Early to Middle Pleistocene Catastrophic Flood Deposits, the Dalles, Oregon

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THESIS APPROVAL

The abstract and thesis of David Irving Cordero for the Master of Science in Geology were presented May 7, 1997 and accepted by the thesis committee and the department.

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AN ABSTRACT OF THE THESIS OF David Irving Cordero for the
Master of Science in Geology presented May 7, 1997.

Title: Early to Middle Pleistocene catastrophic flood deposits, The Dalles, Oregon

A roadcut on Highway 197, three kilometers southeast of The Dalles, Oregon, exposes a sequence of Quaternary sediments and five buried paleosols. The sediments, paleosols, and associated tephras at this site provide evidence of a Quaternary history of catastrophic flooding in the Columbia Basin extending back at least 700 ka and of an early eruption (ca. 600 ka) of Mount Adams. Four sedimentary units are exposed in this cut: Holocene loess, late Wisconsin Missoula Flood slackwater deposits, five pre-late Wisconsin catastrophic flood slackwater deposits bearing well developed paleosols, and late Tertiary Dalles Formation volcaniclastics. All but the oldest are predominantly silts and fine sands. Several of the paleosols contain scattered gravel of varied lithologies, including granite, consistent with a catastrophic flood origin.

Each paleosol contains a Bk or K horizon ranging in carbonate development from Stage II to Stage IV; therefore, each period of soil development represents
between 20,000 and 100,000 years. The latest-Pleistocene (between 15 and 12 ka) Missoula Flood deposits and overlying loess exhibit very limited soil development with virtually no pedogenic carbonate. Each of the paleosols must consequently represent a much longer period of soil formation. Thus, several floods must have occurred prior to the late Pleistocene.

Several of the paleosols contain abundant volcanic ash. Paleosol 3 contains numerous rounded pumice clasts up to 1.4 cm in diameter. Microprobe analysis of this pumice resulted in a similarity coefficient of 0.95 with the Dibekulewe tuff of Nevada, age circa 600 ka and source unknown (Sarna-Wojcicki and others, 1985). The high similarity coefficient correlates the pumice at The Dalles with the Dibekulewe tuff and implies that the sediments deposited with the pumice are of middle Pleistocene age. If these are catastrophic flood deposits, then this type of flooding was occurring prior to the late Wisconsin. Based on chemistry, location and known geologic record, a probable source of the Dibekulewe tuff, which is much coarser at The Dalles than in Nevada, is early activity at Mount Adams in the Southern Washington Cascades.
EARLY TO MIDDLE PLEISTOCENE CATASTROPHIC FLOOD DEPOSITS,
THE DALLES, OREGON

by

DAVID IRVING CORDERO

A thesis submitted in partial fulfillment of the
requirements for the degree of

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in
GEOLOGY

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This work is dedicated to Dr. John Eliot Allen who knew and appreciated the geology of the Pacific Northwest. He helped to increase many people’s understanding of geology through his teaching in the Department of Geology at Portland State University and in his many articles, books, and lectures. To those with an interest in geology, he was a role model and mentor.

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Linda Easley, Branch Manager, Holgate Branch Multnomah County Library, suggested the inclusion of an index to facilitate location of information. This feature may enhance this work for future researchers.

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CHAPTER I

INTRODUCTION

The present investigation is a study of the origin and age of fine-grained sediments and associated paleosols and tephras exposed in a roadcut at The Dalles, Oregon. This study aims to determine whether these sediments are of eolian or fluvial origin, and how they are related to the extensive loess and catastrophic flood deposits found on the Columbia Plateau.

A remarkable episode in the geologic history of the Pacific Northwest is a period of catastrophic flooding that occurred during the Quaternary. The mid-to lower Columbia River Basin in Washington and Oregon (Figure 1) contains evidence of several episodes of catastrophic flooding, gigantic floods much larger than any in historic times. The idea of catastrophic flooding in the Pacific Northwest was proposed by J. Harlen Bretz in the early 1920's (Bretz, 1923).

Evidence of catastrophic flooding in the Columbia Basin consists of two types, erosional and depositional. Erosional evidence includes features such as scablands (networks of great coulees and dry waterfalls) eroded into basalt, underfit streams, truncated spurs, high level divide crossings, and streamlined hills of loess (Baker, 1978; Allen and others, 1986). Depositional evidence consists of ice-rafted erratic boulders and cobbles, coarse gravel deposits in the form of giant bars and
Figure 1. Map of mid- to lower Columbia River Basin. (From U.S. Department of the Interior, 1947, The Columbia River.) On inset map shows location of study site near The Dalles, Oregon.
deltas, giant ripples on some gravel bars, and fine-grained, often rhythmically bedded, slackwater deposits (Baker, 1978; Allen and others, 1986).

From such evidence Bretz and colleagues were able to determine the geologic processes that created a very unusual landscape, Washington's Channeled Scablands (Bretz and others, 1956) (Figure 2). They deduced that a giant flood, the Spokane Flood, had passed through the area. Eventually they found evidence for more than one great flood (Bretz and others, 1956). More recent work has shown that over 90 floods may have occurred in late Wisconsin time, 15,300 - 12,700 ka (Atwater, 1986; Waitt, 1985). Floods of this time interval are known today as the Missoula Floods or Bretz Floods (Allen and others, 1986). Tantalizing but somewhat ambiguous evidence of yet older cataclysmic flooding has been found by several workers (Bretz and others, 1956; Baker, 1978; McDonald and Busacca, 1988b; Busacca, 1991; Busacca and McDonald, 1994) and is the subject of current research and discussion (Baker and others, 1991; McDowell, 1991; O'Connor and Waitt, 1995).

In low areas that served as side channels for Missoula Flood waters are deposits of silt and fine sands. These are a fine-grained facies of slackwater sediments deposited as a consequence of reduction in velocity of the flood waters, often due to ponding as a result of constrictions in the main channel or by ponding in side valleys to the main channel. While the origin of these slackwater deposits was at one time as uncertain as the origin of the Channeled Scablands, they are now
Figure 2. Map of Channeled Scablands in eastern Washington (from Waitt, 1985). • Roadcut on Highway 197 southeast of The Dalles, Oregon. • indicate sites of bedded flood sediments: B = Burlingame Canyon; Ba = Badger Coulee; Bu = Buena; Ca = Camas; Co = Cowlitz Valley; Cr = Crescent Bar; CB = Cumings Bridge; CR = Castle Rock; H = Horse Lake Canyon; L = Latah Creek; Le = Leavenworth; M = Mabton; Ma = Malden; N = Ninemile Creek; P = Priest Valley; R = Rock Island bar; S = Sanpoil Valley; T = Touchet; Tu = Tucannon Valley; TB = Tammany bar; V = Vantage; W = Willamette Valley section; WB = White Bluffs; Z = Zillah.
Larger dot pattern shows maximum extent of Cordilleran Ice Sheet.
Small dot pattern shows maximum extent of glacial lakes Missoula and Columbia. Lined pattern shows the Channeled Scablands, Willamette Valley, and other areas inundated by Missoula Floods.
recognized as flood deposits (Baker, 1978; Waitt, 1985).

Another of the outstanding geologic features of the Columbia Basin is a mantle of loess over much of the area (Busacca, 1991). The Palouse region of southeastern Washington contains the thickest deposits; loess depths can exceed 75 m (Busacca, 1991). Wheat production is dominant in the region which prior to farming was covered by native grasses. It is an area of rolling hills. In much of the western portion of the Columbia Basin loess forms a discontinuous cover of variable thickness near Missoula Flood channels, including the Columbia River. While loess is generally not prominent in the Cascades Range, a thick deposit, the Portland Hills Silt, mantles the hills near Portland, Oregon to a maximum depth of 37 m (Lentz, 1977).

The depositional history of the loess is more complicated. A connection between loess and glaciation has long been recognized (Ruhe, 1969; Pye, 1987). On the Columbia Plateau great quantities of older loess were eroded by the catastrophic floods and redistributed along the lower Columbia River and its tributary valleys as slackwater deposits. These fine-grained sediments were in turn picked up by the wind and redeposited as eolian sediments (dune sands and loess). In many cases it is almost impossible to distinguish between eolian and fluvially deposited silts and fine sands. The situation is complicated because at various times during the Quaternary, soils developed on many of these deposits obscuring the original sedimentary features (Busacca, 1991). Some of these soils and sediments were subsequently removed by erosion, others were covered by younger
deposits including tephras erupted by Cascade volcanism. When the landscape stabilized, a new soil began to form, often on the underlying paleosol creating compound soils which obscured relationships further.

A roadcut on Highway 197 near The Dalles, Oregon exposes fine-grained sediments, a sequence of paleosols, and tephras (Figure 3). This exposure helps to establish a chronology of Quaternary geologic and climatic events, including Pleistocene catastrophic flooding, loess deposition, paleoclimate, and Cascade volcanism, here, and elsewhere on the Columbia Plateau. Based on lithology and mineralogy, all but the lowest sediments have a Columbia River provenance. Prominent in the exposure are five well-developed paleosols with strong carbonate horizons and extensive bioturbation (krotovina and root casts are abundant) indicating that they are much older than 10,000 ka (Birkeland, 1984). A tephra, tentatively correlated with the Dibekulewe Tuff (F. Foit, Washington State University Geoanalytical Laboratory, written communication, 1993), indicates that one of the paleosols formed circa 600,000 ka. If this is indeed a catastrophic flood deposit, and I believe the evidence indicates this, it extends the range of this type of flooding throughout a much longer period of the Pleistocene than has been generally recognized. If these sediments are loess, and not flood deposits, stratigraphic and mineralogical evidence indicates that catastrophic flood deposits are most likely the source of most of the loess in the Columbia Basin (Busacca, 1991), so again these deposits would tend to indicate a much longer record of floods.
Figure 3. Roadcut on Highway 197 southeast of The Dalles, Oregon. North end of roadcut is to the left, center of roadcut at right.
This project is an investigation of the sediments exposed in the roadcut near The Dalles, Oregon. The objectives of this study are to: (1) describe the stratigraphy of this site, (2) determine the nature and genesis of the sediments exposed in this cut, (3) characterize the paleosols, (4) identify and correlate, if possible, any tephras found within the section, (5) determine, or at least constrain, the age of the various deposits and soils exposed here, (6) correlate these deposits with those of a similar nature elsewhere on the Columbia Plateau and in Western Oregon, and (7) suggest a course of future work in this area.
CHAPTER II

REGIONAL GEOLOGY: BACKGROUND AND LITERATURE REVIEW

PHYSIOGRAPHIC PROVINCES

The Columbia Plateau

The study area is located in the Columbia Plateau physiographic province of Oregon (Orr and others, 1992). It is bounded by the Cascade Range on the west, the Okanogan Highlands on the north, the Northern Rocky Mountains on the east, and the Blue Mountains of northeastern Oregon and southeastern Washington on the east and south (Figure 4). The northern area is characterized by a subdued topography that resulted from huge outpourings of basaltic lavas during Miocene times. These lavas, the Columbia River Basalt Group (CRBG), form bedrock in most of the province. The relatively flat "plateau" thus formed is actually a sort of basin, the Columbia Basin (Reidel and others, 1994).

The basalts in the western and central parts of the Columbia Plateau are folded by a series of broad anticlines and synclines, the Yakima Fold Belt (YFB), which strikes mainly east-west (Figure 4) (Reidel and others, 1994). The Dalles Basin is one of the synclines in this fold belt, and to its northwest the Columbia Hills-Ortley anticline is a structure whose intersection with the Columbia River marks the head of the Columbia Gorge through the Cascade Mountains. The
Cascades themselves are deformed and continue to be built on a broad anti-clinorium, the Cascade Arch, which trends at nearly a right angle to the Yakima folds. Downcutting by the Columbia River has been able to keep pace with development of many of these folds as they have grown, and the river has generally maintained its course across them. In several areas, such as The Dalles basin, the river’s location has been influenced by the folding, and it runs within and parallel to the syncline axis (Beeson and Tolan, 1987). Due to local blockages (landslides, lava flows, etc.) the synclines often served as sedimentary basins accumulating thick sections of sediments which contain clues to the geologic history of eroded highland areas. The extreme eastern portion of the province is hardly deformed and forms the Palouse Slope (Fecht and others, 1987; Reidel and others, 1994). Much of it is covered with the Palouse Soil which is primarily loessial in origin.

Bedrock on most of the Columbia Plateau is the Miocene Columbia River Basalt Group which in many places, especially the basins, is covered by late Miocene-Pliocene sedimentary units (the Ellensburg, Dalles, and Ringold formations), Quaternary loess (Palouse Formation), or Missoula Flood deposits (Reidel and others, 1994). Interfingering with all of these sediments are tephras which originated at Cascade volcanoes. Some of these tephras make excellent time markers and are widely used for correlation (Mazama ash, St. Helens S, Glacier Peak). Times of landscape stability are marked, in places, by paleosols developed on whatever units were at the surface at the time. These are finding some use in
correlation (Busacca, 1991) and are also indicative of the relative ages as thousands of years are required for soil formation.

The Cenozoic geologic history of the Pacific Northwest includes several unusual events. These related events are: the great outpourings of the Columbia River Basalts, and the Missoula Floods which created the Channeled Scabland. Unique, but more familiar, is the Columbia River Gorge, which was also influenced by these unusual events. The Columbia River Basalts of Miocene age created a relatively flat surface, the Columbia Plateau (or Columbia Plain of Baker and others, 1987), which when combined with the great Missoula Floods led to the creation of the Channeled Scabland. The latter two phenomena are Quaternary in age, directly associated with Cordilleran Glaciation. The Channeled Scabland contains both erosional and depositional landforms that attest to the passage of these great catastrophic floods. Similar features are found within the Columbia River Gorge through which the flood waters passed as they flowed towards the Pacific Ocean.

The Cascade Range

The Cascade Range Physiographic Province (Figure 5) is located immediately to the west of the study area (Orr and others, 1992). It is a volcanic arc located along the Cascadia subduction zone and has been active since the late Eocene (Hammond, 1989; Orr and others, 1992). It extends 1,000 km in a north-south direction between Mount Lassen in northern California and Mount Garibaldi in
Figure 5. Map of major late Quaternary stratovolcanoes of the Cascade Range (from McKee, 1972).
southern British Columbia. The range is widest, 250 km, in northern Washington and narrowest, 50 km, in northern California. At the latitude of the Columbia River Gorge it is about 80 km wide but increases in width both to the north and south. The range has an average elevation of about 1,500 m but is dominated by huge stratovolcanoes some of which rise to over 4,000 m. There are three subprovinces: the North Cascades, the Western Cascades, and the High Cascades (Hammond, 1989; Orr and others, 1992).

In northern Washington, the North Cascades consist of scattered composite cones of Quaternary age built on a well-dissected basement of chiefly late Paleozoic to Mesozoic metamorphic and plutonic rocks. South of Snoqualmie Pass (47°25’N) the range can be divided into the Western Cascades, a deeply eroded complex of Eocene to Miocene volcanic rocks, and the High Cascades, the more easterly part of the range characterized by young (late Cenozoic), mostly unaltered, volcanic rocks upon which sit the great Quaternary composite cones that form the dominant peaks of the Cascade Range. The Cascades are characterized by predominantly andesitic volcanism but contain rocks from mafic to rhyolitic compositions (Luedke and Smith, 1991). The stratovolcanoes of the High Cascades are predominantly mafic andesite composite cones of Late Pliocene to Holocene age. Several of these volcanoes were active during deposition and development of the units exposed at the roadcut in The Dalles.
This range is important in the context of this study in several ways. First, it includes several active stratovolcanoes that potentially deposited tephras within the study area. These tephras, once identified, are excellent stratigraphic time markers because each layer was essentially laid down over a very brief period, and each possesses a distinct geochemical signature. In this respect the loess and slackwater deposits of the Pacific Northwest may be similar to the loess in New Zealand which contains abundant material for tephrochronology (Campbell, 1986). Most other areas of loess accumulation are far removed from potential sources of tephra.

Because the slackwater deposits and loess in the Columbia Basin were deposited in somewhat restricted areas controlled by local conditions and because these deposits were often partially dissected, the presence of any tephras within the deposits may be one of the few means of correlation between exposures in different parts of the region.

Second, the range creates a rain shadow to its east, due to the prevailing westerly air flow at this latitude. Average annual precipitation on the east side of the range at The Dalles is 355 mm/year compared to 917 mm/year at Portland on the west side (Oregon Climate Service Data archives, monthly means and extremes (1961-1990) [Accessed 20 Aug 1995]). Also, air masses moving over the area are subject to adiabatic warming which results in higher evaporation rates than in surrounding areas. This environment results in characteristic pedogenic processes that can leave their signatures in the soils that form on the Columbia Plateau.
While Quaternary climates varied, it is reasonable to assume that throughout the Pleistocene The Dalles basin was in a rainshadow, possibly modified by pluvial conditions (Smiley and others, 1991).

These conditions are responsible for the numerous calcareous horizons that occur within the paleosols found in this and other sites on the Plateau (Retallack, 1990). These calcic horizons make these old soils distinctive and have been noted by geologists working in the region. Paleosols can be used for correlation and have been used for this purpose elsewhere on the Columbia Plateau (McDonald and Busacca, 1990). Beyond the plateau, especially west of the Cascade crest, wetter climatic regimes result in an absence of the calcic horizons and other methods of correlation are required, such as tephrochronology. Resistant horizons within the paleosols on the Plateau may have served to protect these soils and other easily eroded features, especially in areas subjected to catastrophic flooding.

Finally, the presence of the Cascade Range across the path of the Columbia River restricts the river to a narrow gorge as it traverses the mountains. In addition to the accumulation of volcanic materials, the range is structurally uplifted, a pattern best expressed in the Cascade Arch, which is well exposed throughout the Columbia River Gorge (Allen, 1984). The head of the Gorge is situated a short distance west of the study site. This constriction of the river valley as it enters the gorge resulted in substantial ponding of catastrophic flood waters within The Dalles Basin from hydraulic damming. This caused flood sediments to be deposited.
Ponding allowed both the flood waters and flood sediment to reach an elevation of about 305 meters (Allen and others, 1986; O'Connor and Waitt, 1995), well above the 204 meter elevation of the study site.

**Quaternary Volcanism.** Three large composite volcanoes are located to the west and northwest of the study area: Mount Hood in Oregon, and Mount St Helens and Mount Adams in Washington. As the area is located in the zone of the prevailing westerlies, these volcanoes are the most favorably situated for having deposited tephras on this site. Of the three, only Mount St. Helens is notable as a tephra producer (Sarna-Wojcicki and others, 1983). However, explosive eruptions from several more distant volcanoes have produced widespread tephras in the Pacific Northwest (Sarna-Wojcicki and Davis, 1991). Tephras from Glacier Peak, Mount St. Helens, and Mount Mazama have previously been identified in Missoula Flood deposits and loess within the Columbia Basin, primarily in Washington (Waitt, 1985; Busacca, 1991; Busacca and McDonald, 1994). Of these, Mount St. Helens tephras are most common.

Glacier Peak has erupted mostly lavas and tephras of dacitic composition. Its age is believed to be less than 750,000 years old (Luedke and Smith, 1991) as all its rocks exhibit normal polarity. Pyroclastic materials have become more prominent in younger eruptions. About 12 ka it erupted a series of tephras which are found in much of the western United States, including sites in the Columbia Basin. These tephras, Glacier Peak ash beds G, M, and B, covered much of the Pacific Northwest.
east of the Cascade Range and are found at many sites in the Columbia Basin. Age is estimated to be between 11.7 ka and 11.2 ka (Sarna-Wojcicki and others, 1991; Busacca and McDonald, 1994). Porter (1987) and Beget (1981, 1984, 1990) describe Glacier Peak’s tephras and eruptive history.

