The Soil Chronosequence Along the Cowlitz River, Washington

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Chapter F

The Soil Chronosequence Along the Cowlitz River, Washington

By DAVID P. DETHIER

U.S. GEOLOGICAL SURVEY BULLETIN 1590

SOIL CHRONOSEQUENCES IN THE WESTERN UNITED STATES

DEPARTMENT OF THE INTERIOR
DONALD PAUL HODEL, Secretary

U.S. GEOLOGICAL SURVEY
Dallas L. Peck, Director

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FOREWORD

This series of reports, "Soil Chronosequences in the Western United States," attempts to integrate studies of different earth-science disciplines, including pedology, geomorphology, stratigraphy, and Quaternary geology in general. Each discipline provides information important to the others. From geomorphic relations we can determine the relative ages of deposits and soils; from stratigraphy we can place age constraints on the soils. Field investigations and mineralogic and sedimentologic studies provide information on the nature and types of deposits in which soils form. As a result of our work, we have estimated rates of soil formation, inferred processes of soil formation from trends in soil development with increasing age, and obtained information on the types of weathering that occur in various areas. In return, soil development and soil genesis have provided data on the age of landforms, the timing and duration of sedimentation, and, in some cases, the history of climatic fluctuations.

Between 1978 and 1983, a coordinated and systematic study was conducted on soil development in different types of geologic deposits in the Western United States. The goals of this project, led by the late D.E. Marchand and subsequently by M.N. Machette, were to learn whether rates of chemical, physical, and mineralogic transformations could be determined from soil chronosequences; how these rates vary in different mineralogic and climatic environments; and how accurately soils can be used for such problems as estimating the ages of deposits, periods of landscape stability, and timing of fault movements. This series of reports presents data from several soil chronosequences of that project.

More than 100 analyses on more than 1,000 samples were performed on soils collected in the Western United States. Some results have appeared in various books, journals, and maps (for example, Harden and Marchand, 1977, 1980; Burke and Birkeland, 1979; Dethier and Bethel, 1981; Marchand and Allwardt, 1981; Meixner and Singer, 1981; Busacca, 1982; Harden, 1982a,b; Harden and Taylor, 1983; Machette, 1983; Machette and Steven, 1983; Busacca and others, 1984; Machette and others, 1984; Reheis, 1984). In the reports in this series, the basic field information, geologic background, and analytical data are presented for each chronosequence, as well as some results additional to the previous publications.

One of the most significant aspects of these chronosequence studies is that in every study area, many soil parameters change systematically over time, or with the age of deposits. As Deming (1943) emphasized, it is this recurrence of correlation in such different conditions that is most significant to geologic and pedologic studies. In relatively moist areas, such as coastal and central California, such soil properties as percent clay or reddening of soil colors change most systematically over time. In more arid regions, such as in the Bighorn basin of Wyoming, calcium carbonate and gypsum contents best reflect relative ages of the deposits. A few parameters--for example, elemental composition of sands or clays--appear to be comparable between areas so diverse in climatic setting.

Numeric age control has enabled us to estimate rates of soil development. In some places, we have been able to compare rates between different areas. For example, in central California, rates of clay accumulation were found to be most rapid during the initial stages of soil development; the rates declined with increasing age. The straightest lines for regression were on a log-log scale. In coastal California, rates of clay accumulation appeared to be much higher than in central California. This difference in rates could be due to parent material (the coastal soils that we studied formed on reworked shale and sandstone, whereas central California soils were developed in granitic alluvium), and (or) the differences in rates could be due to eolian additions of clay. In the Bighorn basin of Wyoming, rates of clay accumulation, as well as most other soil properties, increased linearly over time, with no apparent decrease in initial rates.

The data we present here suggest many opportunities for further interpretation. For example, we may learn how climate, vegetation, and mineralogy affect the rates of clay formation or organic-matter accumulation. In some study areas, we present data for rare-earth elements, which could be used to examine how each element reacts in different weathering environments. These examples are only a fraction of the possible future studies that could be conducted on the data presented here.

J.W. Harden
Editor

CONTENTS

FIGURES

TABLES

SUPPLEMENTARY TABLES

SOIL CHRONOSEQUENCES IN THE WESTERN UNITED STATES

The Soil Chronosequence Along the Cowlitz River, Washington

By David P. Dethier

Abstract

Soils on terraces along the Cowlitz River, southwestern Washington, form a chronosequence developed under cool, moist conditions during most of Quaternary time. Soils range from thin, young (A/C) soil profiles on late Holocene surfaces to weathering profiles more than 10 m thick on the early or middle Pleistocene Logan Hill Formation. Glacial outwash deposits underlie four principal terraces and are correlated with glaciations of the Cowlitz River valley by ice that flowed westward from the Cascade Range. Deposits include late Wisconsin Evans Creek Drift, pre-Wisconsin(?) Hayden Creek Drift, middle(?) or late Pleistocene Wingate Hill Drift, and the early or middle Pleistocene Logan Hill Formation. Soils developed in volcanic sand and gravel derived from volcanic rocks show systematic changes over time in such properties as depth to unweathered material, clay content of the B horizon, rubification (color hue and chroma), clay films, and pH. Losses of such oxides as CaO and Na_2O, and gains of dithionite-extractable Fe and 1-μm clay content, show progressive, time-related changes. The loss of CaO can be used to estimate the ages of the terrace deposits. The mass of dithionite-extractable Fe and pedogenic clay in Cowlitz soils suggests that weathering rates in southwestern Washington are higher than those reported for chronosequences in California.

INTRODUCTION

Loess-mantled gravel terraces along the Cowlitz River, southwestern Washington, record early to late Quaternary glacial events. Terrace profiles are graded to moraines which formed at the terminus of large valley glaciers that advanced westward along the Cowlitz valley from source areas on Mount Rainier, Mount Adams, and adjoining alpine areas. During at least two glacial events, the Cowlitz glacier terminated more than 100 km southwest of Mount Rainier, making it one of the largest valley glaciers in the conterminous United States. Terraces along the Cowlitz River range from well-preserved late Holocene surfaces near the present channel to dissected surfaces of the deeply weathered Logan Hill Formation (Snavely and others, 1958). Despite abundant tephra and organic matter in many glacial and interglacial deposits, the chronology of pre-late Wisconsin glaciation in western Washington is not well dated, but some ages can be estimated.

