) of floodwaters entering the Vantage Reach along low-angle tributary valleys and interfluves.

The occurrence of coarse, angular bar material reported at elevations near 1,000 ft (305 m) in Schnebly Coulee by Bretz (1930) was investigated. Test pits were conducted at approximately 40-ft (12-m) elevation intervals (see Figure 14). Near 1,100 ft (335 m), within an adjacent Ryegrass Coulee tributary, the presence of slackwater rhythmites was observed underlying angular basalt gravels (see Figure 15). In addition, ice-rafted erratics were observed on the surface of this deposit. The presence of slackwater deposits suggests these angular gravels are related to Pleistocene flood processes. However, sorted materials, crystalline fragments, and clean basaltic sand lenses reported by Bretz (1930) were not observed in the deposit. Therefore, these angular basalt gravels were interpreted as fluvial transported weathered bedrock or slope wash.

A northeast- to southwest-trending modified eddy bar deposit was documented between 700 ft and 740 ft (213 m and 226 m) along a low-angle interfluve bench separating the mouths of Schnebly and Rocky coulees (Figure 14). The total length of this flood bar is approximately 0.75 mi (1.2 km) with a width of 0.25 mi (0.4 km). The margins have been incised by subsequent down cutting in Schnebly and Rocky coulees.

This flood bar was classified as a modified eddy bar based on its location, nature of composition, and identifiable lateral gradation from channel to slackwater deposits upvalley. It is comprised of poorly sorted material ranging in size from large boulders to fine-grained sand. Fine-grained, rhythmically bedded sediments can be traced from the bar deposit through upvalley stream cuts for a distance of 1 mi (1.6 km) up to an elevation of 1,000 ft (305 m). No evidence of foreset bedding was observed as would be expected within a pendant bar. The surface of the deposits lacks noticeable channeling common to expansion bars. In addition, the stratigraphy of the deposit is not consistent

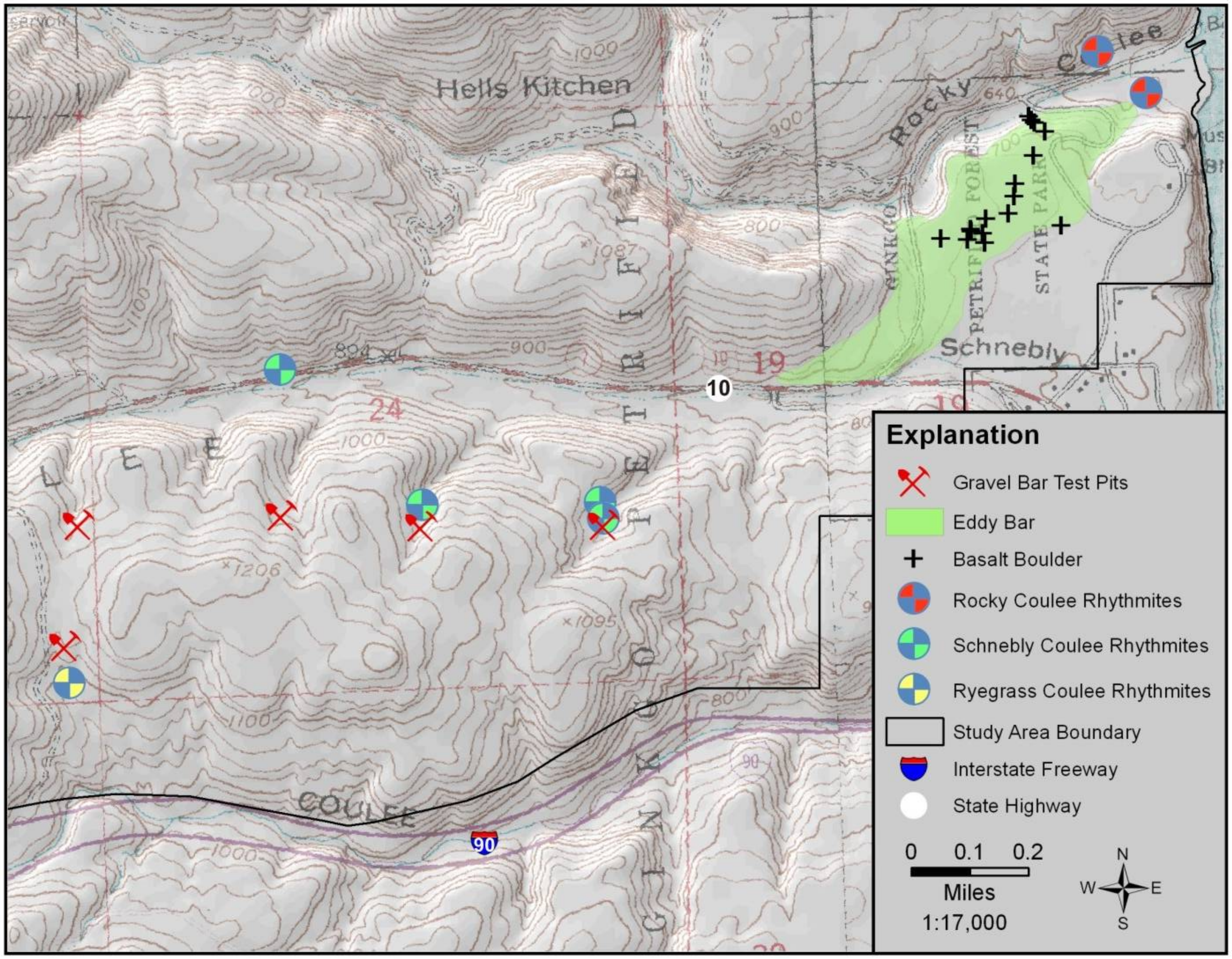


Figure 14. Distribution of flood channel deposits and slackwater rhythmite exposures in a portion of Ginkgo Petrified Forest State Park. Note the location of channel gravel bar deposit test pits.

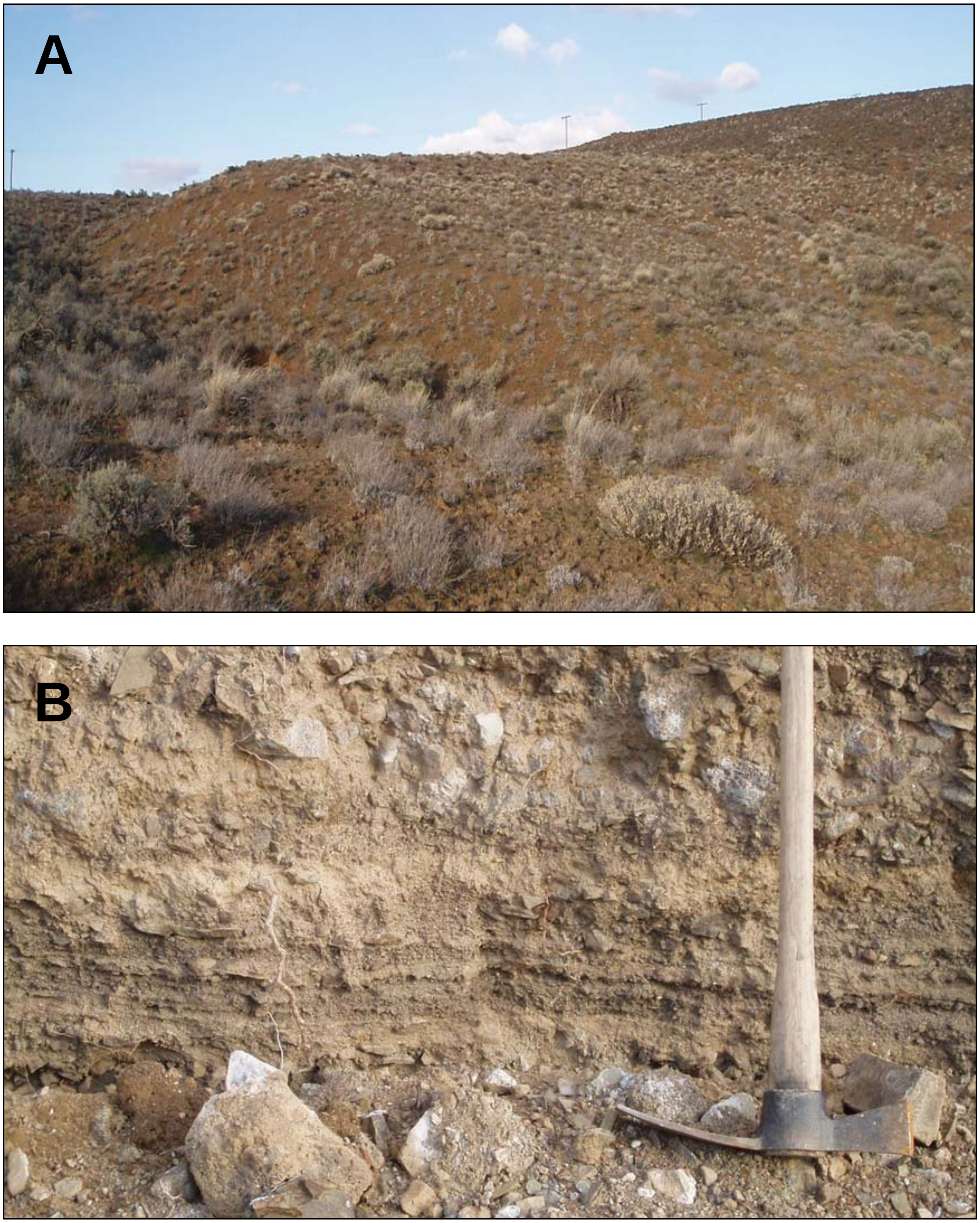


Figure 15. Angular basalt deposit overlying mixed-grained rhythmites in Ryegrass Coulee. Part A provides a view of the angular basalt deposit looking north. Note the telephone poles in distance for scale (approximately 30 ft/10 m in height). Part B provides a close-up view of mixed-grain (basaltic and crystalline) rhythmites underlying angular gravel deposit near 1,100 ft (335 m).

with the coarse-to-fine upward succession of sediment associated with expansion bars.

The top 22 ft (6.7 m) of the eddy bar was examined within a road cut on the Old Vantage Highway and classified into three units (see Figure 16). Unit 1, the top 31 in. (78 cm), was comprised of poorly bedded mixed-grain (basaltic and crystalline) sand and silt. Unit 1 was underlain by Unit 2's 14 ft-7 in. (4.5-m) layer of poorly sorted boulders, cobbles, gravels, and sands comprised of basaltic, crystalline, and silt-clast materials. The lowest unit, Unit 3, was comprised of mixed-grained basaltic and crystalline rhythmites. The total depth of this unit was not determined; however, the upper 57 in. (146 cm) contained 37 rhythmite couplets ranging in width from 5 in. to 0.2 in. (13 cm to 0.5 cm).

This eddy bar classification is consistent with the site, situation, and stratigraphy of an eddy bar examined by Fryxell and Cook (1964) at the mouth of the Tucannon River along the southeast Washington's Snake River valley. Both deposits have an upper unit comprised of poorly sorted material underlined by rhythmically bedded basaltic and crystalline sand couplets that grade to fine-sand couplets upvalley. The presence of silt-clast boulders comprised of sedimentary material was reported in both eddy bars. If normal stream processes were responsible for these deposits, silt-clast boulders could not have mixed and settled uncompromised in surface flow regimes necessary to transport large (> 9ft²/0.04 m²) basaltic boulders.

The surface of the eddy bar contains no less than 15 basalt boulders measuring a minimum of 36 ft² (3.4 m²) in exposed cross-sectional area (see Figure 17). The largest of the 15 basalt boulders has an exposed cross-sectional area of 168 ft² (15.6 m²). The majority of these boulders consist of Frenchman Springs basalt; however, at least one is comprised of Rosa basalt (see Figure 18). Both types of basalt are abundant in the

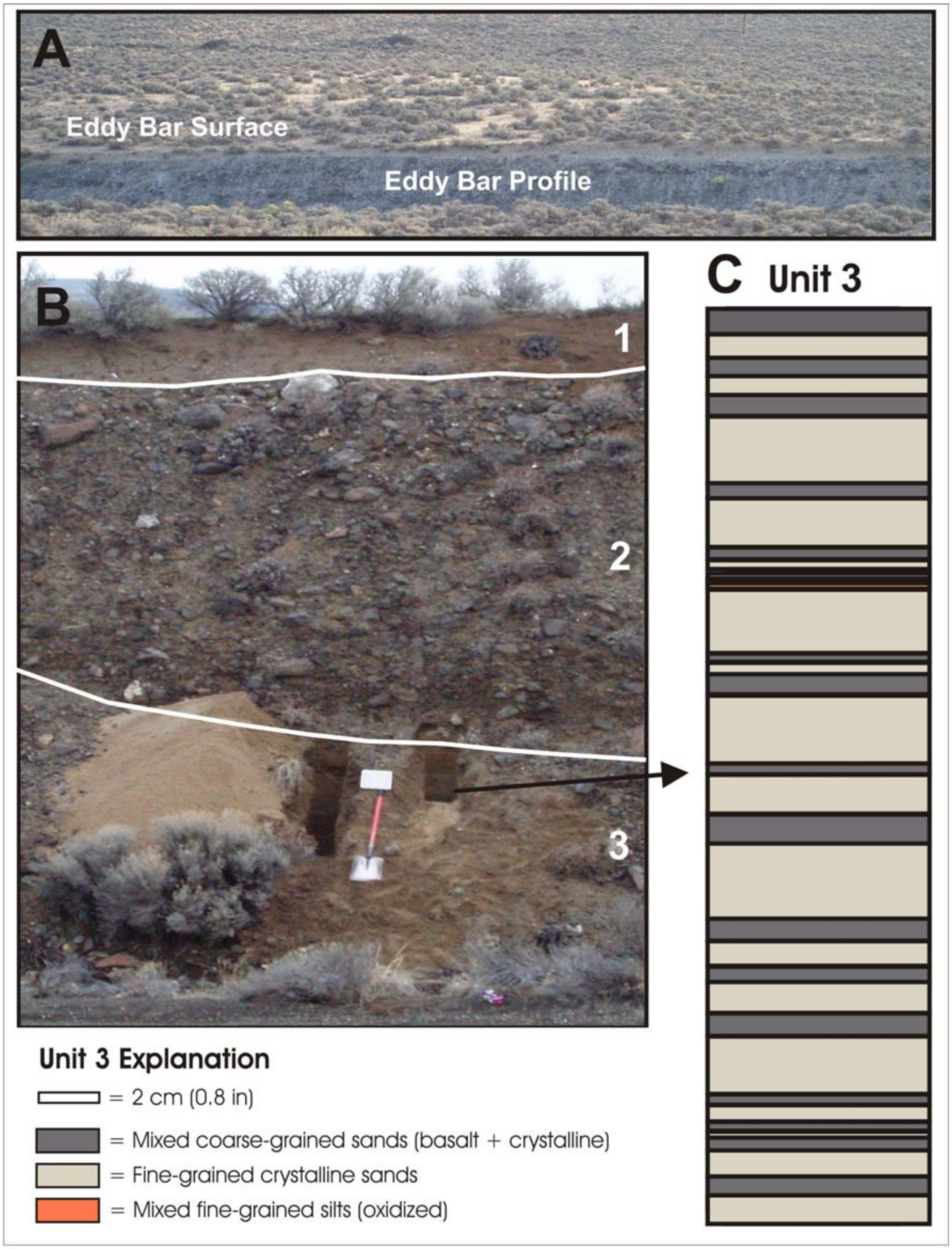


Figure 16. Pleistocene eddy bar profile and stratigraphic description. Part A: oblique view of eddy bar deposit looking east. Part B: stratigraphic units (1) poorly bedded mixed-grained sand and silt, (2) poorly sorted boulders to gravels, and (3) rhythmically bedded basaltic and crystalline sands. Part C: detailed stratigraphy of Unit 3.

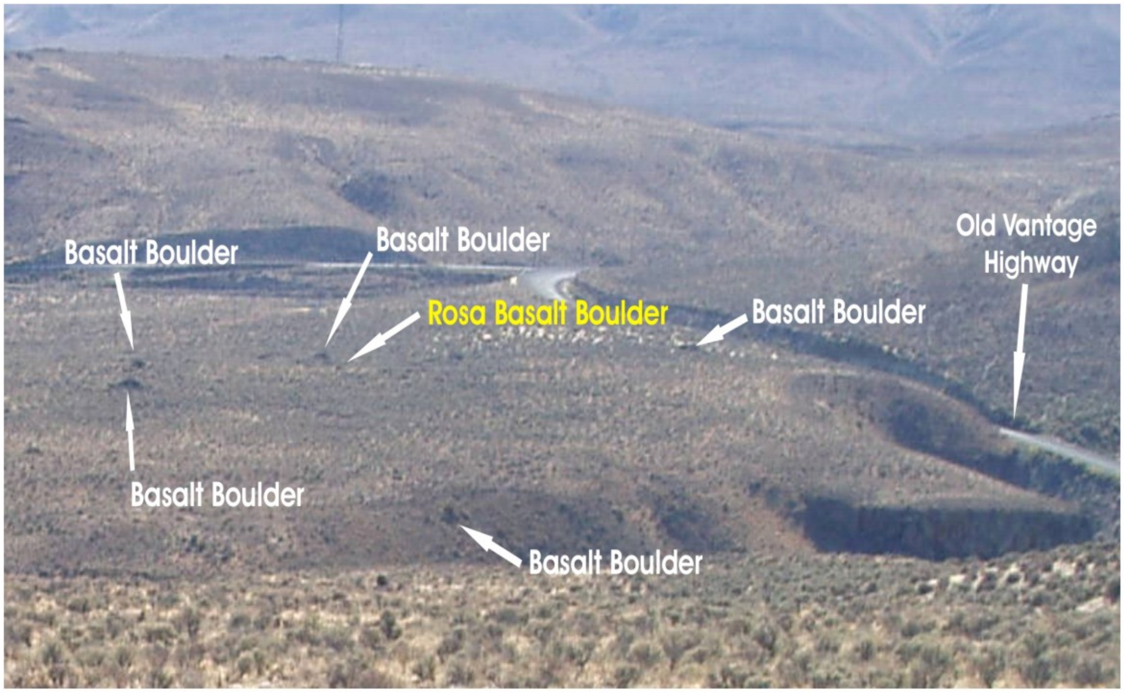


Figure 17. Oblique view looking southwest at basalt boulders on surface of modified eddy bar deposit. Note Rosa basalt boulder in center of photograph.

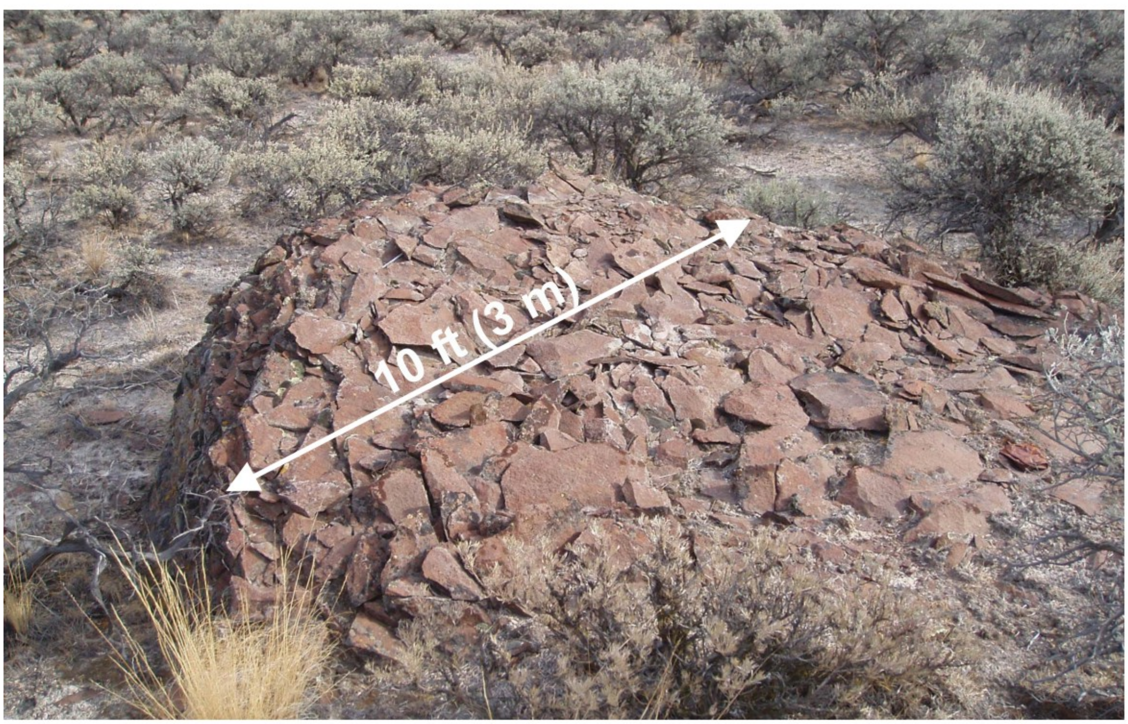


Figure 18. Erratic Rosa basalt boulder on surface of modified eddy bar deposit.

study area; however, the nearest Rosa basalt outcrop is nearly 1 mi (1.6 km) to the southwest. Their isolation on the surface of an eddy bar away from adjacent toe-slopes indicates either (a) the basalt boulders were transported locally via rock fall or landslide and traveled northwest 0.33 mi (0.53 km) to 1.0 mi (1.6 km) along a flat eddy bar surface, (b) the Frenchman Springs basalts are residual features of the basalt bench and the Rosa basalt boulder was transported to the surface via flood currents, or (c) the basalt boulders originated from the Frenchman Gap vicinity and were deposited as bedload by exiting high-energy flood currents. Due to the site and situation of these boulders, located < 300 ft (91 m) above the Columbia River channel bed, and the presence of the Rosa basalt boulder, the latter hypothesis is favored.