Mount St. Helens, the youngest of the great Cascade volcanoes became active about 40 ka (Luedke and Smith, 1991). During most of its history its products have been predominantly dacitic. This changed about 2.5 ka when it became more bimodal in composition. Prior to the 1980 eruption Mount St. Helens consisted of a very symmetrical cone built mostly during the last 2,500 years and only slightly modified by glaciation. Since its inception 40 ka Mount St. Helens, except for possibly Glacier Peak, has been the most consistent producer of tephra of any Cascade volcano (Hammond, 1989). Because of its age Mount St. Helens cannot be considered as a source of tephras found in suspected older flood and loess deposits. Set C tephra, which may consist of one or more beds, has been found at many sites in the Columbia Basin as well as at Summer Lake, Oregon, Tule Lake, California, and several sites in the Lahontan Basin of western Nevada (Sarna-Wojcicki and others, 1991). The age of this tephra is estimated to be between 33.7 ka and 37.6 ka (Sarna-Wojcicki and others, 1991). Mullineaux (1986) summarizes the pre-1980 tephras of Mount St. Helens.

Mount Mazama in southern Oregon had a climactic eruption about 6,845 B.P. (Bacon, 1990) which resulted in a widespread tephra, the Mazama ash, and the
formation of a 9 km diameter caldera which today contains Crater Lake. Tephra from the Mount Mazama climactic eruption is the most widespread Holocene tephra in the conterminous United States (Sarna-Wojcicki and others, 1991). Its age is between 6.7 and 6.85 ka (Sarna-Wojcicki and others, 1991). It has been found at numerous sites in the Columbia Basin (Busacca, 1991, Busacca and McDonald, 1994), throughout much of central and eastern Oregon, as well as at many sites in the Lahontan Basin, Nevada (Sarna-Wojcicki and others, 1991).

Mount Adams is a compound stratovolcano, the second largest in the Cascade Range with a volume of about 200 km$^3$ (Hildreth and Lanphere, 1994). It is located along the Cascade Crest 50 km east of Mount St. Helens. Its summit elevation is 3,742 m. Its oldest exposed rocks are dated at ca. 520 ka (Hildreth and Lanphere, 1994). Its most characteristic eruptive products are lava flows of andesitic composition. Mafic andesite and basalt occur in lesser amounts (Hammond, 1989; Hildreth, 1990). It is generally lacking in pyroclastic materials. Mount Adams is located in the center of a Quaternary, predominantly basaltic, volcanic field with over 60 vents less than 1 Ma (Hildreth and Lanphere, 1994). It is built on a basement of Oligocene to Miocene Cascade-Arc rocks.

Mount Hood is an andesitic and dacitic stratovolcano probably less than 700,000 years old (Sherrod, 1990; Luedke and Smith, 1991). It has been modified by glacial erosion. No widespread tephras have been reported in the geologic literature (Swanson and others, 1989).
Mount Jefferson, the second highest peak in Oregon, 3,199 m, is a deeply eroded cone. Its early history, ca. 290 ka, is one of strong pyroclastic activity followed by eruption of numerous andesitic lava flows (Conrey, 1990). Following a period of quiet and glacial erosion several dacite domes and flows were emplaced, ca. 70 ka. Presumably during this period an extensive tephra was deposited east of the volcano in the central Oregon area (Conrey, 1990). Age of these tephras is uncertain. Busacca and others (1992, p. 283) mention an early Wisconsin eruption from Mount Jefferson. No other extensive tephras are reported in the literature.

Mount Rainier, the tallest peak in the Cascade Range at 4,392 m, is a heavily glaciated volcano and supports the single largest glacier system in the conterminous United States (Harris, 1988). Rainier is somewhat younger than 1 Ma and is built predominately of flows of andesitic composition (Pringle, 1990; Luedke and Smith, 1991). Lahars and debris flows have been common in Mount Rainier's history, but no widespread tephras are reported (Pringle, 1990). Busacca and others (1992, p. 283) mention an early to middle Wisconsin (pre-Fraser) eruption from Mount Rainier. Its estimated age is 70 to 30 ka (Swanson and others, 1989).

Mount Baker is a heavily glaciated volcano about 400,000 years old (Wood, 1990; Luedke and Smith, 1991) located in northern Washington. It is built primarily of andesitic flows with only a small proportion of pyroclastic materials (Wood, 1990).
FINE-GRAINED DEPOSITS

One of the notable geologic features of the Columbia Plateau and some adjacent portions of the Columbia Basin is a mantle of silt and fine sand over much of the area (Busacca, 1991). Most of this material is eolian, principally loess, but some exposures, especially at lower elevations, are fluvio-lacustrine, chiefly Missoula Flood slackwater deposits. Dune sands occur locally and are much less extensive than loess. Interstratified with these deposits are tephas. Tephra is also eolian though thicker deposits in valley bottoms are generally the product of sheet wash and mass wasting from valley slopes. Deposits of volcanic ash are locally important due to the proximity of the Cascade Range. Paleosols formed during times of landscape stability are found in many of these deposits. The tephas and paleosols offer excellent potential for dating and correlation throughout the Columbia Basin.

Dune sands

A prominent area of dune sands is found near Moses Lake, Washington. Other areas of sand dunes are located near The Dalles, Oregon, on both sides of the Columbia River. Much of this latter sand was covered by water backed up by The Dalles Dam. Eolian sand covers much of the east-central Pasco Basin (Bjornstad and others, 1991). The particles of dust that are deposited as loess drop primarily out of suspension in contrast to dune and coversands which are moved along primarily by saltation and therefore have a coarser grain size distribution.
Loess.

Loess is probably the most abundant Quaternary deposit on land (Catt, 1988). In North America the classic area for loess is in the Midwest (Ruhe, 1969; Flint, 1971; Miller and others, 1984), where it forms a large belt along much of the valley of the Mississippi River and its major tributaries from Illinois and Iowa south to Louisiana. Within the Columbia Basin loess is found at elevations ranging from about 25 meters at river level to about 1,000 meters on the slopes of the Blue Mountains (Johnson and Makinson, 1988).

Identification of a deposit as loess is usually based on a combination of three criteria: (1) it has a distinctive grain size distribution (Figure 6), mainly in the silt range; (2) the deposit thins with distance from a source area; and (3) loess tends to blanket the topography. Loess often contains fossil terrigenous mollusks, in which case it can be easily distinguished from fluvial and lacustrine loess-like deposits. No mollusk fossils have been found within the study area and are indeed rare within loess of the Columbia Plateau, probably due to dissolution of carbonate in A horizons. Loess is commonly unconsolidated and often is seemingly nonstratified and a relatively homogeneous sedimentary deposit (Flint, 1971).

Loess is characterized by a distinct grain size distribution with a predominance of grains from 10-50 microns in diameter and with a prominent mode between 20 and 30 microns (Pye, 1987). The mean abundance of this size fraction is somewhere between 40 and 50% of the total sediment (Pecsi, 1968).
Figure 6. Typical cumulative grain-size distribution curves of loess from: A - Siberia (Péwé, 1981); B - Kansas (Swineford and Frye, 1945); C - Alaska (Péwé, 1951); D - Tajikistan (Goudie and others, 1984). From Pye, 1987.
In fact, this is often called the "loess fraction". Finer material, clay, averages 5-30%, while sand averages 5-10%. The sand is usually fairly fine, grading into the silt fraction. While these figures are not universally accepted, they are representative of what most authors regard as the distinctive grain size of loess (Catt, 1988). Deposits with more than about 10% sand are not considered loess. The maximum grain size in loess is between 125 to 250 microns, very fine to fine sand (Pye, 1987).

Loess has a fairly characteristic mineralogy and composition. Quartz grains compose over half of the silt-sized particles (Pecsi, 1968). Enrichment of carbonates is common in loess in drier climates. Loess of glacial origin starts as rock flour supplied by glaciers to their valley trains from which it is picked up by the wind and often carried for considerable distances before being deposited. In the Pacific Northwest this process occurred during the Quaternary along the Columbia River especially after each of the Missoula floods (Fryxell and Cook, 1964; Allen and others, 1986; Baker, 1978). Therefore the distribution of loess is tied to these major drainages.

Loess is the most widespread and voluminous of the fine-grained sediments to be deposited on the Plateau. The source area of the loess is well constrained as being sediments of the flood plains of the Pleistocene Columbia River system, especially in and around the Pasco Basin (Busacca, 1991; Busacca and McDonald, 1994). On the Columbia Plateau great quantities of older loess were eroded by the
Missoula Floods and redistributed further along the Columbia River and its tributary valleys as slackwater deposits, especially prominent in the Pasco, Dalles, and Portland Basins and in the Willamette Valley. Much of this fine-grained material was then picked up by the wind and redeposited.

It is often extremely difficult to distinguish loess from fluvially deposited silts and fine sands (Pye, 1987). A major reason for similarity is that water-lain deposits are the source of much of the eolian materials. In the case of the Missoula Flood deposits, eolian sediments, loess, were a major source of fine-grained material transported by the floods (Busacca and McDonald, 1994). Also, paleosols developed on many of these deposits obscure the original sedimentary features. Many of the paleosols are compound soils, formed during more than one period, often with new parent material added which further obscures relationships.

The Palouse Formation. In the Pacific Northwest the thickest deposit of silt, the Palouse Formation, is found in the Palouse region of southeastern Washington where loess depths can exceed 75 m (Foley, 1982; Busacca, 1991). Thickness, however, is variable. This material has received relatively little attention until recently (Foley, 1982; McDonald and Busacca, 1988a; Busacca, 1991; Busacca and McDonald, 1994), especially in comparison with the underlying Columbia River Basalt Group and the coeval Missoula Flood deposits. The Palouse Formation contains numerous loess units, paleosols, flood-cut unconformities, and slackwater sediments (McDonald and Busacca, 1988a). Busacca (1989) states that the loess of
the Columbia Plateau preserves a record of geologic and pedologic events that may extend throughout the Quaternary Period. Foley (1982) worked out a chronology for the Palouse Formation based on tephrochronology, paleosol development, and paleomagnetism.

McDonald (1987) continued work on the stratigraphy by looking at many more sites in the Palouse. Busacca and McDonald (1994) have studied the problem of the source of the Palouse loess and present evidence that suggests the slackwater sediments from cataclysmic floods served as the source for much of the Palouse loess throughout the Pleistocene.

Portland Hills Silt. A mantle of micaceous silt, up to 37 m thick, covers the higher hills around Portland, Oregon above an elevation of about 120 m (Lentz, 1977). It is known as the Portland Hills Silt (Lowry and Baldwin, 1952). While most early workers described the silt in similar ways, interpretations of its origin varied widely. Some thought it was water deposited, others that it was the product of residual weathering of basalt; some believed it to be eolian in origin (loess) (Theisen, 1958), while others favored a mixed origin (Treasher, 1942). J. S. Diller (1896) was probably the first to mention these sediments, and he noted their resemblance to the loess found in the Mississippi Valley (Lentz, 1977). R. C. Treasher (1942) briefly described "the heavy silt cover of the Portland area" and compared it to loess of the Palouse region which he had studied earlier. He seems to have lumped together several silt units (i.e., the Willamette Silt) and believed the
Silts were of complex origin, in part eolian. Lowry and Baldwin proposed the name "Portland Hills Silt" in 1952 for the massive silt mantling the Tualatin Mountains (Portland Hills) and suggested it might be a formation. They correlated the Portland Hills Silt with the Ringold and Palouse formations of southeastern Washington.

A. A. Theisen (1958) demonstrated, on the basis of grain-size, mineralogy, and distribution, that the Portland Hills Silt was of eolian origin, hence loess and compared it to classic loess deposits from the Midwest and the Columbia Basin (Palouse Formation). He showed that the Portland Hills Silts thin away from the Columbia River which indicated it as the source area of the loess. He determined the age to be Pleistocene or younger on the basis of stratigraphic and geomorphic relations. Theisen also noted the importance of the Spokane flood(s) as a source of sediment and briefly discussed the climatic conditions that would allow winds to pick up and carry these sediments into the surrounding hilly terrain. He recognized that the loess, instead of being completely homogeneous, was actually composed of at least two units in some of the areas he studied. Finally, Theisen mentioned the fact that volcanic glass may be present in varying amounts throughout the loess, and that this would not be at all unusual considering the proximity of the Cascade Range.

Lentz (1977) came to the same conclusion. He demonstrated that the Portland Hills Silt is indeed a product of eolian deposition, therefore loess. Lentz observed
that thicker exposures may reveal up to four units of loess as thick as 8.5 m separated by buried paleosols and tentatively correlated these with major glacial deposits in the Puget Sound area of western Washington. Lentz (1977) considered the loess to be Pleistocene, between 700,000 and 34,400 years B.P.. McDowell (1991) notes that the Portland Hills Silt is overlain by the Willamette Formation and may interfinger with the Boring Lava suggesting an age of 700,000 B.P. to mid-Wisconsin. Based on grain morphology and its heavy mineral suite, Lentz concluded that the Portland Hills Silt has an upper Columbia River provenance.

Like Theisen (1958), Lentz (1977) concluded that easterly winds blowing down the Columbia Gorge picked up the silt from the basin and dropped it as they rose over the surrounding hills. Similar winds still affect the area today although they were probably more common during the Pleistocene as a result of the influence of ice sheets in the Cascades and in northern Washington and Idaho on the climate (Kutzbach, 1987; Wright, 1987). Similar circumstances are responsible for the mantle of loess elsewhere along the Columbia River and in the Channeled Scabland (Busacca and McDonald, 1994).

**Fluvial silts and sands**

The origin of fine-grained deposits at low elevations along the courses of Missoula floods is often difficult to determine. There are several reasons for this. Water-laid deposits can have similar particle size characteristics to eolian deposits. The two are often interbedded. Alluvial deposits served as primary source areas
from which wind picked up dust to later deposit as loess. This resulted in similar mineralogies (Busacca and McDonald, 1994). There is no question as to the ability of wind to entrain and deposit sediments of this type. This process is commonly observed today in glacial and desert areas (Pye, 1987).

How does one differentiate between eolian loess and fluvial slackwater deposits? The following are evidence that suggest an eolian origin of loess: its characteristic grain size distribution; it blankets the topography (including the top of hills); it often contains fossil land snails; and it lacks stratification. On the contrary, slackwater deposits should be found only at lower elevations, should generally not contain fossils of land snails, and may contain clasts of a larger size than that which the wind is capable of transporting. They may also contain fossils of aquatic species if wet conditions persisted.

**Willamette Formation.** Much of the relatively flat floor of the Willamette Valley of western Oregon contains a surface layer of silts and fine sands deposited by water. These silts are highly micaceous (muscovite) and contain erratic rocks of various sizes. The Willamette Formation was originally known as the Willamette Silt and is defined as "parallel bedded silt and fine sand, with erratic pebbles and boulders" (Allison, 1953). It thins above an elevation of 60 to 90 m, but extends to 122 meters. Erratic stones include rock types foreign to the Willamette watershed such as granite, granodiorite, gneiss, and slate. The mineralogy and petrology indicate a Columbia River provenance quite unlike that of the Willamette
watershed (Allen and others, 1986; McDowell, 1991). The silts often have prominent bedding which is essentially horizontal. The silts are present below an elevation of 120 meters. Its origin has been long debated, but it is now generally acknowledged that much, if not all, of the silt was deposited by Missoula Floods which were hydraulically ponded near Kalama, Washington, flooding the valley as far south as Eugene, Oregon (McDowell, 1991). McDowell (1991) considers the Willamette Formation to be of late Wisconsin age and very similar to the Touchet Beds of southern Washington (Waitt, 1980, 1985; Allen and others, 1986).

Current interpretation of the Willamette Formation generally divides it into two parts: older silty to sandy, low-energy deposits probably laid down by multiple floods and younger deposits resulting from a single large flood (McDowell, 1991). These younger deposits are of two facies: cross-bedded sandy to bouldery high-energy deposits found near constrictions in the paths of the flood waters and more widespread plane-bedded, silty, low-energy deposits.

The Willamette Formation has four members: the Wyatt, Irish Bend, Malpass, and Greenback (McDowell, 1991; Reckendorf, 1993). The Irish Bend member is the main unit of the Willamette Formation. The Irish Bend member resembles the Touchet Beds in many ways as described by McDowell (1991). There is disagreement over whether the bedding within the Willamette Formation is a result of separate floods or hydraulic surging within a single flood (McDowell, 1991; Reckendorf, 1993).
There seem to be two phases of deposition, and therefore two phases of floods with the most recent phase being constrained to the time between 15,300 and 12,700 B.P. (Waitt, 1985). The earlier phase may be 35,000 to 40,000 B.P. (McDonald and Busacca, 1992), in which case no ice sheet may have been present to form a dam to impound Lake Missoula. There are two possible hypotheses for the age of the Willamette Formation according to McDowell (1991). A first phase due to middle Wisconsin flooding, and a late phase due to the classic late Wisconsin Missoula Floods. Or both phases may be due to late Wisconsin flooding, but this would require reconciling Waitt's flood chronology with Balster and Parsons' (1969) soil chronology (McDowell, 1991).

The record in the Willamette Valley is complex, based on a mixture of lithostratigraphic units and geomorphic surfaces. Following the main period of flooding, in the late Wisconsin, at least nine geomorphic surfaces formed (McDowell, 1991).

The mineralogy of the silts of the Willamette Formation is unlike that of the Cascade Range to the east or the Coast Range to the west. It indicates a Columbia River/Rocky Mountain provenance (Lowry and Baldwin, 1952). Abundant muscovite mica is one of the primary, easily distinguished indicators, being common in plutonic and metamorphic rocks of northern Washington and Idaho and southern British Columbia but not common in the extrusive rocks of western Oregon (Beeson, M. H., personal communication, 1991).
CATACLYSMIC MISSOULA FLOOD AS DEVELOPED BY BRETZ

The Columbia River Valley and adjacent parts of the Columbia Plateau in Washington and Oregon contain evidence of several episodes of catastrophic flooding (Baker, 1978; Allen and others, 1986; McDonald and Busacca, 1988b; Busacca, 1991). Catastrophic flooding in this case refers to truly giant floods several orders of magnitude larger than any in historic times. The idea of catastrophic flooding in this area was first proposed by J. Harlen Bretz (1923). Bretz was studying the geomorphology of an area of highly unusual topography which he named "the Channeled Scablands" (Figure 2). This area in east-central Washington is a network of great, mostly dry, stream channels and waterfalls eroded into the loess-mantled Columbia River Basalts. Associated with these unusual erosional features are depositional features, some of which are also on a grand scale.

Bretz concluded, after considering and rejecting other hypotheses, that the only possible explanation for the strange landforms was a giant flood of enormous volume and short duration (Bretz, 1923). He came to call it the "Spokane Flood" and felt it was in some way related to Pleistocene glaciation. Bretz hypothesized that the great flood overwhelmed and overflowed the normal stream valleys, quickly cut new channels or modified old ones, stripped great quantities of sediment and even solid rock from many places, and deposited these sediments as bars and other flood deposits. During the flood the area resembled a braided stream
on a grand scale. Bretz’s idea created great controversy, even consternation, in the
geologic community, as it seemed to support a catastrophist viewpoint and was
vigorously rejected for many years (Allen and others 1986). It was suggested that
the erosion Bretz credited to the Spokane Flood could have been accomplished
gradually by "normal" meltwater streams draining the Cordilleran Ice sheet during
the last glaciation. This latter idea conformed better to contemporary
interpretations of uniformitarianism (Allen and others, 1986).