Terrace deposits along the Cowlitz River are composed of sandy gravel overlain by a layer of silt or very fine sand. Thicknesses of both layers are variable. Fine material may be as thick as 5 m, and the gravel is commonly several meters to tens of meters thick. The unstratified, well-sorted nature of the fine material suggests that these surface deposits are primarily eolian. Field and laboratory studies demonstrate that pumiceous material is also present in most of the capping deposits, but no discrete layers of tephra were observed. Gravel is mixed into the loess blanket where the loess is less than about 1 m thick, but the contact between the two units is generally sharp. Most soils are developed through the silt and into the gravel. Field evidence thus suggests that the eolian material accumulated soon after deposition of the glaciofluvial gravel. Most of the terraces can be traced upstream into moraines. The upper contact of the gravel deposits is likely isochronous with maximum stands of the Cowlitz glacier, or with lengthy stillstands during its retreat. Loess deposition probably ceased within a few tens to hundreds of years after retreat of the Cowlitz ice, allowing the growth of vegetation and initiation of soil development.

Outwash terraces and their mantling loess along the Cowlitz River provide perhaps the best opportunity in the Pacific Northwest to study soil sequences developed in andesitic parent material in a humid climate. The soils form a chronosequence because parent material, vegetation, average climate, and other variables are similar among the sites and have remained relatively constant over an extended period of the Quaternary. Properties that display predictable patterns over time can be used to characterize and correlate soils developed on Quaternary surfaces and to estimate their ages. For example, soil chronology of the Cowlitz area could be applied where there are similar parent materials, climatic settings, and vegetation in the Northwestern United States, British Columbia, Alaska, and at higher elevations in the Western United States. Comparison of Cowlitz soils to soil chronosequences on similar parent materials at drier sites in much of the Western United States permits evaluation of climate as a variable.

In this report I first discuss the geology, estimated ages, and Quaternary history of terrace deposits along the Cowlitz River. I then present field observations and selected laboratory analyses of soils from these deposits as a basis for discussion of soil development over time in the Cowlitz area.

GEOGRAPHY, CLIMATE, AND VEGETATION

The Cowlitz River heads at the Cowlitz Glacier on Mount Rainier and, with its major tributaries, drains a large area (3,870 km^2 at Toledo) of the Cascade Range between Mount Rainier and Mount Adams in southwestern Washington (fig. 1). The Cowlitz River flows west from the mountainous terrain for about 130 km and turns south near Toledo to flow to the Columbia River. Terraces that flank the Cowlitz along much of its course are best preserved in a 35-km reach between Toledo and

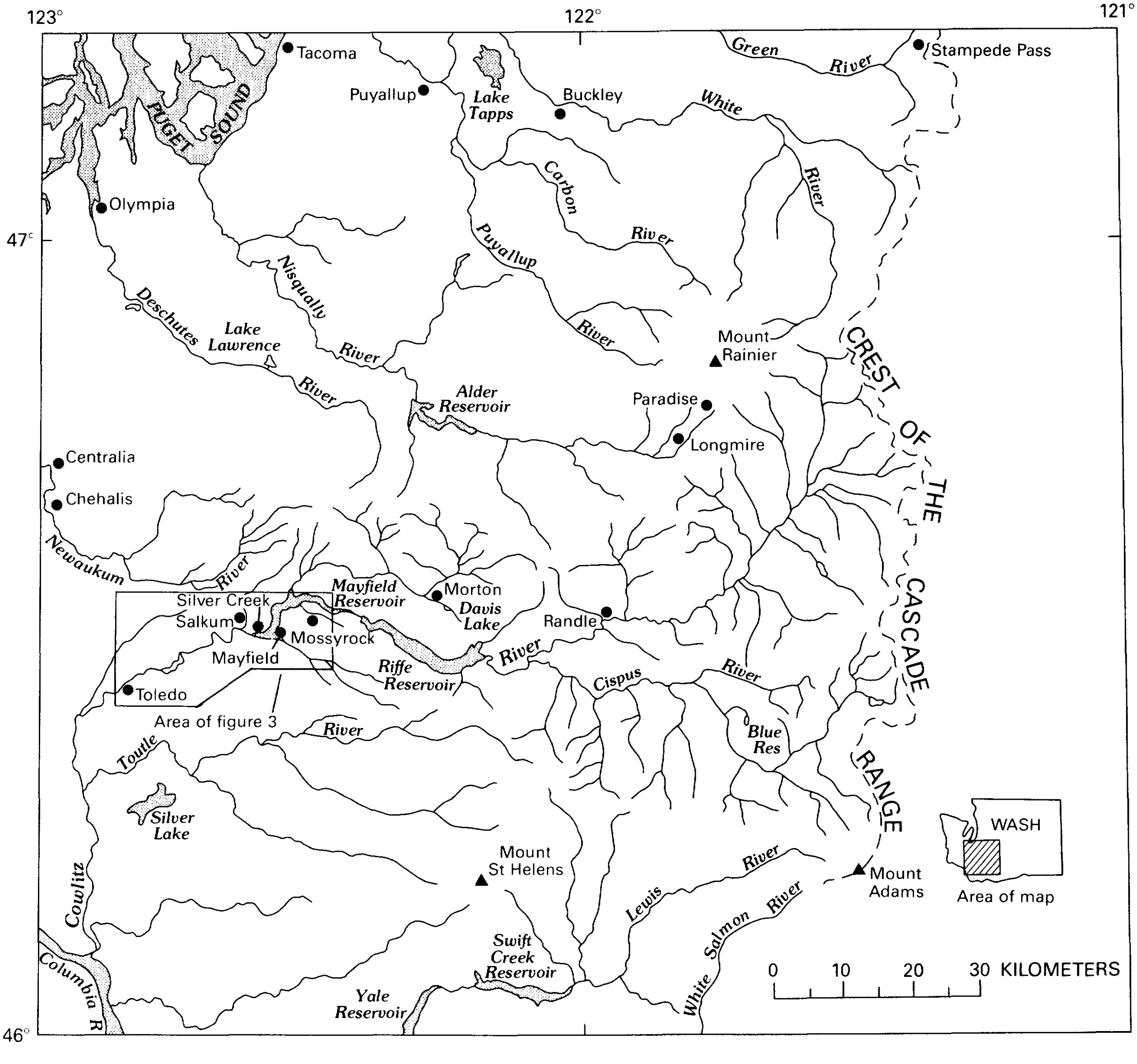


Figure 1. Index map of Cowlitz River area, Washington. Stipple pattern represents major water bodies, including Puget Sound.