This inquiry is consistent with previous research in the Vantage Reach by Cochran (1978) and Dunbar (1998) in the reporting of Pleistocene flood channel deposits. The presence of a 1.9 mi (3 km) eddy bar was reported by Cochran in Johnson Creek to an elevation of 1,150 ft (351 m), approximately 350 ft (107 m) higher and over 1 mi (1.6 km) larger in extent than reported within. Dunbar reported an eddy bar in an unnamed tributary south of Johnson Creek up to an elevation of 1,060 ft (323 m), approximately 260 ft (79 m) higher than reported within. Furthermore, unreported gravel bars are visible along the eastern slope of the CRV, opposite the study area, up to approximately 1,100 ft (335 m).

The cause for variation in the extent of floodbar deposition between the study area and nearby tributaries in the Vantage Reach is not known. Subsequent Pleistocene flooding, Holocene down-cutting, and the construction of State Route 10 in the 1920s through Schnebly Coulee has altered the eddy bar reported within, and its extent may be underestimated based on the lack of remaining field evidence. Another potential source for this variance is the methodology used to delineate flood channel from slackwater deposits. Rhythmites exposed in the study area up to 1,000 ft (305 m) were interpreted as upvalley extensions of the eddy bar observed in the Schnebly drainage. However, the extent of poorly sorted boulder to gravel deposits has been used to delineate channel (eddy) from slackwater deposits. Neither Cochran (1978) nor Dunbar (1998) report stratigraphic criteria used to delineate flood channel from slackwater deposits.

Slackwater Deposits

Slackwater deposits were the most abundant form of Pleistocene flood evidence found throughout the study area. This abundance indicates low-energy currents associated with slackwater deposits dominated flood processes acting in the study area. Two distinct types of slackwater deposits were observed. The most common were ice-rafted erratics. Less common were slackwater facies, such as outcrops of rhythmically bedded sands and silts and broad expanses of surface crystalline sands.

Ice-Rafted Erratics

Ice-rafted erratics were easily visible in the field due to a lack of extensive groundcover and the contrast of crystalline minerals with the indigenous basalt. Figure 19 summarizes the spatial distribution of ice-rafted erratic deposits encountered within the study area. A total of 337 erratic deposits were sampled and classified into four distinct types (Figure 12). Significant patterns were found within the distribution of erratic deposit types (see Appendix A). The most common type of deposit was isolated erratics, making up 57% of the sample (see Figure 20). Low-density erratic clusters were also common, making up 39% of the sample. Less common, yet more substantial in number

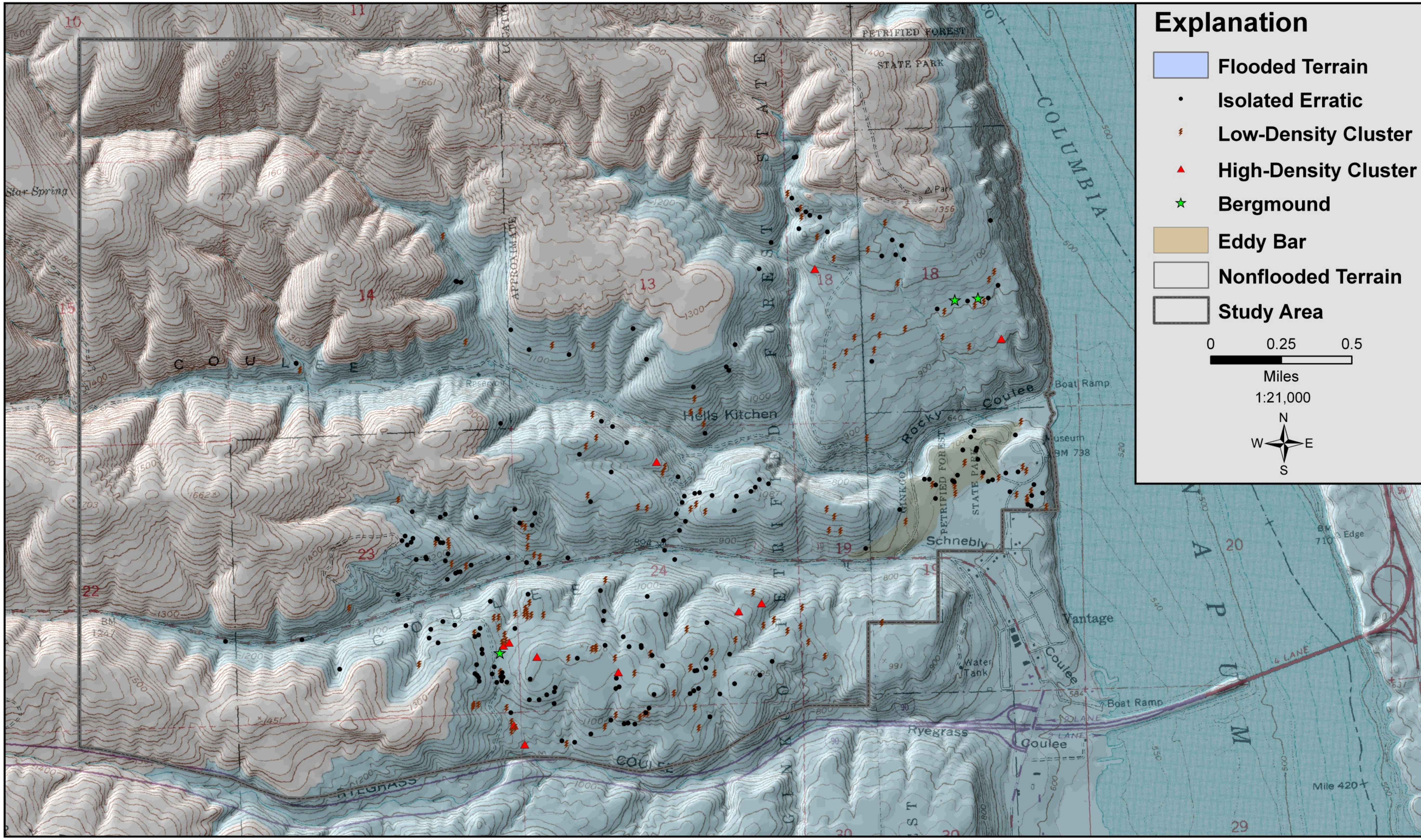


Figure 19. Distribution map of ice-rafted erratic deposits in Ginkgo Petrified Forest State Park.

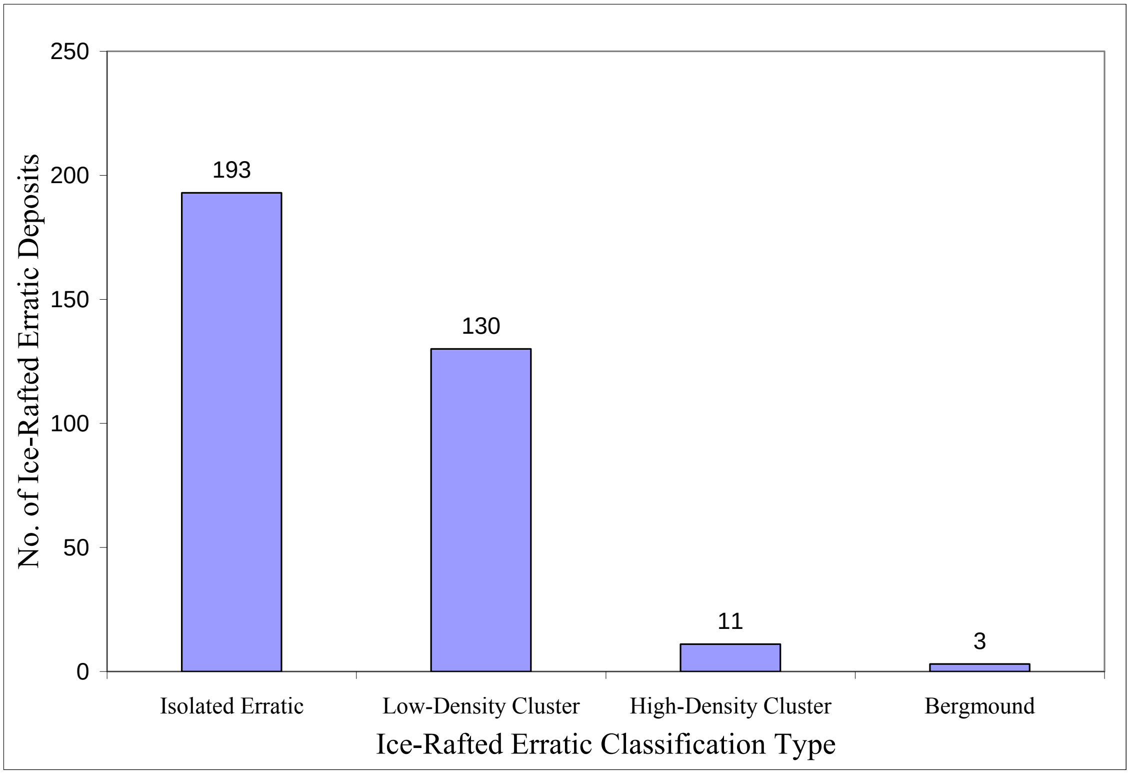


Figure 20. Frequency of ice-rafted erratic deposit classification types in Ginkgo Petrified Forest State Park. $N = 337$.

of individual erratics, were high-density erratic clusters and bergmounds making up the remaining 4% of the sample, 3% and 1%, respectively. Due to the common occurrence of isolated and low-density erratic clusters throughout the Channeled Scabland, the study concentrated on providing detailed examination of the unique high-density cluster and bergmound deposits (see Figure 21).

Eleven high-density erratic clusters were documented with a maximum diameter of 95 ft (29 m) and surface area of 2,885 ft^2 (268 m^2). The highest high-density erratic cluster was surveyed at 1,218 ft (371 m) with a maximum diameter of 61 ft (18.5 m) and a 1,593-ft^2 (148-m^2) surface area (see Table 1). Three bergmound deposits were documented with a maximum diameter of 73 ft (22.3 m) and surface area of 2,982 ft^2

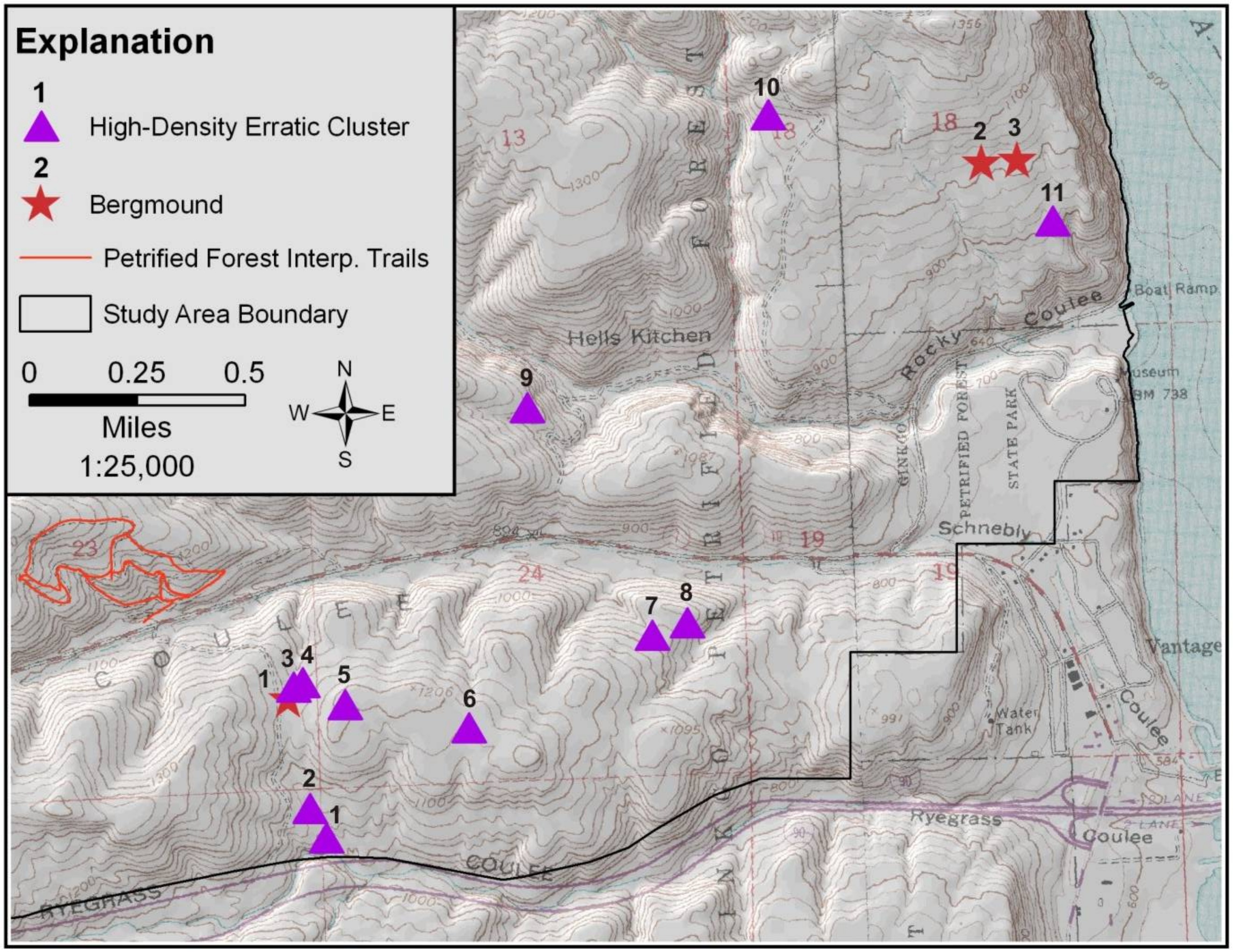


Figure 21. Distribution of high-density erratic cluster and bergmound deposits in Ginkgo Petrified Forest State Park. Note the clustering of deposits near the Ryegrass-Schnebly divide, as well as in the vicinity of the Columbia River channel. See Table 1 for description of each numbered deposit. Interp. = interpretive.

Table 1

High-Density Erratic Cluster and Bergmound Topographic Variables

Deposit type and number	Elevation		Maximum diameter		Surface area		Drainage location (coulee)
	(ft)	(m)	(ft)	(m)	(ft²)	(m²)	
High-density erratic cluster							
1	1,038	316	42	12.8	1,238	115	Ryegrass
2	1,068	326	43	13.2	1,389	129	Ryegrass
3	1,154	352	43	13.1	1,184	110	Schnebly
4	1,155	352	75	22.9	2,271	211	Schnebly
5	1,218	371	61	18.5	1,593	148	Ryegrass
6	1,194	364	73	22.2	2,885	268	Ryegrass
7	979	298	54	16.7	1,539	143	Schnebly
8	972	296	95	29.0	2,820	262	Schnebly
9	1,025	312	56	16.8	1,701	158	Rocky
10	1,105	337	48	14.6	1,270	118	Rocky
11	917	280	44	13.5	1,335	124	Rocky
Bergmound							
1	1,162	354	73	22.2	2,982	277	Schnebly
2	1,031	314	46	14.1	1,528	142	Rocky
3	1,030	314	69	21.0	2,885	268	Rocky

(277 m²). The highest bergmound was surveyed at 1,162 ft (354 m). This high bergmound also possessed the largest diameter and surface area of the bergmound deposits. All bergmounds possessed topographic relief of > 10 ft (1.5 m).

Bergmounds in the study area are consistent with the description used in the Johnson Creek area of the Vantage Reach by Fecht and Tallman (1978) and the Cold Creek Valley by Bjornstad et al. (2006); however, they differ in frequency by elevation. Fecht and Tallman reported bergmounds with low-topographic relief (< 10 ft/1.5 m) up to 985 ft (300 m). Bjornstad et al. reported bergmounds to be restricted to elevations between 600 ft and 1,000 ft (183 m to 305 m). Given a 1,200 ft to 1,250 ft (366 m to 380 m) estimated maximum height of flooding in the Cold Creek Valley, these data imply icebergs of sufficient size to generate bergmounds occupied at least 200 ft (61 m) of the upper lake surface (Figure 5). This research surveyed a bergmound in a Schnebly Coulee tributary at 1,162 ft (354 m), approximately 160 ft (49 m) higher than any bergmound reported in the Lake Lewis Basin (see Figure 22). The remaining two bergmounds were surveyed at 1,030 ft and 1,031 ft (314 m; Figure 21). While marginally higher bergmound elevations should be expected between the Vantage Reach and the down river Cold Creek Valley, the cause for the 160-ft (49-m) variance in maximum elevation of bergmounds between the study area and the Cold Creek Valley, as well as the Johnson Creek area, is not directly identifiable.

In addition to bergmounds, eight high-density erratic clusters were surveyed above 1,000 ft (305 m). Overall, these data indicate the 200 ft (61 m) of floodwater inferred to be necessary for icebergs to generate bergmounds in the Cold Creek Valley is

Figure 22. Looking southeast at high-elevation bergmound deposit located on divide separating Ryegrass and Schnebly coulees. Bergmound was surveyed at 1,162 ft (354 m). Refer to Figure 21 and Table 1 for location, maximum diameter, and surface area of bergmound. Note the scale of erratic located in the lower right corner.

not concurrent with the Vantage Reach. Given the maximum extent of flooding at 1,263 ft (385 m), the iceberg responsible for the highest high-density erratic cluster required less than 45 ft (14 m), and the highest bergmound approximately 100 ft (30 m), of water to reach their final resting elevations (Table 1). The comparable range in diameter, surface area, and elevation between high-density erratic clusters and bergmounds indicates icebergs responsible for their origin were comparable in size, thus leaving topographic relief as the criteria used to delineate the deposit types (see Figure 23).