At first it was pointed out, as the chief weakness, that Bretz proposed no
source for the tremendous amounts of water that his flood hypothesis required
(Allen and others, 1986). Despite lacking a source for the flood waters, Bretz
pointed out that evidence of catastrophic flooding could be found not only in the
Channeled Scablands but also in the lower Columbia Valley between Washington
and Oregon; in portions of the Snake, Yakima, John Day, Deschutes, and other
tributaries to the Columbia River; and even in the distant Willamette Valley.

Later, Bretz (1930a) thought he had found a source for his flood waters: Lake
Missoula, a Pleistocene, ice-dammed lake in western Montana a short distance
northeast of the Channeled Scablands. It had been described by J. T. Pardee in
1910. Glacial Lake Missoula, the largest of several proglacial lakes impounded by
Cordilleran Ice (Richmond & others, 1965), developed whenever the Pend Oreille
Lobe of the Cordilleran Ice sheet blocked the Clark Fork drainage in the Idaho
panhandle. The lake thus created rose until it was, at a maximum, about 700 m
deep. A recent estimate by O'Connor and Baker (1992) gives a maximum volume of about 2,184 km$^3$. The lake occupied the Clark Fork, Bitterroot, Flathead, and other deep intermontane valleys in the Rocky Mountains of western Montana.

Initially, Bretz lacked evidence for rapid draining of the lake (Allen and others, 1986). Opposition remained strong. So he continued to refine his hypothesis with more field work and expressed his ideas in a series of papers (Bretz, 1930a, 1930b, 1932b). However, a number of geologists became interested in the problem and began critically examining the field evidence, something that had been lacking in previous refutations of Bretz's ideas. Ira Allison (1932) recognized evidence for enormous amounts of water in the affected areas but attributed this to one or more large but temporary ice jams in and above the Columbia Gorge. He argued that this would produce the same features that Bretz attributed to the Spokane Flood but without the need for such huge amounts of water.

Not until 1940 (Allen and others, 1986) was Bretz's explanation of the water's source verified. Pardee (1940, 1942) realized that Glacial Lake Missoula had drained rapidly, probably due to a failure of its ice dam. His evidence that the lake drained suddenly included giant ripple marks, flood scoured channels, and bars of gigantic proportions created by eddies in the great currents associated with the rapid movement of large volumes of water within the lake basin (Pardee, 1940). Bretz now had the evidence he needed to connect Glacial Lake Missoula to the
Channeled Scabland. It was indeed the source of the Spokane Flood. Bretz could explain his flood by failure (complete or partial) of the glacial dam which led to a rapid draining of the lake and the release of an enormous amount of water (Bretz and others, 1956). Estimates for maximum discharge are somewhat greater than 17,000,000 m³/s (O'Connor and Baker, 1992). This compares with a maximum discharge on the Mississippi River of 70,000 m³/s in 1927 (Parrett and others, 1993). From the area of the ice dam the water had an unobstructed route to the Channeled Scabland.

Even with the supporting evidence of a source for the flood waters, opposition continued to be strong, mainly due to a feeling that Bretz's hypothesis defied uniformitarianism (Allen and others, 1986). In 1952 Bretz returned to the Channeled Scabland for his last field work in the area. During the course of this field work and aided by aerial photographs and new, more detailed topographic maps, Bretz discovered giant current ripples on the surface of many of the great gravel deposits. These ripples were similar to those described by Pardee (1940) on the floor of Lake Missoula. The ripple marks there indicated strong current flow consistent with a rapid draining of the lake and a great flood over the Columbia Plateau. The ripples Bretz discovered indicated that the gravel deposits were indeed giant bars, products of fluvial depositional processes on a grand scale and not erosional remnants of a formerly more widespread gravel fill as R. F. Flint (1938) had argued. This latter interpretation was the point of view taken by several
eminent geologists who were trying to refute Bretz's hypothesis of a giant flood. In 1956 Bretz published a paper carefully refuting all alternative hypotheses (Bretz and others, 1956).

By the mid-1950s Bretz recognized evidence for several floods in the affected area (Bretz and others, 1956). Richmond and others (1965), in summarizing Pleistocene events on the Columbia Plateau, allude to at least three floods of widely different age simply as "catastrophic floods". By 1969 Bretz was referring to the floods as "The Lake Missoula Floods" (Bretz, 1969). V. R. Baker (1973, 1978) recognized "at least five major catastrophic flood events" and called them the "Missoula floods". The primary evidence for multiple floods cited by these authors is the stratigraphic relationships of flood deposits and loess units and the presence of significant paleosols that developed on some of the older loess units but also on some of the flood gravel deposits.

While at first Bretz concentrated on studying the erosional features of the Channeled Scablands, he soon realized that depositional features, giant bars of gravel and fine-grained slack-water deposits, also existed and contained important clues to the geologic history of the area. Much of his later studies were concerned primarily with this aspect of the giant floods (Bretz and others, 1956) and the evidence provided by the depositional features emerged as a key element in convincing any still skeptical geologists that cataclysmic flooding had indeed occurred.
Eventually, after much debate and examination of the field evidence, Bretz’s ideas came to be accepted (Allen and others, 1986). The course of the flood waters is now well recognized, starting at Glacial Lake Missoula, spilling through the Channeled Scablands, ponding behind the narrows at Wallula Gap and at the head of the Columbia Gorge near The Dalles, Oregon. After flowing out into the Portland basin the flood waters again backed up behind a hydraulic dam caused by a narrowing of the Columbia Valley at Kalama, Washington, and inundated the Willamette Valley (Allen and others, 1986). Eventually the waters drained out of the affected areas via the lower Columbia River to the Pacific Ocean.

**Bretz’s Ideas Developed by Other Workers**

Another, smaller, catastrophic flood was recognized by Malde (1968). It originated during a highstand of Lake Bonneville which overflowed, cut down through relatively soft material, and drained down the Snake River before flowing into the lower Columbia River (Malde, 1968). The flood eventually stopped when more resistant rock was encountered by the downcutting waters exiting the lake basin. While the origin and scale of this flood differ from those of the Missoula Floods, it produced similar landforms, though on a smaller scale due to lower discharge rates, about 935,900 m$^3$/s (Jarrett and Malde, 1987). Present evidence indicates the date of the Bonneville Flood as between 14,500 and 14,000 ka (Currey, 1990). Evidence of the Bonneville Flood is not found in the Columbia River valley; the last downstream deposits are found near Lewiston, Idaho.
In the 1970s research related to the Missoula Floods was concerned primarily with the paleohydraulics and hydrodynamics of the flooding (Baker, 1973, 1978) within the Channeled Scablands and near the site of the glacial dam. Baker (1978) recognized "at least five major catastrophic flood events". Examination of the slackwater deposits left by the great floods was conducted in order to better determine the number and age of the floods. It had been noted that fine-grained flood deposits were often rhythmically bedded (Figure 7). Did this denote many floods, as paleosols within both fine and coarse-grained deposits seemed to indicate? Baker (1973) suggested that each flood could leave multiple layers, thus requiring fewer floods to produce a given number of layers.

Outside of the Channeled Scabland, research concentrated on backflooded tributaries of the Columbia River. Waitt (1980, 1985), studying rhythmically bedded sand and silts in the Walla Walla and lower Yakima valleys, saw evidence for about forty late-Pleistocene floods. Atwater (1984, 1986), examining evidence in the Sanpoil Valley of northeastern Washington, interpreted at least 89 floods. These late Wisconsin floods are well dated due to the presence of Mount St. Helens tephras and an overlying layer of Mazama ash. The age of the classic episode of late Wisconsin flooding has been cited as 12.7-15.3 ka on the basis of radiocarbon dates, tephrochronology, and varve counts (Waitt, 1980, 1985; Atwater, 1986).

Evidence for several floods consists of layers of eolian sand, loess, volcanic ash, and colluvium as well as "normal" fluviatile sediments intercalated with the
Figure 7. View of Missoula Flood slackwater rhythmites in Burlingame Canyon, Walla Walla County, Washington.
flood deposits. Paleosols are developed on some of these units indicating long periods of landscape stability and minimal deposition.

McDonald and Busacca (1988a) have taken another approach by looking at the loess islands within the Channeled Scabland/Palouse area. There they have found what they interpret as interbedded flood and loess deposits. In eastern Washington loess is up to 75 m thick and contains several well-developed paleosols and tephras. By examining the stratigraphic relations they are attempting to better constrain the sequence of events during the Pleistocene on the Columbia Plateau.

E. V. McDonald (1987) in a study of the Palouse loess comments on the use of the term "events" and "episode" as they relate to the Missoula Floods. He defines an "event" as one flood, while an "episode" might consist of several flood events.

Busacca (1991) discusses loess distribution patterns on the Columbia Plateau and the source areas for two of the loess units. His interpretation is that this loess was deposited as a result of episodes of catastrophic flooding, the source for the eolian sediment being areas of slackwater sediments. This is based on an analysis of loess thickness, distribution patterns, and distribution of grain-size. He indicates that these results are based on detailed studies of only the two most recent of dozens of units within the Palouse Formation. Similar studies of deeper and older units within the Palouse loess very likely would yield similar results, and by implication point to paleofloods back to >700,000 B.P..
Recently Smith (1993) has added new insights to the sedimentology of the slackwater deposits as well as the paleohydraulics and hydrodynamics of the flooding. He argues that most floods produced one layer of sediment, but some produced several. Smith looked at deposits primarily outside of the Channeled Scabland proper, including one site down river from Wallula Gap.

Most work on Missoula flooding has been concentrated in flood-affected areas of eastern Washington. In the early 1990s O'Connor and Waitt (1995) started examining flood related features in the Columbia Gorge and between the Gorge and Wallula Gap. Bretz (1925) looked at this area early in his study of the Spokane Flood and recognized scabland, high divide crossings, great gravel bars, and slackwater deposits. In addition, these features and others were studied by Hodge (1931, 1934) and Allison (1932, 1941) who reached radically different ideas as to how they were formed. Hodge ascribed these features to more or less normal stream processes operating during the Pleistocene. Allison believed they were caused by several ice blockages caused by the constriction of the Columbia at the Gorge.

Bretz is now acknowledged as a very perceptive geologist (Allen and others, 1986). Today, it is generally recognized that there is good evidence for many of these great floods, which are often referred to as the "Bretz" or "Missoula Floods". Research and debate continues with the aim of determining the number, magnitudes, and chronology of flood events. An especially important question is
whether these great floods were restricted to the latest Pleistocene time interval of 12,700 to 15,300 years B.P. or occurred over a much longer period throughout the Quaternary. Researchers are attempting to answer these questions by looking at a variety of locations within the area affected by the floods. This thesis is an effort to answer this question.

**Older cataclysmic floods**

Older cataclysmic floods have recently received increased attention in the literature, but as early as 1956 Bretz recognized evidence for older floods (Bretz and others, 1956). According to Allen and others (1986), Bretz recognized that some of the features he attributed to catastrophic flooding were more deeply weathered than others, indicating that they had formed at an earlier time. Bretz and others (1956) concluded that the Cheney-Palouse Scabland tract was older than the western portion of the Channeled Scablands based upon both physiographic evidence and degree of weathering.

Baker and Nummedal (1978) discussed pre-Wisconsin flooding in the Channeled Scablands. Paleosols developed on coarse flood gravels and in fine-grained deposits, as well as intervening loess deposits, are all cited as evidence of several floods that occurred prior to the late Wisconsin. The most complete section is an exposure in a railroad cut near Marengo, Washington. The cut reveals two coarse-grained flood units separated by three loess units, each of which is capped by a calcic paleosol. One of these paleosols is well developed and contains a K
horizon. Baker and Nummedal (1978) correlate the lower flood gravel with exposures at Revere, Macall, and in Old Maid Coulee. All of these locations are in southeastern Washington.

Baker and others (1991) in summarizing the history of catastrophic flooding on the Columbia Plateau mention McDonald and others' (1988b) use of the stratigraphic record preserved in loess to document an episode of flooding prior to 790 ka and as many as six major episodes of flooding during the past 300,000 to 500,000 years. They also mention an episode of flooding during the middle Wisconsin.

Bjornstad and others (1991) have searched for evidence of older floods by examining stratigraphic relations in Washington's Pasco Basin, site of temporary Lake Lewis which backed up behind Wallula Gap during Missoula Floods. Based in reversed magnetic polarity, they recognize cataclysmic flood deposits older than 770 ka. In addition to the deposits discussed by Baker and Nummedal (1978) and mentioned above, they have recognized deposits with reversed magnetic polarity at Poplar Heights, Vernita Grade, and at Yakima Bluffs.

A period of middle Pleistocene flooding discussed by Bjornstad and others (1991) is recognized on the basis of well developed paleosols with K horizons characteristic of Stage III to Stage IV pedogenic carbonate development. The authors discuss several locations where flood deposits of this age have been studied: Kiona Quarry, South Bombing Range Road, Leslie Road, and Oak Street,
all in the southwestern Pasco Basin. The minimum age for the K horizon at Leslie Road, based on Th/U dating is about 0.20 Ma (Bjornstad and others, 1991). These paleosols are developed in coarse-grained flood deposits. These authors also note that exposures of coarse-grained gravels of late Wisconsin age overlying deposits from older floods are widespread in the Pasco Basin and that the younger deposits are characterized by only weakly developed soils (Stage I).

A site, FMEF, in the central Pasco Basin which exposes three sequences of fine-grained flood deposits, is cited by Bjornstad and others (1991) as possibly correlating with early, middle, and late Pleistocene flood deposits exposed elsewhere in the Pasco Basin. The correlation of the upper, younger unit, is based on the presence of Mount St. Helens set S tephra. The lower units each exhibit paleosols with more extensive development including bioturbation. Clastic dikes in the lower and middle units are truncated by the upper unit. Wood from within one of the clastic dikes was radiocarbon dated at >32 ka. The deposits just discussed are plane-laminated sands. Exposures of two rhythmite facies fine-grained deposits older than late Wisconsin are cited by the authors. These are at Cummings Bridge and at Yakima Bluffs (Bjornstad and others, 1991).

Bjornstad and others (1991) also discuss loess deposits within the Pasco Basin. They recognize five units, L1 through L5, based on stratigraphic position, degree of soil development, palaeomagnetic polarity, and color. The lowest and oldest loess, L1, they infer to be late Pliocene to early Pleistocene based primarily
on the siliceous nature of its paleosol. Loess L2 is interpreted as early Pleistocene. It has a well developed K horizon with as much as 4 m of Stage III to IV carbonate. L2 has reverse polarity. Unit L3 contains paleosols with Stage II to IV carbonate. It has normal polarity. Th/U dating of pedogenic carbonate suggest an age between 75 and 79 ka (Bjornstad and others, 1991). They correlate this unit with the Palouse Formation of the Palouse region east of the Pasco Basin. Like all these units it contains multiple paleosols.

L4 loess contains weak to moderately developed paleosols which exhibit Stage I and II carbonate development (Bjornstad and others, 1991). Mount St. Helens set M tephra is found within this unit. A middle to late Wisconsin age is assigned to this unit (Bjornstad and others, 1991) based on both the age of the tephra and the stage of soil development. L5, the youngest unit, is late Wisconsin in age, with weakly developed soils exhibiting little or no carbonate accumulation. This unit contains Mount St. Helens set S, Glacier Peak G and B, and Mount Mazama tephras.

Kiver and others (1991) have also added significant information to the study of "older Wisconsin Floods". They cite evidence of "older Wisconsin Flooding" in the Channeled Scablands and adjacent areas based on correlation of tephras and radiocarbon dating of charcoal from sedimentary units. These authors emphasize an episode of middle Wisconsin flooding during the period from about 40 ka to about 30 ka.
Exposures along Latah Creek near Spokane, Washington, show at least 15 floods flowed into Glacial Lake Spokane or Glacial Lake Columbia during middle to late Wisconsin times. Unconformably overlying these rhythmites is an upper sequence of subaerially deposited flood sediments. Both lower and upper units contain coarse and fine-grained beds. Waitt (1985) interprets both units as late Wisconsin, but Kiver and others (1991) consider them to be older and represent the period of middle Wisconsin flooding. This interpretation is based on evidence that indicates Glacial Lake Columbia did not have a high stand during the late Wisconsin that would have extended it into the area of Latah Creek.

Other sites yielding evidence of middle Wisconsin flooding are at Malden gravel pit and at Willow Creek, both in the central Channeled Scablands (Kiver and others, 1991). Both contain flood deposits capped by smectite-bearing paleosols. A series of rhythmites in the Tucannon River Valley is also correlated with this period of flooding (Kiver and others, 1991). Interpretation is again based on paleosol evidence and lack of Mount St. Helens set tephra.

A. J. Busacca (1991) has continued to look for evidence of pre-Wisconsin flooding by studying paleosols and tephras within loess in the Palouse of Washington. He suggests that these loess islands may contain the most complete record of Missoula Flooding on the Columbia Plateau. Some of the loess units deep in the section are reversely magnetized indicating an age greater than 750 ka. He associates each loess pulse with an associated large catastrophic flood event.
Deep paleosols and loess are poorly exposed and little studied at this time. Numerous exposures are found throughout the Columbia Plateau. Excellent ones are found near the towns of Connell, Dusty, Washtucna, and Winona, Washington. Outstanding among these is WA-9, 7.5 km west of Washtucna, Washington. This site is just one of several roadcuts through a large loess island that was eroded on several occasions during the Pleistocene. Six unconformities exist in Roadcut 9. All deposits in this exposure are normally magnetized. Paleosols at WA-9 are weakly to strongly developed. This site is cited by Busacca (1991) as one with features demonstrating that scabland flooding controlled timing of eolian deposition and soil development. Mazama and Mount St. Helens set C tephras are found at this site.

McDowell (1991) summarizes information about Missoula Flood deposits in Oregon's Willamette Valley, in particular the Greenback and Irish Bend Members of the Willamette Formation (formerly the Willamette Silt). She correlates the Irish Bend Member with the Touchet Beds of southern Washington. However, she feels this unit may more likely correlate with older Missoula Flood deposits if there is really a paleosol developed on this unit (McDowell, 1991).
CHAPTER III

METHODS

FIELD METHODS & SAMPLING PROCEDURES

Site Selection

USDA soil surveys state that many of the silt loam soils in this area, the Walla Walla series for example, were formed in loess (Green, 1982). Prior to field work, investigation started by analyzing topographic and geologic maps (Beaulieu, 1977; Farooqui and others, 1981) and USDA soil surveys of Wasco and adjacent counties (Green, 1972, 1982; Mayers, 1964). Examination of the maps combined with evaluation of the soil survey maps/air photos allowed me to determine areas that were likely to have exposures of fine-grained sediments. Also, persons familiar with the area were asked if they knew of good exposures of loess, rhythmtes, or other fine-grained deposits. Potential sites were field checked to determine if adequate exposures actually existed.

Exposures generally recognized (Farooqui and others, 1981; Allen and others, 1986) as deposits of loess at higher elevations and fine-grained slackwater deposits at low elevations were examined and compared. Standard field tests (Birkeland, 1984; Soil Survey Staff, 1981) for assessment of texture and other parameters were performed, and samples were collected to determine the nature of the materials at
selected sites. The Dalles Group was examined and samples were collected from several localities for purposes of comparison with various units especially flood deposits and loess. Exposures of coarse-grained flood deposits were also examined and compared with fine-grained deposits.

This initial reconnaissance of sites and materials in the field was not limited to the area immediately south of the Columbia River in Wasco County. It included a search for and examination of similar materials in Hood River, Sherman, Gilliam, and Morrow counties in Oregon; examination of classic exposures of both coarse- and fine-grained flood deposits in Washington (Baker and Nummedal, 1978; Allen and others, 1986), loess and paleosols in southeastern Washington (McDonald and Busacca, 1989), including Burlingame Canyon (Waitt, 1987); and in the greater Portland area (Lentz, 1977): Portland Hills Silt (loess) and stratified silts along the Clackamas River (fine-grained flood deposits).