Mayfield. In this area, nearly flat to moderately dissected terraces are separated by steep terrace risers. Terrace morphology is interrupted locally by till and bedrock ridges and is bounded on the south and east by rolling hills developed in Tertiary bedrock. A low drainage divide separates the Cowlitz terraces from Quaternary outwash deposits to the north, along the west-flowing Newaukum River.

The present climate of most of Lewis County is maritime, marked by cool, wet winters, and warm, drier summers. Glacierized areas near the crest of the Cascade Range are considerably colder and receive about 80 percent more precipitation than the terraced areas east of Toledo (fig. 2). Annual precipitation on the present Cowlitz Glacier is probably about 2,400 mm, whereas values in the 30 km east of Toledo range from 1,250 to 1,500 mm (U.S. Weather Bureau, 1965). Mean annual temperature near Toledo (elevation 36 m) averages about 11 °C, and the frost-free season is about 165 days, whereas an upland weather station at Stampede Pass (elevation 1200 m) northeast of Mount Rainier has an average value near 4 °C. Average monthly values for these stations (fig. 2) are moderate, and typical of maritime climates.

Existing glaciers on Mount Rainier have an equilibrium-line altitude (ELA) of about 2,100 m (Burbank, 1979). Crandell and Miller (1974) and Porter (1977) used glacial-geologic evidence to suggest that the ELA was about 1,000 m lower during the maximum extent of late Pleistocene ice. Palynologic evidence (Barnosky, 1981; Heusser, 1977) indicates that changes in temperature beyond the glaciation limit in western Washington were about 6 °C during the most recent glacial-interglacial cycle.

Palynologic data and radiocarbon ages from two locations in southwestern Washington provide some information about middle and late Wisconsin climate in the study area (Barnosky, 1981, 1984; Heusser and Heusser, 1980). Climate 30,000 years ago (at 30 ka) was similar to that of the present, but sharply cooler periods marked by tundra vegetation occurred between about 25 and 18.5 ka, and at about 14 ka. Since about 12 ka, climate has warmed considerably, although brief cooler periods may have occurred in latest Pleistocene and early Holocene time. Holocene climate was warmest shortly before about 7 ka, and was slightly cooler and wetter after about 4 ka, a time of neoglaciation in much of the Western United States (Waitt and others, 1982; Barnosky, 1984). The age and stratigraphic position of pollen spectra from interglacial deposits near Puyallup reported by Easterbrook and others (1967) is now uncertain. However, the fossil pollen assemblages are similar to those described from the late Wisconsin glacial-interglacial cycle and from parts of other nearby interglacial deposits (Heusser and Heusser, 1981).

When European settlers first arrived in the upper Cowlitz River area in about 1840, terraces from Toledo to Mossyrock supported areas of prairie vegetation, and old-growth coniferous forests covered parts of the terraces and adjacent uplands (Soil Conservation Service, 1987). Forested areas have been logged once or twice except for small patches near the highest ridges and along the Cascade crest south of Mount Rainier. Second-growth stands of Douglas fir (Pseudotsuga menzeseii), fir (Abies sp.), hemlock

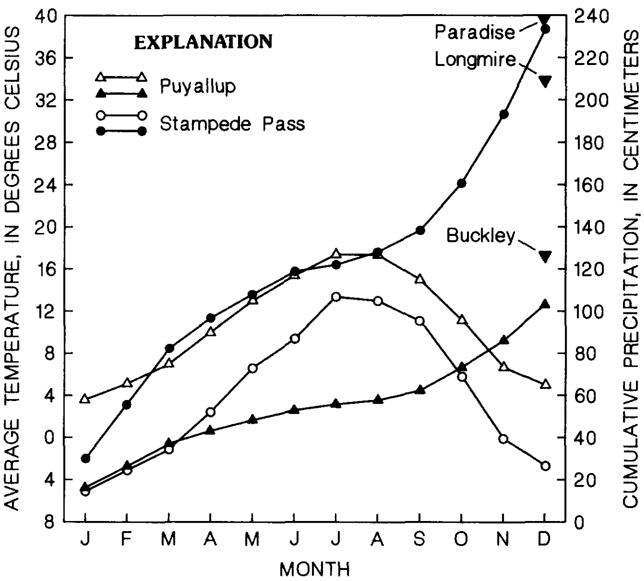


Figure 2. Average monthly temperature (open symbols) and cumulative annual precipitation (solid symbols) for lowland (Puyallup) and upland (Stampede Pass) stations in western Washington. Cumulative annual precipitation values for three other stations are also plotted. Data from Crandell and Miller (1974).

(Tsuga heterophylla), and red cedar (Thuja plicata) are commonly mixed with alder (Alnus rubra), maple (Acer macrophyllum) and willow (Salix sp.), particularly in poorly drained areas. Remnant stands of old growth indicate that hemlock, Douglas fir, and true fir were the major forest components before logging began. Hemlock dominance for about the past 4,000 years is also suggested by the data of Barnosky (1981, 1984). Franklin and Dyrness (1973) gave a detailed account of modern vegetation in southwestern Washington.

Topography in the study area is level to gently rolling on terrace surfaces and moderate to steep on terrace risers and where drainages have cut through glacial deposits into Tertiary bedrock. Terrace-surface slopes are generally less than 2 °. In areas away from major tributary streams, local relief ranges from 4 m to 15 m and increases with terrace age. Elevations of the major terraces range from about 40 to more than 500 m, but most of the area between Toledo and Mossyrock lies between 100 and 200 m.