Chamness (1993) reports the generation of bergmound topography in the Cold Creek Valley resulting from iceberg protection of underlying slackwater deposits from

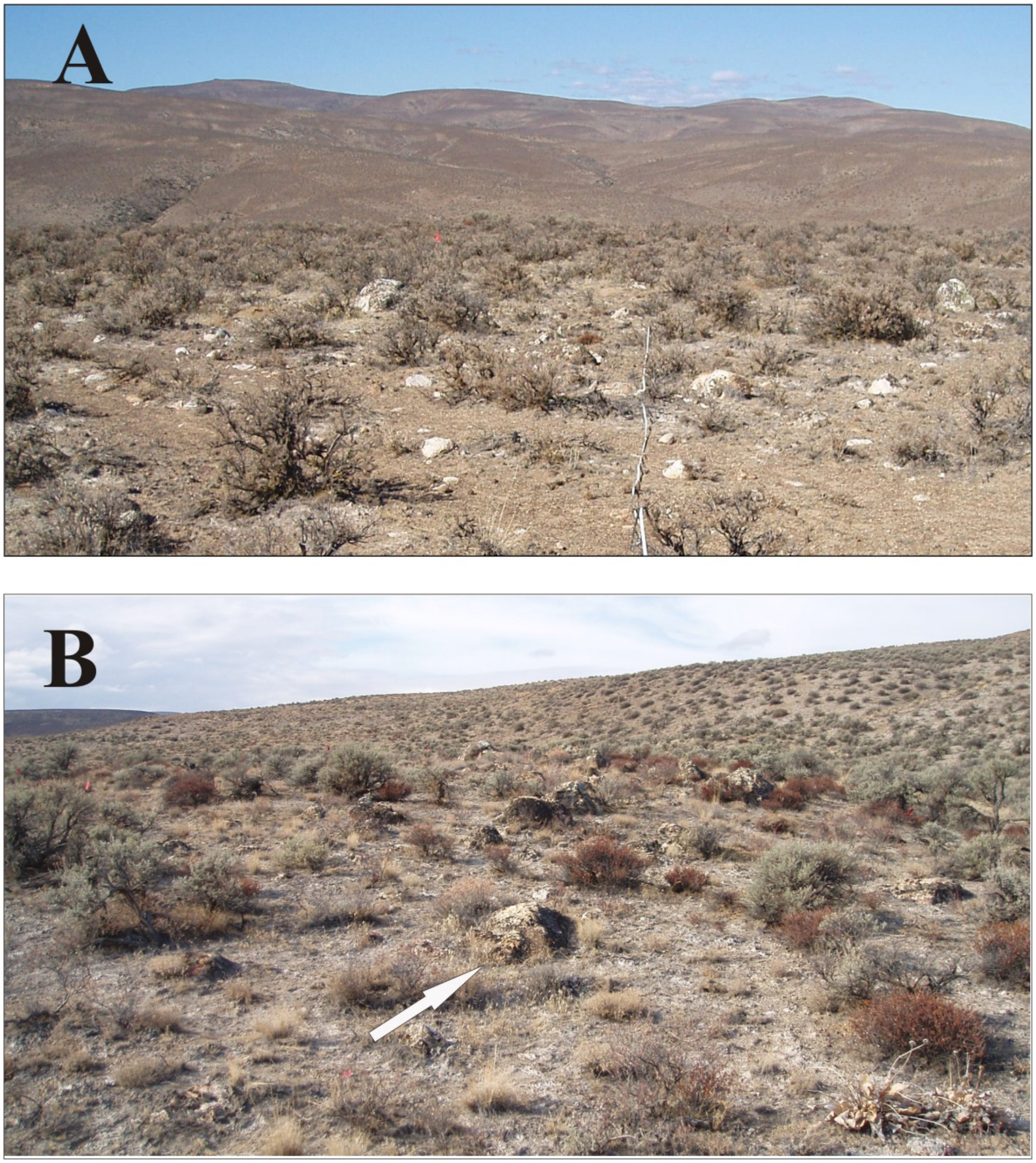


Figure 23. Examples of a high-density erratic cluster and bergmound deposit in Ginkgo Petrified Forest State Park. Part A exhibits a high-density erratic cluster at 1,218 ft (371 m). Note the measuring tape distance of approximately 26 ft (8 m) used to conduct surface area (diameter) measurements. Part B exhibits a bergmound at 1,030 ft (314 m). Erratic with arrow measured 44 in. (112 cm) in length (left to right in photograph). Note the topographic rise in Part B used to delineate the two high-density erratic deposits.

waning flood current erosion (Figure 4). Based on Chamness's hypothesis, the absence of flood transportable, fine-grained sediments surrounding a grounded iceberg would prohibit bergmound formation, thus leaving only a high-density cluster of erratics atop a flood resistant surface as evidence of iceberg deposition. Another potential origin for high-density erratic clusters is a lack of sufficient waning flood currents to erode surrounding sediments, thus development of bergmound topography through posticeberg deposition erosion. Especially in the case of high-elevation deposits, the competence of waning floodwaters to effectively move large-grained sediment may have resulted in iceberg ablation without topographic relief. Holocene erosion of bergmounds is a third potential origin for high-density erratic cluster deposits. Fecht and Tallman (1978) attribute the low relief, relative scarcity, and absence of fine-grained debris within bergmounds in the Johnson Creek vicinity to extensive Holocene erosion of flood deposits. The nearly 4 to 1 ratio of high-density erratic clusters to bergmounds may indicate the study area has undergone extensive Holocene erosion. However, this interpretation is considered least likely based on the 4% frequency of nonburied erratics.

Slackwater Facies

Rhythmites were the most distinct form of slackwater facies observed. Due to the extent of Holocene deposition within the study area, the identification of rhythmite beds was limited to stream and road cut exposures. Figure 14 summarizes the spatial distribution of identified rhythmite exposures.

Two types of rhythmite facies were observed at distinct elevations. It should be noted the southwestern park boundary does not include portions of Schnebly and Ryegrass Coulee below 700 ft (213 m). Therefore, only flood features located near the mouth of Rocky Coulee are reported. At elevations < 700 ft (213 m) rhythmites consist of thin (< 1 in./2.54 cm), fine-grained silt couplets (see Figure 24). Along the north and

Figure 24. Rhythmite exposure in the mouth of Rocky Coulee. Note the absence of mixed, coarse-grained sands and gravels. Crack in exposure measured for scale.

south walls of Rocky Coulee, near the existing Columbia River shoreline, two outcrops of exposed rhythmite beds were observed. Each rhythmite layer provides evidence of low-energy deposition by either a flood surge or separate flood event. The lack of contrasting sediment sizes within alternating rhythmites indicates little variation existed between successive deposition energy levels. The scarcity of unaltered outcrops, their thin, fine-grained composition, and low elevation of rhythmites suggest they were either significantly modified by subsequent flooding or they represent low-magnitude flood events during the late stages of late-Pleistocene flooding. The latter is favored based on the absence of mixed crystalline and basaltic sands and gravels.

The remaining rhythmites were observed at elevations > 700 ft (213 m). The most significant exposure of rhythmites exists in Unit 3 of the modified eddy bar (see Figure 25). With the exception of one rhythmite exposure located in the Ryegrass Coulee

Figure 25. Mixed-grained rhythmites observed in Unit 3 of the Schnebly Coulee eddy bar. See Figure 16 for description of eddy bar stratigraphic units. Note 5-in. (13-cm) handle of trowel for scale, as well as unconformity with overlying Unit 2.

drainage, these exposures occur in Schnebly Coulee tributaries and align topographically with the downslope eddy bar, and are interpreted as an upvalley extension of this channel deposit. The Schnebly Coulee rhythmites consist of bedded couplets of gravel, mixed-grain (crystalline and basaltic) coarse- to fine-sands, and silts. Nearly all rhythmite facies were found underlying angular basalt gravels. The abrupt unconformity with the overlying angular basalt gravels indicates potential erosion of the underlying rhythmites by a subsequent flood surge or flood event.

Throughout elevations < 1,100 ft (335 m), coarse-grained, crystalline sands were common at the surface. Due to the ubiquitous nature of crystalline sand deposits, they were not formerly documented using GPS coordinates. Lacking formal sedimentary structures, they are interpreted as Pleistocene slackwater deposits based on their elevation within known flooded terrain. Their presence indicates laminated sand deposits settled while hydraulically pooled water behind Sentinel Gap occupied and drained from the study area. Subsequent exposure to surface eolian and fluvial processes likely eroded and transported fine-grained sediments leaving concentrated remnant, coarse-grained crystalline sands forming a semidesert, pavement surface.

The presence of low-elevation slackwater facies in the study area is consistent with the findings of Mullineaux et al. (1978) who reported the presence of Mount St. Helens Set S tephra within low-elevation, fine-grained slackwater facies near Wanapum Dam and Vantage. However, no evidence of Mount St Helens Set S tephra was observed in study area exposures, thus I was not able to determine a relative age of the exposures.

Quantitative Analysis of Ice-Rafted Erratic Variables

One Sample Chi-Square Analysis

The largest erratic observed in each low-density cluster, high-density cluster, and bergmound deposit, as well as each isolated erratic was sampled for one sample chi-square analysis. Overall, 337 erratics were sampled by rock type, elevation, aspect, slope angle, size, and surface burial. Significant statistical patterns were identified and are reported in Table 2. For results of one sample chi-square analysis see Appendix A.

Table 2

One Sample Chi-Square Results of Ice-Rafted Erratic Variable Analysis

	Ice-rafted erratic variable							
Test results	Erratic class type	Rock type	Elevation class	Aspect	Slope angle	Erratic size class	Exposure	Geomorphic map unit
χ^2	307.26	756.90	65.69	208.64	74.23	74.95	283.33	483.45
V	0.16	0.33	0.07	0.79	0.18	0.08	0.05	0.59

Note. For all tests $N = 337$; χ^2 = chi-square test statistic.

A moderate Cramer's *V* relationship significance strength score (0.33) was found within the sample of erratic rock types. Eighty percent of the erratics sampled were granitic, comprised of either granodiorite or granite (see Figure 26). Quartzite was the next most common rock type, making up 8% of the sample, followed by diorite (7%), and gneiss (4%), with the remaining 1% unidentified. Potential erratic basalt rock types were not considered based on the abundance of indigenous basalt and subjective in situ versus erratic origin delineation. This pattern suggests icebergs in the study area were derived from a portion of the Purcell Lobe ice dam, or an alternative iceberg source, that contained predominately granitic rock types.

A weak Cramer's *V* relationship significance strength score (0.07) was found within the sample of erratics by elevation class. Erratics were documented between 641 ft (195 m) and 1,263 ft (385 m), a total range of 622 ft (190 m). Approximately 44% of erratics were located between 1,100 ft and 1,200 ft (335 m and 365 m; see Figure 27). These data suggest the majority of icebergs documented migrated into the study area along high-magnitude floods requiring water depths of at least 620 ft (189 m).

A strong Cramer's *V* relationship significance strength score (0.79) was found within the sample of erratics by aspect. The majority of erratics (71%) were observed on south- to east-facing slopes, with the highest frequency along south-facing slopes (see Figure 28). These data suggest patterns of iceberg deposition were influenced by variations in eddy currents, wind, and the direction of receding floodwater.

A weak Cramer's *V* relationship significance strength score (0.18) was found within the sample of erratics by slope angle. Sixty-four percent of erratics were observed on moderate-angle slopes between 7º and 21º (see Figure 29). However, 32% of erratics

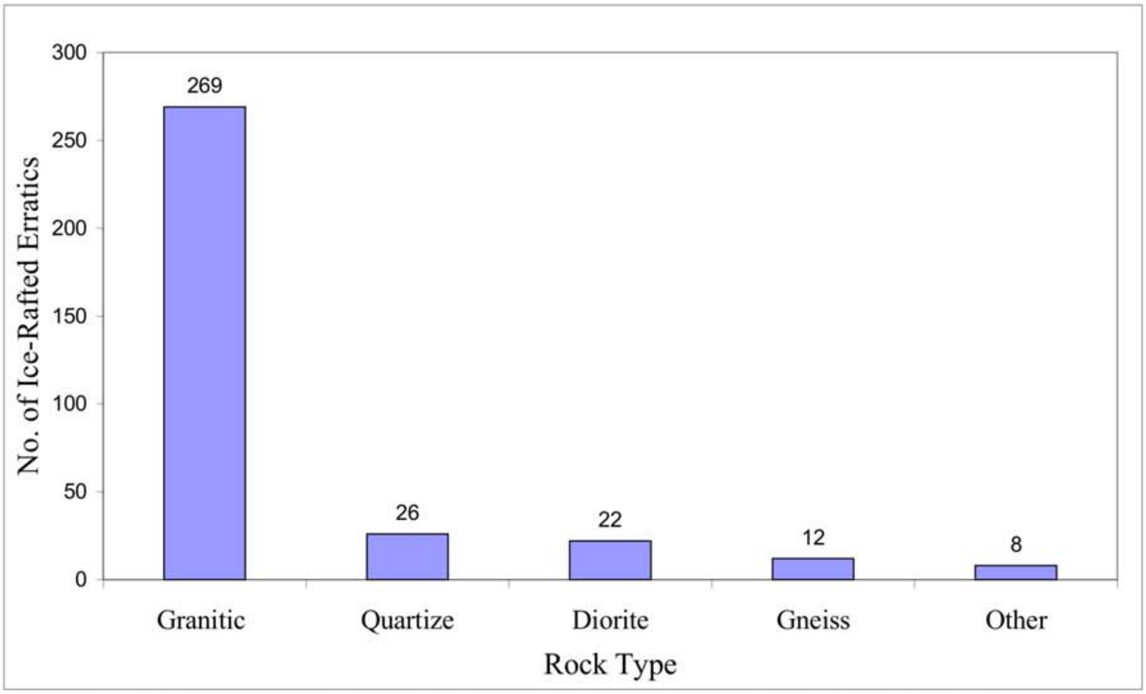


Figure 26. Frequency of ice-rafted erratics by rock type in Ginkgo Petrified Forest State Park. Basalt rock types not included, $N = 337$.

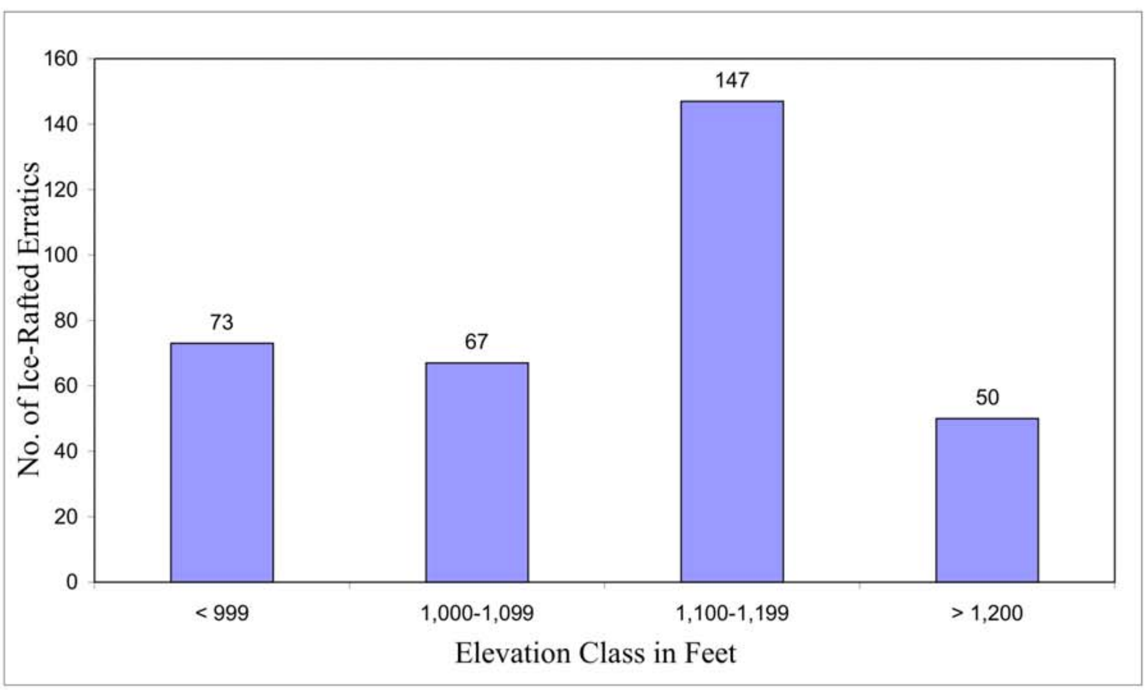


Figure 27. Frequency of ice-rafted erratics by elevation class in Ginkgo Petrified Forest State Park. $N = 337$.

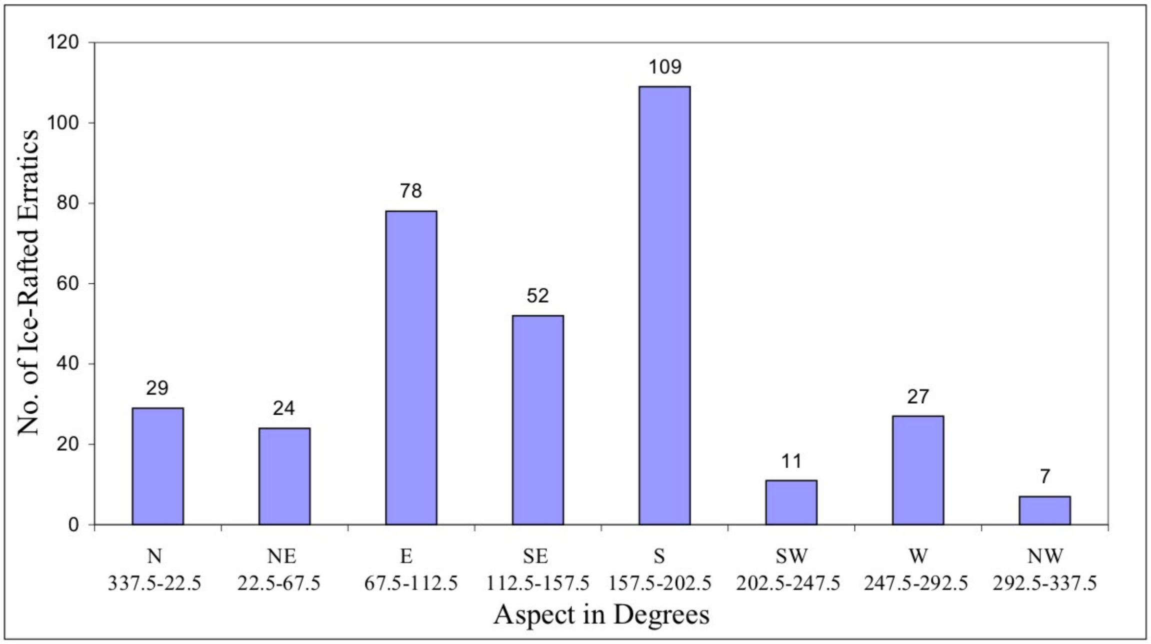


Figure 28. Frequency of ice-rafted erratics by aspect in Ginkgo Petrified Forest State Park. $N = 337$.

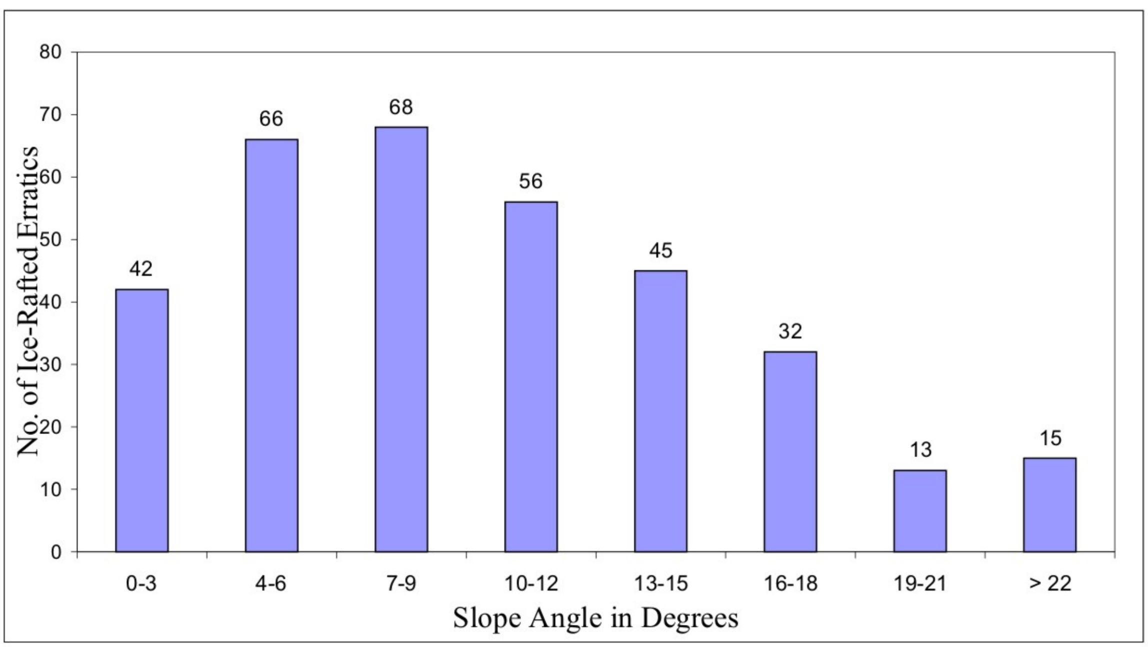


Figure 29. Frequency of ice-rafted erratics by slope angle in Ginkgo Petrified Forest State Park. $N = 337$.

were found on low-angle slopes between 0º and 6º, with the remaining 4% found on steep-angle slopes > 21º. These data suggest eddy currents and wind patterns likely contributed to the delivery of erratics to moderate slopes, and that study area topography was a significant factor controlling to the distribution of erratic by slope angle.