Photographs and samples were taken at several of these locations for comparison with exposures and samples from the primary study area. Photographs and sketches were made to provide a record of details of the exposures, such as paleosols, bedding, root traces, burrows, and structure. Exposures of known tephras, Mount Mazama and Mount St. Helens 1980, were examined and samples were collected from several sites (Table I).

Eventually one site, at The Dalles, was selected as the focus of study. The site was measured in order to construct a cross section of the study site and plot
sample localities. Stratigraphic and structural features were noted and recorded. Sediments and soils were sampled and field tested using standard techniques (Birkeland, 1984; Soil Survey Staff, 1981). Special attention was given to color and texture. Soil descriptions were recorded. Soil and rock colors of sedimentary units and paleosol horizons were recorded using Munsell color book (Munsell, 1992). Digging was undertaken to expose the base of the roadcut which had become covered with debris shed by the roadcut over time. A stratigraphic section was compiled based primarily of soil structure.

**TABLE I**

**TEPHRA SAMPLING SITES**

<table>
<thead>
<tr>
<th>SITE</th>
<th>DESCRIPTION</th>
<th>LOCATION</th>
<th>ELEV</th>
<th>ROAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD#5</td>
<td>Celilo Converter Station</td>
<td>Sec 6 T1N R14E</td>
<td>730</td>
<td>Celilo Conv Station</td>
</tr>
<tr>
<td>GIL5</td>
<td>2 mi E of John Day River</td>
<td>Sec 20 T1S R19E</td>
<td>545</td>
<td>Hwy 206</td>
</tr>
<tr>
<td>GIL7</td>
<td>Mikkalo-Rock Creek Rd.</td>
<td>Sec 7 T1S R21E</td>
<td>910</td>
<td>Mikkalo-Rock Cr.</td>
</tr>
<tr>
<td>WC#8</td>
<td>Deschutes Canyon</td>
<td>Sec10 T4S R14E</td>
<td>800</td>
<td>Deschutes River Rd</td>
</tr>
<tr>
<td>LIND</td>
<td>East Lind, WA, Hwy 21</td>
<td>Sec 8 T17N R34E</td>
<td>1352</td>
<td>Hwy 21</td>
</tr>
<tr>
<td>WAI</td>
<td>MP 3.2 Hwy 730 (WA)</td>
<td>Sec 4 T6N R31E</td>
<td>375</td>
<td>Hwy 730</td>
</tr>
</tbody>
</table>

Representative samples were collected for all potential stratigraphic units, including paleosol horizons. Collection was based on visual examination and field tests. Location of each sample was recorded in field notes and in many cases with a colored flag on the outcrop. Outcrops were examined for sedimentary and pedogenic structures, tephra, and fossils. Descriptions based on examinations and
field tests were recorded and supplemented with photographs. Nails with numbered colored flagging tape were used to record sample collection sites and other pertinent sites.

Description of Soils

Standard field tests (Birkeland, 1984; Soil Survey Staff, 1981) for assessment of texture and other parameters were performed in the field. All soils in the section were described. Descriptions of these soils contains standard terminology developed by the Soil Survey Staff (1981) and the terminology proposed by Gile and others (1966) and Machette (1985) for calcareous soils (Table II). One additional soil structure, “nodular” is used to describe locust burrow casts (Hugie and Passey, 1963) that are abundant at the site.

**TABLE II**

CLASSIFICATION OF CALCAREOUS SOILS IN FINE-GRAINED SOILS, AFTER GILE AND OTHERS (1966)

Stage I: few filaments or faint calcareous coatings on soil grains

Stage II: few to common nodules of varying hardness with a calcareous matrix

Stage III: many nodules and internodule fillings coated with carbonate; voids can be filled with carbonate

Stage IV: laminar horizon of nearly pure carbonate usually overlying a horizon of Stage III development
LABORATORY ANALYSIS

Grain-size

The methods used in laboratory grain-size analysis were standard methods chosen after consulting several sources and are those indicated in Carver (1971) and by Folk (1974). The basic procedure consisted of pre-analysis treatment of samples to prepare them for grain-size analysis. This included disaggregation and dispersal. The actual particle-size analysis included wet sieving to separate the sand and mud fractions, dry sieve analysis of the sand-sized fraction, and pipette analysis of the silt- and clay-sized fractions. Sand fractions were examined by binocular, and in some cases petrographic, microscope to characterize the mineralogy of samples and search for tephra and fossils.

Sample treatment consisted of air drying for at least two weeks. Each sample was split with a representative portion of about 150 grams being prepared for further analysis while the bulk of each sample was stored in labeled plastic bags. Pre-analysis treatment consisted of disaggregation which included removal of substances that interfere with dispersal, i.e., carbonates and organic matter. Peds and clumps were broken using gloved fingers or a rubber stopper. Some samples rich in carbonate or other cement were carefully crushed with a mortar and pestle and treated with acid. Each soil/sediment sample was thoroughly mixed and further split to obtain about 50 grams for grain-size analysis. The excess portion of each
sample was archived in small labeled plastic bags. Organic matter was removed using hydrogen peroxide.

Approximately 50 grams of soil from each sample was weighed and then placed in a 400 ml beaker. To each beaker, 50 ml of dispersant (sodium hexametaphosphate) was added, along with 100 ml of water. Each sample was stirred for approximately three minutes to ensure that the sample was well mixed. Samples were allowed to soak for 12 to 24 hours. Each sample was subjected to ultrasound for 3 minutes (Lewis, 1984) to break down the soil structure.

After dispersal, all samples were treated with hydrogen peroxide to remove organic matter. Samples cemented with carbonate were treated with dilute hydrochloric acid and stirred until reaction stopped. Mechanical disaggregation was sometimes helpful at this point for well cemented samples. Samples were wet sieved through a #230 sieve (0.063 mm, 0.002 inches) via funnel to a graduated cylinder. A maximum of 1,000 ml of water was used for wet sieving (total water not more than the capacity of the graduated cylinder). Material passing through the sieve was collected in the graduated cylinder and subjected to pipette analysis using the method described by Galehouse (1971).

A computer spreadsheet was constructed to calculate pipette withdrawals according to the formula given by Galehouse (1971). A high degree of cementation made it impractical to attempt to analyze the grain-size in some samples.
The coarse fraction remaining on the sieve was oven-dried and weighed to prepare it for dry-sieving using the method of Ingram (1971). Each sample was placed atop a sieve stack and mechanically shaken for 3 minutes. Fractions were then weighed and subtracted from the initial weight. Sediment passing the #230 sieve to the pan was added to the cylinder for pipette analysis.

**Carbonate Content**

The method used to determine carbonate content was a widely used gaseometric CaCO$_3$-dissolution technique (Dreimanis, 1962; Machette, 1985; McRae, 1988; Gale and Hoare, 1991) in which a known weight of sample is treated with hydrochloric acid, the resulting volume of CO$_2$ is measured, and the carbonate content calculated. The procedure consisted of disaggregation of the sample, using a rubber stopper, followed, if necessary, by grinding with a mortar and pestle to produce a powder. The sample was split and a portion analyzed using a Chittick apparatus (Figure 8). Approximately 5 grams of sample was used for each analysis of samples with Stage I or II carbonate content; soils with Stage III or IV carbonate required 1 gram or less of sample, but this varied depending on carbonate content. The use of a smaller sample was necessary in order to prevent water from exceeding the capacity of the measuring tube in the Chittick apparatus. Each analysis was allowed to run for five minutes, during which time the sample was stirred by a magnetic stirrer.
Figure 8. Diagram of Chittick apparatus for measuring carbonate content.
Results were standardized using a sample of calcite. As a check on precision some samples were analyzed several times. Samples with anomalous results, very high or very low carbonate content, were analyzed at least twice. Barometric pressure and ambient temperature were measured and recorded as volume of CO₂ given off by the reaction is dependent on both these variables. The technique and analytical precision of the method are discussed by Dreimanis (1962).

Mineralogy

The coarse sand fractions of all samples subjected to grain-size analysis were microscopically examined to determine mineralogy. The dominant mineralogy was noted. In particular, all samples were examined for the presence of muscovite mica.

Tephra

In addition to searching for tephras in the field, the coarse sand fractions of all samples subjected to grain-size analysis were microscopically examined for tephra. I looked mainly for pumice fragments and glass shards. One stratigraphic unit contained a significant amount of tephra with macroscopic sized pumice clasts. Samples of this pumice were extracted from the bulk sample material of this unit, mechanically separated from the matrix and cleaned with the help of an ultrasound bath and a magnetic stirrer. This tephra was sent to Washington State University's Geoanalytical Laboratory for microprobe analysis and identification.
Paleontology

All coarse sand fractions were microscopically examined for the presence of microfossils, such as phytoliths.
CHAPTER IV

DESCRIPTION OF STUDY SITE

LOCATION

The study site (Figure 9) is a roadcut located in Wasco county on the northeast side of Highway 197 about 3 km (1.6 miles) southeast of its junction with Interstate Highway I-84 immediately east of The Dalles, Oregon. It is in the SE 1/4, NW1/4, Sec. 7, T1S, R14E, Willamette Meridian and Base Line (Figure 9). The latitude is 45°35′15″N and the longitude is 121°07′15″W. The roadcut has a maximum height of 15 m and is 340 m in length. The elevation at the top of the cut is about 204 m. The lithologies on the west side of the road are poorly exposed. Adjoining the roadcut on its northwest end is an excavation that exposes an additional 40 meter long portion of the upper end of the section.

This site is in the drainage of Threemile Creek which stream, 2 km to the west of the site, has an elevation of 108 m. Threemile Creek discharges into the Columbia River at The Dalles. The Columbia River is located about 2.5 km northwest of this site. Just east of The Dalles, at the base of the Dalles Dam, the river has a normal elevation of 22 m. The elevation of 204 m at the site places it below the maximum high water line of about 305 m (Allen and others, 1986;
Figure 9. Topographic map of study site at The Dalles, Oregon. Contour interval: 40 feet. Latitude: 45°35'15"N, longitude: 121°07'15"W.
O'Connor and Waitt, 1995) for Missoula Flood waters ponded immediately east of the Columbia Gorge.

The site is near the western edge of the Deschutes-Umatilla Plateau (Figure 4), which is itself a part of the Columbia Plateau. The Cascade Range is immediately west of the Deschutes-Umatilla Plateau. As a result, the site is favorably located as a potential repository of volcanic ash being 65 km northeast of Mount Hood, 100 km southeast of Mount St. Helens, and 70 km south of Mount Adams. Mount Hood can be seen from the site, as can the head of the Columbia River Gorge (Figure 10) at the west end of The Dalles Basin.

PHYSIOGRAPHY OF SITE

The site is in an area of moderately rolling hills (Figure 11) along the boundary between the relatively flat valley floor of The Dalles Basin and the gently undulating uplands of the Deschutes Plateau. Slopes are steepest towards the west as the uplands are dissected by the valley of Threemile Creek. Slopes in the immediate study area vary from about 3 percent to about 55 percent. Maximum relief within 3 kilometers of the site is about 315 meters. Locally, gullies interrupt the more gentle topography. Irregular topography due to landsliding is common along the edges of The Dalles Basin (Beaulieu, 1977). Large scale erosional and depositional features formed by catastrophic flooding also contribute to the physiography of the area (O'Connor and Waitt, 1995).
Figure 10. View northwestward across The Dalles Basin towards the head of the Columbia River Gorge. The Gorge is located above roadcut (A) = study site in catastrophic flood deposits.
Figure 11. Physiography of site southeast of The Dalles, Oregon. View looking north. The Columbia Hills (Washington) form the skyline. A = northern end of study site roadcut exposes Missoula Flood deposits. B = roadcut in Dalles Fm. Sevenmile Hill forms skyline.
The immediate study area is a westward-facing slope, part of a kilometer long west-southwest-trending ridge. The roadcut which forms the exposure was made approximately transverse to the trend of the ridge. At the northwest end of the roadcut is a cut where sandy silt was removed. Beyond this is a small drainage which separates the roadcut from a second roadcut which exposes volcaniclastic sediments of The Dalles Formation (Figures 10 and 12).

GEOLOGY

Surficial deposits in the area include recent alluvium, colluvium, eolian sands, loess, both facies of catastrophic flood sediments, and volcanic ash. The site is located within The Dalles basin, a syncline, that has collected primarily volcaniclastic sediments, collectively known as the Dalles Formation (O'Connor and Waitt, 1995). Farooqui and others (1981) suggested elevating the Dalles Formation to group status. Their Dalles Group so defined consists of five formations: Chenoweth, Alkali Canyon, Deschutes, Tygh Valley, and McKay formations. The Chenoweth Formation occupies the Dalles basin and immediately underlies loess and catastrophic flood sediments. A search of the recent literature reveals that these rocks are today generally referred to as the Dalles Formation (Allen and others, 1986; O'Connor and Waitt, 1995; Orr and Orr, 1996) in preference to the Dalles group. They will be referred to as a formation in this report.
The Dalles Formation forms bedrock in the immediate study area and throughout much of the Dalles basin and also occurs in the area of Hood River. The Dalles Formation is a volcaniclastic debris fan with a source in the Cascade Range to the west of The Dalles basin. It consists of lithic tuffaceous sandstone, siltstone and shale interbedded with agglomerate and tuff. The Dalles sediments are generally well-indurated. Coarser laharic deposits are dominant to the west while finer deposits are predominant to the east (Farooqui and others, 1981). A second roadcut 200 m northwest of the study site at The Dalles exposes agglomerate with clasts up to 2.5 m in diameter (Figure 12). Some of the strata exposed in this second roadcut contain abundant white pumice clasts.

The age of the Dalles Formation is late Miocene to early Pliocene (Farooqui and others, 1981; O'Connor and Waitt, 1995). It is correlated with the Deschutes Formation and the Troutdale Formation (Farooqui and others, 1981; Allen and others, 1986) which accumulated in other basins.

Underlying The Dalles Formation, as well as the entire Columbia Plateau, and widely exposed at the surface, is the Columbia River Basalt Group of middle to late Miocene age (Farooqui and others, 1981). These basalts are particularly well exposed in the walls of the narrows of the Columbia River between Biggs, Oregon, and the mouth of the John Day River. Landslides of various sizes are found throughout The Dalles basin, especially close to the river where hillslopes underlain by the Dalles Formation were undercut by Missoula Flood waters (Beaulieu, 1977).
Figure 12. Dalles Formation in a roadcut 200 meters north of study site. View is to the northeast. Highway 197 is in foreground, road to Celilo Converter Station in distance.
Evidence of catastrophic flooding is abundant in The Dalles basin and includes scabland, huge gravel bars with giant ripples on their surface, slackwater sediments, and scattered erratic rocks (Allen and others, 1986). Missoula floods were hydraulically dammed at the northward bend in the Columbia River near the west end of The Dalles by the Columbia Hills/Ortley anticline, temporarily ponding the flood waters to form "Lake Condon" (Allen and others, 1986). Lake Condon not only occupied the Dalles basin but extended up river as far as Wallula Gap (Allen and others, 1986). Maximum flood stages indicate flood waters reached a maximum elevation of 305 m in this area (Allen and others, 1986; O'Connor and Waitt, 1995). This maximum high-water elevation is based on the maximum elevations of erratic boulders thought to have been ice-rafted to their various locations and stranded as the waters of Lake Condon receded and on the maximum elevations of divides crossed by the flood waters. The largest erratic near the site is a granitic boulder at the crest of McCoy Road, elevation of 286 m (940'), approximately 7.3 km east of the roadcut. It is located in the SW1/4, SE1/4, Sec. 34, T2N, R144E, Willamette Meridian and Base Line, Wasco County, Oregon. Also, most areas below 305 m elevation are lacking residual soil and regolith.

Stratigraphy

Three distinctive units are exposed by this roadcut (Figures 13 and 14) and a fourth is covered by colluvium at the base of the cut. The uppermost, or youngest unit, Unit 1, is loess. It is from one to two meters thick and unindurated.
Figure 13. View of major stratigraphic units exposed at north end of study site. Unit 4 is not exposed here.

Figure 14. Diagram of major stratigraphic units exposed at north end of study site. Same view as Figure 13.
Unit 2 underlies Unit 1 at the northwest end of the roadcut. It is a generally massive sandy silt containing scattered pebbles and lenses of coarse sand. Unit 2 has a maximum exposed thickness of 4m and is only poorly indurated. It lies unconformably on Unit 3 which is a distinctive unit containing several paleosols, some of which are well indurated. The lower contact of Unit 3 is covered. Maximum exposed thickness is six meters. Some digging is required to expose Unit 4 at the base of the roadcut. It consists of well indurated sandstone and pebbly conglomerate.

Structure

The major structural feature within the general study area is the Yakima Fold Belt (Figure 4), in particular the Columbia Hills/Ortley anticline and the Dalles syncline. The sediments and paleosols exposed in the roadcut at The Dalles are broadly convex in shape but this would seem to be due to the influence of the land surface at the time the paleosols formed and not to any folding in response to compressive forces. In any case, the paleosols are generally parallel to the present land surface. Several clastic dikes and a fault are exposed in the roadcut. All units are cut by these features except for Unit 1.

CLIMATE

This site, located in the rain shadow created by the Cascade Range, has a steppe (semi-arid) climate and somewhat extreme temperatures (Green, 1982;
Lydolph, 1985). The Cascades, to the west, block the moisture and the moderating influences of maritime air masses originating over the Pacific Ocean. The continental nature of the climate is moderated by maritime air masses moving through the Columbia River Gorge from the west and the Rocky Mountains to the north and east that keep most of the bitterly cold continental Arctic air masses from penetrating into the area in winter.

Average annual precipitation is about 355 mm (Oregon Climate Service Data Archives, monthly means and extremes (1961-1990) [Accessed 20 Aug 1995]). About 75% of the precipitation occurs during the winter months, mostly as rain. Less than 10% occurs from June to August. The mean annual temperature is 13°C. Summer temperatures are warm. The average maximum temperature in summer is 31°C, with the highest recorded temperature being 43°C. Winters are cold, but not severe. The average minimum temperature in January is -1°C, with the lowest recorded temperature being -21°C (Stemes, 1978).

Located in the mid-latitudes, the predominant climatic factors are the amount of insolation and the prevailing westerly winds, which carry moist air masses originating over the Pacific Ocean eastward (Lydolph, 1985; Curran, 1994). Orographic lifting due to the Cascade Range causes heavy precipitation on the west side of that range. As air masses move to lower elevations on the east side they are warmed by compression and are able to hold more water vapor. This not only causes a rain shadow on the east side of the range but also causes high rates of
evaporation. This influences not only the flora and fauna of the region, but also its soil formation.

Wind is a common occurrence in this area (Oregon Climate Service Data Archives, selected wind reports from Oregon locations [Accessed 15 Sep 1995]). Differential heating between the areas east and west of the Cascades often produces a large pressure gradient, and the winds find a relatively easy, if constricted, path through the Columbia River Gorge. Located just outside the eastern entrance to the Gorge, the site has moderate and frequent winds in all seasons. During the summer, winds generally are from the west, while in winter they blow from the east. When the fields are bare due to plowing, dust is often moved by the wind, sometimes obscuring visibility.