GEOLOGIC SETTING AND SOIL PARENT MATERIALS

Quaternary deposits along the Cowlitz River are composed primarily of andesite debris derived, in part, from Tertiary volcanic rocks of the Cascade Range. The range consists of middle to late Quaternary volcanoes constructed on a platform of Eocene to Pliocene(?) volcanic rocks and arkosic sandstone and siltstone. Quaternary volcanic rocks in the Cowlitz basin are chiefly andesitic flows and breccias with subordinate dacite units (Fiske and others, 1963; Hammond, 1980). Tertiary volcanic rocks east of Mossyrock include flows, interlayered volcaniclastic units, and limited exposures of Miocene granodiorite. Pyroxene-bearing andesite and basalt are the most common rock types; some basalt contains sparse phenocrysts of olivine. Terrestrial sedimentary rocks and intermediate volcanic rocks are found west of Mossyrock; coal-bearing units are common in the continental sedimentary rocks (Snavely and others, 1958; Roberts, 1958). Roberts (1958) and Snavely and others (1958) noted a fine-grained fluvial and lacustrine unit (Wilkes Formation) overlying Eocene volcanic rocks and directly underlying the Quaternary sequence. The Wilkes Formation is of Miocene age and contains dacitic lahars and alluvium that resemble Quaternary volcaniclastic rocks of the Cascades. These easily eroded fluvial deposits, and the middle Tertiary sandstones, doubtless contributed to terrace material in its principal exposure area west of Mossyrock. Gravel in the terrace-forming deposits, however, is mainly andesite and basalt (Bethel, 1982).

In Quaternary time, the eastern part of the study area received substantial quantities of tephra erupted from Cascade volcanoes. Upper Pleistocene and Holocene tephra is locally more than 1 m thick east of Mossyrock; older Mount St. Helens deposits are apparently thinner (Mullineaux and others, 1975; Barnosky, 1981, 1984). Crandell and Miller (1974) reported a radiocarbon age of greater than 38 ka (W-950) for a local deposit of pyroclastic material overlying till on the slopes of Mount Rainier. Pumiceous material is also a common component in lahars preserved in lower(?) and middle Pleistocene sections at a variety of locations in western Washington (Crandell and others, 1958).

Most of the tephra and the pumiceous material in lahars is dacitic in composition, but pyroxene andesite and altered volcanic rock are also common. Lahars probably flowed down the slopes of Mount Rainier and into the Cowlitz River repeatedly during the Quaternary. The tephra and lahars contributed Quaternary volcanic debris to the Cowlitz River drainage, adding material to outwash and loess deposits by direct deposition or by fluvial and eolian redeposition.

QUATERNARY GEOLOGY OF THE COWLITZ RIVER VALLEY

Snavely and others (1958) and Roberts (1958) noted several ages of glacial deposits derived from Mount Rainier and recognized deep weathering of materials in some terrace areas along the Cowlitz River valley. Weigle and Foxworthy (1962) recognized glacial outwash from four different periods in the area west of Mossyrock. Crandell and Miller (1974) subsequently mapped glacial deposits along the Cowlitz River and used weathering criteria to group some of Weigle and Foxworthy's (1962) terrace deposits into single units. Crandell and Miller recognized four principal ages of deposits from Pleistocene alpine glaciers in major drainages of the Mount Rainier region: Wingate Hill Drift, Hayden Creek Drift, Evans Creek Drift, and McNeeley Drift (table 1). They suggested that the Logan Hill Formation is likely a glacial outwash deposit of early to middle Pleistocene age. Dethier and Bethel (1981) mapped terraces developed on outwash west of Mossyrock at a scale of 1:62,500 and subdivided

Table 1. Nomenclature of Quaternary deposits in the Cowlitz River area, Washington

Southern Puget lowland[1]	Western Cascade Range[2]	This report
--	--	Late Holocene alluvium
--	Garda Drift	Latest Pleistocene(?) outwash
--	McNeeley Drift	Evans Creek Drift: late outwash
Vashon Drift	Evans Creek Drift	early outwash
Olympia-age interglacial sediment	--	--
High Fraser terrace[3]	--	Pre-Evans Creek(?) outwash
McCleary drift[4]	Hayden Creek Drift	Hayden Creek Drift: late outwash
Puyallup Formation	--	--
		middle outwash
--	--	early outwash
	\	till, undivided
Stuck Drift	Wingate Hill Drift	Wingate Hill Drift and outwash
Alderton Formation	--	--
Orting Drift	Logan Hill Formation	Logan Hill Formation

[1]Crandell and others (1958).
[2]Crandell (1969); Crandell and Miller (1974).
[3]Carson (1970); Colman and Pierce (1984).
[4]Informal name proposed by Colman and Pierce (1984) for deposits previously mapped as Salmon Springs Drift by Carson (1970). The Salmon Springs Drift is now known to be about 800 ka at its type locality (Easterbrook and others, 1981) and is thus much older than these deposits.

Crandell and Miller's (1974) units on the basis of topographic position and terrace gradients.

Most major terraces along the Cowlitz River can be traced to moraines or probable ice-marginal positions of Cowlitz River glaciers (Crandell and Miller, 1974). Cowlitz River gravel terraces west of Mossyrock are 10 km to more than 20 km wide (fig. 3). Extensive surfaces probably formed as a result of aggradation during glacial advances and lengthy stillstands, followed by downcutting after deglaciation. In most cases terraces can be recognized by lateral continuity, elevation, or stratigraphic relations beneath the terrace. However, certain surfaces of Hayden Creek age and terrace remnants that lie between the major Hayden Creek and Evans Creek surfaces cannot be grouped with a specific terrace on the basis of their topographic position or stratigraphy. Areally restricted terraces such as these are problematic. They may record major glacial cycles poorly or represent (1) minor stillstands, (2) readvances during overall glacial retreat, (3) lateral erosion into older outwash material during downcutting, or (4) base-level changes resulting from other causes such as tectonism.

Although Crandell and Miller (1974) noted sparse outcrops of deeply weathered till in the Cowlitz drainage and Snavely and others (1958) reported till within the Logan Hill Formation, Logan Hill gravel deposits cannot be traced with confidence to specific till outcrops. However, gravel beneath the Wingate Hill surface can be traced east to surface outcrops of deeply weathered Wingate Hill till, and the oldest of the Hayden Creek terraces heads in an area of subdued morainal topography about 4 km upvalley from the Wingate Hill margin. The youngest Hayden Creek terrace apparently heads northeast of Mossyrock. Evans Creek terraces can be traced to terminal moraines located near Randle, 25 km upvalley from the eastern border of the area shown in figure 3.