A weak Cramer's *V* relationship significance strength score (0.08) was found within the sample of erratics by size class. The frequency of erratic size was based on exposed cross-sectional area (length x width). Nearly three-quarters (72%) of the erratics were < 3 ft^2 (0.3 m^2) in area (see Figure 30). However, 19% of erratics were > 5 ft^2 (0.5 m^2) in area, the largest with an area of 85 ft^2 (7.9 m^2). These data suggest the typical iceberg deposited in the study area was either relatively small in size or was comprised mostly of clean ice. However, the presence of large erratics indicates icebergs of variable size and loads were capable of migrating into the study area.

Figure 30. Frequency of ice-rafted erratics by exposed cross-sectional area class in Ginkgo Petrified Forest State Park. *N* = 337.

A weak Cramer's *V* relationship significance strength score (0.05) was found within the sample of erratics by surface exposure. Ninety-six percent of erratics were observed buried within the surface to some degree (see Figure 31). This dominant pattern suggests Holocene geomorphic processes have resulted in primarily deposition, and that more erratics are likely present below the surface.

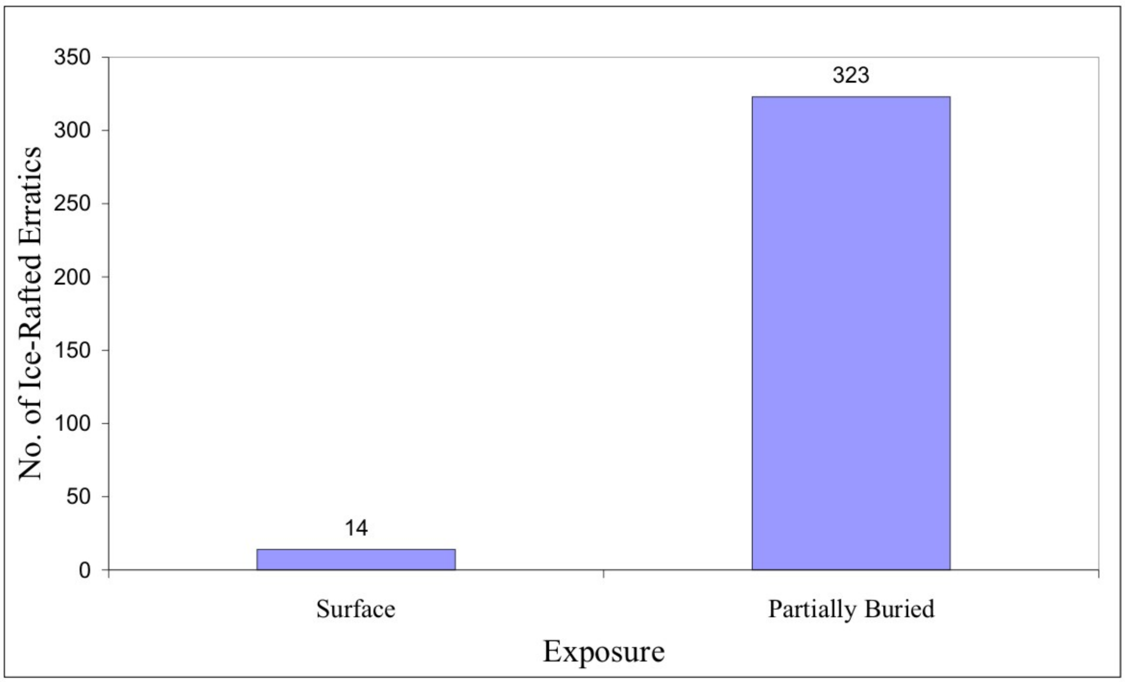


Figure 31. Frequency of ice-rafted erratics by extent of exposure in Ginkgo Petrified Forest State Park. $N = 337$.

The distribution of erratic deposits reported within are not wholly consistent with research in the Pasco Basin by Bjornstad et al. (2006), who reported an increase in erratic frequency downslope. This research identified a high frequency of erratic deposits between 1,100 ft and 1,200 ft (335 m to 365 m), which suggests topographic variables other than elevation have produced a variance in the frequency of erratic deposits. Potential contributing processes included wind and eddy current circulation patterns.

Two Sample Chi-Square Analyses

The widespread spatial distribution and large sample size of ice-rafted erratics documented in the study area provided an opportunity for two sample chi-square analysis of erratic variable datasets. Two sample chi-square statistical tests identified significant relationships between erratic variables of size and classification type, elevation and size, elevation and slope angle, elevation and aspect, and slope angle and size. Cramer's *V* relationship test results indicate a moderate to weak range of relationship strength between variables found to be significantly related (see Table 3). For detailed results of two sample chi-square tests of significantly related erratic variables see Appendix B.

A moderate Cramer's *V* relationship significance strength score (0.28) was found between erratic size and classification type. In general, high-density cluster and bergmound deposits contained larger erratics than low-density cluster and isolated erratic deposits. Sixty-eight percent (88 of 130) of the largest erratics observed within low-density clusters, and 80% (155 of 193) of isolated erratics, were < 3 ft^2 (0.28 m^2) in cross-sectional area. Only 7% (1 of 14) of the largest erratics observed in high-density clusters and bergmounds were < 3 ft^2 (0.28 m^2). Conversely, 21% (27 of 130) of the largest erratics observed within low-density clusters, and 14% (26 of 193) of isolated erratics, were > 5 ft^2 (0.46 m^2) in cross-sectional area, while 79% (11 of 14) of the largest erratics observed in high-density clusters and bergmounds were > 5 ft^2 (0.46 m^2). These data suggest icebergs responsible for deposition of high-density clusters and bergmounds were larger than those responsible for low-density clusters and isolated erratics.

A moderate Cramer's *V* relationship significance strength score (0.28) was found between erratic elevation and size. In general, the smallest erratics were observed along

Table 3

Two Sample Chi-Square Results of Ice-Rafted Erratic Variable Analysis

Variable	Elevation class	Aspect	Slope angle	Erratic size	Erratic type
Elevation class					
χ^2		25.99	73.89	79.99	
V		0.16	0.27	0.28	
Aspect					
χ^2	25.99				
V	0.16				
Slope angle					
χ^2	73.89			24.21	
V	0.27			0.16	
Erratic size					
χ^2	79.99		24.21		52.96
V	0.28		0.16		0.28
Erratic type					
χ^2				52.96	
V				0.28	

Note. Ice-rafted erratic surface exposure data excluded based on failure to meet chi-square test assumptions. For all tests $N = 337$; χ^2 = chi-square test statistic.

the margins of flooded terrain (> 1,200 ft/366 m). Only 2% (2 of 93) of erratics with a cross-sectional area > 3 ft^2 (0.28 m^2) were observed > 1,200 ft (366 m). One of these exceptions was an 8.4-ft^2 (0.78-m^2) erratic located within a high-density erratic cluster deposit located at 1,218 ft (371 m). This occurrence, although significant, does not refute the general association of smaller icebergs grounding within higher elevations of flooded terrain as 84% (102 of 121) of erratics < 1 ft² (0.09 m²) were observed above 1,100 ft (335 m). However, it does indicate the transport of icebergs sufficient in size to deposit a high-density of erratic debris can occur within marginal flood elevations. The relationship of decreasing erratic size with increasing elevation cannot be extended to elevations throughout the study area. Seventy-four percent (47 of 64) of erratics observed with a cross-sectional area > 5 ft² (0.46 m²) were observed between 1,000 ft and 1,200 ft (305 m and 366 m). In addition, 64% (7 of 11) of high-density erratic cluster and 100% (3 of 3) of bergmound deposits were observed within this elevation range. These data support the interpretation that icebergs sufficient in size to transport large erratics (> 3 ft²/0.28 m²), as well as high-density deposits of erratic debris, were concentrated in the study area between 1,000 ft and 1,200 ft (305 m and 366 m).

A moderate Cramer's *V* relationship significance strength score (0.27) was found between erratic elevation and slope angle. Sixty-two percent of erratics (26 of 42) located on nearly flat surfaces (slope angles between 0º-3º) were below 1,000 ft (305 m). Above 1,000 ft (305 m), 76% (200 of 262) of erratics were found on slopes > 7º. Additionally, 80% (40 of 50) of erratics > 1,200 ft (366 m) were located on slopes > 7º. These data suggest erratics < 1,000 ft (305 m) were prone to deposition along low-angle slopes (0º-6º), while erratics > 1,000 ft (305 m) were prone to deposition along moderate- to steep-slopes (> 7º). This pattern is consistent with the prevalence of back-slope and talus slope environments > 1,000 ft (305 m) which possess moderate- to steep-slope angles and the common occurrence of low-angle slope and floodplain surfaces < 1,000 ft (305 m).

However, the 38% (16 of 42) frequency of erratics on nearly flat surfaces > 1,000 ft (305 m) is likely associated with the presence of basalt flow top and interfluve pass environments which do commonly occur at elevations > 1,000 (305 m).

A weak Cramer's *V* relationship significance strength score (0.16) was found between erratic elevation and aspect. Under 1,000 ft (305 m), 80% (58 of 73) of erratics were observed along aspects between 67.5º and 247.5º (east to southwest). Between 1,000 ft and 1,100 ft (305 and 335 m), 81% (54 of 67) of erratics were observed along east-to-southwest aspects. However, between 1,100 ft and 1,200 ft (335 m and 366 m) only 66% (98 of 147) of erratics were observed along east-to-southwest aspects with 34% (49 of 147) found along 247.5º to 67.5º (west-to-northeast) aspects. Above 1,200 ft (366 m), 80% (40 of 50) of erratics were observed along east-to-southwest aspects. These data suggest icebergs were generally delivered to south- to east-facing slopes either by dominant wind patterns documented in the region by Busacca and McDonald (1994), south- to east-trending eddy currents, or by receding floodwater currents exiting to the Columbia River. The moderate frequency of icebergs stranded along topographic barriers opposite the direction of draining floodwaters between 1,100 ft and 1,200 ft (335 m and 366 m) suggests wind and eddy current circulation patterns in this elevation zone were more variable, and were influenced by interfluve pass and flow top surfaces.

A weak Cramer's *V* relationship significance strength score (0.16) was found between erratic slope angle and size. Seventy-five percent (91 of 121) of erratics < 1 ft^2 (0.09 m^2) in cross-sectional area were observed on moderate to steep slopes (> 7º). In addition, 62% (76 of 123) of erratics 1 ft^2 to 2 ft^2 (0.09 m^2 to 0.18 m^2) in area were observed on slopes > 7º. These data contribute to the interpretation of the smallest erratics concentrated at marginal flood elevations along slopes > 7º. One high-density erratic cluster deposit was observed > 1,200 (366 m) atop a nearly flat surface. This pattern suggests only small icebergs, or icebergs free of dense erratic loads, were capable of populating marginal floodwater depths dominated by moderate- to steep-angled slopes.

Landscape Geomorphology

Study area landforms were examined at the landscape-scale to identify relations between landform attributes and Pleistocene flood processes. For descriptions of geomorphic mapping units see Table 4. Figure 32 conveys the spatial distribution of geomorphic map units within the study area.

Basalt Flow Top/Pass

The majority of basalt flow top surfaces in the study area were comprised of Rosa member basalt. This complex landform mapping unit was divided into nonfluvial (1a) and fluvial (1b) subunits based on elevation (Figure 32). Basalt flow top surfaces above 1,263 ft (385 m) were classified as nonfluvial, while those under were classified as fluvial. Both units were characterized by low-slope angles (0º-6º) and the presence of lithosols. Low-angle basalt interfluve pass surfaces were included within this mapping unit due to their lithic, topographic, and spatial relation to basalt flow top landforms. Blockfields were also found in the study area, but due to the limited scale of aerial photography and complexity in their delineation from exposed basalt bedrock, they were also included in this mapping unit.

Based on the presence of nonfluvial flow top/pass landforms outside known Pleistocene flood terrain, their relative age was estimated as late-Miocene to the present.

Table 4

Geomorphic Mapping Unit Descriptions

Unit	Landform	Definition	Slope angle	Dominant processes	Relative age
1a	Nonfluvial basalt flow top/pass	Low-angle basalt flow surface. Includes blockfields. Situated outside known Pleist. flooded terrain.	0º-6º	Erosion	Pre-Pleist.
1b	Fluvial basalt flow top/pass	Low-angle basalt flow surface. Includes blockfields. Situated within known Pleist. flooded terrain. Pleist. flood deposits common on surface.	0º-6º	Erosion/ deposition	Pleist.
2	Loess island	Isolated eolian silt/sand deposits. Occur on low to moderate slopes within distinct vegetation types.	0º-21º	Deposition	Pleist./ post-Pleist.
3	Erosional basalt mid-slope	Erosional basalt surface on shoulder, back, and foot slopes. Evidence of surface weathering, fluvial and eolian erosion. Limited to moderate slopes.	7º-21º	Erosion	Pleist./ post-Pleist.
4	Depositional mid-slope	Mixed alluvium, colluvium, and eolian deposits of local composition. Limited to moderate slopes. Excludes distinct alluvial fan and loess island deposits.	7º-21º	Deposition	Post-Pleist.

Table 4 (continued)

Unit	Landform	Definition	Slope angle	Dominant processes	Relative age
5	Scabland escarpment	Basalt erosional feature formed by fluvial processes. Limited to steep slopes near Columbia River channel.	22+º	Erosion	Pleist.
6	Landslide	Unstratified and poorly sorted mass wasting deposits. Excludes talus slopes.	7º-80°	Deposition	Pleist./post-Pleist.
7	Talus	Cone- to apron-shaped rock fall deposits. Excludes landslides and blockfields.	7º-80º	Deposition	Pleist./post-Pleist.
8	Alluvial fan	Cone-shaped, low- to moderate-angle surface comprised of alluvium deposits of local origin.	0º-21º	Deposition	Post-Pleist.
9	Floodplain/ fluvial terrace	Low-angle alluvial plain surface comprised of local alluvium deposits.	0º-6º	Deposition	Post-Pleist.
10	Floodbar	Poorly sorted Pleist. flood deposits. Mixed basaltic and crystalline sediments range from large boulder to sand.	0º-6º	Deposition	Pleist.

Note. Pleist. = Pleistocene.

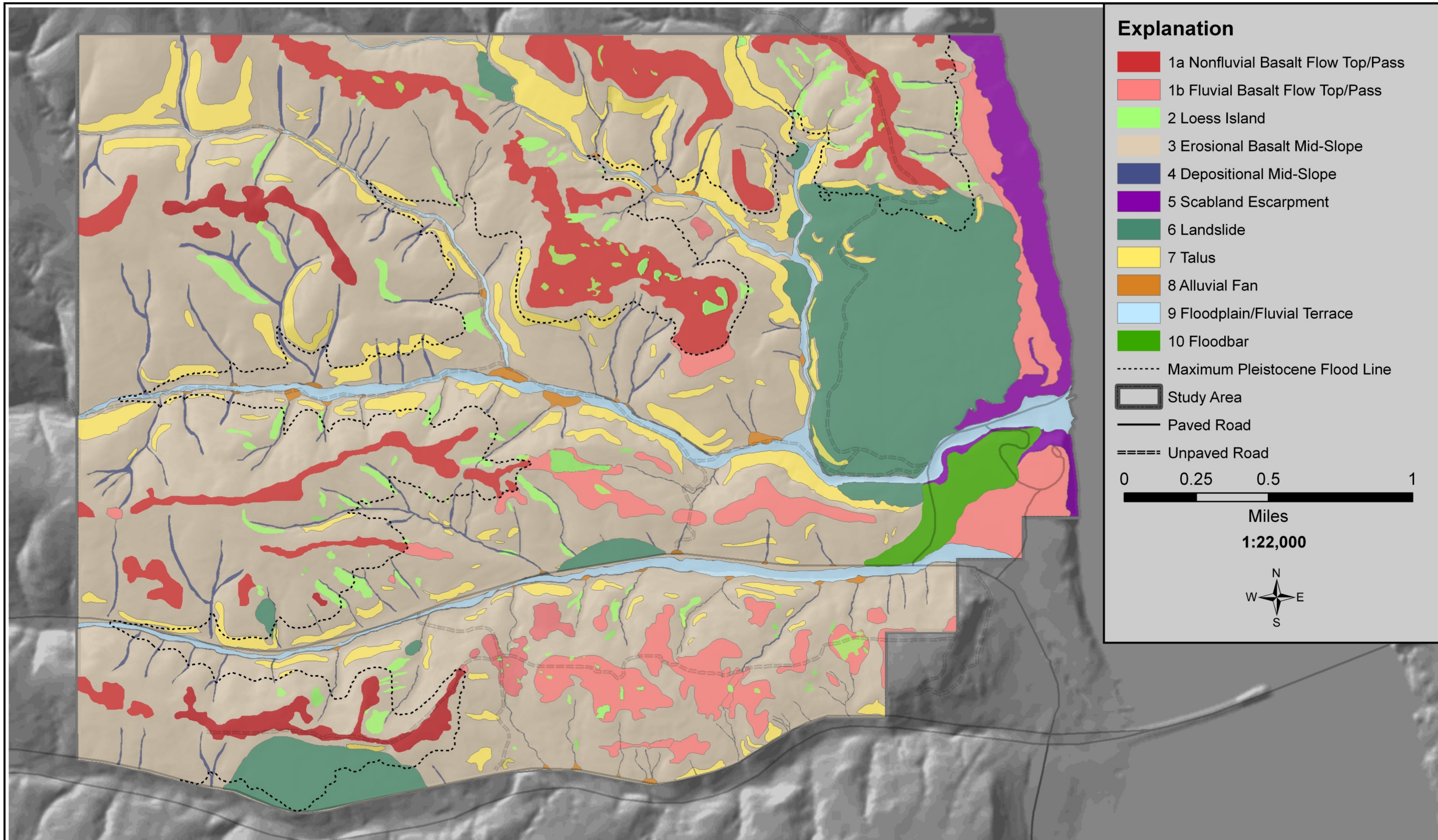


Figure 32. Geomorphic map of the northern portion of Ginkgo Petrified Forest State Park. For map unit descriptions see Table 4.

This subunit was most frequently observed in the Rocky Coulee drainage. Due to its exposure to surface winds and solar radiation, this subunit appeared dominated by eolian erosion and physical weathering. Loess islands and isolated pockets of 1980 Mount St. Helens ash were common and most visible along leeward east-to-northeast aspects.

In contrast to nonfluvial, fluvial basalt flow top/pass surfaces possessed fewer, smaller loess islands and a diversity of Pleistocene flood deposits, indicating these surfaces were modified during Pleistocene flood events. This pattern suggests at least some loess deposition on these surfaces is of pre-late Pleistocene origin. However, erosional processes similar to nonfluvial surfaces have dominated these surfaces during the Holocene and may have contributed to the erosion of loess deposits.

A significant relationship of ice-rafted erratic deposition within this subunit was observed (Appendix A). Overall, 28% (93 of 337) of the erratics sampled occurred within this subunit (see Figure 33). All four erratic deposit types were observed indicating a wide size range of icebergs were stranded on basalt flow top landforms. Furthermore, 64% (7 of 11) of the high-density erratic clusters observed within the study area were observed within this subunit. In addition, coarse-grained, crystalline sands were common on the surface, indicating eolian processes have modified slackwater deposits. The prevalence of erratics and this subunit above 1,100 ft (335 m) indicates high-magnitude flood events were likely responsible for the delivery of icebergs to most flow top/pass surfaces. Subsequent Holocene erosional processes active on this subunit are likely factors contributing to the visibility of erratic deposits on this surface.