Loss of soil moisture is high as there are few clouds and little rain, especially during the summer season when the sun is high in the sky, and day lengths are long (12 to 15 hours per day) (Curran, 1994; U.S. Naval Observatory, Sunrise/Sunset/Twilight and Moonrise/Moonset/Phase [Accessed 20 Aug 1995]). Air moving down from surrounding mountains warms by compression and can evaporate water from surfaces over which it moves. Vegetation is primarily grasses which only provide minimal shade to ground surfaces. Winds common to the area also cause drying of ground surfaces and increased transpiration from plants which in turn leads to decreased soil moisture.
VEGETATION

This area is a part of the broad steppe (grassland) shrub-steppe region that occupies much of Oregon and Washington east of the Cascade Range (Franklin and Dyrness, 1973). The native vegetation, prior to settlement, consisted of grasses, mostly short bunch grasses such as *Agropyron spicatum* (blue bunch wheatgrass), *Festuca idahoensis* (blue bunch fescue) and *Poa sandbergii* (Sandberg's bluegrass), with sagebrushes (*Artemisia tridentata*, *A. rigida*) and *Purshia tridentata* (bitter brush) in drier areas (Franklin and Dyrness, 1973), and a scattering of trees along stream courses. Due to the semi-arid climate few trees could grow in this area prior to irrigation, with the exception of *Robinia pseudoacacia* (black locust) which was extensively planted for shade and windbreaks. Today, irrigated cherry orchards are extensive at lower elevations immediately west of the site. Most of the area is used for growing wheat, which is today the dominant plant in the area.

SOILS

A modern surface soil and at least five underlying paleosols are exposed at this site (Figure 13). The exact number of paleosols is difficult to determine as some of the paleosols are complex and were probably developed by more than one period of soil formation due to burial followed by erosion. The horizons in these buried soils are essentially parallel to the present landscape (Figure 13). All the paleosols are truncated by an unconformity upon which rests Unit 2, the massive
sandy silt. The surface (modern) soil is forming on loess which has accumulated upon the other units.

The soils, both paleosols and modern, are described in some detail as they form much of the evidence of the geologic events that I have been investigating. Also, the paleosols and their preserved trace fossils, along with the unconformity, are the most notable features at this site. The sediments exposed in this cut, upon which the soils developed, can be generally characterized as massive silts and massive sandy silts. Several of the paleosols contain pebbles and/or tephras.

**Surface soils**

Green (1982) assigned the surface soils in the immediate study area to the Anderly, Duart, and Walla Walla Series. All are Typic Haploxerolls. These well drained soils are Mollisols formed mostly in loess on uplands. The Duart Series contains an appreciable amount of volcanic ash (Green, 1982). In the immediate study area Duart Series soils seem to overlie the Dalles Formation, while the Walla Walla Series tends to occur on thicker accumulations of silt (loess or fluvio-lacustrine) derived from the upper Columbia River system. The Anderly soil has developed on a south-facing slope. In addition to variations in slope and parent material, differences in soil type are also due, over the broader area of the Columbia Basin, to variation in precipitation. Aridisols are generally forming in areas where the mean-annual precipitation is less than 230 mm (Busacca, 1991). Table III is a profile of the surface soil that has developed at the north end of the exposure.
TABLE III

PROFILE OF WALLA WALLA SERIES SURFACE SOIL AT NORTH END OF THE DALLES SITE. THIS SOIL HAS DEVELOPED ON HOLOCENE LOESS AND OR LATEST MISSOULA FLOOD SANDY SILT. IT IS A TYPIC HAPLOXEROLL.

A - 0 to 15 cm, dusky yellowish brown (10 YR 2/2, dry) silt loam; weak fine granular structure; soft; friable; slightly plastic; many fine roots; many irregular pores; gradual boundary.

Bw -15 to 56 cm, dark yellowish brown (10YR 4/2, dry) silt loam; coarse prismatic structure parting to weak subangular blocky; slightly hard, friable, slightly sticky and slightly plastic; many fine roots; many irregular pores; gradual boundary.

C - 56 to 117 cm; moderate yellowish brown (10YR 5/4, dry) coarse silt loam; massive; slightly hard, very friable; few roots; many swallow burrows, some small mammal (rodent) burrows, few small insect burrows. Depth to bedrock is over 3 meters at this point.

Soils in the broader area form an orderly pattern related to geology, slope, climate, and vegetation. Most soils are silt loams developed on a mantle of loess and fine-grained flood deposits. Volcanic ash is common in many of the soils. Some are formed in colluvium. Steep areas are usually underlain by Columbia River Basalts which are exposed in these settings. At the base of cliffs and along stream courses, soils are formed on alluvium and or colluvium. Where soils are thinner than about one meter, patterned ground is common, forming low mounds surrounded by stones on gentle slopes and as stone stripes on steep slopes. These soils are used primarily for growing wheat and other dryland farming, also for
pasture. At lower elevations in The Dalles area there are orchards of cherries and some other fruits (Green, 1982).

Paleosols

The most notable features of the buried soils at this site are their colors and structure (calcium carbonate accumulation and evidence of bioturbation). The colors are predominantly moderate yellowish brown and pale grayish orange. Soil structural features prominent at this site include abundant cementation, nodular structure, and abundant krotovina (burrows). Cementation of soils in arid climates is due primarily to the accumulation of calcium carbonate in the B horizon. B and K horizons are the most distinctive features of this site. All exhibit soil development that can be classed as moderate to strong (Stage II-IV carbonate development of Gile and others, 1966).

B horizons are characterized by a well developed “nodular” soil texture, the result of extensive bioturbation. While the terms “nodular” and “nodules” are not part of the standard terminology used for description of soils (Soil Survey Staff, 1993), they describe this particular structure extremely well. Researchers working on similar paleosols in Washington have used and defined these terms (Foley, 1982; McDonald, 1987, McDonald and Busacca, 1988a). These nodules are very prominent in many of the horizons within the Unit 3 paleosols. They are generally cylindrical and average about one centimeter in diameter. They were created by soil organisms, primarily cicadas (Hugie and Passey, 1963) and earthworms
(Retallack, G. J., personal communication, 1992). Precipitation of carbonate has taken place preferentially on the exterior, for the most part, of these structures. As a result, the paleosols have a very characteristic structure. The exteriors of root traces are similarly cemented, but these structures are much less abundant with only small rootlets preserved, and therefore do not contribute much to the overall structure of these soils. Rodent burrows (krotovina) also are highly calcareous as a result of deposition of calcite at the edge of the burrow. They are common in lower horizons in most of the paleosols.

K (petrocalcic) horizons are characterized by moderate to strong accumulations of secondary carbonate and, sometimes, lesser amounts of silica and are strongly cemented. Structure is massive to platy. Carbonates occur as continuous coatings on peds and as seams, both horizontal and vertical. Horizontal seams are often several centimeters thick and contain more carbonate than silt or sand. While these structures cut across the nodular structure, the nodules themselves are more highly cemented in K horizons. A coarse blocky structure is also evident in K and B horizons with seams of secondary carbonate deposited on the edges of the blocks which often are 20 to 50 cm wide.

C horizons are generally unaltered parent material of fine-grained flood deposits. Some horizons that might be generally classified as unaltered do contain mammalian krotovina with secondary carbonate deposited on the exterior. The presence of the burrow acts to channel subsurface water movements and directs
preferential deposition of secondary cements. The texture of these materials, silt and fine sand would seem to be conducive to burrowing activities at a greater depth than might normally be the case with other subsoil materials.

Few primary sedimentary structures were noted, except that each younger deposit seems to have occurred on top of the well developed B horizon of a soil that had developed since the previous sediments had been deposited. The stage of soil development had advanced to the point where it offered resistance to erosion, while the A horizons appear to have been stripped away or altered by later soil forming processes after burial by the overlying sediment (as described by McDonald, 1987).

Because no bedding is visible, stratigraphic units are distinguished on the basis of paleosol development. Evidence for the designation of these units as buried soils includes: (1) morphology similar to other paleosols (Palouse Formation) and to modern soils formed in arid climates, (2) presence of trace fossils (plant roots and krotovina), and (3) numerous phytoliths.
CHAPTER V

RESULTS

The results of field work and laboratory analysis are reported in this section under several headings. The stratigraphy of the study site is based on the combined results of both field and laboratory analysis. The stratigraphy is reported first to provide a framework for discussing the results of the analysis of grain-size, carbonate content, mineralogy, and soil texture.

STRATIGRAPHY OF SITE

Field and laboratory analyses reveal that four major units occur at this site (Figures 13 and 14). The uppermost unit, Unit 1 (Figures 15), is a thin mantle of loess. Along the northwest end of the cut it rests on Unit 2 while along the southeast end it rests on Unit 3. Unit 2 is a much thicker, relatively massive sandy silt with scattered pebbles and faint sedimentary structures. It is interpreted as late Wisconsin Missoula Flood rhythmite deposits. The largest portion of the site is occupied by a series of well-developed paleosols, Unit 3, that rest unconformably on the local bedrock, the Dalles Formation, designated Unit 4. Units 1 and 2 rest unconformably on Unit 3.
Figure 15. Detail of Unit 1: Loess. Note the soil, the Walla Walla series, that has developed in the loess (Green, 1982). Shovel handle, with red flagging, is 42 cm in length.
Unit 1: Loess

The uppermost and therefore youngest unit has a uniform silty texture with a weak prismatic structure (Figure 15). It is thinnest, about one meter, where the cut traverses the crest of the ridge, and thickens to a maximum of about two meters at the northwest end of the cut where it is also well exposed in the excavation at right angles to the road. This sediment is the uppermost unit along the whole length of the roadcut. This unit is interpreted as loess deposited since the time of the last Missoula Flooding at this site so its age is less than about 12,700 B.P. This interpretation is based on its silt loam texture which is slightly finer than the underlying unit and its prismatic soil structure. A weakly developed soil, the Walla Walla series, is forming on the loess (Figure 15). It lacks carbonate deposition.

The weak to moderate prismatic jointing of the Bw horizon is characteristic of loess (Pecsi, 1968; Pye, 1987) and is an indication of soil development. Organic content is somewhat high as indicated by the dark color. Soil texture is silt loam. Abundant roots and scattered burrows are found in this soil.

Unit 2: Massive Sandy Silt

Unit 2 is well exposed along the northwest end of the roadcut (Figure 16) and in an adjoining excavation to the north. It is predominantly a fine sandy silt with some coarse basaltic sand lenses and a few lenses of sandy gravel. Unit 2 is somewhat massive in appearance, exhibiting only a faint bedding due to thin and discontinuous sandy layers. Several clastic dikes and pipe-like intrusions filled
Figure 16. View of Unit 2: Missoula Flood sandy silts, at north end of roadcut. A faint bedding is present. Person is pointing to location of cobbles.
with coarse to fine sand are scattered throughout the length of the exposure. The portion of this unit exposed in the excavation is the site of numerous burrows (Figure 17) dug and occupied, during the summer, by bank swallows (*Riparia riparia*). When the birds leave their nests to migrate south the burrows become home to various arthropods, notably *Latrodectus mactans*, the black widow spider, several of which were observed during field work.

Some scattered pebbles and cobbles of various lithologies occur within Unit 2 (Figure 18). Many of these pebbles are basaltic, some are granitic, and others are metamorphic. Most are rounded to subangular. The largest cobble found *in situ* in Unit 2 was eight centimeters in diameter. A piece of greenish quartzite 28 cm long was found as float at the base of the unit. Several smaller pieces were also found within a short distance of the larger one. It is unclear whether this rock came from the exposure or is due to human agency. However, the rock type is exotic to the area. Unit 2 has a maximum exposed thickness of four meters. The lowest portion of the unit is covered by debris from the cut. It is unclear therefore how much of Unit 2 is unexposed, but it is estimated at approximately two meters judging from what can be seen of the relations that are exposed. What is exposed, however, indicates that this unit rests unconformably on an eroded surface cut into Unit 3. There is no evidence of a former soil paralleling this contact, and some evidence, such as possible ripup clasts, that indicates that this is a former erosion surface. On the basis of this evidence this unit is interpreted as latest Wisconsin Missoula Flood.
UNIT 1

UNIT 2

Figure 17. View of excavation at north end of roadcut showing burrows of the bank swallow (*Riparia riparia*). Modern soil is developed on loess (Unit 1) which rests on Missoula Flood deposits (Unit 2). This exposure is approximately six meters in height.
Figure 18. Pocket of pebbles of various lithologies in Unit 2, Missoula Flood deposits.
(ca. 15,300-12,700 ka, Waitt, 1985) slackwater sediments deposited on a surface cut by the flood waters.

The portion of Unit 2 exposed in the roadcut exhibits a faint apparent stratification with layers about 15 - 20 cm thick. Layers are not planar but somewhat wavy. Careful examination reveals a slight textural and color change more or less coinciding with this stratification. These layers are interpreted as Missoula Flood rhythmites. Winds blowing through the cut may have accentuated this stratification. It is not apparent in the walls of the excavation at the north end of the roadcut, which is somewhat sheltered from the wind. This somewhat sheltered position may explain the extensive burrows in the excavation while the roadcut contains none of the avian burrows. A faint stratification is apparent in the walls of the excavation, but it is less obvious than that seen along the roadcut side.

**Unit 3: Paleosol Unit**

Five paleosols (Figure 19) were distinguished based on field characteristics and laboratory analysis. These five paleosols are more or less horizontal and occupy most of the exposure. The boundaries between each paleosol are abrupt, marked by both a distinct color change and different soil structures. The paleosols are numbered 1 through 5 (Figure 20) with 1 being the youngest and highest in the section. These paleosols exhibit several distinctive features: color, morphology, carbonate content, and evidence of bioturbation. Two colors are typical, with darker (brownish) Bt, Btk, or K horizons overlying lighter (tan) Bk or C horizons.
Figure 19. View showing the five paleosols of Unit 3. The recent soil developed in a thin deposit of loess is visible at the top of the cut. This view is near the middle of the roadcut, which is 15 m deep at this point. The lower four meters of section are not exposed due to a covering of material sloughed from the face of the cut.
Figure 20. Diagrammatic cross-section of the five paleosols of Unit 3. Same view as in Figure 19.
The highly micaceous, non-volcanic mineralogy of the paleosol sediments indicates an upper Columbia River provenance, therefore, not Dalles Formation. All the paleosols contain abundant secondary carbonate and some secondary silica. The carbonate coats peds, root traces, and burrows. It also occurs as seams and veins (Figure 21). Stages of calcium carbonate morphology exhibited by these ancient soils vary from Stage II to Stage IV (Table II) (Gile and others, 1966). The paleosols all show evidence of extensive bioturbation in the form of numerous krotovina (Figure 22) and root casts. The upper boundary of Unit 3 is an erosion surface; the lower boundary is irregular and may also be an erosion surface. The lower boundary is not well exposed.

Few original sedimentary structures could be found in this unit. The texture of this unit varies from silt to fine sandy silt. Several of the paleosols contain a very few scattered pebbles of varied lithologies. The largest was found at the base of the 5th or lowest paleosol. It was a rounded vesicular basaltic cobble 14 cm in largest diameter. Several other basaltic cobbles were found within four meters of this one. A quartzite cobble, measuring 9 x 6.5 x 4 cm, was found near the base of paleosol 4 (Figure 23). The lowest portions of Unit 3 are generally not exposed, being covered by regolith that has wasted from the face of the cut. The five paleosols are described below in Table IV.

Paleosol 1. This is the uppermost, therefore youngest paleosol. It is 2.2 m thick. Dry color on a sunny day is dark yellowish brown (10YR 4/2) to moderate
Figure 21. Carbonate horizon of Paleosol 5, Unit 3. The lumps are the fossil burrows of insects, such as cicadas, which are cemented with carbonate. Several veins and seams of carbonate are visible.
These fossil burrows of small mammals are generally 1.5 to 2 centimeters in diameter. Their exteriors are preferentially cemented with carbonate.
Figure 23. Quartzite cobble in situ in Paleosol 4, Unit 3, two views. In the upper photo the silty sand surrounding the cobble is damp. Length of wheat seed head is five centimeters.
yellowish brown (10YR 5/4). It has developed mainly in silt and fine sand.

Paleosol 1 is moderately developed as evidenced by carbonate accumulation of one horizon with Stage II+ and two horizons with Stage II. It is generally only slightly calcareous, except for a zone approximately 20 cm thick which reacts very strongly to dilute hydrochloric acid and which has a carbonate content of >40% (Table V). This is the second highest carbonate content encountered in the whole section. It is unusual as this zone is not heavily cemented other than a few thin stringers of carbonate. The carbonate content was checked several times, also, the field reaction to acid was repeated on several occasions. This paleosol has a moderate nodular structure, along with the presence of scattered small burrows and few fine root traces (Table IV). A rodent incisor was found in the 2Btk3 horizon. The A horizon is missing; it probably is now part of the Bw horizon of the loess soil above it.

**Paleosol 2.** This paleosol is 3.4 m thick. Dry color on a sunny day is very pale orange (10YR 8/2) at the top to grayish orange (10YR 7/4) near the base. It is moderately developed, but appears to have developed to a greater extent than paleosol 1 as it is thicker and exhibits Stage III carbonates. Cementation is weak to strong (Stage I to III). Veins and stringers of carbonate are common. Fine filaments of carbonate are common as a result of deposition on numerous rootlets. Nodular structure is moderate to well developed. Larger burrows are few. A very few small pebbles were recovered from this paleosol. The A horizon of the soil is
### TABLE IV

**DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS.**

<table>
<thead>
<tr>
<th>HORIZON</th>
<th>DEPTH (m)</th>
<th>THICKNESS (cm)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modern Soil</td>
<td>0 - 0.25</td>
<td>25</td>
<td>Dark yellowish brown (10YR 4/2) dry, silt loam; massive, loose, non-sticky, non-plastic; non-calcareous; abundant very fine roots; gradual lower boundary</td>
</tr>
<tr>
<td>Bw</td>
<td>0.25 - 1.90</td>
<td>165</td>
<td>Moderate yellowish brown (10YR 5/4) dry, silt loam; moderate coarse prismatic structure; loose, non-sticky, slightly plastic; non-calcareous; numerous fine roots; scattered small (&lt;2 cm) burrows; abrupt wavy lower boundary</td>
</tr>
<tr>
<td>Paleosol 1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2Btk1</td>
<td>1.90 - 2.10</td>
<td>20</td>
<td>Very pale orange (10YR 8/2) dry, silt loam; massive, friable, slightly sticky, slightly plastic; violently effervescent, weakly cemented except for some horizontal seams of carbonate to 2 cm thick; abrupt wavy lower boundary; Stage II carbonate</td>
</tr>
<tr>
<td>2Btk2</td>
<td>2.10 - 2.60</td>
<td>50</td>
<td>Moderate yellowish brown (10YR 5/4) dry, silt loam; massive, friable, slightly sticky, slightly plastic; slightly calcareous; abundant fine roots traces, few medium root traces; scattered small (&lt;2 cm) burrows; abrupt lower boundary; Stage I carbonate</td>
</tr>
<tr>
<td>2Btk3</td>
<td>2.60 - 2.80</td>
<td>20</td>
<td>Grayish orange (10YR 7/4) dry, silt loam; massive and coarse platy structure; friable, non-sticky, non-plastic; very calcareous, weakly cemented except for horizontal 1 cm thick stringers of carbonate in a zone 20 cm thick; abrupt lower boundary; Stage II+ carbonate</td>
</tr>
</tbody>
</table>
### TABLE IV

DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS.
(continued)