Gradients of Quaternary terraces (fig. 4) generally converge downstream (Dethier and Bethel, 1981). Terraces have an average gradient of about 3 m/km, but steepen dramatically near moraines and ice-marginal positions inferred from till-outwash contacts. Near Toledo, Logan Hill and Wingate Hill terraces are found at about 90 m and 50 m, respectively, above the Evans Creek surface. Because these older surfaces display local relief of at least 10 m in some locations, the Logan Hill and possibly the Wingate Hill terraces are probably composite surfaces. The Hayden Creek and younger terraces display considerably less relief, and individual surfaces can be easily distinguished.

Age Control for Glacial Fluvial Units

The Cowlitz soils developed in the following time-stratigraphic units, listed from young to old: (1) late Holocene alluvium; (2) latest Pleistocene(?) outwash; (3) late and early outwash deposits of the Evans Creek Drift; (4) outwash deposits of pre-Evans Creek(?) age; (5) late, middle, and early outwash deposits of the Hayden Creek Drift; (6) outwash of the Wingate Hill Drift; and (7) outwash(?) of the Logan Hill Formation. Absolute age assignments are uncertain for units older than Evans Creek outwash, but development of weathering rinds in these deposits (Colman and Pierce, 1981) and sparse ^{14}C and K/Ar ages in southwestern Washington help constrain deposit ages (table 2).

The stratigraphy and dating of glacial deposits in western Washington are in flux (Colman and Pierce, 1984; Easterbrook and others, 1985), but a number of recently published observations and dates discussed below have helped clarify regional glacial-interglacial stratigraphy. Quaternary glacial deposits in western Washington were produced both from the Puget lobe of the Cordilleran ice sheet and from large valley glaciers that flowed from the Cascade Range (Waitt and Thorson, 1983). Puget Lobe and Cascade Range deposits have a limited area of overlap, hampering regional correlation in southwestern Washington. Because continental and alpine advances were coeval during at least the three most recent glaciations (Colman and Pierce, 1984), it is possible that ages for parts of the Cowlitz sequence can be estimated from dating of the continental deposits.

The penultimate continental drift in southwestern Washington (high Fraser terrace of Carson, 1970) has weathering rinds that suggest early Wisconsin deposition correlative with oxygen-isotope stage 4. Amino-acid analysis of shell in the penultimate continental drift from northwestern Washington (Possession Drift) suggests that this deposit is older than 60 ka and possibly older than 80 ka (Easterbrook and others, 1982). Shell has amino-acid ratios that suggest that the Double Bluff Drift, which lies beneath Possession Drift, is older than 100 ka and probably older than 200 ka (Easterbrook and Rutter, 1982). The informal McCleary drift deposit (Colman and Pierce, 1984) of southwestern Washington lies beneath the high Fraser terrace, underlies interglacial estuarine deposits, and probably correlates with oxygen-isotope stage 6. An age of 150 ka or greater is also indicated by weathering rinds, soil color, and soil thickness of this drift in an area southeast of Olympia, Washington (Lea, 1983).

Dating and correlation of drift units older than McCleary deposits is hampered by the absence of surface exposures of older drifts and the limited number of stratigraphic exposures. Continental drift originally thought to represent the penultimate glaciation (Crandell and others, 1958) is interbedded with magnetically reversed sediment and tephra dated (by the fission-track method) at about 800 ka (Easterbrook and others, 1981). The oldest drift unit at Mount Rainier lies within a sequence of normally polarized sediment and beneath an andesite flow dated at about 300 ka (Crandell and Miller, 1974). Porter and Clayton (1982) mapped two tills interlayered with lavas, which gave minimum ages of 0.7 Ma and 1.7 Ma for glaciations in the headwater area of the Cowlitz River along the Cascade crest. However, the extent of ice during these glaciations is not known, and the drift units have not been mapped away from the Cascades. Ages listed in table 2 reflect uncertainties in isotopic ages and correlation, particularly for the pre-Wisconsin terraces. However, ages are sufficiently well constrained to assess the relative and, in some cases, absolute rate of development of soil properties.