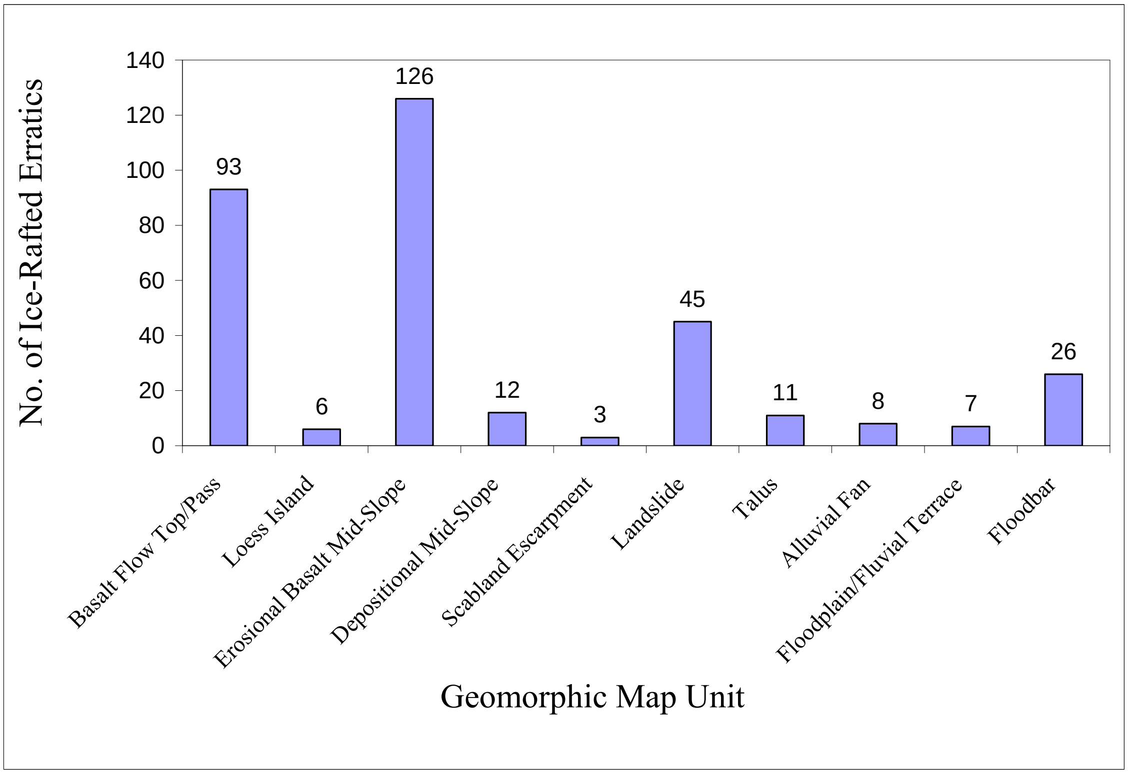


Figure 33. Frequency of ice-rafted erratics by geomorphic mapping unit in Ginkgo Petrified Forest State Park. *N* = 337.

Loess Islands

Loess islands were observed atop low-angle nonfluvial and fluvial basalt flow top/pass and mid-slope (7º-21º) basalt surfaces. Although observed along south and west aspects, loess islands were concentrated along east and north aspects (Figure 10). *Artemisia tridentata* was commonly observed on the surface indicating relatively deep deposit depth in comparison to surrounding *A. rigida* dominated lithosol substrate. Loess islands were more common, and generally larger in size, above known Pleistocene flood elevations indicating either loess deposition was prone to higher elevations or Pleistocene flooding has influenced their frequency and size. Less than 2% (6 of 337) of the erratics sampled were observed directly on loess islands (Figure 33). This low frequency can be attributed to insufficient sampling or the deposition of loess after the occurrence of Pleistocene flooding. This interpretation is consistent with the reporting of widespread absence of loess < 1,100 ft (335 m) in Johnson Creek by Cochran (1978).

Erosional Basalt Mid-Slope

The erosional basalt mid-slope mapping unit was widespread and characterizes a basalt landform situated on moderate-angle (7º-21º) shoulder, back, and foot slopes dominated by erosional processes. A significant pattern of erratic deposition was observed on this landform (Appendix A). Overall, 38% (126 of 337) of erratics sampled were observed on this landform (Figure 33). Due to the large extent of this landform, this high frequency of erratic deposition is expected. However, 86% (126 of 146) of all erratics sampled on moderate slopes were observed within this mapping unit. In addition, the frequency of erratics sampled here and within fluvial basalt flop tops (65% of erratics sampled), indicates the surface exposure of erratics is more prevalent on landforms dominated by erosional processes. Furthermore, 27% (3 of 11) of the high-density erratics clusters were observed within this unit, and 91% (10 of 11) of all high-density clusters were observed on landforms dominated by erosional processes.

Depositional Mid-Slope

The depositional mid-slope mapping unit characterizes landforms situated downslope of erosional mid-slopes along moderate-angle slopes (7º-21º) comprised of mixed alluvium, colluvium, and eolian deposits. This mapping unit was primarily confined to slopes adjacent to tributary and arroyo drainage channels, and excluded discernable loess island, landslide, talus, and alluvial fan landforms. Less than 4% (12 of 337) of erratics sampled were observed within this mapping unit (Figure 33).

Undocumented erratics were observed within active drainage channels and excluded from analysis based on the high probability of movement from their original location of deposition. However, with the exception of low-elevation rhythmites discussed earlier at the mouth of Rocky Coulee and within Unit 3 of the Schnebly Coulee eddy bar, the remaining rhythmite exposures observed within the study area were located within this mapping unit (Figure 14). This pattern suggests upvalley slackwater flood currents responsible for the deposition of rhythmites were active along existing depositional surfaces. In addition, the preservation of rhythmites was provided by subsequent depositional events. The low frequency of erratics is attributed to potential burial by subsequent Holocene depositional processes.

Scabland Escarpment

The scabland escarpment mapping unit was characterized by a steep-angle (> 21º) basalt landforms resulting from fluvial erosional processes. The cliff-like basalt features associated with this mapping unit were sculpted by high-energy Pleistocene flood currents that were limited to elevations < 1,100 ft (335 m) and the vicinity of the Columbia River channel. Unlike other erosion-dominated landforms, scabland escarpments were generally devoid of flood deposits. Less than 1% (3 of 337) of erratics sampled were observed within this mapping unit (Figure 33). However, high-elevation floodbar deposits were visible along small alcoves in the eastern bank of the scabland escarpment landform across the Columbia River from the study area. This interpretation of scabland topography is consistent with the findings of Bretz (1930) and Cochran (1978). Bretz reported scabland topography in the Vantage Reach < 1,100 (335 m), while Cochran reported the excavation of Columbia River basalts by Pleistocene flood currents

< 1,100 ft (335 m) in the Johnson Creek drainage.

Landslide

The landslide mapping unit was delineated from depositional mid-slope, talus, and alluvial fan mapping units by the presence of an identifiable head scarp, unstratified or poorly sorted deposits, hummocky terrain, and deranged or irregular tributary orientation. Discernable landslides were observed along south- and east-facing slopes in localities where Vantage interbed deposits underlay Frenchman Springs member basalts (Figure 8). This association suggests saturation and/or instability of the Vantage interbed is a primary factor contributing to mass wasting in the study area.

Two significant landslide deposits were observed overlying Vantage interbed deposits. The largest was observed along a south-facing slope draining into Rocky Coulee; the other was located within marginal flood terrain along a south-facing slope draining into Ryegrass Coulee (Figure 32). The Rocky Coulee landslide is approximately 1 mi^2 (2.59 km^2) in area, while the Ryegrass Coulee landslide is approximately 0.25 mi^2 (0.65 km^2) in area (J. E. Powell, personal communication, July 13, 2005). The foot slope of the Rocky Coulee landslide appears to have redirected Rocky Coulee to the south. It is plausible that a translational landslide of this scale dammed Rocky Coulee impounding a lake in the vicinity of present day Hell's Kitchen. Further investigation of lacustrine and landslide features is necessary to validate this preliminary hypothesis.

All four types of erratic deposits, and coarse-grained, surface crystalline sands, were observed on the Rocky Coulee landslide, while no Pleistocene flood deposits were observed on the Ryegrass Coulee landslide. Overall, 13% (45 of 337) of erratics sampled were observed on the Rocky Coulee landslide surface (Figure 33). One high-density erratic cluster, containing the largest erratic observed in the study area (85 ft^2/7.9 m^2), and two bergmounds were observed (Figure 21). Evidence of Holocene erosion was observed along the base of the largest erratic (see Figure 34).

Figure 34. Large ice-rafted erratic located on the Rocky Coulee landslide. Largest ice-rafted erratic (10 ft/3.1 m length x 8.5 ft/2.6 m width) documented in the study area at 1,105 ft (337 m). Note the distinct boundary of lichen development on erratic surface (arrow) indicating surface erosion.

This pattern of erosional evidence is consistent with the occurrence of the remaining ten high-density erratic clusters on erosional surfaces. However, the presence of bergmounds on this landform suggests large icebergs stranded on this slope were underlain by fine-grained sediments exposed to erosive waning flood currents. The 70-ft (21-m) variation in elevation between the deposits may be responsible for the variation between the two ice-rafted deposit types. Therefore, the presence of high-density erratic cluster and bergmound deposits on this landform can be attributed to (a) variations in the erosive potential of waning flood waters responsible for bergmound construction or (b) variations in Holocene geomorphic processes acting on the landslide surface. The latter is favored based on the presence of a higher elevation bergmound on a basalt flow top pass in the study area, the measurable evidence of Holocene erosion acting on the high-density cluster site, and the common observance of nearly buried low-density erratic deposits and isolated erratics in the vicinity of the two bergmounds. The presence of bergmounds and a high-density erratic cluster on the landslide surface indicates the relative age of initial or substantial mass movement of the landform surface predates late-Pleistocene flooding.

Talus

The talus mapping unit was characterized by cone- to apron-shaped rock fall deposits occurring on moderate- to steep-angle slopes (7º-80º). Due to the limited scale of aerial photography, small-scale escarpments were included within this unit. However, blockfields occurring on low-angle slopes (0º-6º) were excluded. Talus slopes were observed throughout the study area, indicating physical weathering of basalt via rock fall and in place is common. Less than 4% (11 of 337) of erratics sampled were observed on talus slopes (Figure 33). This low frequency is attributed to the limited accessibility of steep-angle slopes to sampling and the potential for Holocene burial of erratic deposits. However, the presence of erratics on the surface of talus indicates the talus was in place at the time of iceberg deposition or the basalt has weathered since erratic deposition. The presence of erratics suggests low-energy flood processes were active at times along talus or basalt slopes in contrast to presumably high-energy flood currents responsible for removal of talus during formation of scabland escarpments.

Alluvial Fan

The alluvial fan mapping unit was characterized by alluvial deposits on low- to moderate-angle slopes (0º-21º). Alluvial fans were delineated from depositional mid-slope and floodplain mapping units by their discernable cone- to apron-shaped aerial signature and common occurrence as a transitional landform situated along interfaces of moderate- to steep-gradient tributaries with low-angle floodplain surfaces. Pleistocene flood deposits were rare on alluvial fan surfaces. Only 2% (8 of 337) of erratics sampled were observed on these surfaces (Figure 33). This low frequency is attributed to predominant Holocene development of alluvial fans.

Floodplain/Fluvial Terrace

The floodplain/fluvial terrace mapping unit was characterized by low-angle alluvial surfaces incised by active and relict drainage channels. Inundation of the Columbia River floodplain by Wanapum Dam has substantially reduced the surface area of this mapping unit. The most significant floodplain/fluvial terrace locations were observed within Rocky Coulee, near its mouth and within the Hell's Kitchen area. Construction of Interstate 90 and State Route 10 has significantly altered the floodplain/fluvial terrace surfaces of Ryegrass and Schnebly Coulee, respectively.

In general, ice-rafted erratic sampling was only conducted along the margins of this mapping unit, due to the potential for Holocene disturbance of the relation of erratic site and situation to its parent iceberg. Accordingly, only 2% (7 of 337) of erratics sampled were observed within this mapping unit (Figure 33). However, fine-grained rhythmites were observed in this unit near the present mouth of Rocky Coulee (Figure

14). These data indicate that most recent Pleistocene floods down the Columbia River valley were of low magnitude, leaving low-energy rhythmite deposits near the margins of the existing reservoir, or the existing rhythmite outcrops were somehow isolated from initial surge and waning flood currents of higher magnitude flood events. The latter interpretation is preferred as no coarse crystalline gravels were observed.

Eddy Floodbar

The eddy floodbar deposit constitutes the final landform mapping unit. This landform is characterized by poorly sorted basaltic and crystalline (mixed) sediments underlined by mixed-grain rhythmites. The eddy floodbar has been modified along its northern, eastern, and southern boundaries by subsequent Pleistocene flooding and adjacent coulee drainage Holocene runoff. The absence of Vantage interbed and overlying Frenchman Springs member basalt from the east side of the Old Vantage Highway road cut, in which the eddy floodbar was exposed, suggests the original basalt flow top landform and underlying Vantage interbeds were excavated by high-energy flooding, leaving the Museum member basalt exposed along the margins of the deposit.

Eight percent (26 of 337) of erratics sampled were observed on the surface of the eddy floodbar (Figure 33). In addition, 15 large basalt boulders were observed on the surface. Overall, these data indicate (a) excavation of Vantage interbed and Frenchman Springs member basalts occurred prior to eddy floodbar deposition, (b) iceberg deposition on the eddy floodbar surface indicates it was exposed to subsequent flood events, and (c) the basalt boulders observed on the eddy floodbar surface indicate its proximity to high-energy flood currents may be responsible for subsequent modifications.

Pleistocene Flood Interpretation

Frequency and Magnitude of Pleistocene Flooding in the Vantage Reach

Based on evidence of pre-late Pleistocene-aged flood deposits in the adjacent western Quincy and Pasco basins, it is logical that flooding extended spatially from the western Quincy Basin to the Pasco Basin via the Vantage Reach. Therefore, it is plausible flooding of the study area extends prior to the late-Pleistocene and into the pre-late Pleistocene. However, the extent of pre-late Pleistocene flooding is unknown at this time.

Late-Pleistocene occupation of the CRV by the Okanogan Lobe of the Cordilleran Icesheet near Grand Coulee determined the magnitude and frequency of flooding in the Vantage Reach via the CRV and lower Crab Creek conduits. Stratigraphic evidence in the northwest CRV indicates cataclysmic floods inundated the region while the CRV was ice-free (Waitt, 1994). It is therefore plausible a pre-Okanogan Lobe ice dam flood down the CRV was responsible for the deposition of ice-rafted erratics within marginal flood elevations (> 1,200 ft/366) of the study area, as well as the transport of large icebergs observed > 1,000 ft (305 m).

As the Okanogan Lobe advanced, it eventually dammed the Columbia River, forming glacial Lake Columbia behind its ice dam (Figure 3). Subsequent outburst floods from glacial Lake Missoula invaded glacial Lake Columbia and were routed southwest through the Channeled Scabland. During the maximum extent of the Okanogan Lobe, flooding of the Vantage Reach was likely focused in lower Crab Creek with low-magnitude flooding into the CRV via the western Quincy Basin cataracts. As the Okanogan Lobe ice dam receded, outburst flood events were routed through the Grand Coulee across the Quincy Basin and down the CRV and lower Crab Creek drainages. If the hypothesis of glacial Lake Columbia outlasting glacial Lake Missoula is accepted, the final flood events through the Vantage Reach can be attributed to the emptying of glacial Lake Columbia, or an alternate source to glacial Lake Missoula, down the CRV (Atwater, 1986). Based on the presence of Mount St. Helens tephra observed in the Vantage Reach, the last floods down the CRV were at least 13,000 yr BP.

Stages of Pleistocene Flooding

Pleistocene flood features identified within this inquiry, as well as previous research in the Vantage Reach and adjacent Quincy and Pasco basins, indicates three identifiable stages of flooding acted within the study area (Baker et al., 1991).

The Erosional Stage

The initial stage of flooding was characterized by landscape-scale erosional processes. The amplified competence of floodwaters exiting the flood channel constriction at Frenchman Gap excavated Grande Ronde and Wanapum Basalts lining the Columbia channel and nearshore landscape. The scabland escarpments common to the Columbia River channel provide solid evidence of these remarkable erosional forces. During high-magnitude events the existing river and nearshore interfluve topography would have acted as a temporary channel bed. High-energy flood processes acting along the channel bed surface likely excavated basalt flows by undermining the soft, vulnerable Vantage interbed sediments along the Columbia River channel. Evidence of this erosion exists along the extensive interfluve bench surrounding the Ginkgo Petrified Forest Interpretive Center facilities. Less obvious evidence of erosional processes exist in the absence of widespread loess < 1,100 ft (335 m).

Waxing Stage

The second stage of flooding initiated as floodwater entering the Vantage Reach, via the CRV and lower Crab Creek, exceeded the outflow potential at Sentinel Gap. These scenarios caused floodwaters to hydraulically pool and inundate adjacent tributary environments above the height of initial erosive flood surges. As floodwaters encountered an impounded Vantage Reach, erosive, high-energy currents transitioned into low-energy depositional currents due to a distinct rise in base level, resulting in the deposition of bedload sediments along the margins of the flood channel. The Schnebly Coulee eddy bar located on the stripped basalt interfluve bench provides evidence of these processes. The basalt boulders located on the surface of the eddy bar may be attributed to deposition of bedload originating from the Frenchman Gap vicinity during subsequent flood events.

Outside the main flood channel, suspended sediments were deposited as slackwater features. The common observances of coarse-grained crystalline sands in the study area < 1,100 ft (335 m) are interpreted as remnants of these processes. Along the margins of flooding, slackwater rhythmites were deposited. Icebergs floating on the temporary lake surface migrated into slackwater tributary environments along eddy and wind currents (see Figure 35). Evidence of these processes exists in the study area with erratics observed > 3 mi (4.2 km) west of the Columbia River channel.