<table>
<thead>
<tr>
<th>HORIZON</th>
<th>DEPTH (m)</th>
<th>THICKNESS (cm)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>2Bk1</td>
<td>2.80 - 3.72</td>
<td>92</td>
<td>Moderate yellowish brown (10YR 5/4) dry, silt loam; moderate nodular structure, otherwise massive, coarse irregular structure outlined by whitish veins, friable, slightly sticky, slightly plastic; slightly calcareous; moderate nodular development, scattered small burrows, few fine roots; abrupt lower boundary; Stage I carbonate</td>
</tr>
<tr>
<td>2Bk2</td>
<td>3.72 - 4.12</td>
<td>40</td>
<td>Very pale grayish orange (10YR 7/2) dry, fine sandy loam, few small pebbles; loose, friable, non-sticky, non-plastic; very calcareous, weakly cemented except for horizontal stringers of carbonate; 2 rodent incisors collected, few burrows; abrupt wavy lower boundary; Stage II carbonate</td>
</tr>
<tr>
<td>Paleosol 2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3Btk</td>
<td>4.12 - 5.32</td>
<td>120</td>
<td>Yellowish brown (10YR 6/4) dry, silt loam; moderate nodular structure, coarse irregular structure outlined by whitish veins, friable, slightly sticky, slightly plastic; slightly calcareous; scattered burrows (to 3 cm); abrupt lower boundary; Stage II carbonate near the top; Stage II carbonate near the bottom</td>
</tr>
<tr>
<td>3K</td>
<td>5.32 - 5.52</td>
<td>20</td>
<td>Very pale grayish orange (10YR 7/2) dry, silt loam; very hard, many veins of carbonate 1 cm thick, average ped size 1.5 cm; irregular lower boundary; stage IV carbonate</td>
</tr>
</tbody>
</table>
**TABLE IV**

DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS. (continued)

<table>
<thead>
<tr>
<th>HORIZON</th>
<th>DEPTH (m)</th>
<th>THICKNESS (cm)</th>
<th>DESCRIPTION</th>
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</thead>
<tbody>
<tr>
<td>3Btk</td>
<td>5.52 - 6.32</td>
<td>80</td>
<td>Yellowish brown (10YR 6/4) dry, silt loam; moderate nodular structure, coarse irregular structure outlined by whitish veins, friable, slightly sticky, slightly plastic; abrupt lower boundary; Stage II carbonate</td>
</tr>
<tr>
<td>3Bk1</td>
<td>6.32 - 6.44</td>
<td>12</td>
<td>Very pale grayish orange (10YR 7/2) dry, silt loam; massive, friable, non-sticky, non-plastic; many stringers of carbonate to 0.5 cm thick; gradual lower boundary over a thickness of 5 cm; Stage III carbonate</td>
</tr>
<tr>
<td>3Bk2</td>
<td>6.44 - 7.48</td>
<td>104</td>
<td>Yellowish brown (10YR 6/4) dry, silt loam; massive, loose, non-sticky, non-plastic; calcareous with strong reaction to acid; numerous scattered burrows (to 3 cm) strongly cemented on exterior, interiors friable to strongly cemented; abrupt lower boundary; Stage II carbonate</td>
</tr>
<tr>
<td><strong>Paleosol 3</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4Bt</td>
<td>7.48 - 8.20</td>
<td>72</td>
<td>Moderate yellowish brown (10YR 5/4) dry, silt loam; moderate nodular structure, coarse irregular structure, friable, non-sticky, non-plastic; slightly calcareous; scattered fine white root traces; abrupt lower boundary; Stage I carbonate</td>
</tr>
<tr>
<td>4Btk</td>
<td>8.20 - 8.52</td>
<td>32</td>
<td>Pale yellowish brown (10YR 6/2) dry, fine sandy loam with common fine pebble size pumice clasts; well developed nodular structure, coarse granular structure; hard, non-sticky, non-plastic; 1 - 2 cm thick stringers and widely spaced vertical seams of carbonate, otherwise, moderately calcareous; abrupt lower boundary; Stage III carbonate</td>
</tr>
</tbody>
</table>
TABLE IV

DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS.
(continued)

<table>
<thead>
<tr>
<th>HORIZON DEPTH (m)</th>
<th>THICKNESS (cm)</th>
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<tbody>
<tr>
<td>4C 8.52 - 8.73</td>
<td>21</td>
<td>Yellowish brown (10YR 6/4) dry, sandy loam with numerous fine pebble size pumice and other clasts; moderately developed nodular structure; soft, friable, non-sticky, non-plastic; non-calcareous; few fine roots; abrupt lower boundary; Tephra layer</td>
</tr>
<tr>
<td>5Btk 8.73 - 9.28</td>
<td>55</td>
<td>Yellowish brown (10YR 6/3) dry, fine sandy loam; strong nodule development, moderately developed very coarse columnar structure; hard, firm, non-sticky, non-plastic; very strongly cemented, violently effervescent, abrupt smooth lower boundary; Stage III carbonate</td>
</tr>
<tr>
<td>5Bk1 9.28 - 9.57</td>
<td>29</td>
<td>Very pale grayish orange (10YR 7/2) dry, fine sandy silt loam; massive, friable, non-sticky, non-plastic; weakly effervescent except for stringers to 2 cm thick; numerous fine roots, few burrows; gradual lower boundary over a thickness of 9 cm; Stage II+ carbonate</td>
</tr>
<tr>
<td>5Bk2 9.57 - 10.54</td>
<td>97</td>
<td>Pale yellowish brown (10YR 6/2) dry, fine sandy silt loam; massive, friable, non-sticky, non-plastic; common fine roots, effervescent; numerous calcareous burrows (2.0-2.5 cm diameter); gradual lower boundary over a thickness of 16 cm; Stage II+ carbonate</td>
</tr>
<tr>
<td>5Bk3 10.54 - 11.04</td>
<td>50</td>
<td>Pale yellowish brown (10YR 6/2) dry, fine sandy silt loam; massive, slightly hard (forms a weak non-continuous ledge), friable, non-sticky, non-plastic; effervescent; few burrows; gradual lower boundary over a thickness of 10 cm Stage II carbonate</td>
</tr>
</tbody>
</table>
### TABLE IV

DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS.

(continued)

<table>
<thead>
<tr>
<th>HORIZON</th>
<th>DEPTH</th>
<th>THICKNESS</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>5Bk4</td>
<td>11.04 - 11.26</td>
<td>22</td>
<td>Very pale grayish orange (10Y 7/2) dry, fine sandy silt loam, scattered pebbles of varied lithologies; massive, friable, non-sticky, non-plastic; effervescent; scattered burrows; gradual lower boundary over a thickness of 5 cm; Stage II carbonate</td>
</tr>
<tr>
<td>5Bk5</td>
<td>11.26 - 11.46</td>
<td>20</td>
<td>Moderate yellowish brown (10YR 5/4) dry, silt loam; friable, non-sticky, non-plastic; effervescent; few burrows (&lt;2.5 cm); gradual lower boundary over a thickness of 4 cm; Stage II carbonate</td>
</tr>
<tr>
<td>Paleosol 5</td>
<td></td>
<td></td>
<td>Grayish orange (10YR 7/4) dry, fine sandy loam with some coarse sand and scattered pebbles (&lt;5 mm); strong nodule development (locust krotovina?), moderately developed very coarse columnar structure cut by numerous vertical calcareous seams; hard, friable, non-sticky, non-plastic; very strongly cemented, moderately to violently effervescent, gradual lower boundary over a thickness of 12 cm; Stage IV+ carbonate</td>
</tr>
<tr>
<td>6K</td>
<td>11.46 - 12.26</td>
<td>80</td>
<td>Yellowish brown (10YR 6/4) dry, fine sandy loam; strong nodule development, moderately developed very coarse columnar structure; hard, friable, non-sticky, non-plastic; very strongly cemented, violently effervescent, gradual lower boundary over a thickness of 11 cm; Stage III carbonate</td>
</tr>
<tr>
<td>6Btk1</td>
<td>12.26 - 12.76</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>HORIZON</td>
<td>DEPTH</td>
<td>THICKNESS</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>---------</td>
<td>-------</td>
<td>-----------</td>
<td>-------------</td>
</tr>
<tr>
<td>6Btk2</td>
<td>12.76 - 13.16</td>
<td>40</td>
<td>Very pale grayish orange (10YR 7/2) dry, fine sandy loam; strong nodule development, moderately developed very coarse columnar structure; hard, friable, non-sticky, non-plastic; very strongly cemented, violently effervescent, gradual lower boundary over a thickness of 8 cm; Stage III carbonate</td>
</tr>
<tr>
<td>6Bk1</td>
<td>13.16 - 13.32</td>
<td>16</td>
<td>Moderate yellowish brown (10YR 5/4) dry, fine sandy loam; strong nodule development, moderately developed very coarse columnar structure; hard, friable, non-sticky, non-plastic; very strongly cemented, violently effervescent, abrupt lower boundary; Stage III carbonate</td>
</tr>
<tr>
<td>6Bk2</td>
<td>13.32 - 13.86</td>
<td>54</td>
<td>Moderate yellowish brown (10YR 5/4) dry, fine sandy loam; strong nodule development, moderately developed very coarse columnar structure; hard, friable, non-sticky, non-plastic; very strongly cemented, violently effervescent, gradual lower boundary over a thickness of 9 cm; Stage III+ carbonate</td>
</tr>
<tr>
<td>6Bk3</td>
<td>13.86 - 14.51</td>
<td>65</td>
<td>Very pale grayish orange (10YR 7/2) dry, silt loam; friable, non-sticky, non-plastic; weakly effervescent; massive; gradual lower boundary over a thickness of 12 cm; Stage I carbonate</td>
</tr>
<tr>
<td>6C</td>
<td>14.51 - 15.11</td>
<td>69</td>
<td>Pale yellowish brown (10YR 6/2) dry, sandy loam; massive, friable, non-sticky, slightly plastic; very slightly calcareous; numerous fine root traces; gradual wavy lower boundary over a thickness of 25 cm</td>
</tr>
</tbody>
</table>
TABLE IV

DESCRIPTION AND MEASURED SECTION OF UNIT 3 PALEOSOLS.
(continued)

<table>
<thead>
<tr>
<th>HORIZON DEPTH (m)</th>
<th>THICKNESS (cm)</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dalles Formation</td>
<td>15.11 - ??</td>
<td>&gt;20 Pale yellowish brown (10YR 6/2) dry; sandy-silty conglomerate; massive, hard, slightly calcareous; lower boundary not exposed</td>
</tr>
</tbody>
</table>

missing, probably truncated by whatever deposited the sediment which paleosol 1 has formed in.

**Paleosol 3.** Paleosol 3 contains a significant tephra. This tephra consists of a large number of rounded pumice lapilli which make up approximately five percent of the sediment in this ancient soil. This paleosol is 1.3 m thick. It occurs at a depth of 7.0 m. The dominant color, dry, is moderate yellowish brown (10YR 5/4). This paleosol is dominated by a well developed calcic horizon with Stage III carbonate. Nodular structure is well developed. Carbonate deposition on former rootlets is common. Larger burrows are extremely rare. A few pebbles of varied lithologies were found in this unit. The A horizon of the soil is missing, probably truncated by the erosive event preceding the sediment deposition on which paleosol 2 is developed.

**Paleosol 4.** Two colors dominate this paleosol: yellowish brown (10YR 6/3) in the upper portion and pale yellowish brown (10YR 6/2) below. This paleosol is
<table>
<thead>
<tr>
<th>HORIZON</th>
<th>CARBONATE</th>
<th>GRAVEL</th>
<th>SAND</th>
<th>SILT</th>
<th>CLAY</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Percent</td>
<td>Percent</td>
<td>Percent</td>
<td>Percent</td>
<td>Percent</td>
</tr>
<tr>
<td>Loess</td>
<td>A</td>
<td>0.2</td>
<td>0.0</td>
<td>23.7</td>
<td>65.0</td>
</tr>
<tr>
<td></td>
<td>Bw</td>
<td>0.0</td>
<td>0.0</td>
<td>17.7</td>
<td>68.8</td>
</tr>
<tr>
<td>Paleosol 1</td>
<td>Btk1</td>
<td>43.6</td>
<td>0.0</td>
<td>11.7</td>
<td>60.7</td>
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<td>Btk2</td>
<td>1.3</td>
<td>0.0</td>
<td>15.9</td>
<td>73.6</td>
</tr>
<tr>
<td></td>
<td>Btk3</td>
<td>27.3</td>
<td>0.0</td>
<td>21.8</td>
<td>67.8</td>
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<tr>
<td></td>
<td>Bk1</td>
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<tr>
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<td>Bk2</td>
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<td>16.8</td>
<td>76.5</td>
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<tr>
<td>Paleosol 2</td>
<td>Btk</td>
<td>0.6</td>
<td>0.0</td>
<td>21.1</td>
<td>73.4</td>
</tr>
<tr>
<td></td>
<td>K</td>
<td>30.6</td>
<td>0.0</td>
<td>14.2</td>
<td>70.5</td>
</tr>
<tr>
<td></td>
<td>Btk</td>
<td>11.3</td>
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<td>6.3</td>
<td>85.4</td>
</tr>
<tr>
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<td>Bk1</td>
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<td>0.0</td>
<td>8.3</td>
<td>85.5</td>
</tr>
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<td>Paleosol 3</td>
<td>Bt</td>
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<td>0.1</td>
<td>26.3</td>
<td>69.1</td>
</tr>
<tr>
<td></td>
<td>Btk</td>
<td>10.9</td>
<td>5.0</td>
<td>28.7</td>
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</tr>
<tr>
<td></td>
<td>C</td>
<td>0.7</td>
<td>1.0</td>
<td>24.1</td>
<td>68.6</td>
</tr>
<tr>
<td>Paleosol 4</td>
<td>Btk</td>
<td>10.0</td>
<td>0.1</td>
<td>23.1</td>
<td>69.4</td>
</tr>
<tr>
<td></td>
<td>Bk1</td>
<td>17.4</td>
<td>0.0</td>
<td>17.8</td>
<td>73.9</td>
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<td>14.5</td>
<td>0.0</td>
<td>34.0</td>
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<td>22.3</td>
<td>73.1</td>
</tr>
<tr>
<td></td>
<td>Bk5</td>
<td>14.1</td>
<td>0.1</td>
<td>27.7</td>
<td>70.2</td>
</tr>
<tr>
<td>Paleosol 5</td>
<td>K</td>
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<td>0.5</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Btk1</td>
<td>2.8</td>
<td>0.0</td>
<td>44.3</td>
<td>53.9</td>
</tr>
<tr>
<td></td>
<td>Btk2</td>
<td>0.1</td>
<td>0.1</td>
<td>48.1</td>
<td>49.4</td>
</tr>
<tr>
<td></td>
<td>Bk1</td>
<td>46.5</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>Bk2</td>
<td>6.2</td>
<td>0.2</td>
<td>46.2</td>
<td>49.8</td>
</tr>
<tr>
<td></td>
<td>Bk3</td>
<td>18.0</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
<tr>
<td></td>
<td>C</td>
<td>8.2</td>
<td>n.a.</td>
<td>n.a.</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

Note: n.a.: not available, a result of incomplete disaggregation due to silica cementation
3.1 m thick. Its upper surface is at a depth of 8.3 m below the present ground surface. The nodular layer is well developed and is approximately one meter thick. It is well cemented by carbonate deposits on the exterior of nodules and as veins and stringers (Stages III and II+ carbonates). The lower portions of this paleosol contain abundant burrows and are a distinctive aspect of this exposure. The dominant grain-size of this unit is fine sand. Silt forms a large portion of the sediment. A very few scattered cobbles and pebbles of varied lithologies are present in this paleosol. The A horizon of the soil is missing, probably truncated by the event that deposited the sediment on which paleosol 3 developed. The age of paleosol 4 is probably 70,000+ years based on degree of soil development.

Paleosol 5. This paleosol is 11.7 m below the present land surface. It is 1.9 m thick. Grayish orange (10YR 7/4) is the color of the uppermost part of this soil; moderate yellowish brown (10YR 5/4) is typical of the lower portion. Paleosol 5 is very strongly developed. The upper portion of this paleosol is a petrocalcic horizon that is very well developed, Stage IV. Morphologically, the zone of carbonate accumulation is expressed as a resistant ledge-forming unit. It is very hard, probably because there is significant silica cementation in addition to calcite cementation. Disaggregation of samples was incomplete, even with repeated treatment in HCl.

The upper portion of paleosol 5 forms a very prominent ledge with a more or less vertical face about one meter thick. The ledge protrudes from the face of the
cut about 20 to 40 cm. It consists of strongly cemented nodules with stringers and seams of carbonate. Vertical seams have developed along a coarse columnar structure in the soil. Some veins or seams are up to one centimeter thick. Horizontal plates of stage IV carbonate occur in a zone about 10 cm thick below the upper nodular zone and form the base of the ledge.

Filaments of carbonate, and silica, are common along root traces. Larger burrows are few to common. This soil was developed in a silty fine sand with scattered pebbles and cobbles. The largest cobble recovered was vesicular basalt with a maximum diameter of six centimeters. The A horizon of the soil is missing, probably truncated by the sediment deposit on which paleosol 4 is developed. The age of this paleosol is probably >100,000 years.

Unit 4: Dalles Formation

The Dalles Formation is poorly exposed in this roadcut. It is covered by debris shed from higher portions of the cut. The uppermost part of the Dalles Formation was exposed by digging. It is a well indurated pebbly sandstone. Abundant lithic fragments are of extrusive igneous origin; both basaltic and andesitic clasts. Mica is not common; where found, it is biotite. Parts of this unit are highly reactive when tested with hydrochloric acid indicating a high carbonate content. Laboratory analysis indicates that silica is an important cement in this unit as treatment with HCl did not lead to disaggregation. Evidence of bioturbation is
scant. What appear to be a few small calcareous root traces were noted. The Dalles Formation is well exposed in a second roadcut 200 m to the northwest (Figure 12).

STRUCTURE OF SITE

Clastic Dikes.

Several clastic dikes are found at the north end of the roadcut, cutting through Unit 2, the massive sandy silt. They do not cut Unit 1 loess. The clastic dikes vary in width from less than 1 cm to a maximum of 12 cm. One prominent dike cuts through Unit 3, the paleosol unit, near the north end of the exposure (Figure 24). This dike strikes N76°E. It is widest at the bottom, 12 cm, and narrows towards the top. This clastic dike cuts through almost the entire paleosol section. It appears to be truncated by the Holocene loess of Unit 1. Several smaller clastic dikes at the southeastern end of the roadcut stop abruptly at horizontal seams of carbonate. Several of the dikes show some bifurcation. These are at the margins of the roadcut and are particularly common in the fine sandy silt, Unit 2, at the northwest end of the cut. The clastic dikes are composed of more or less vertical layers of sand, silt, and in some cases clay (Figure 25). Most exhibit several layers of alternating grain size as if injection occurred several times.

In addition to clastic dikes there are several other clastic intrusions of various shapes. In the massive fine sandy silt, Unit 3, toward the north end of the roadcut are two pipe-like structures with a vertical orientation. The largest of these is 74 cm in diameter. Both are filled with sand that is coarser-grained than the
Figure 24. Clastic dike cutting through Unit 3 paleosols.
Figure 25. Detail of lamination in clastic dike shown in Figure 24.
surrounding sediments. Usually located near clastic dikes are several oddly shaped intrusions that consist of finely laminated sandy silt (Figure 26). A clastic dike which is emplaced along a fault (Figure 27) cuts obliquely through the south end of the section.

**Fault.**

A fault (Figure 27), with a clastic dike intruded along the fault plane, is the major structural feature. It is located in the southeastern end of the roadcut where it cuts the paleosols of Unit 3. Maximum offset occurs in the lower portion of the exposure where paleosols 3, 4 and 5 cannot be traced directly across the fault. Paleosol 3, with its distinctive pumice clasts could be found on the northwest side directly up to the fault, but no pumice could be found southeast of the fault. Maximum offset may be as much as 1.5 meters. Offset along the fault dies out towards the upper portions of the section. Unit 1 is not cut by this feature. The fault has an almost vertical dip, and strikes N6°E to N15°E, but is somewhat curved. The clastic dike is about five centimeters wide and was intruded along the fault plane. It is filled with sand in the middle and clayey silt on either side.