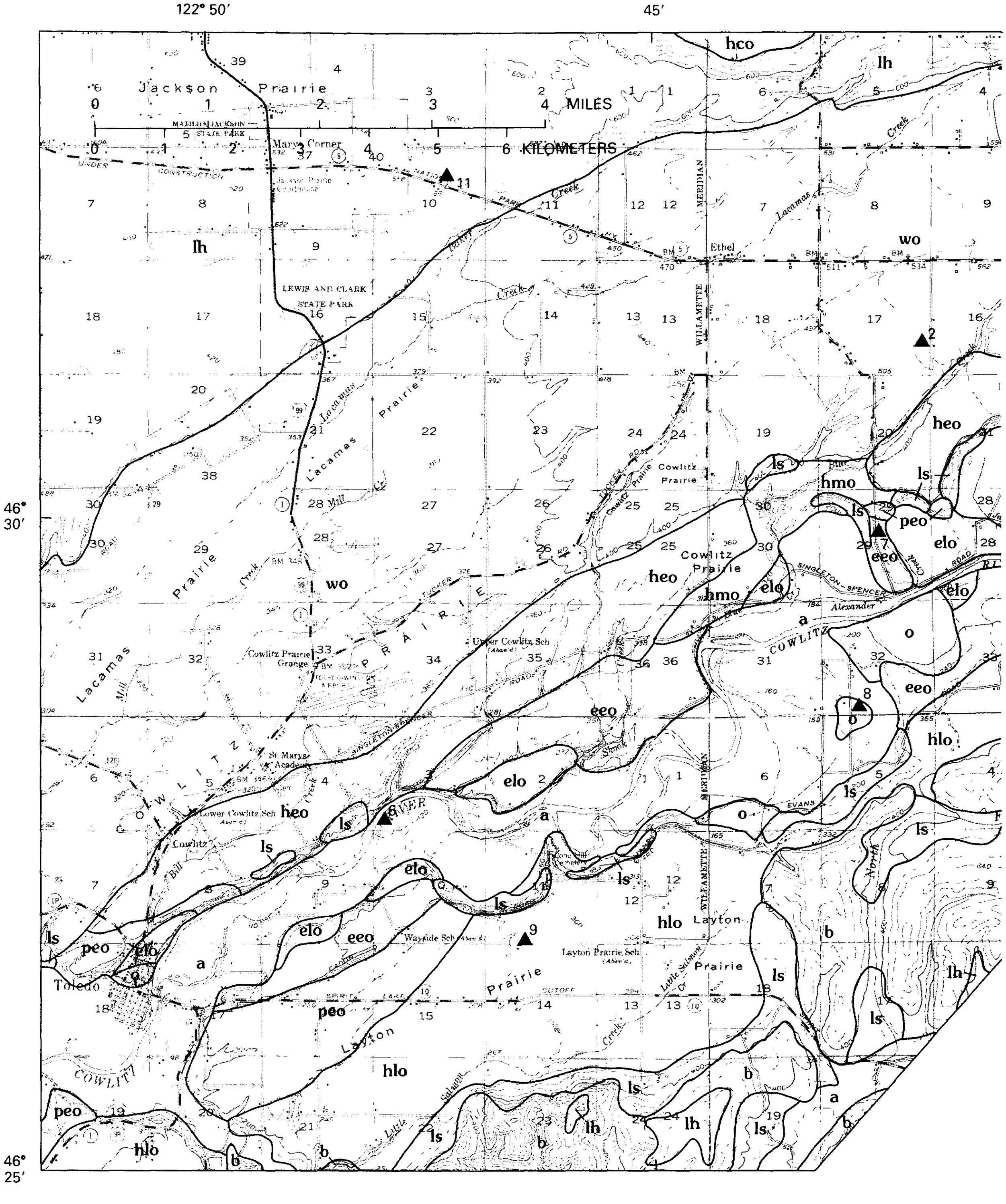
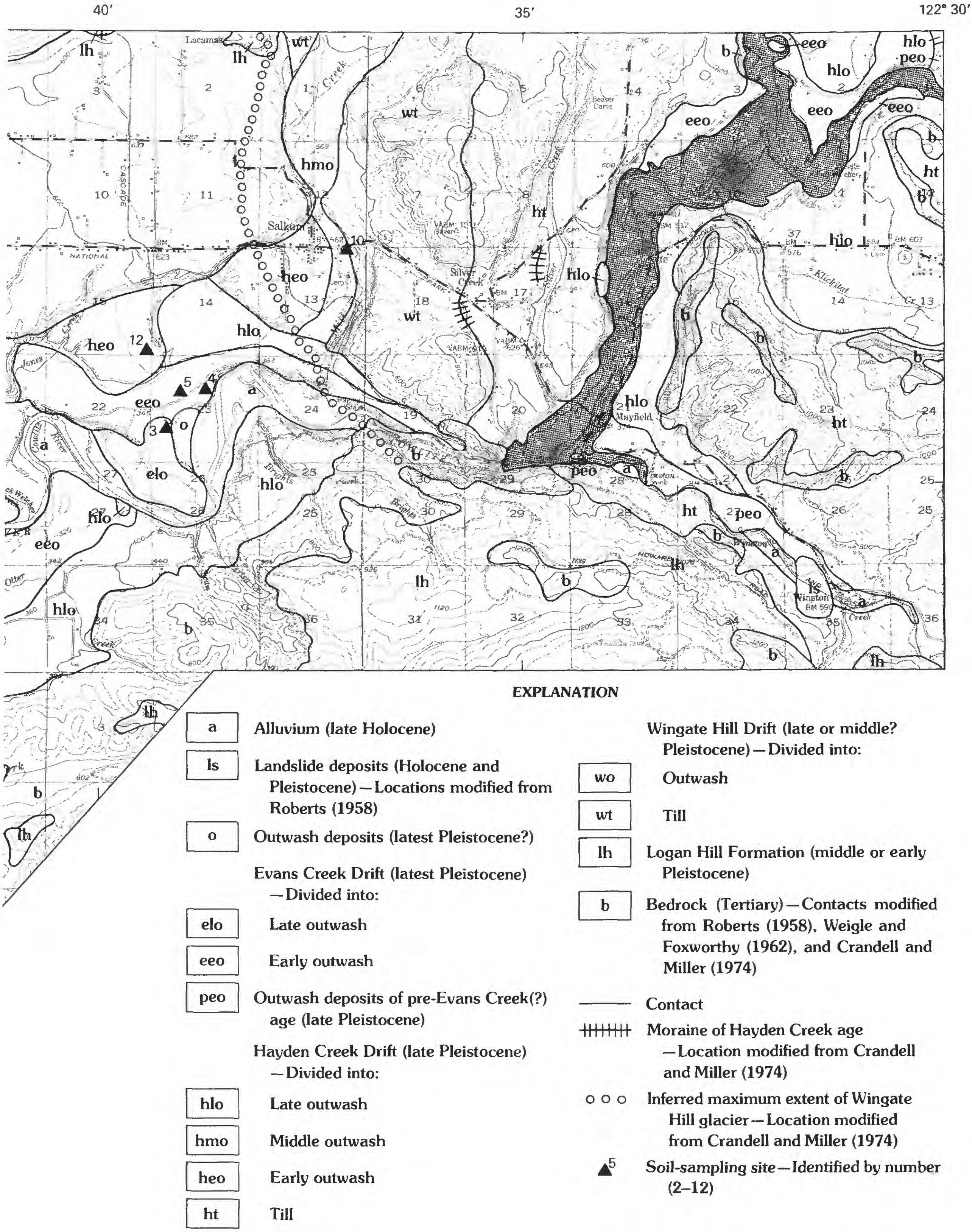


Figure 3. Quaternary and bedrock geology along Cowlitz River in central Lewis County, Wash. (modified from Dethier and Bethel, 1981). Base from U.S. Geological Survey, 1:62,500, Castle Rock, Toutle, 1953; Centralia, Onalaska, 1954. Contour interval 40 and 80 ft. See figure 1 for location.