Waning Stage

The final stage of flooding initiated as the discharge of floodwaters through Sentinel Gap exceeded the influx of water entering the Vantage Reach. During this stage, floodwater drained from tributary landscapes, grounding icebergs within slackwater environments of the study area. Grounded icebergs eventually melted, leaving hundreds

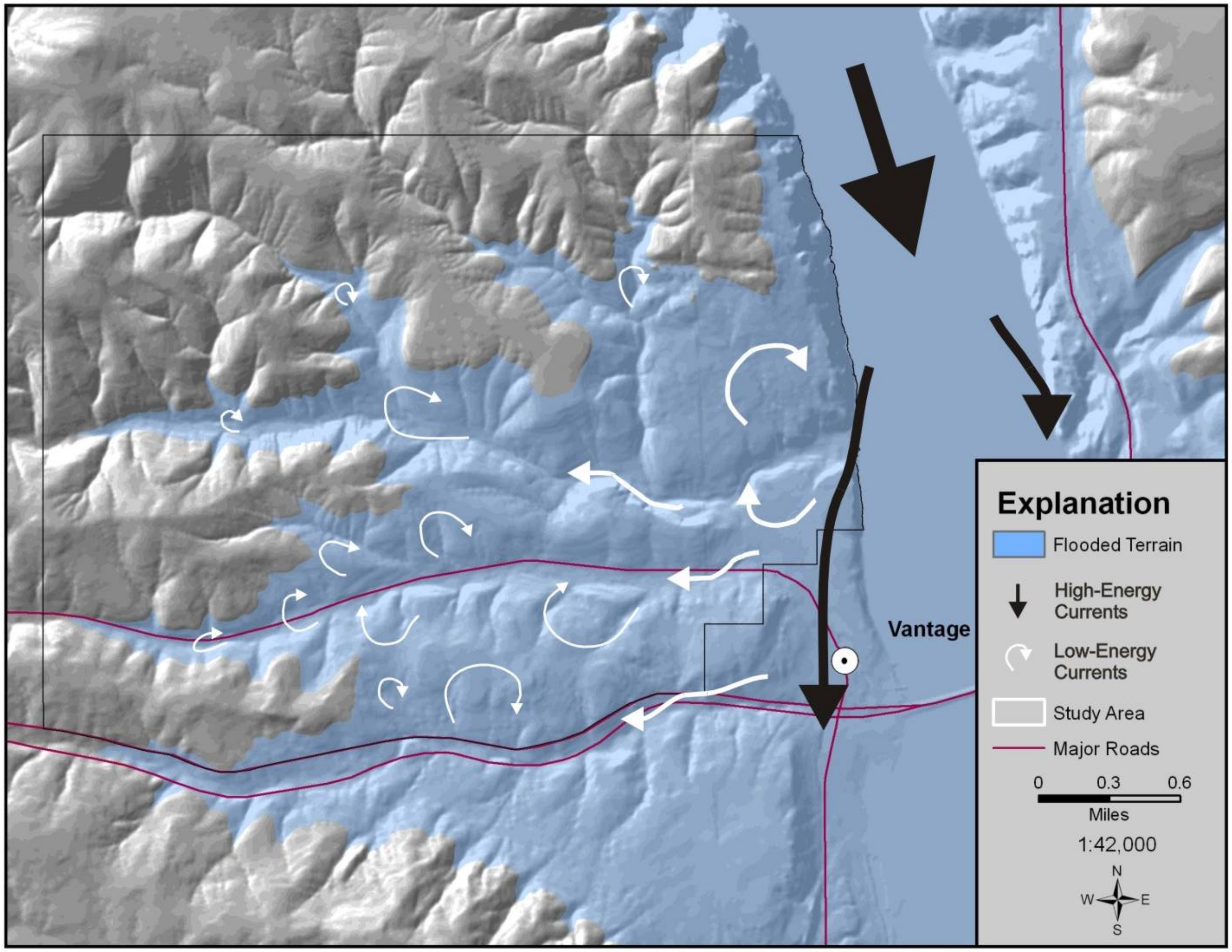


Figure 35. General Pleistocene flood processes in the northern Vantage Reach. Current energy based on surveyed flood features in Ginkgo Petrified Forest State Park.

of ice-rafted erratic deposits as evidence of their final resting place. Waning flood currents exiting the study area likely produced incised channels due to a rapid drop in base level, as well as the presence of unconsolidated channel and slackwater deposits.

The length of time necessary to drain floodwaters from the Vantage Reach was determined by the magnitude of flooding into the reach, and the extent of glacial Lake Lewis. Based on hydraulic modeling by Benito and O'Conner (2003), it is plausible that during high-magnitude flood events, multiple days would have been required for the waxing and waning stages to occur. When floodwaters were not sufficient to initiate hydraulic pooling behind Sentinel Gap, flood processes would have been limited to the erosional stage in the study area.

CHAPTER VI

INTERPRETIVE RECOMMENDATIONS

An intended outcome of this thesis is to interpret evidence of Pleistocene flooding documented within to the general public. Interpretation can be defined as the art of communicating relevant concepts and relationships to individuals within the context of their own values and experience (WSPRC, 2003). The IAF interpretive goals, themes, opportunities, and media recommendations prescribed below are designed to enhance Ginkgo Petrified Forest State Park interpretive planning processes.

Goals of Ice Age Flood Interpretation

The following goals were developed to guide the development of the park's IAF interpretive themes and opportunities (a) increase visitor orientation to IAF interpretive opportunities found in Ginkgo Petrified Forest State Park, as well as other primary IAF interpretive sites of the Channeled Scabland; (b) enhance visitor understanding of the extent of cataclysmic flooding from glacial Lake Missoula on the park landscape; (c) increase visitor recognition of IAF features and processes responsible for their occurrence; (d) provide permanent, seasonal, and volunteer park staff with researched, accurate IAF facts and knowledge pertaining to the park landscape; (e) provide barrier free IAF interpretive opportunities; and (f) nurture, in visitors, a land use ethic that promotes public awareness and stewardship of IAF resources and related natural heritage.

The success of interpretation is determined by outcomes such as knowledge gained, changes in attitude, and the resulting actions taken by visitors due to interpretive experiences. As a result of their experiences with IAF interpretive media visitors will be exposed to the following concepts (a) the constriction in the CRV at Sentinel Gap forced floodwaters from glacial Lake Missoula to hydraulically pool, forming a temporary lake that inundated the park landscape up to 1,263 ft (385 m), nearly 700 ft (213 m) above the existing Columbia River; (b) recognizable features such as ice-rafted erratics, floodbars, and scabland topography are evidence of IAF; and (c) the behavior of the Okanogan Lobe of the Cordilleran Icesheet determined the magnitude and frequency of IAF in the CRV.

As a result of their experiences with IAF interpretive media visitors will have the opportunity to be (a) awed at the magnitude of flooding necessary to inundate the park landscape under nearly 700 ft (213 m) of water; (b) fascinated by the unique processes that delivered slackwater and flood channel deposits to the landscape; (c) inspired to learn more about IAF and their impacts on the landscape of eastern Washington and human land use patterns; and (d) motivated to help protect unique IAF resources.

As a result of their experiences with IAF interpretive media visitors will be motivated to (a) share their knowledge and experiences of IAF interpretation with others in a positive manner; (b) learn more about the natural history of the area by attending interpretive programs, asking questions, reading books, etc; (c) visit other interpretive sites along the proposed IAF National Geologic Trail; and (d) exhibit respectful behavior toward IAF resources and park interpretive facilities.

Interpretive Themes and Network of Opportunities

In order to organize the communication of IAF themes within the park, a three-level network of interpretive opportunities is proposed. The primary objective of each level is to capture the visitors' attention and inspire them to develop a positive, memorable IAF interpretive experience.

Level 1-Orientation

Effective enticement and orientation strategies are critical to the success of the IAF interpretive network. The objective of Level 1 media is to entice potential visitors to seek IAF interpretation, provide previsit and on-site orientation to interpretive hubs, and promote the park as the western gateway to the proposed IAF National Geologic Trail. Previsit orientation begins at the visitor point of origin and transitions to on-site orientation as the visitor encounters the park landscape.

Level 2-Interpretive Hubs

The second level, interpretive hubs, provide detailed orientation and interpretation of IAF resources within the hub vicinity. A three-hub network is proposed for the park. The primary hub is located at the Ginkgo Petrified Forest Interpretive Center. A secondary hub is proposed at the Petrified Forest Interpretive Trail, with a tertiary hub proposed for the Wanapum day-use area (see Figure 36). Although the tertiary hub is located outside the study area, it is included in this treatment of the entire park network.

The Ginkgo Petrified Forest Interpretive Center Hub

The interpretive center hub provides a spectacular view of Sentinel Gap and the sheer cliffs of Grand Ronde and Wanapum basalt lining the Columbia River. This facility provides opportunities for barrier free access to self-guided indoor and outdoor interpretation, a day-use picnic area, restroom facilities, and adequate tour bus access. The following IAF thematic messages are prescribed for this vicinity (a) you are located in the Vantage Reach of the CRV, at the western gateway to the Channeled Scabland;

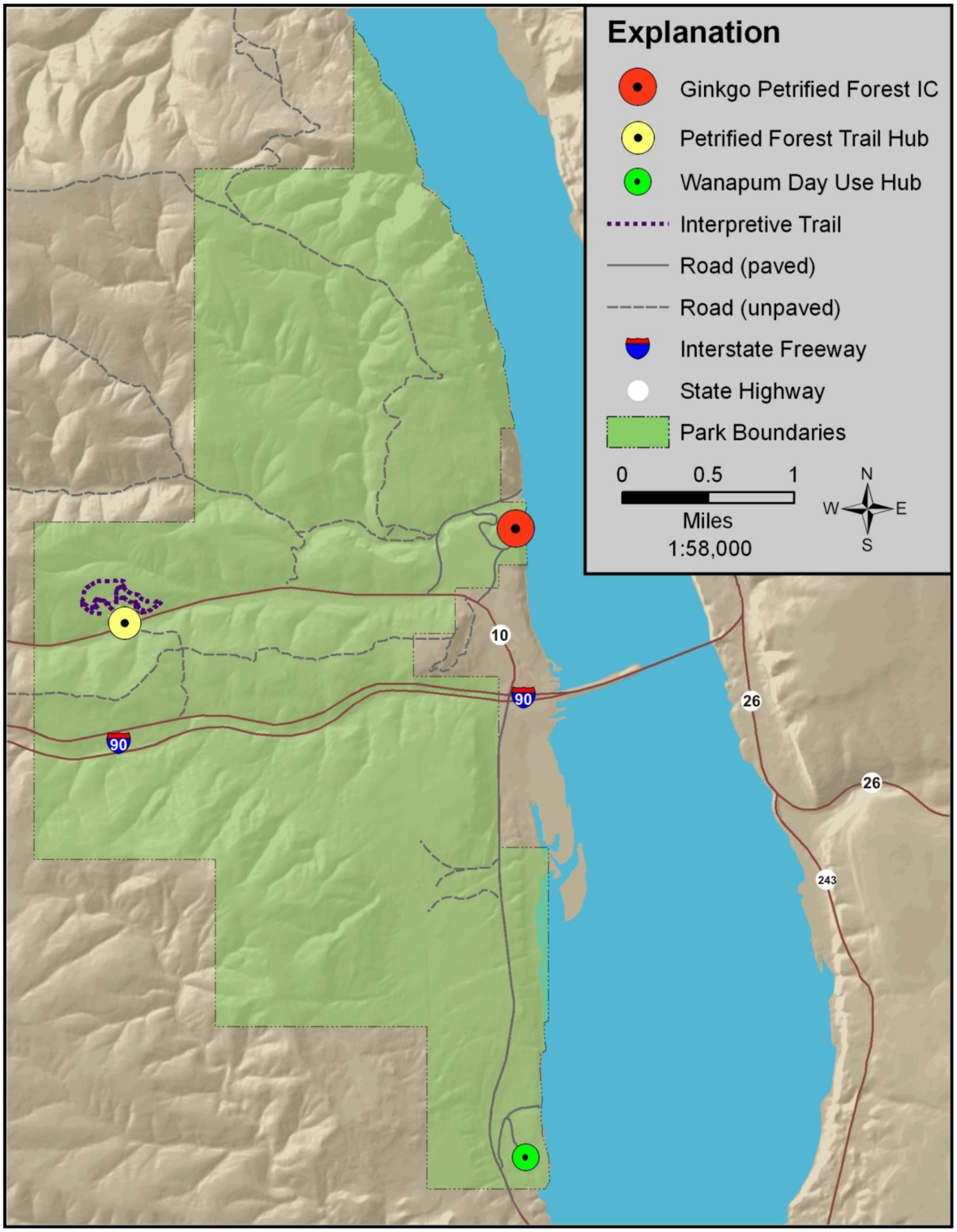


Figure 36. Ginkgo Petrified Forest State Park-Ice Age Floods interpretive hub network map. IC = interpretive center.

where the planet's youngest basalt plateau documents the largest flood events known in the geologic history of the continent; (b) during the last Ice Age, approximately 20,000 to 12,000 yr BP, periodic ice dam failures of glacial Lake Missoula, located in western Montana, induced multiple cataclysmic floods down the CRV; (c) the frequency and magnitude of IAF in the Vantage Reach was determined by the behavior of the Okanogan Lobe of the Cordilleran Icesheet; (d) in this vicinity, the largest floods from glacial Lake Missoula were nearly 800 ft (783 ft) deep, approximately 520 ft higher than the surface you are on; (e) the sheer cliffs of scabland basalt visible from here record the enormous erosive power of flood surges entering the Vantage Reach from Frenchman Gap; (f) during each cataclysmic flood, more water entered the Vantage Reach then could exit Sentinel Gap, forming a temporary glacial lake known as Lake Lewis; (g) floodbar deposits located directly across the river record the transition of high-energy, erosive flood currents into low-energy eddy currents; (g) as glacial Lake Lewis eventually drained, icebergs floating on the lake surface grounded leaving hundreds of ice-rafted erratics to mark their final resting place; (h) during cataclysmic floods, it would have taken days for glacial Lake Lewis to drain from the landscape, and (i) recognizable flood deposits such as ice-rafted erratics, misplaced basalt boulders, and a modified eddy bar are visible on the surface separating the interpretive center from the Vantage Highway.

The Petrified Forest Interpretive Trail Hub

The interpretive trail hub is located approximately 2 mi (3.2 km) west of the interpretive center hub. This hub offers scenic hiking opportunities, self-guided outdoor petrified log exhibits, a restroom facility, a day-use picnic area, and tour bus access. The following IAF thematic messages are prescribed for this vicinity (a) you are now standing near the high shoreline of glacial Lake Lewis, a temporary lake which occupied this landscape during cataclysmic floods from glacial Lake Missoula; (b) floodwaters from glacial Lake Missoula carried icebergs from the foothills of the Rocky Mountains into this landscape; (c) Erratics deposited by grounded icebergs can be found a distance of more than three miles from, and nearly 700 ft above, the existing Columbia River shoreline; (d) the ice-rafted erratic, visible to the south, traveled hundreds of miles in an iceberg that eventually grounded on this slope; and (e) evidence of large icebergs grounded in this landscape exist in the form of large high-density erratic deposits.

The Wanapum Day-Use Hub

The Wanapum day-use area is located approximately 3 mi (4.8 km) south of the interpretive center. This hub offers a full spectrum of amenities including overnight camping, showers, restrooms, swimming access, day-use picnic areas, and a public boat launch. The following IAF thematic messages are prescribed for this hub (a) in this vicinity, the largest floods from glacial Lake Missoula were nearly 800 ft (783 ft) deep, approximately 690 ft higher than the existing river shoreline; (b) portions of the Wanapum boat launch, campground, and day-use areas are located atop IAF deposits; (c) rhythmites exposed along the Columbia River shoreline record evidence of IAF events; and (d) based on evidence of Mount St. Helens ash in nearby flood deposits, the most recent IAF passed down the CRV approximately 15,000 calendar years ago.

Level 3-Story Point Sites

The third level of the interpretive network, story point sites, are the specific locations in the park where visitors are exposed to thematic IAF messages prescribed for each hub location. At story point sites visitors can interact with interpretive media, the landscape, or the resource itself to gain valuable and memorable interpretive experiences.

Proposed story point sites for the interpretive center hub include (a) an outdoor IAF orientation kiosk, (b) a barrier-free Columbia River viewpoint, (c) indoor IAF exhibits, (d) Schnebly Coulee eddy bar profile viewpoint, (e) misplaced basalt boulders located on eddy bar surface, (f) bergmound deposit viewpoint located on landslide north of the interpretive center; and (g) a viewpoint at the largest erratic surveyed. For specific locations of story point sites within this interpretive hub see Figure 37.

Proposed story point sites of the interpretive trail hub include (a) an outdoor IAF orientation kiosk, (b) the Petrified Forest Interpretive trailhead, (c) a proposed IAF loop trail junction, (d) ice-rafted erratic located in vicinity of proposed IAF loop trail, (e) the 1,263 ft glacial Lake Lewis shoreline marker, and (f) a proposed Iceberg Pass viewpoint. For specific locations of story point sites within the interpretive trail hub see Figure 38.

Proposed story point sites of the Wanapum day-use area interpretive hub include (a) proposed outdoor orientation kiosk, (b) proposed IAF trailhead, (c) exposed river shoreline rhythmite outcrops, and (d) the boat launch area. For specific locations of story point sites within the Wanapum day-use area see Figure 39.

Interpretive Media Recommendations

IAF interpretive recommendations are organized by Level 1 media followed by specific suggestions for each interpretive hub and associated story point sites. Interpretive hub media recommendations are followed by proposed steps toward implementation.

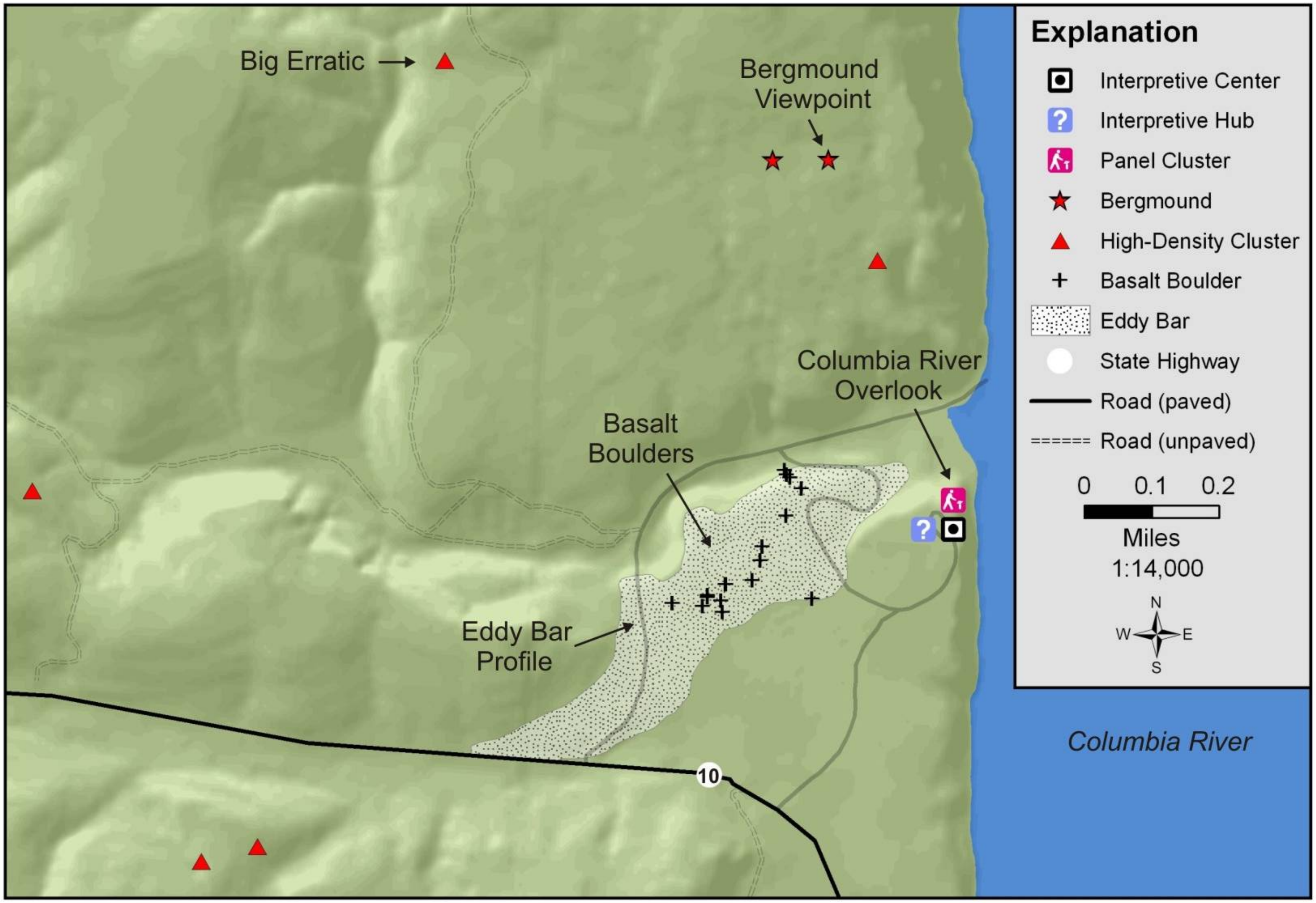


Figure 37. Potential story point locations within the Ginkgo Petrified Forest Interpretive Center hub.