The fault/clastic dike cuts Unit 3 and continues down into Unit 4, the Dalles Formation sandstone in the lower portion of the roadcut. There is no evidence of soil development within the clastic intrusion. No slickensides were found. Relationships are difficult to observe because of covered sections, plants growing in the fault zone, and the steep slope of the cut, especially near the top of the
Figure 26. Detail of laminated clastic intrusion, north end of roadcut.
Figure 27. Fault near south end of roadcut.
exposure. Also, material washing down from above tends to mask portions of the exposure.

LABORATORY ANALYSIS

Grain-Size

Sieve and pipette analyses, as well as field tests, show the sediments exposed at this site, with the exception of the Dalles Formation, are silts and very fine sandy silts (Figure 28). Mean grain size varies from 0.080 to 0.033 mm (fine sand to silt), but is generally between 0.065 to 0.041 mm (all silt). The coarsest materials are cobbles. Cobbles are a major constituent of Unit 4, the Dalles Formation. Cobbles and or pebbles have also been found in Unit 2, and paleosols 2, 3, 4, and 5 of Unit 3. With the exception of paleosol 5 gravel is very rare in Unit 3. The lithology of the gravel is quite varied. It includes granite and quartzite, rock types exotic to The Dalles Basin. Excluding gravel, the coarsest material is found in Unit 2 and consists of coarse to very coarse sand that occurs as thin and discontinuous lenses in a unit that is otherwise a very fine sandy silt.

In Unit 3 the coarsest material is in paleosol 5. The mean grain size of paleosol 5 is very fine sand. This unit is also the only one in which the sand fraction approximated half of the sediment (Table V). In all units sampled, the silt fraction is dominant, representing from 49.4 to 85.5 percent of the sediment. The
Figure 28. Grain-size distribution of Unit 3 sediments at The Dalles.
clay fraction varies from 1.8 to 27.6 percent, being highest in Bt and Btk horizons and lowest in Bk and C horizons (Table V).

Mineralogy

Examination of the coarse sand fraction of all units showed a similarity in mineralogy and therefore provenance for all units except the Dalles Group. Muscovite mica is prominent in all the units with the exception of the Dalles Formation. Composition of the coarse sand from several samples in Units 1, 2, and 3, based on microscopic examination, is: predominantly sub-angular quartz (40% to 60%), and feldspar (30% to 40%), with muscovite (5% to 10%) and other minerals (1% to 7%). Rock fragments are very rare (<1%). Hornblende, epidote, augite, and opaques form the majority of the heavy mineral suite along with minor hypersthene.

Except for the Dalles Formation which has a Cascade Range provenance of andesites, dacites, and basalts, the sediments have a Columbia River provenance with abundant muscovite mica and gravel of exotic lithologies.

Carbonate Content

Carbonate content of the sediments varies from 0 to over 46 percent (Table V). The samples with the highest CaCO3 content come from zones containing carbonate seams and veins or with abundant cemented nodules. Several zones are well indurated by carbonate and are relatively hard forming ledges and ridges (Figure 21). The zones with abundant carbonate represent Stage II through IV soil
carbonate accumulation (Table II). These zones are up to 30 cm thick. Some samples remained cemented even after treatment with hydrochloric acid, indicating the presence of silica as a cementing agent. Foley (1982) and McDonald (1987) report similar cements in the paleosols of the Palouse.

Paleontology

Very few fossils are preserved at this site. Fossil mollusks were neither found at this site nor any of the other sites of The Dalles region that I visited. A rodent incisor was recovered from the site, Unit 3, paleosol 1, the 2Btk3 horizon (Figure 29). Calcified and silicified (?) root traces are common at this site. A more or less complete root system of a shrub of some sort (sagebrush?) was found and photographed in situ near the top of paleosol 3 (Figure 30).

Tephra

Microscopic analysis of the coarse sand fraction of 35 samples from all units and paleosols revealed that 22 samples contained traces of tephra. In most samples where tephra was observed it consists of glass shards, mostly portions of pumice bubble walls. Paleosol 3, contains actual pumice clasts. These clasts, macroscopic in size, account for a significant proportion (~5%) of this unit. This tephra is a frothy white pumice and occurs as pebbles up to 1.5 cm in diameter. Most pumice clasts in this unit are between 2 and 5 mm in largest dimension. In outcrop fine sand and silt cemented to the surface of these clasts tends to hide the fact that this is pumice, appearing instead to be concretions. Treatment with HCl did not remove
Figure 29. Rodent incisors from Paleosol 1.
all of the sediment from the clasts in most cases, indicating some of the cement is silica, possibly derived from the clasts themselves.

The Geoanalytical Laboratory of Washington State University reported that the analytical results on the glass from the tephra in paleosol 3 are excellent with low standard deviations (Table VI) (F. Foit, Washington State University Geoanalytical Laboratory, written communication, 1993). A search of their database resulted in a similarity coefficient of 0.95 with the Dibekulewe tuff in Nevada described by Sarna-Wojcicki and others (1985). A similarity coefficient of 0.94 resulted from a match with an unknown tephra from an area 20 miles east of Klamath Falls, Oregon (Tule Lake?). The similarity coefficient over 0.92 is an acceptable match and 0.95 is considered a good match (F. Foit, personal communication, 1995). Explanations of the similarity coefficient and its use in tephrochronology can be found in Davis (1985, p. 3) and in Busacca and others (1992). The method is that of Borchardt and others (1972).
TABLE VI

GLASS CHEMISTRY OF TEPHRA SAMPLE #244, PALEOSOL 3, UNIT 3

<table>
<thead>
<tr>
<th></th>
<th>Weight Percent</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe$_2$O$_3$</td>
<td>1.42</td>
<td>0.22</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>3.49</td>
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</tr>
<tr>
<td>K$_2$O</td>
<td>4.07</td>
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<tr>
<td>MgO</td>
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<td>0.02</td>
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<tr>
<td>CaO</td>
<td>0.62</td>
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</tr>
<tr>
<td>TiO$_2$</td>
<td>0.07</td>
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<tr>
<td>Al$_2$O$_3$</td>
<td>12.84</td>
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<td>SiO$_2$</td>
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<tr>
<td>Cl</td>
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<td>0.01</td>
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</tbody>
</table>

Analyses normalized to 100 weight percent
Number of shards analyzed: 16
CHAPTER VI

DISCUSSION AND INTERPRETATION

This discussion considers three topics: (1) the origin of the sediments exposed in the roadcut near The Dalles; particularly those of Unit 3, (2) the age of these sediments estimated from the degree of soil development and tephrochronology; and (3) the implications of these findings for the middle to late Pleistocene history of the region.

The origin of the sediments at the study site may be determined by comparing their characteristics with those of dune sands, loess, fluvial sediments, and the fine-grained facies of the Missoula Flood deposits. The age of the deposits can be constrained by comparison with other similar deposits and with tephras of known age. A better understanding of the Pleistocene history of the Columbia Basin may be gained by understanding the origin and age of these sediments from the Dalles Basin.

ORIGIN OF SEDIMENTS

Table VII summarizes the characteristics of the sediments found at the study site and other fine-grained sediments found in the Columbia Basin. The only fossils recovered from this site seem to be post-depositional: rodent incisors,
# TABLE VII
CHARACTERISTICS OF FINE-GRAINED SEDIMENTS IN COLUMBIA BASIN

<table>
<thead>
<tr>
<th>TYPE OF DEPOSIT</th>
<th>CHARACTERISTICS</th>
</tr>
</thead>
<tbody>
<tr>
<td>DUNE SAND (after Pettijohn and others, 1987)</td>
<td>Very well sorted sand, often cross-bedded, found at lower elevations close to river</td>
</tr>
<tr>
<td>LOESS (after Pecsi, 1968)</td>
<td>Well sorted, 40%-50% silt, massive, found at various elevations, thick deposits missing below maximum Missoula Flood elevation</td>
</tr>
<tr>
<td>MISSOULA FLOOD FINE-GRAINED FACIES (after Smith, 1993)</td>
<td>Moderately-well sorted, sand-silt, some pebbles and cobbles may be present, often graded bedding (fining upwards) produces rhythmsites much thicker than varved lake beds, wavy-plane lamination in sandy beds, very thin to very thickly bedded, found below maximum Missoula Flood elevation</td>
</tr>
<tr>
<td>COLUMBIA RIVER SEDIMENTS MAIN CHANNEL FACIES (after Blatt, 1982)</td>
<td>Poorly - moderately sorted, bedded sands, gravels, imbrication of clasts, foreset beds, scour and fill cross bedding, found close to river level (22 m at The Dalles), may be present at higher elevations in paleochannels</td>
</tr>
<tr>
<td>COLUMBIA RIVER SEDIMENTS OVERBANK FACIES (after Blatt, 1982)</td>
<td>Well - moderately sorted, sands and muds, plane bedding, thinly laminated - medium bedded, found in flood plains (~22 m near The Dalles, but varies), may be present in paleovalleys at higher elevations</td>
</tr>
<tr>
<td>Unit 1</td>
<td>Well sorted, 66% silt, massive, elevation 204 m</td>
</tr>
<tr>
<td>Unit 2</td>
<td>Moderately sorted sandy silt, 30% sand, 55% silt, scattered pebbles, lenses of coarse sand, faint wavy bedding, graded - massive bedding, elevation ~200 m</td>
</tr>
<tr>
<td>Unit 3</td>
<td>Moderately-well sorted silty sands and sandy silts, 50% sand in some strata, 85% silt in others, scattered pebbles, including abundant rounded pumice clasts in one stratum, elevation ~200 m</td>
</tr>
<tr>
<td>Unit 4</td>
<td>Poorly-moderately sorted, conglomerate-sandstone, elevation ~190 m, (Cascade provenance)</td>
</tr>
</tbody>
</table>
burrows, phytoliths, and roots and traces of roots. They do not provide evidence of depositional conditions.

**Characteristics of Dune Sands**

Sands deposited by the wind are well sorted with generally little silt or clay. Cross-bedding is common in dune sands. The characteristics of dune sands (Table VII) do not match the characteristics of the sediments found at the study site. Most of these sediments are silts or contain a substantial percentage of silt. While some portions of Units 2 and 3 contain considerable sand, these units are not well sorted and contain a large percentage of silt (Table V). No cross-bedding is evident at the study site, but this means little as original sedimentary structures have been overprinted by pedogenesis in most units at this site. Lenses of coarse sand and gravel are found in Unit 2. The presence of gravel in Units 2 and 3 is not consistent with eolian deposition.

**Characteristics of Loess**

As mentioned above, loess has a distinctive grain size distribution (Figure 6). The grain size distribution of Unit 1 at The Dalles is similar, 65% - 69% silt (Table V). The percentage of sand, about 20%, is somewhat high for loess, but this site is relatively close to a likely source of sand. Unit 1 contains no pebbles. This supports an eolian origin, as do the prismatic soil structure and vertical cliff faces exhibited by Unit 1. Unit 1 is loess.
Unit 2 contains considerable sand, some of it quite coarse-grained, but the mean grain-size is silt (Figure 28). It also contains numerous pebbles, often in groups. This is inconsistent with loess. In discussing the origin of the Portland Hills Silt, Lentz (1977) argues that the presence of scattered pebbles does not by itself rule out the possibility of eolian origin. Lentz found a few stones during his investigation, all of which were concretionary, a product of pedogenesis. It has been suggested that pebbles in loess could have moved downslope from exposures at higher elevations. Because some of the pebbles in Unit 2 have lithologies that are exotic to the area it is unlikely that they were transported by slope processes. Unit 3 also contains scattered pebbles, some of exotic lithologies, making it unlikely that it is loess.

Characteristics of Fluvial Sediments

Deposits of the main channel of rivers such as the Columbia are coarse-grained, composed predominantly of gravel and sand (Pettijohn and others, 1987). There are also commonly current indicators, such as scour and fill bedding (Blatt, 1982; Pettijohn and others, 1987; Smith 1993). These are not present in the sediments at the study site. There are no point bar deposits or other evidence of migrating channels. Overbank deposits are finer-grained than channel deposits, often with a high proportion of clay. The sediments of Units 2 and 3 are dissimilar to these. The differences in texture and sedimentary structures would seem to rule out any correlation with either of these environments.
Characteristics of Fine-grained Missoula Flood Sediments

The grain size of the fine-grained Missoula Flood sediments varies between coarse sand and silt often forming a rhythmite couplet, sandy at the base and fining upwards to silt (Waitt, 1985; Smith, 1993) (Figure 7). Localized pockets or thin layers of coarse to very coarse sand, often basaltic in composition occur (Waitt, 1985). Pebbles and cobbles of various sizes are also often present, sometimes in groups and other times singly (Waitt, 1985). These stones are of varied lithologies, but it is significant that a substantial number are exotic as compared to the local bedrock, which is often Columbia River Basalt. The mineralogy of the Missoula Flood sediments is very similar to that of loess, from which they are in part derived. It consists primarily of quartz and feldspar with some muscovite and mafic minerals. Units 2 and 3 share many similarities with these sediments.

Characteristics of Sediments at Study Site

As previously discussed, four sedimentary units occur at the study site. With the exception of Unit 4, the sediments at the study site are predominantly silts, fine-sandy silts, and silty fine-sands. An upper Columbia River provenance is indicated by abundant muscovite in Units 1, 2, and 3 (absent from Unit 4). Granitic and metamorphic pebbles are found in Units 2 and 3. Unit 4 is coarser-grained. It is mineralogically and lithologically unlike the younger units, being volcaniclastic with a Cascadian provenance. The origin of Unit 4 is consistent with deposition by streams draining the east side of the Cascade Range. The texture, lithology, and
stratigraphic position of Unit 4 are compatible with those of the Dalles Formation, and I interpret it to be Dalles Formation.

While Units 1, 2, and 3 have similar mineralogies, they differ in texture, especially grain size. No pebbles are found in Unit 1. Unit 1 is interpreted to be Holocene loess. As discussed above, Units 2 and 3 are dissimilar to loess, dune sands, or normal fluvial deposits. How do the characteristics of the sediments in Units 2 and 3 at the study site near The Dalles compare to Missoula Flood deposits? The grain-size and sorting are similar. The presence of scattered pebbles of varied lithologies is most consistent with the fine-grained facies of the Missoula Flood deposits. Unit 2 contains significant lenses of coarse sand and some stones. Excluding the stones, this is the coarsest of all the units above Unit 4, the Dalles Formation.

Unit 3, in which the paleosols are developed, has a grain size that varies from silt to fine sandy silt (Table V). Four of the strata of Unit 3 yielded pebbles or cobbles (Table V): Paleosols 2, 3, 4, and 5. The presence of pebbles argues strongly for a fluvial origin and is inconsistent with an eolian origin. During this discussion when referring to stratigraphic units within Unit 3 the terms “Paleosol 1”, 2 etc. will be used. This system is used since there are no other recognizable stratigraphic markers in Unit 3; therefore, this serves as a means of locating different portions of the exposure. Paleosol 3 contains abundant, about 15 percent by weight, rounded pumice clasts which are a type of pebble.
The stones in Unit 3, like those in Unit 2, are large and of recognizable lithologies, including granitic and metamorphic rock types. These did not form as a result of pedogenesis and again are inconsistent with deposition by wind. Basaltic pebbles may have come from the local area, but may also have been transported considerable distances as basalt is the bedrock that underlies almost the entire Columbia Plateau. Granitic and metamorphic rocks, on the other hand, must have been transported into the area by the Columbia River. Their presence in units 2 and 3, along with abundant rounded pumice clasts in paleosol 3, is most consistent with deposition by catastrophic flooding under ponded or slackwater conditions. If the A horizons of the paleosols are missing, as they appear to be, it may be that they were eroded, by flood waters, down to the resistant K horizons. This would not be the case if the sediments were dropped by the wind and would be less likely if the deposits were left by normal overbank deposition.

The question of origin depends heavily on the presence of the pebbles, cobbles, and rounded pumice clasts. They all indicate water deposition. How did the larger stones get deposited? The Missoula Floods are known to have transported icebergs (Allen and others, 1986) that could transport rocks of various sizes and an upper Columbia provenance. As periglacial conditions are thought to have occurred (Baker, 1978) during glacial epochs, some of the stones may have been transported in frozen ground eroded and carried by the floods.
Unit 3 is dominantly silt and fine sand. The upper portion of Unit 3 (Paleosols 1 and 2) is finer than the lower portion (Paleosols 3, 4, and 5; see Table V). Also, there is a general fining-upwards trend in most of the paleosols (Table V). Loess, especially close to its source, can and does contain a significant percentage of sand (Pye, 1987). But Paleosol 5 is dominantly sand, therefore it is not loess. Paleosol 3 is dominantly fine gravel and sand, again, this unit is not loess. All paleosols except the uppermost contain some gravel, a further indication that these sediments were not wind deposited. Units 2 and 3 are not eolian. The uncertainty in the origin of unit 3 is due to the impact of soil development. The soil forming process, especially as advanced as in this unit, destroys or greatly reduces the clarity of primary sedimentary textures and fabrics.

It is my belief that the evidence indicates that units 2 and 3 are both slackwater deposits from catastrophic floods. The evidence for this consists of: (1) an upper Columbia River provenance, (2) the texture, sandy silts and silty fine sands, (3) scattered pebbles, (4) truncated paleosols to the K horizon, and (5) several fining upwards sequences. Therefore, this site is important in that it helps to establish a chronology of Quaternary geologic and climatic events, including Pleistocene catastrophic flooding, loess deposition, and Cascade volcanism, here, and elsewhere on the Columbia Plateau.
AGE OF TEPHRA

The Geoanalytical Laboratory of Washington State University reported a similarity coefficient of 0.95 for the pumice in paleosol 3 with the Dibekulewe tuff (F. Foit, Washington State University Geoanalytical Laboratory, written communication, 1993). The similarity coefficient of 0.95 is considered a "good" match (Davis, 1985). Davis (1985) states that a similarity coefficient of 0.95 or greater generally indicates correlation. Sarna-Wojcicki and others (1980) agree but suggest using multiple analyses of a tephra layer. Busacca and others (1992) recommend using multiple correlation methods as a good practice. They have successfully tried comparison of ilmenite phenocrysts. For this thesis, identification based on the 95% correlation is sufficient, but a more detailed analysis of this tephra could include petrographic analysis and comparison with the Dibekulewe ash bed and others. See Table VIII for a comparison of this analysis with that of other widespread tephras.