40′
35′
122° 30′
EXPLANATION
a Alluvium (late Holocene)
ls Landslide deposits (Holocene and Pleistocene)—Locations modified from Roberts (1958)
o Outwash deposits (latest Pleistocene?)
Evans Creek Drift (latest Pleistocene)—Divided into:
elo Late outwash
eeo Early outwash
peo Outwash deposits of pre-Evans Creek(?) age (late Pleistocene)
Hayden Creek Drift (late Pleistocene)—Divided into:
hlo Late outwash
hmo Middle outwash
heo Early outwash
ht Till
Wingate Hill Drift (late or middle? Pleistocene)—Divided into:
wo Outwash
wt Till
lh Logan Hill Formation (middle or early Pleistocene)
b Bedrock (Tertiary)—Contacts modified from Roberts (1958), Weigle and Foxworthy (1962), and Crandell and Miller (1974)
Contact
Moraine of Hayden Creek age—Location modified from Crandell and Miller (1974)
Inferred maximum extent of Wingate Hill glacier—Location modified from Crandell and Miller (1974)
Soil-sampling site—Identified by number (2–12)

Late Holocene Alluvium

Late Holocene sand and gravel lie beneath the lowest terrace, which forms the modern flood plain 2 to 5 m above the active channel of the Cowlitz River. The oldest trees on the surface are less than 250 years old, and much of the terrace is inundated during large floods. Oxidation of these deposits is shallow, a few tens of centimeters at most. Although the gravelly sand of flood-plain channel deposits is not covered with windblown silt, overlying fine sand makes the lowest terrace texturally similar to the older surfaces. The thickness of the alluvial deposits is probably several meters to several tens of meters.

Latest Pleistocene(?) Outwash and Outwash Deposits of the Evans Creek Drift

At least three mappable surfaces east of Toledo record deposition of outwash from the Cowlitz glacier when it terminated near or east of Randle (fig. 1). The lowest and youngest of these surfaces (latest Pleistocene? outwash) rises some 15 m above the modern flood plain, overlies gravelly deposits at least 3 m thick, and is capped with less than 0.3 m of fine sand and silt. Oxidation in these deposits extends to an average depth of 0.5 m. The surface is preserved as isolated remnants in two areas (fig. 3). Two higher groups of outwash terraces, the late Evans Creek and

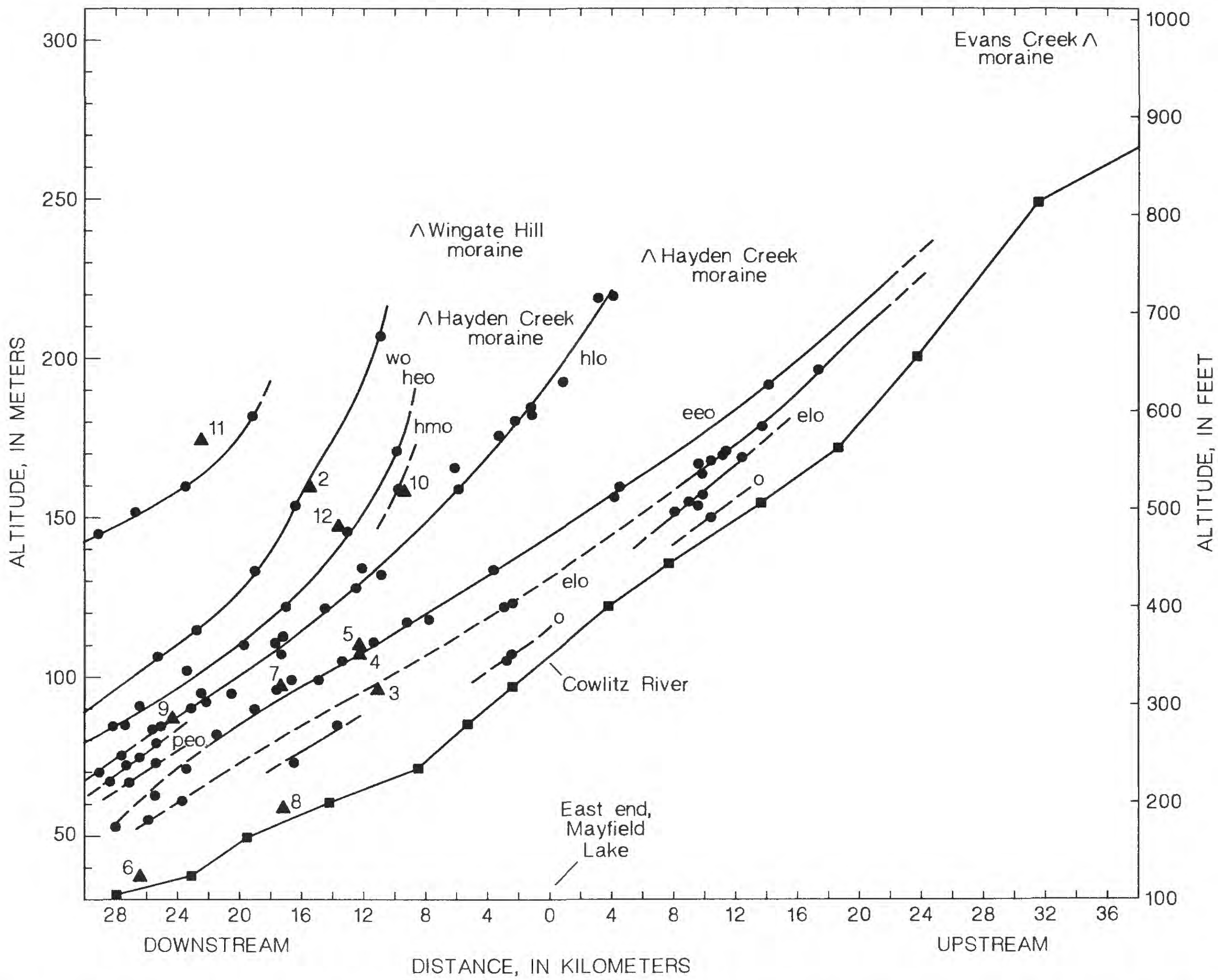


Figure 4. Pleistocene terraces along Cowlitz River upstream from Toledo, Wash. Geologic units correspond to those in figure 3. Profiles are shown as dashed lines where correlation is uncertain. Soil-sampling sites described in text are indicated by numbered triangles (see fig. 3 for location). Modified from Dethier and Bethel (1981).

early Evans Creek terraces, rise 5 to 15 m above the latest Pleistocene(?) terrace, which is an inset cut into the younger of these surfaces. The higher early Evans Creek terrace forms a nearly continuous surface that is laterally extensive only near the east end of Mayfield Lake. Both of the Evans Creek outwash deposits are at least 5 m thick, capped with 0.5 to 2.0 m of loess, and oxidized to a depth of about 1 m. The loess cap is thicker on the late Evans Creek surface at most exposures.