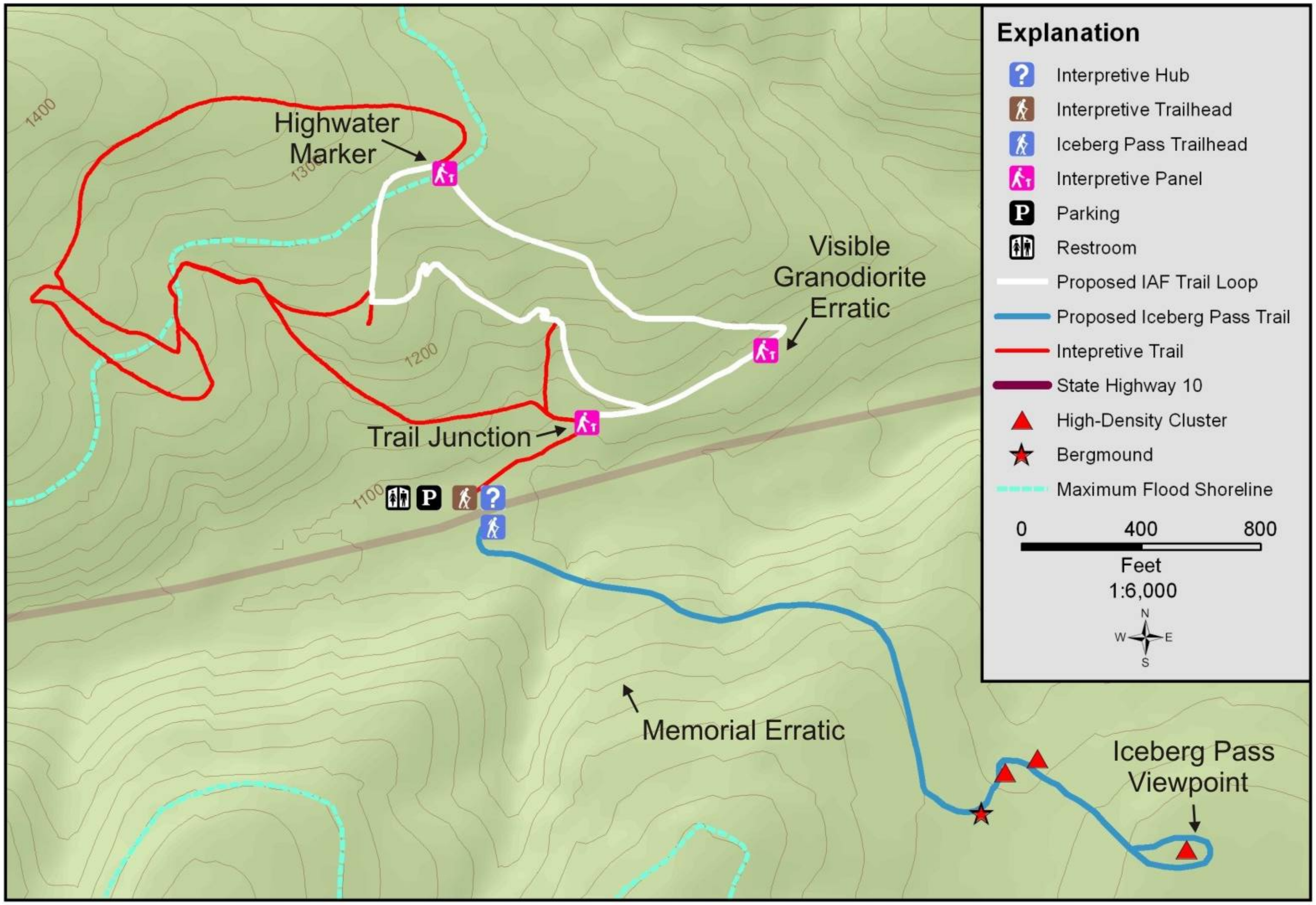


Figure 38. Potential story point locations and proposed interpretive trail routes within the Petrified Forest Interpretive Trail hub. IAF = Ice Age Floods

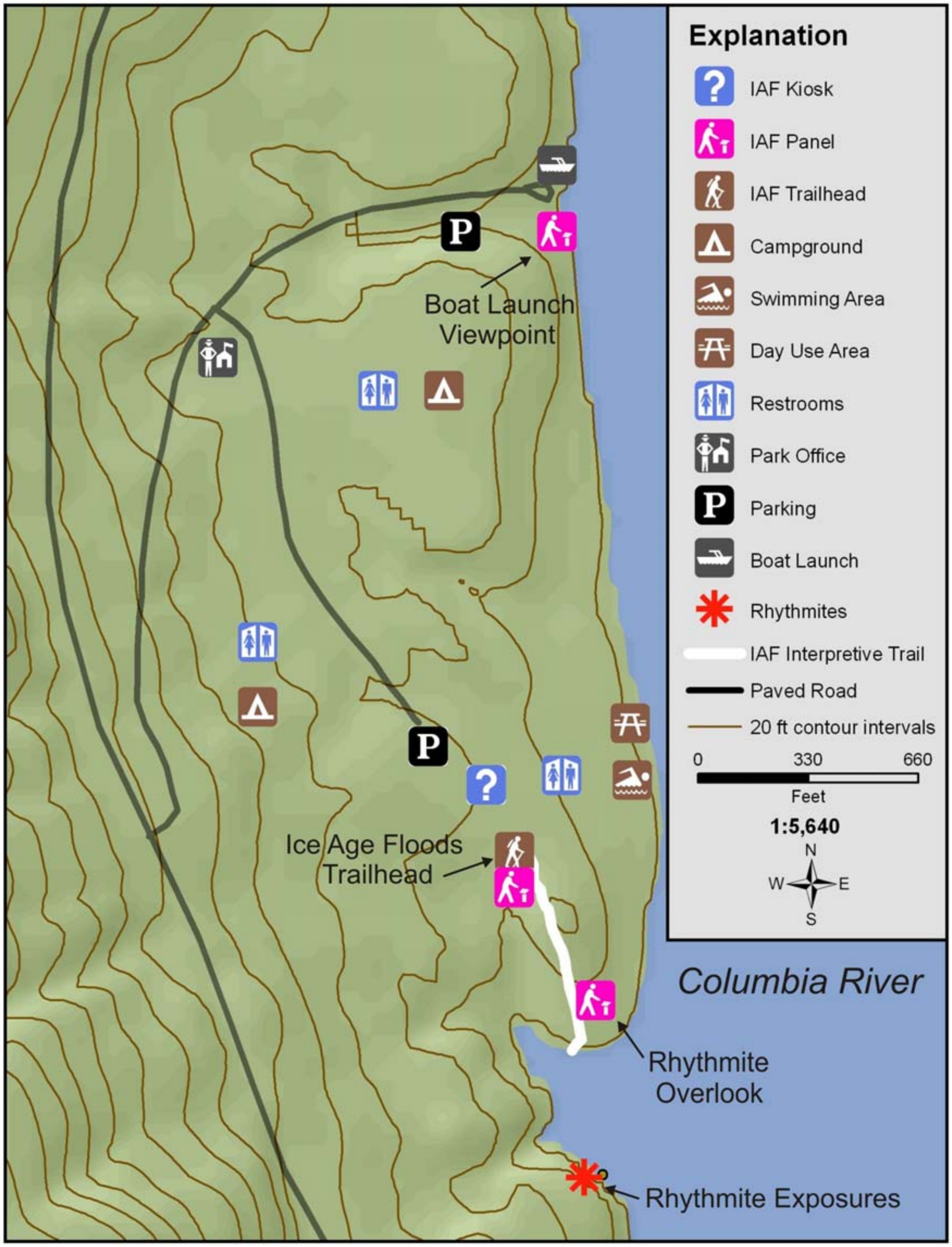


Figure 39. Potential story point locations within the Wanapum day-use area interpretive hub. IAF = Ice Age Floods.

Interpretive Network Orientation

Website Enhancements

The Internet is a valuable resource for previsit enticement and orientation. Recommendations include (a) expansion of the WSPRC homepage to include a link to an IAF web page, which provides an overview of IAF history; (b) indexing of the IAF web page to link keywords to the existing park page; (c) revision of the park web page to include an interpretive network map; and (d) networking with other state and local agency and tourism organization links to enhance the accessibility of park interpretive opportunities. This project will require consultation and administrative authorization to assure compliance within agency web site and media requirements.

Interstate 90/State Route 10 Sign Plan

Interstate 90 is a vital transportation corridor linking the Puget Sound to the inter-mountain west. Recommendations include coordination with Washington Department of Transportation to provide orientation to IAF interpretive opportunities in the park and the Channeled Scabland. Prime locations for IAF orientation include the Ryegrass rest area, located 10 mi (16.1 km) west of the park, and an elevation of 1,263 ft (285 m) along Interstate 90 and State Route 10. IAF media at the Ryegrass rest area site should include a regional IAF map with orientation to the park. IAF media at the 1,263 ft (285 m) sites should include a scenic byway road sign which contains an IAF logo and message informing travelers of the boundary location of the Channeled Scabland.

To improve visitor recognition, the IAF logo used at the Channeled Scabland boundary should appear on Interstate 90 and State Route 10 signage to the park and specifically the interpretive center, interpretive trail, and Wanapum day-use area.

Development of the IAF logo is currently in progress and its use should be coordinated with other IAF planning projects.

Ice Age Floods Brochure

Recommendations include design and publication of a brochure to provide enticement and spatial orientation to park IAF interpretive opportunities. Content should include a comprehensive IAF map, concise directions to park interpretive hub locations, primary themes resulting from this research, and context of the park within the larger IAF history. Distribution of brochure should extend to regional and statewide IAF and Columbia River interpretive facilities and regional tourism marketing locations.

Ice Age Flood Travel Guide

Recommendations include contracting services for the development and publication of an IAF travel guide to entice potential visitors and enhance the statewide IAF interpretive network. The travel guide should provide management messages, spatial orientation, and concise way-finding to IAF facilities and remote field sites within the proposed IAF National Geologic Trail. This guide should also provide background information concerning the natural and cultural significance of IAF features.

Ginkgo Petrified Forest Interpretive Center

As the primary interpretive hub, the interpretive center is the target destination for previsit and on-site orientation. Due to the existing petrified wood interpretation at this site, IAF media should compliment, not diminish this interpretive focus. However, this hub also serves as a potential primary orientation hub to the regional IAF National Geologic Trail. Therefore, hub media messages should consider a national audience.

Interpretive Hub Kiosk

The proposed interpretive center hub kiosk should have the capacity for two phenolic orientation panels and be placed in an easily recognized, barrier-free location (Figure 37). One panel should provide regional IAF spatial orientation, including the park landscape's site and situation within the Channeled Scabland and the Lake Lewis Basin. The second panel should convey primary park IAF messages and orientation to story points using an interpretive network map.

Outdoor Interpretive Sign Plan

A barrier-free interpretive panel cluster comprised of two phenolic panels is recommended within view of the Columbia River landscape (Figure 37). The interpretive panel cluster should be located along the exterior of the observatory to provide outdoor IAF interpretation. One panel should convey IAF messages related to the Columbia River and view of scabland basalt and elevated gravel bars lining the river. The second panel should be located within the viewshed of Sentinel Gap and convey IAF messages related to the glacial Lake Lewis and surrounding basalt landscape.

Indoor Interpretive Exhibits

The following IAF interpretive media are proposed to compliment existing interpretive messages within the interpretive center. First, there should be development of an IAF exhibit, consisting of two panels in a located consistent with the geologic timeline of the overall exhibit design. Exhibit concepts should include the influence of the Cordilleran Icesheet on IAF routes and the classification of deposits associated with Cordilleran Icesheet and glacial Lake Lewis. Another alternative is to include these concepts within an interactive stream table that would allow for the manipulation of the

Columbia River drainages network by visitors to mimic the influence of advancing and receding glaciers of drainage patterns and sources of flood transported icebergs. Second, there should be development of an interactive exhibit illustrating the diversity and origin of ice-rafted erratics deposited within the park landscape. Exhibit concepts should include a display of diverse ice-rafted erratic specimens, thematic text, and a map to orient visitors to potential iceberg origins. Interactive components should include secured, but hand accessible, ice-rafted erratics and indigenous basalt, and a puzzle framework to integrate problem solving with the origin of erratics. Puzzle pieces, representing icebergs containing erratics, should be designed to provide spatial recognition of erratic origins in the context of geographic locations. Third, there should be coordination with regional outreach partners in the production of a thematic video to highlight the IAF history of the Columbia River within the Vantage Reach. The scope of this media should address the known geologic history of the Vantage Reach landscape, including Miocene sequence of flood basalt inundation, fossil log petrifaction and exposure, landscape climate change, IAF heritage, and landscape and transportation corridor changes attributed to construction of Wanapum Dam.

Educator's Packet

Information regarding the IAF heritage of the park and the Channeled Scabland is found primarily in scientific publications and is not readily available to educators and outreach organizers. Therefore, a need exists to develop interactive worksheets and information guides to aid educators and outreach groups utilizing the park. Due to the variety of potential student and special groups, assessment of target user group needs is recommended prior to development of worksheets and guided interpretive opportunities.

Petrified Forest Interpretive Trail

The interpretive trail hub is the primary trail complex within the park. Due to the existing petrified wood exhibits at this site, IAF media should compliment this interpretive focus, while expanding park hiking opportunities.

Interpretive Hub Kiosk

The proposed interpretive trail hub kiosk should have the capacity for two phenolic orientation panels and be placed within the existing day-use area (Figure 38). One panel should provide park level IAF orientation. This panel should convey primary IAF messages related to the extent of glacial Lake Lewis and orientation to IAF hiking opportunities. The second panel should be reserved for additional themes to be treated within the scope of the comprehensive park interpretive master plan.

Ice Age Flood Trail Sign Plan

Ice-rafted erratics deposited along the margins of glacial Lake Lewis are visible along the eastern route of the existing interpretive trails. In addition, the eastern loop of the existing trail system transects the maximum known elevation of the glacial Lake Lewis shoreline. Therefore, a conversion of approximately 0.75 mi (1.2 km) of the existing self-guided trail into an IAF interpretive loop trail is proposed (Figure 38).

The proposed IAF trail sign plan consists of three phenolic interpretive panels. The first panel is proposed at the southern junction of the IAF trail with the existing Petrified Forest trail (Figure 38). This panel should convey spatial orientation to the trail loop and introduce the primary IAF message for the trail. The second panel is proposed within view of two visible ice-rafted erratics. One comprised of granodiorite is located just south of the trail. The second is a memorial erratic placed on the adjacent northfacing slope to honoring a Civilian Conservation Corps member who died during construction of the site in the 1930s. In addition, this panel location provides visitors with views of the Columbia River and Iceberg Pass. This panel should convey IAF messages related to iceberg transport and deposition within the research study area. The third panel is proposed near the northeastern trail junction at an elevation of 1,263 ft (385 m). This panel should convey thematically the maximum extent of ice-rafted erratics in the study area and provide context to the spatial extent of glacial Lake Lewis.

Iceberg Pass Guided Interpretive Trail

A guided interpretive trail route is proposed to access high-density erratic cluster and bergmound deposits located within the interfluve pass separating the Ryegrass and Schnebly drainages (Figure 38). The trail route would utilize the existing access road located south of interpretive trail parking area. Due to the primitive conditions of the access road, and the abundance of petrified wood in the vicinity, the trail is not recommended for year-round open access. Guided hike interpretive messages should convey topographic relationships between the interfluve pass environment and iceberg deposition during occupation of the landscape by glacial Lake Lewis.

Wanapum Recreation Day Use Area

The primary function of the Wanapum day-use area hub is to inform day-use visitors and campers of IAF interpretive opportunities within the park. Sources for IAF interpretation in this hub vicinity were obtained through existing IAF literature.

Interpretive Hub Kiosk

The proposed Wanapum day-use area interpretive hub kiosk should have the capacity for two phenolic orientation panels placed near the day-use area in a barrier-free location (Figure 39). One panel should provide IAF orientation to the park IAF interpretive network. This panel should incorporate primary IAF interpretive messages within the hub vicinity including orientation to the proposed IAF Heritage Trail. The second panel should be reserved for additional themes to be treated within the scope of the comprehensive park interpretive master plan.

Ice Age Floods Heritage Trail Sign Plan

An extensive outcrop of IAF rhythmites exists along the Columbia River shoreline south of the day-use swimming area. Therefore, a self-guided interpretive trail is proposed to interpret these unique flood deposits (Figure 39). The proposed IAF Heritage Trail sign plan consists of two phenolic interpretive panels. The first panel is proposed at the existing trailhead located along the southern end of the primary day-use parking area. This panel should provide spatial orientation to the trail and convey the primary IAF message of the trail. A second panel is proposed along the existing trail near the shoreline of the Columbia River. This panel should convey concepts related to the flood processes responsible for visible IAF deposits.

Boat Launch Area Interpretive Panel

A single phenolic interpretive panel is proposed near the Wanapum boat launch. This panel should provide spatial orientation of IAF features to boaters accessing the Wanapum reservoir. In addition, this panel should provide orientation to the park IAF interpretive network.

Steps Toward Implementation

Implementation is essential to the success of the proposed IAF interpretive network. Each proposed interpretive project must undergo three stages of development

(a) the procurement of funding and necessary permits, (b) media concept and detailed design, and (c) fabrication and installation. A two-phase implementation strategy is proposed for the interpretive recommendations provided by the outcome of this research. Table 5 outlines the high-priority phase 1 interpretive projects. Table 6 outlines phase 2 interpretive projects likely requiring multiple funding sources.

It should be noted the timeline associated with each individual project is directly dependant on the availability of funding and permit review. In order to secure funding, all possible sources should be investigated including potential grants, in-kind contributions, resources and support from private nonprofit organizations, and other strategic opportunities. Permitting considerations for proposed interpretive media recommendations will require consultation and coordination with appropriate local, state and federal regulatory entities, including state and federal historic preservation personnel.

Table 5

Proposed Phase 1 Ice Age Flood Interpretive Network Development

Project title	Location	Brief description	Cost estimate
Website enhancements	Agency headquarters	Ice Age flood Web page development.	Staff determined
Ice Age floods brochure	Park network	Design, publication, and distribution of folded 4 in. x 9 in. semigloss, color print brochures.	Design: staff Publication: (Qty: 10,000) $5,000
Educator's packet	Interpretive center hub	Development and publication of fact sheets and worksheets.	$2,000
Ice Age floods interpretive hub	Interpretive center hub	Design, construction, and installation of a kiosk structure and two phenolic panels.	$20,000
Outdoor interpretive sign plan	Interpretive center hub	Design, fabrication, and installation of two phenolic panels.	$12,000
Ice Age floods interpretive hub	Interpretive trail hub	Design, construction, and installation of a kiosk structure and a phenolic panel.	$14,000
Ice Age floods interpretive trail sign plan	Interpretive trail hub	Design, fabrication, and installation of three phenolic panels.	$18,000
Interstate/highway sign plan	Ryegrass rest area, Interstate 90, and State Route 10	Design, fabrication, and installation of four road signs and an orientation panel.	$20,000

Table 6

Proposed Phase 2 Ice Age Flood Interpretive Network Development

Project title	Location	Brief description	Cost estimate
Ice Age flood interpretive hub	Wanapum day-use area hub	Design, construction, and installation of a kiosk structure and a phenolic panel.	$14,000
Ice Age floods heritage interpretive trail sign plan	Wanapum day-use area hub	Design, fabrication, and installation of two phenolic panels.	$12,000
Boat launch interpretive panel	Wanapum boat launch	Design, fabrication, and installation of a phenolic panel.	$6,000
Indoor interpretive exhibits	Interpretive center hub	Concept and detailed design, fabrication, and installation of Cordilleran Icesheet and ice-rafted erratic origin exhibits.	$25,000-$40,000
Interpretive video	Interpretive center hub	Contracting of script development, video and sound production, editing, and fabrication of 10-min video.	$100,000
Ice Age floods travel guide	Park network	Contract services for development, editing, and publication of color print guide.	$10,000-15,000
Iceberg Pass trail development	Interpretive trail hub	Installation of pedestrian gate and grading of trail route.	$8,000-$10,000

CHAPTER VII

SUMMARY

The primary objectives of this thesis were to (a) identity and map the extent of Pleistocene flooding, (b) identify and map the distribution of Pleistocene flood features, (c) interpret geomorphic relations of flood and landform features, (d) interpret flood processes acting in the study area, and (e) develop recommendations for a network of IAF interpretive opportunities to effectively communicate research results to the public.

Extent of Pleistocene Flooding

This research extends the estimated maximum extent of Pleistocene flooding in the Vantage Reach from 1,227 ft (374 m) to 1,263 ft (385 m). The maximum extent of flooding in the study area was determined by the elevation of the highest ice-rafted erratic surveyed north of the interpretive trails. Based on the 480 ft (146 m) elevation of the paleo-Columbia River, the largest flood in the study area was no less than 783 ft (239 m) deep. A flood this deep would extend 158 ft (48 m) above Seattle's Space Needle (605 ft/184 m tall). It is plausible a high-magnitude flood event responsible for high-elevation erratics (> 1,200 ft/366 m) occurred prior to the Okanogan Lobe damming of the Columbia River. No datable material was obtained to confirm this hypothesis.