The Dibekulewe tuff is known from sites in the Lake Lahontan basin in Nevada and at Tule Lake, California (Davis, 1978). Its source is reported in the literature as unknown. Davis (1978) discusses the Dibekulewe ash bed exposed in a roadcut near Carson City, Nevada where it is found as a distinct bed in Lake Lahontan sediments. Figure 21 of Davis (1978) shows the Dibekulewe ash bed as a prominent white layer about 10 to 20 cm thick within the lake beds. This site is the type section for the Dibekulewe ash bed which is an ash composed of glass shards
<table>
<thead>
<tr>
<th>ASH</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>MgO</th>
<th>CaO</th>
<th>TiO₂</th>
<th>Na₂O</th>
<th>K₂O</th>
<th>Cl</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD#1</td>
<td>77.29</td>
<td>12.84</td>
<td>1.42</td>
<td>0.06</td>
<td>0.62</td>
<td>0.07</td>
<td>3.49</td>
<td>4.07</td>
<td>0.14</td>
</tr>
<tr>
<td>Dibekulewe¹</td>
<td>76.9</td>
<td>12.6</td>
<td>1.36</td>
<td>0.05</td>
<td>0.65</td>
<td>0.08</td>
<td>4.12</td>
<td>4.11</td>
<td>NA</td>
</tr>
<tr>
<td>Rockland¹</td>
<td>77.7</td>
<td>12.7</td>
<td>0.91</td>
<td>0.17</td>
<td>0.88</td>
<td>0.16</td>
<td>3.75</td>
<td>3.55</td>
<td>0.11</td>
</tr>
<tr>
<td>Lava Cr.B.¹</td>
<td>76.1</td>
<td>12.6</td>
<td>1.64</td>
<td>0.02</td>
<td>0.55</td>
<td>0.12</td>
<td>3.63</td>
<td>5.18</td>
<td>0.14</td>
</tr>
<tr>
<td>Bishop¹</td>
<td>77.4</td>
<td>12.7</td>
<td>0.75</td>
<td>0.04</td>
<td>0.45</td>
<td>0.06</td>
<td>3.34</td>
<td>5.22</td>
<td>NA</td>
</tr>
<tr>
<td>Mount St. Helens (MSH)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5/18/80²</td>
<td>71.8</td>
<td>15.1</td>
<td>2.6</td>
<td>0.49</td>
<td>2.76</td>
<td>0.44</td>
<td>4.30</td>
<td>1.94</td>
<td>0.10</td>
</tr>
<tr>
<td>Set So²</td>
<td>76.9</td>
<td>13.9</td>
<td>1.4</td>
<td>0.16</td>
<td>4.20</td>
<td>2.22</td>
<td>0.10</td>
<td>0.10</td>
<td></td>
</tr>
<tr>
<td>Set Sg²</td>
<td>73.0</td>
<td>13.8</td>
<td>1.2</td>
<td>0.31</td>
<td>1.48</td>
<td>0.16</td>
<td>4.06</td>
<td>2.09</td>
<td>0.10</td>
</tr>
<tr>
<td>Set Cw²</td>
<td>72.3</td>
<td>12.8</td>
<td>0.8</td>
<td>0.24</td>
<td>1.59</td>
<td>0.10</td>
<td>3.87</td>
<td>2.17</td>
<td>0.06</td>
</tr>
<tr>
<td>Set Sg³</td>
<td>72.57</td>
<td>13.30</td>
<td>1.36</td>
<td>0.32</td>
<td>1.52</td>
<td>0.14</td>
<td>3.91</td>
<td>2.06</td>
<td>0.10</td>
</tr>
<tr>
<td>Set Cw³</td>
<td>71.52</td>
<td>13.20</td>
<td>1.05</td>
<td>0.27</td>
<td>1.58</td>
<td>0.09</td>
<td>3.45</td>
<td>2.11</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Note:

¹ Data from Sama-Wojcicki and others, 1985, Table 3,
   Dibekulewe ash: from Carson City, Nevada; source unknown
   Rockland ash: source near Mount Lassen, California
   Lava Creek B ash: source Yellowstone caldera, Wyoming

² Data from Sama-Wojcicki and others, 1981, Table 85.

³ Data from McDonald and Busacca, 1988, Table 1.

MSH Set S age: 12,900 B.P. [Swift Creek eruptive stage]
MSH Set C age: 33,650 B.P. (36,000-37,600) [Ape Canyon eruptive stage]
and hence is a distal facies of this tephra. It is characterized by a very low Ti content and has a distinctive Fe:Ca:K ratio (Davis, 1978). According to Sarna-Wojcicki and others (1985, note b, Table 3, p. 249) this bed is also found near Oresna, Nevada.

Sarna-Wojcicki and others (1991, Plates 1A and 1B) state that the Dibekulewe ash bed in Nevada and at Tule Lake is slightly younger than the Lava Creek B ash bed which is dated as 0.62 Ma and significantly older than the Rockland ash bed dated at 0.40 Ma. Therefore, they place the age of the Dibekulewe tuff at about 600,000 ka (Sarna-Wojcicki and others, 1991). Interestingly, the Dibekulewe ash has not been recognized at Summer Lake, an important site near Bend, Oregon (Sarna-Wojcicki and Davis, 1991). Its absence from the Summer Lake, Oregon site is not surprising because the record at this site has only been examined back to about 0.4 Ma (Davis, 1985; Sarna-Wojcicki and others, 1991). Future work at Summer Lake may help lead to a better understanding of the relationships between the Dibekulewe tuff and the pumice found at the study site.

The Lava Creek B ash bed, also known as the Pearlette type O ash bed, is a widespread tephra that was erupted from Yellowstone. The site at The Dalles is outside of the known limits of this important tephra (Sarna-Wojcicki and Davis, 1991). The Rockland ash bed occurs in the sections at Tule Lake, California and at Lake Lahontan, Nevada. It is stratigraphically above both the Dibekulewe ash bed
and the Lava Creek B ash bed. Its source is in the vicinity of Lassen Peak, California (Sarna-Wojcicki and Davis, 1991).

Paleosol 3, in which the tephra occurs at The Dalles, is 1.3 m thick. No thickness can be given to the tephra "layer" as it is mixed in a matrix of fine sandy silt. Bioturbation during soil development probably accounts for some of the mixing. If the sediments in which this soil developed were deposited by giant floods, mixing would be expected. The rounded nature of the pumice clasts argues for deposition from water, instead of air fall.

The tephra found at The Dalles is a long distance, about 650 km, from the Lake Lahontan sites where the Dibekulewe tuff is found, but this is within the range of distances covered by silicic ash plumes (Sarna-Wojcicki and others, 1991) and is not unreasonable. The fine-grained nature of the tephra in Nevada indicates those deposits are distal portions of this deposit. The tephra at the study site near The Dalles is coarse (up to 1.5 cm.) and represents the proximal portion of the unit found in Nevada. This correlation constrains the possible sources for the Dibekulewe ash to a Quaternary volcano in northern Oregon or in southern Washington. A source in the Cascades would explain the coarser nature of the tephra at The Dalles.

The Dibekulewe ash is relatively dated to about 600,000 B.P. Mount St. Helens did not exist at that time. Mount Adams is situated in an ideal location to have deposited this pumice at The Dalles. The oldest known rocks at Mount
Adams indicate that it dates to at least ca. 520 ka (Hildreth and Lanphere, 1994). The tephra at The Dalles, Oregon may be one of the few remaining records of an even earlier history of Mount Adams. Sarna-Wojcicki (1996, personal communication) believes this is possible.

Mazama ash is not obvious at The Dalles site. Neither are Mount St. Helens tephras. They may have been disturbed by plowing, because the area is agricultural and prior to the building of Highway 197 was a wheat field. They may also have been removed by sheet wash and or wind. They do occur in valley bottoms in the area, often as rather noticeable layers. This could be interpreted as evidence that the tephra in paleosol 3 was associated with flooding and could be evidence that this unit represents fluvial deposition, not eolian.

AGE OF SEDIMENTS

Two classes of evidence help to date these deposits and clarify the frequency and age of Pleistocene jökulhlaups in the Columbia River/Channeled Scabland drainage system. First, each paleosol contains a Bk or K horizon ranging in carbonate development from Stage II to Stage IV; therefore, each soil would have taken between 20,000 to 100,000 years to form (Alan Busacca, personal communication, 1997). Using Busacca’s developmental sequence, I believe that minimum lengths of time needed to develop each of the paleosols are as follows: Paleosol 1 > 20,000 years (Stage II+); Paleosol 3 > 50,000 years (Stage III);
Paleosols 2 and 4 > 70,000 years (Stages III and IV); and Paleosol 5 > 100,000 years (a thick Stage IV).

The youngest deposits (Unit 2) are believed to represent latest-Pleistocene Missoula Flood events between 15,300 and 12,700 years B.P. (Waitt, 1985). Very little carbonate has accumulated since deposition. Each of the five paleosols must consequently represent a much longer period of soil formation during which carbonate could be concentrated in the soil. Thus several floods must have occurred before the "classical" 15 - 12 ka period of late Pleistocene jokulhlaups began (Waitt, 1985), and long periods of time occurred between each of these periods of catastrophic flooding.

Second, if the tephra in paleosol 3 of Unit 3 is ca. 600 ka, then the maximum age of the sediments containing this tephra is constrained to this date or younger. It is possible that the tephra was deposited elsewhere and later transported to the site and incorporated into the sediments in which paleosol 3 developed. However, this is apparently a very rare tephra, known only from a few occurrences far to the south. The grain size of the tephra in paleosol 3 indicates it is proximal to the source. It seems unlikely that this pumice was transported far by water, or that it is significantly older than the enclosing sediment, as any clastic material on the exterior of the lapilli appear identical to the rest of the matrix present in paleosol 3. Also, the age indicated by the tephra is consistent with the amount of time indicated by the stage of soil development in this and the younger paleosols. If at some time
in the future paleosols 4 or 5 are shown to have a reverse magnetic signature, this would be a further indication that paleosol 3 could well be half a million years old.

Evidence of age provided by stage of soil development, along with stratigraphic position, and correlation of the tephra in paleosol 3 are strongly suggestive that the ages of the paleosols in Unit 3 are significantly older than the classic period of Missoula Flooding. The nature of the sediments is consistent with their deposition by water, not wind. The strong implication is that catastrophic flooding did occur at earlier time periods than the classic late Wisconsin.

Laminations within the fault zone and clastic intrusions are consistent with deposition in a saturated environment and may indicate several episodes of activity. Lack of extensive soil development within these features, along with the sequence of sediments they cut across, implies they are relatively recent, probably about 12 to 15 ka.

**STRATIGRAPHY OF SITE**

While this may not be a complete section (due to erosion), the base of the sedimentary deposits is exposed at this site as the Dalles Formation occurs at the base of the section.

Evidence for erosion between deposition of sediments is characterized by lack of the upper horizons of the buried soils; the A and Bt horizons are missing. In some cases the C horizon of one soil is found directly above an older soil's K
horizon of platy secondary carbonate (and silica), which must have formed as a subsoil horizon.

Erosion of A horizons by normal slope processes does not seem particularly likely as the paleosols are relatively horizontal, and the general topography at the immediate site does not seem susceptible to extensive erosion.

Unit 2 is a fine-sandy silt deposited by late Wisconsin Missoula flooding (ca. 15,300-12,700 ka). This unit is capped by a thin layer of loess on which a weakly developed modern soil with little carbonate occurs. Unit 2 rests on a major erosion surface cut into the sediments of Unit 3 on which five paleosols developed indicating several episodes of deposition and soil formation. Each of these paleosols has a strong carbonate horizon and extensive bioturbation (krotovina and root casts). The extent of soil development indicates that they are all much older than 15,300 to 12,700 ka, and that each paleosol took several tens of thousands of years to form. These old soils are remarkably similar to paleosols developed in loess and flood deposits in the Palouse and Channeled Scablands of eastern Washington (McDonald and Busacca, 1988a; 1989).

**FAULT AND CLASTIC DIKES**

The paleosols of Unit 3 are essentially parallel to the present ground surface, which indicates that little if any folding has occurred at this site. The faulting seems to be related to the emplacement of the clastic intrusions as the two are similar in geometry, morphology, and sedimentology. Similar relations are
observed elsewhere in Missoula Flood slackwater deposits of the Columbia Basin.

Cooley and others (1996) studied the mechanism and timing of emplacement of clastic dikes in the Touchet beds in the Walla Walla Valley in Washington. They also looked at faulting. They report that:

Analysis of the relationship between the various parameters strongly suggests that an earthquake or a series of earthquakes near the end of the cycle of Missoula floods was responsible for the emplacement of the vast majority of the clastic dikes. Gravity-driven lateral spreading of semi-consolidated Touchet Beds resulted in ground cracking and slumping that was concurrent with the downward injection of saturated sediment. Lateral spreading and dike emplacement were more intense along the gently-sloped northern margin of the basin which was inherently less stable than the relatively flat interior. The cracks gradually widened and the dikes developed their sheeted structure as the infiltration of water promoted intervals of slumping and infilling.

The relationships at The Dalles lead to a similar conclusion: both dikes and faulting are a result of movement of sediments saturated by Missoula Flooding. Seismicity probably served as a triggering factor. Slopes are steep in the area and landslides are common in The Dalles Basin.

Because the fault appears to be covered by Unit 1 loess, it is younger than any of the paleosols but older than the Holocene loess so faulting is pre-Holocene.

From its overall form and the sediments within it that are similar to the other clastic intrusions, I think it was last active at the same time, during latest Wisconsin Missoula Flooding. Hence, its age is 12 - 15 ka. Due to covered sections it is extremely difficult to determine the exact nature of this structure.
SIGNIFICANCE OF SITE

In addition to Missoula Flood deposits of latest Pleistocene age, deposits I attribute to much older catastrophic flood events are preserved here. Pieces of evidence for the antiquity of these latter deposits are the presence of a 600,000 ka tephra and the well developed paleosols they contain. Each paleosol contains a Bk or K horizon ranging in carbonate development from Stage II to Stage IV, in contrast with the modern soil, developed on the most recent flood deposits and loess, which contains virtually no carbonate and has been forming for close to 12,000 years. Therefore, each paleosol has very likely taken much more than 12,000 years to form. Each of the five paleosols must consequently represent a much longer period of soil formation during which carbonate could be concentrated in the soil. Thus, several floods must have occurred before the "classical" 15 - 12 ka period of late Pleistocene jökulhlaups began (Waitt, 1985), and long periods of time occurred between each of these "ancient Missoula Floods". These paleosols are very similar to paleosols found in the Palouse and reported by Baker (1978) and McDonald and Busacca (1988b). The combined effects of catastrophic flooding, volcanic activity, eolian deposition, other "normal" erosional processes, and soil formation have resulted in a complex record. While this record is often difficult to decipher, the features just discussed make the attempt worthwhile.
CHAPTER VII

CONCLUSIONS

STRATIGRAPHY OF SITE

The base of the section exposed by this roadcut consists of Unit 4, volcaniclastic sedimentary rocks of the Dalles Formation of late Tertiary age and Cascade provenance. Overlying this are five paleosols of Unit 3, almost horizontal in attitude and parallel to the present land surface. These paleosols, and the sediments in which they developed, are of Early to Middle Pleistocene age and upper Columbia River provenance. The sediments are fine sandy silts containing scattered pebbles of varied lithologies. They were deposited by paleofloods associated with Pleistocene glaciation. Contained within these silts are several tephras, one of which is correlated with the Dibekulewe ash and therefore has an age of 600,000 B.P. Unconformably overlying the paleosols at the north end of the roadcut is Unit 2 composed of rhythmites of the classical period of Missoula flooding, 12-15 ka. These sediments also contain scattered pebbles of varied lithologies. The uppermost unit 1 is a thin deposit of Holocene loess in which a modern soil is developing.

A small fault cuts these Pleistocene sediments obliquely at the southeastern end of the exposure. Several clastic dikes also cut the silts and associated paleosols.
Laminations within the fault zone and clastic intrusions are consistent with deposition in a saturated environment and may indicate several episodes of activity. Lack of extensive soil development within these features, along with their stratigraphic position, indicates their most recent activity is late Pleistocene, about 12 to 15 ka.

**NATURE OF THE DEPOSIT**

The sediments exposed at this site are silts and fine sands of Quaternary age and Columbia River provenance. Most of the sediments and paleosols are of Pleistocene age, with a thin covering of Holocene loess (Unit 1) in which a modern soil is developing. Underlying these sediments are volcaniclastic deposits of the late Tertiary Dalles Formation (Unit 4).

The mineral suite of the Quaternary sediments, especially the presence of muscovite, indicates a Columbia River provenance unlike that of the underlying Dalles Formation which has a Cascade provenance. The mineralogy of the deposit is essentially identical with those of the Palouse Formation to the east and the Portland Hills Silt to the west. This exposure shows remarkable uniformity of grain size throughout, except for scattered occurrences of pebbles and coarse basaltic sands.
ORIGIN OF SEDIMENTS

The present investigation offers data which strongly support a catastrophic flood origin for the sediments of Unit 3. This is based on the presence of scattered pebbles, many of exotic origin, which suggests a fluvial origin. Ice rafting during catastrophic floods, which are known to have occurred in the area, is a likely explanation for these stones.

The massive nature of the deposits suggests rapid deposition, such as during a flood. While the massive nature of the deposits could be explained by extensive bioturbation or by eolian deposition, neither of these seems likely. The scattered pebbles seem to eliminate the possibility that these deposits are primarily wind deposited (loess). Furthermore, even the C horizons of the paleosols do not show traces of bedding. Only a catastrophic flood could explain water laid deposits at this elevation above the valley bottom.

Particle size studies show a high sand content which is more consistent with a fluvial origin than with loess. No unequivocal buried A horizons were found at this site. Erosion by flood water would explain a lack of A horizons and upper portions of B horizons. Each soil was stripped by floodwater to the more coherent carbonate rich horizons. The elevation of this site, well below that of the maximum Pleistocene flood stages in this area of 305 m (Allen and others, 1986; O'Connor and Waitt, 1995), is consistent with a fluvial mode of deposition. None of many loess exposures of fine-grained sediments above maximum flood stage examined
by the author revealed paleosols remotely resembling those found at the site at The Dalles. Also, all had a finer grain size. All of these factors support a significant conclusion: large jokulhlaups occurred throughout the Pleistocene and were not restricted to the late Wisconsin. This agrees with similar conclusions from other areas of the Columbia Plateau presented by Busacca (1989), Baker and others (1991), and Bjornstad and others (1991).

AGE OF SEDIMENTS

The sediments of Unit 3 exposed at The Dalles site have been extensively altered by soil forming processes and contain at least five well developed paleosols, all of which exhibit characteristics indicative of formation in an arid climate and with an active soil fauna. The extent of soil development in these paleosols each having a carbonate horizon that took at least 20,000 years to develop indicates that these sediments are older than 15,300 to 12,700 B.P. period of classical Missoula Flooding. Correlation of the tephra in paleosol 3 with the Dibekulewe ash indicates that the middle part of the section was deposited circa 600,000 B.P. The source of the tephra may have been Mount Adams. The two paleosols below paleosol 3 probably show reversed magnetic polarity. Underlying the sediments of Unit 3, and constraining their maximum age, is the late Tertiary Dalles Formation.
CHAPTER VIII

FUTURE WORK

The results of this study indicate that several lines of investigation could be pursued in the future. First, the further refinement of the correlation of this tephra with the Dibekulewe ash needs to be pursued, maybe by examining the ash for phenocrysts and comparing the compositions with those of that ash. Because the tephra in paleosol 3 probably correlates with the Dibekulewe event of 600,000 B.P., then there is a high probability that the two paleosols deeper in the section may be old enough to be reversely magnetized. Thus, a paleomagnetic study is warranted as a means of constraining the age of the lower part of the section at this site.

A more detailed examination of the tephra at this site is warranted. It should attempt to answer questions such as the following. Can any of the tephra (grains) found at other levels in the section at The Dalles be correlated? Can the Mazama ash or any of the Mount St. Helens tephras be found at the site?

Other sites in the area need to be investigated, both to look for tephra and paleosols that may correlate with those at The Dalles site. As the Quaternary history of this area is better known, it will provide important information, not only about catastrophic floods but also about Cascade volcanism. In particular, it may be possible to further constrain the source of the Dibekulewe ash. It has been
suggested (Sarna-Wojcicki, personal communication, 1996) that it may be an early pumice from Mount Adams.

Can any of the paleosols be correlated with those (geosols) described in the Palouse and Channeled Scabland (McDonald and Busacca, 1990)? Also, the rodent incisor needs to be dated. Since it was found high in the section within Unit 3 it may be possible to obtain a carbon-14 date. It also needs to be identified as to animal genus.
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