The maximum extent of flooding determined by this research advances the hypothesis of a progression of hydraulically dammed pools, lowering in elevation from basin to basin, as floodwaters encountered constrictions in the CRV en route to Wallula Gap. A slight increase (13 ft/4 m) in pool elevations between the Vantage Reach and the Pasco Basin (1,250 ft/380 m) was identified and is attributed to hydraulic pooling of floodwaters behind Sentinel Gap. Given the marginal extent of variation in maximum inundation levels between these adjacent basins it is plausible that glacial Lake Lewis extended from Wallula Gap into the study area.

Spatial Distribution of Pleistocene Flood Features

Erosional flood channel features documented in the study area included extensive scabland escarpments along the Columbia River, scoured basalt flow top surfaces adjacent to scabland escarpments up to 1,100 ft (335 m), and a stripped interfluve bench located between the interpretive center and State Route 10.

Depositional flood channel features were confined to elevations < 800 ft (245 m) indicating subfluvial deposition from floodwaters exiting Frenchman Gap occurred within 300 ft (91 m) in elevation from the paleo-Columbia River channel. Flood channel deposits were documented in the form of a modified eddy bar deposit and large basalt boulders. The presence of 37 individual rhythmite couplets underlying an unsorted unit of the eddy bar deposit indicates multiple flood events are recorded in this location.

The most abundant slackwater deposits documented in the study area were ice-rafted erratics. Erratic deposits were classified as (a) isolated (57%), (b) low-density cluster (39%), (c) high-density cluster (3%), and (d) bergmounds (1%). Of the erratic deposit types, bergmounds and high-density erratic clusters were found to be the most significant due to their rare reported frequency outside the Pasco Basin and their close proximity to erosional flood channel features. The highest bergmound was surveyed in the Schnebly Coulee drainage at 1,162 ft (354 m). This research extends the reporting of bergmound elevations by 160 ft (49 m), based on the 1,000 ft (305 m) limit of bergmounds reported in the Pasco and Walla Walla basins. The highest high-density erratic cluster was surveyed in the Ryegrass Coulee drainage at 1,218 ft (371 m). The comparable range in maximum diameter, surface area, and elevation between high-density erratic cluster and bergmound deposits indicates icebergs responsible for their origin were comparable in size and/or volume. The origin of high-density erratic clusters in the study area is therefore attributed to (a) deposition of large icebergs containing dense loads of erratic debris atop erosional surfaces devoid of significant slackwater or fine-grain sediments, (b) the lack of sufficient waning flood currents to erode sediments and generate bergmound topography, or (c) the erosion of low-relief bergmound topography by Holocene erosional processes.

This research determined approximately 100 ft (30 m) of water was necessary to transport large icebergs responsible for the generation of bergmounds. This modifies the 200-ft (60-m) estimated water depth required for bergmound generation in the Pasco Basin. Furthermore, no less than 45 ft (14 m) of water was necessary to transport icebergs responsible for the generation of high-density erratic clusters. Potential factors contributing to the variance in elevation of large iceberg deposition between the adjacent basins include wind velocity and topography. Increased or more consistent wind velocities may have delivered large icebergs to higher elevations of flooded terrain. Furthermore, the presence of moderate- to steep-angled slopes may have provided for iceberg migration into higher elevations prior to deposition on erosional basalt flow top/pass landforms.

One sample chi-square analysis found significant relations within the distribution of all ice-rafted erratic variables documented during field surveys. The dominant erratic rock types sampled were granitic, comprised of either granodiorite or granite. Erratics were documented between 641 ft (195 m) and 1,263 ft (385 m) with the highest frequency of erratics between 1,100 ft and 1,200 ft (335 m and 366 m). The majority of erratics were documented along east to south aspects (67.5º to 202.5º) and moderate slopes (7º-21º). The majority of erratics were small to moderate in size (> 3ft²/0.3 m²) exposed cross-sectional area) and observed partially to nearly buried. The largest single erratic documented was 85 ft² (7.9 m²) in exposed cross-sectional area, located in a high-density erratic cluster deposit located north of the interpretive center.

Rhythmites were documented in the study area between 600 ft and 1,100 ft (183 m and 335 m). At low elevations (< 700 ft/213 m) within Rocky Coulee, rhythmite exposures were thin and comprised of fine-grained silt couplets. At higher elevations (> 700 ft/244 m), rhythmites were comprised of mixed, coarse-grained sands and gravels observed underlying angular basalt gravels containing erratic sediments.

Below 1,100 ft (335 m) surficial, coarse-grained crystalline sands were observed in many locations throughout the study area. Based on their location within known Pleistocene flood terrain, and the absence of indigenous crystalline sediments, they were interpreted as remnant, laminated slackwater deposits likely influenced by subsequent surface eolian and fluvial erosion.

Relations of Pleistocene Flood and Landscape Features

The abundance of slackwater deposits reported within indicates low-energy currents associated with their deposition dominated flood processes acting in the study area. Two sample chi-square analysis of ice-rafted erratic variables identified significant relationships between erratic deposit type and size, elevation and size, elevations and slope angle, elevation and aspect, and slope angle and size.

Bergmound and high-density erratic cluster deposits were found to contain larger erratics than low-density erratic clusters and isolated erratics. In addition, bergmound and high-density erratic clusters were limited between 917 ft and 1,218 ft (280 m and 371 m), mainly within clustered distributions. These data indicate (a) the association of larger volume icebergs with bergmounds and high-density erratic clusters is not random, and (b) their transport and deposition in the study area were limited to moderate- and high-magnitude floods, requiring flood depths between 437 ft and 758 ft (133 m and 231 m).

As floodwaters drained from the study area, iceberg deposition was associated with topographic features of the landscape. During the highest magnitude flood(s), nearly all icebergs reaching elevations > 1,200 ft (366 m) were small (> 3 ft^2/0.28 m^2) and prone to grounding on east-to-south aspects, and moderate- to steep-angled slopes (> 7º). Based on the high frequency of erratics > 1,100 ft (335 m), the majority of erratics sampled can be attributed to one or more high-magnitude flood events requiring minimum flood depths of 620 ft (189 m) for iceberg deposition. In addition, between 1,100 ft and 1,200 ft (335 m and 366 m), the distribution of erratics by aspect was most diverse indicating variable wind and eddy current patterns along interfluve divide and mid-slope landforms, oriented opposite the direction of draining floodwaters, influenced the clustering and deposition of icebergs in this elevation range. Below 1,000 ft (305 m) iceberg deposition was less common and prone to low-angle slopes (0º-6º) along east to southeast aspects, presumably the general orientation of eddy currents and/or wind patterns responsible for iceberg delivery to these slopes. Erratics in this elevation range are attributed to deposition during low-magnitude flood events, likely containing fewer icebergs of significant volume.

With the exception of scabland escarpments, the majority of erratics sampled were observed on erosional landforms. Conversely, the low frequency of erratics on depositional landforms indicates (a) icebergs were prone to deposition along existing erosional surfaces; or (b) Holocene erosion has exposed erratics located on active erosional surfaces, and buried erratics may remain preserved within depositional landforms. Based on the high frequency of partially buried erratics, the latter interpretation is favored.

All four erratic deposit types were observed on a large translational landslide deposit in the Rocky Coulee drainage located north of the interpretive center. The presence of bergmounds and high-density erratic clusters indicates moderate- to high-magnitude flooding has occurred since the initiation of substantial mass wasting, attributing a late-Pleistocene minimum age of the deposit. It should be noted that other large-scale translational landslides exist in the Vantage Reach below the known extent of flooding. Further investigation of the relation between landslide deposits and Pleistocene flooding is needed.

Interpretation of Flood Processes

The relation of landform and Pleistocene flood processes documented in the study area can be attributed to three identifiable stages of flooding. The initial stage of flooding was characterized by landscape-scale erosional processes. The extreme competence of floodwaters exiting Frenchman Gap created scabland escarpment landforms common to the Columbia River channel and nearshore environment. In addition, the absence of widespread loess < 1,100 ft (335 m) is attributed to erosional processes.

The next stage of flooding initiated as floodwater entering the Vantage Reach exceeded the outflow at Sentinel Gap. This caused floodwaters to hydraulically pool and to inundate adjacent tributary environments. As floodwaters encountered pooled floodwaters in the Vantage Reach, low-energy depositional currents dominated. Bedload sediments were deposited along tributary entrances while laminated sand deposits and rhythmites were deposited along low- to mid-angle slopes and margins of flooded terrain, respectively. During this stage floating icebergs migrated into tributary environments along low-energy eddy currents and dominant wind patterns.

The final stage of flooding commenced as floodwaters exiting Sentinel Gap exceeded the volume of water entering the Vantage Reach. Icebergs grounded as floodwaters drained from the landscape, leaving hundreds of ice-rafted erratics to mark their final resting place. As waning flood currents exited the study area, incision of unconsolidated channel, slackwater, and lacustrine deposits likely occurred. It is plausible high-magnitude floods required multiple days for waxing and waning stages to occur.

Public Interpretation of Research Results

Based on known parameters impacting interpretive opportunities and the location of existing interpretive facilities, a three-level network of interpretive opportunities is recommended to communicate IAF interpretive messages derived from this research. Previsit and on-site orientation strategies within the first level are prescribed to entice visitors to explore the second level, interpretive hubs. Three interpretive hubs are prescribed within Ginkgo Petrified Forest State Park (a) the Ginkgo Petrified Forest Interpretive Center, (b) the Petrified Forest Interpretive Trail, and (c) the Wanapum day-use area. The third level of the network includes story points where visitors can interact with IAF resources or media conveying messages through the landscape.

Based on the desired outcomes of each level in the interpretive network, specific IAF interpretive media was prescribed. Potential IAF interpretive projects resulting from recommendations within range from website enhancement, a Heritage Corridor road sign plan, indoor exhibit renovation, self-guided outdoor interpretive sign plans and trails to publication of orientation and interpretive brochures and guide books.

The development of IAF interpretation media will provide visitors with orientation and knowledge of (a) their location at the gateway to the Channeled Scabland of eastern Washington, (b) the extent of Pleistocene flooding within the park landscape, (c) flood processes responsible flood features of the Vantage Reach, and (d) information necessary to recognize Pleistocene flood features within the park landscape and the greater Channeled Scabland region. IAF interpretation will provide the opportunity for visitors to be fascinated at the magnitude and extent of flooding documented by this research. Furthermore, they will be motivated to share knowledge gained from this research with others in a positive manner and engage in related natural and cultural heritage programming and learning opportunities.

Further Research

Further research of Pleistocene flood features located within the southern portions of the park, not included in this study, is recommended to enhance the overall documentation of flood feature distributions on WSPRC managed lands. Potential exists to further this research through the relative dating of ice-rafted erratics and related slackwater deposits. Potential dating strategies included quantitative analysis of erratic shape and degree of surface weathering frequencies to determine in situ weathering patterns (Bjornstad et al., 2003). Another approach is to further investigate rhythmite exposures for the presence of Mount St. Helens tephra to provide a stratigraphic time marker. Finally, great public interest exists in the origin of ice-rafted erratics. An inquiry of the likely source locations for granitic and perhaps less frequent rock types would be of great interpretive value.

In addition, further interpretive message development is needed of the context of Pleistocene flooding in the overall landscape evolution of the park landscape. Potential research topics include the impacts of climate change on the storage and release of freshwater within the Columbia River Basin, the role of Pleistocene flooding in the development of sand dunes in the Vantage Reach, the relation between regional landslide and Pleistocene flood processes, the influence of Pleistocene flooding on vegetation distribution patterns, and the influence of Holocene depositional and erosional patterns on the park landscape and the stratigraphy of Pleistocene flood features.

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APPENDIXES

Appendix A

One Sample Chi-Square Test Results

Following are the results of one sample chi-square analysis of significantly related ice-rafted erratic variables. For associated Cramer's *V* relationship strength test results, see Table 2.

Table A1

Chi-Square Results of Erratic Classification Type Analysis

	Erratic classification type			
Test results	Isolated	Low-density cluster	High-density cluster	Bergmound
Observed	193.0	130.0	11.0	3.0
Expected	84.25	84.25	84.25	84.25
χ^2	140.38	24.84	63.67	78.36

Note. $\chi^2(3, N = 337) = 307.26$.

Table A2

Chi-Square Results of Erratic Rock Type Analysis

	Erratic rock type				
Test results	Granitic	Quartzite	Diorite	Gneiss	Other
Observed	269.00	26.0	22.0	12.0	8.0
Expected	67.40	67.40	67.40	67.40	67.40
χ^2	603.01	25.43	30.58	45.54	52.35

Note. $\chi^2(4, N = 337) = 756.90$.

Table A3

Chi-Square Results of Erratic Elevation Class Analysis

	Erratic elevation class			
Test results	< 900 ft	1,000-1,099	1,100-1,199	> 1,200
Observed	73.0	67.0	147.0	50.0
Expected	84.25	84.25	84.25	84.25
χ^2	1.50	3.53	46.74	13.92

Note. $\chi^2(3, N = 337) = 65.69$.

Table A4

Chi-Square Results of Erratic Aspect Analysis

	Aspect							
Test results	North	North-east	East	South-east	South	South-west	West	North-west
Obs.	29.0	24.0	78.0	52.0	109.0	11.0	27.0	7.0
Exp.	42.13	42.13	42.13	42.13	42.13	42.13	42.13	42.13
χ^2	4.09	7.79	30.55	2.32	106.17	23.0	5.43	29.29

Note. $\chi^2(7, N = 337) = 208.64$; Obs. = observe; Exp. = expected.

Table A5

Chi-Square Results of Erratic Slope Angle Analysis

	Slope angle in degrees							
Test results	0-3	4-6	7-9	10-12	13-15	16-18	19-21	> 22
Observed	42.0	66.0	68.0	56.0	45.0	32.0	13.0	15.0
Expected	42.13	42.13	42.13	42.13	42.13	42.13	42.13	42.13
χ^2	0.03	13.53	15.89	4.57	0.20	2.43	20.14	17.47

Note. $\chi^2(7, N = 337) = 74.23$.

Table A6

Chi-Square Results of Erratic Size Class Analysis

	Erratic size class in square feet			
Test results	< 1	1-2	3-4	> 5
Observed	121.0	123.0	29.0	64.0
Expected	84.25	84.25	84.25	84.25
χ^2	16.03	17.82	36.23	4.87

Note. $\chi^2(3, N = 337) = 74.95$.

Table A7

Chi-Square Results of Erratic Exposure Analysis

	Exposure	
Test results	Surface	Partially buried
Observed	14.0	323.0
Expected	168.50	168.50
χ^2	141.66	141.66

Note. $\chi^2(1, N = 337) = 283.33$.

Table A8

Chi-Square Results of Geomorphic Map Unit Analysis

	Geomorphic map unit									
Test results	Basalt flow top/pass	Loess island	Eros. mid-slope	Dep. mid-slope	Scabland escarp.	Land-slide	Talus	Alluvial fan	Flood-plain	Flood-bar
Observed	93.0	6.0	126.0	12.0	3.0	45.0	11.0	8.0	7.0	26.0
Expected	33.70	33.70	33.70	33.70	33.70	33.70	33.70	33.70	33.70	33.70
χ^2	104.35	22.77	252.80	13.97	27.97	3.79	15.29	19.60	21.15	1.76

Note. Eros. = erosional; Dep. = depositional; Escarp. = escarpment; $\chi^2(9, N = 337) = 483.45$.

Appendix B

Two Sample Chi-Square Test Results

Following are the results of two sample chi-square analysis of significantly related ice-rafted erratic variables. For associated Cramer's *V* relationship strength test results see Table 3.

Table B1

Chi-Square Results of Erratic Deposit Type and Size Class Analysis

	Erratic deposit type		
Erratic size class in ft²	Isolated	Low-density cluster	High-density cluster/bergmound
< 1			
Observed	89.0	32.0	0.0
Expected	69.30	46.68	5.03
χ^2	5.60	4.61	5.03
1-2			
Observed	66.0	56.0	1.0
Expected	70.44	47.45	5.11
χ^2	0.28	1.54	3.31
3-4			
Observed	12.0	15.0	2.0
Expected	16.61	11.19	1.20
χ^2	1.28	1.30	0.52
> 5			
Observed	26.0	27.0	11.0
Expected	36.65	24.69	2.66
χ^2	3.10	0.22	26.17

Note. $\chi^2(6, N = 337) = 52.96$.

Table B2

Chi-Square Results of Erratic Elevation and Size Class Analysis

	Elevation class in feet			
Erratic size class in ft²	< 999	1,000-1,099	1,100-1,199	> 1,200
< 1				
Observed	9.0	10.0	62.0	40.0
Expected	26.21	24.06	52.78	17.95
χ^2	11.30	8.21	1.61	27.08
1-2				
Observed	37.0	31.0	47.0	8.0
Expected	26.64	24.45	53.65	18.25
χ^2	4.03	1.75	0.56	5.76
3-4				
Observed	12.0	7.0	10.0	0.0
Expected	6.28	5.77	12.65	4.30
χ^2	5.20	0.26	0.56	4.30
> 5				
Observed	15.0	19.0	28.0	2.0
Expected	13.86	12.72	27.92	9.50
χ^2	0.09	3.10	0.0	5.92

Note. $\chi^2(9, N = 337) = 79.99$.

Table B3

Chi-Square Results of Erratic Elevation Class and Slope Angle Analysis

Slope angle in degrees	Elevation class in feet			
	< 999	1,000-1,099	1,100-1,199	> 1,200
0-3				
Observed	26.0	3.0	8.0	5.0
Expected	9.10	8.35	18.32	6.23
χ^2	31.40	3.43	5.81	0.24
4-6				
Observed	18.0	16.0	27.0	5.0
Expected	14.30	13.12	28.79	9.79
χ^2	0.96	0.63	0.11	2.35
7-9				
Observed	10.0	25.0	25.0	8.0
Expected	14.73	13.52	29.66	10.09
χ^2	1.52	9.75	0.73	0.43
> 10				
Observed	19.0	23.0	87.0	32.0
Expected	34.88	32.01	70.23	23.89
χ^2	7.23	2.54	4.01	2.76

Note. $\chi^2(9, N = 337) = 73.89$.

Table B4

Chi-Square Results of Erratic Elevation Class and Aspect Analysis

Aspect in degrees	Elevation class in feet < 999	1,000-1,099	1,100-1,199	> 1,200
337.5-67.5				
Observed	13.0	7.0	25.0	8.0
Expected	11.48	10.54	23.12	7.86
χ^2	0.02	1.19	0.15	0.00
67.5-157.5				
Observed	33.0	25.0	43.0	29.0
Expected	28.16	25.85	56.71	19.29
χ^2	0.83	0.03	3.31	4.89
157.5-247.5				
Observed	25.0	29.0	55.0	11.0
Expected	25.99	23.86	52.34	17.80
χ^2	0.04	1.11	0.13	2.60
247.5-337.5				
Observed	2.0	6.0	24.0	2.0
Expected	7.36	6.76	14.83	5.04
χ^2	3.91	0.09	5.67	1.84

Note. $\chi^2(9, N = 337) = 25.99$.

Table B5

Chi-Square Results of Erratic Size Class and Slope Angle Analysis

	Erratic size class in square feet			
Slope angle in degrees	< 1	1-2	3-4	> 5
0-3				
Observed	12.0	25.0	3.0	2.0
Expected	15.08	15.33	3.61	7.98
χ^2	0.63	6.10	0.10	4.48
4-6				
Observed	18.0	22.0	10.0	16.0
Expected	23.70	24.09	5.68	12.53
χ^2	1.37	0.18	3.29	0.96
7-9				
Observed	21.0	29.0	4.0	14.0
Expected	24.42	24.82	5.85	12.91
χ^2	0.48	0.70	0.59	0.09
> 10				
Observed	70.0	47.0	12.0	32.0
Expected	57.81	58.76	13.85	30.58
χ^2	2.57	2.35	0.25	0.07

Note. $\chi^2(9, N = 337) = 24.21$.