Outwash from the Evans Creek and the latest Pleistocene(?) advances did not reach Davis Lake (fig. 1), but cool climatic episodes are recorded in the palynology of dated cores from the lake and from bogs in unglaciated areas of southwestern Washington (Barnosky, 1984). The two older Evans Creek units were likely deposited during cold intervals from 25 to 20 ka and at about 14 ka, respectively. The Davis Lake cores record a relatively minor episode of tephra deposition at about 21 ka, and 30 cm of sandy tephra lies directly below a site dated by ^{14}C at about 13.5 ka (Barnosky, 1981). These tephras probably originated from eruptions at Mount St. Helens and form a substantial component of the loess associated with the Evans Creek terraces, particularly the younger one. Although palynologic evidence does not suggest a distinct cool period betwen 13 ka and 10 ka, the depth of oxidation of the latest Pleistocene(?) terrace deposits suggests that they could be as old as 12 ka to 10 ka. Barnosky (1981, 1984) showed that the Holocene climate in southwestern Washington was relatively warm until neoglaciation began some time

Table 2. Inferred age of Quaternary terrace deposits near Toledo, Washington

Terrace deposits[1]	Inferred age (ka)	Basis for age assignment and possible correlation with drift of the Puget lowland (PL) or Cascade Range (CR)
Late Holocene alluvium (a)	<0.25	Tree rings.
Latest Pleistocene(?) outwash (o)	8.0-12.0	May correlate with Crandell's (1969) McNeeley Drift (CR) or Beget's (1983) early Holocene deposits in the Cascade Range (CR). Barnosky (1981, 1984) presented no evidence for cool climate in this period.
Late Evans Creek outwash (elo)	13.0-14.0	Cool latest Wisconsin interval in dated cores from southwestern Washington (Barnosky, 1981, 1984). Maximum advance of continental ice (PL) occurred about 14.5 ka (Waitt and Thorson, 1983).
Early Evans Creek outwash (eeo)	22.0-24.0	Age assigned by Barnosky (1984) to Evans Creek (CR) Drift from Cowlitz and nearby valleys.
Pre-Evans Creek(?) outwash (peo)	40-70	Bracketed by Evans Creek Drift (CR) and minimum age for early Hayden Creek Drift. May correlate with Carson's (1970) high Fraser (PL) terrace, inferred to be 60 to 70 m.y. old (Colman and Pierce, 1981, 1984).
Late Hayden Creek outwash (hlo)	>60 130-170(?)	Older than ^{14}C date of 60 ka for the late Hayden Creek Drift near Mount St. Helens (CR; Dethier and Bethel, 1981). May correlate with Possession Drift (PL) dated by amino-acid techniques at 60 to 80 ka (Easterbrook and others, 1982). Weathering-rind data (Colman and Pierce, 1984) from Hayden Creek Drift suggest an age of about 150 ka and correlation with the McCleary drift (PL; informal name) of Colman and Pierce (1984).
Middle Hayden Creek outwash (hmo)	>60 150-280(?)	Truncates early Hayden Creek outwash and is truncated by late Hayden Creek outwash. Elevation and contact relations suggest that middle Hayden Creek outwash terrace deposits are more closely related to early Hayden Creek outwash deposits.
Early Hayden Creek outwash (heo)	>60 150-320(?)	Colman and Pierce (1981) and Colman (written commun., 1983) inferred an age of 150 ka or older from weathering-rind data. May correlate with Double Bluff Drift (PL) of northwestern Washington dated by amino-acid techniques as older than 100 ka and probably older than 200 ka (Easterbrook and Rutter, 1982).
Wingate Hill outwash (wo)	300(?)-600(?)	Colman and Pierce (1981) estimated an age of 300 to 600 ka from 600 ka from weathering-rind data. May correlate with the oldest till exposed on Mount Rainier, which overlies an andesite flow of normal polarity dated at about 300 ka (Crandell and Miller, 1974).
Logan Hill Formation (lh)	630(?) - 1,700(?)	May correlate with Salmon Springs Drift (PL) dated at 840 ka at its type locality (Easterbrook and others, 1981). May correlate with 0.7 and 1.7 Ma tills dated by K/Ar at Tumac Mountain (CR) in the Cowlitz River headwaters (Porter and Clayton, 1982). Minimum age suggested by rate of saprolite formation (Woodward-Clyde Consultants, 1978)

[1]Symbols refer to figure 3.

after about 5 ka. Because glacial advances in the late Holocene were limited to minor expansions (Crandell, 1969), neoglacial terrace elevations should be close to the modern flood plain rather than near the Evans Creek surfaces. I thus conclude that the latest Pleistocene(?) surface represents a stillstand or readvance during retreat of Evans Creek glaciers, erosional lowering of the late Evans Creek terrace between about 14 ka and 10 ka, or early Holocene glaciation (Beget, 1983). The volume of outwash preserved from the Evans Creek advance is relatively small and could be buried easily or eroded during a subsequent major glaciation. Earlier glaciations of similar size may not be preserved in the terrace record along the Cowlitz River, or such glaciations could be represented by remnants of intermediate-elevation terraces found at several locations upstream from Toledo.

Outwash Deposits of the Hayden Creek Drift

Hayden Creek outwash underlies three distinct terraces that compose the most extensive glacial deposits along the Cowlitz River. If terrace remnants between the Hayden Creek and Evans Creek groups (pre-Evans Creek? outwash) are of early Wisconsin age (table 2), then the Hayden Creek terraces are likely pre-Wisconsin in age.

Dethier and Bethel (1981) mapped two broad terraces of Hayden Creek age (early and late) and several small terrace remnants (middle Hayden Creek outwash) between the two in the vicinity of Salkum and downstream near the Cowlitz Prairie. Surfaces designated pre-Evans Creek(?) age (fig. 3) exposed near Toledo lie topographically between the late Hayden Creek and the Evans Creek surfaces and overlie 0.5 to 1.0 m of loess and from 3 m to more than 5 m of gravel. Oxidation of these deposits generally extends 1 to 1.5 m below the surface. The deposits probably resulted from an early or middle Wisconsin glaciation or from reworking of younger Hayden Creek deposits during downcutting. Weathering-rind data and unpublished field observations (S.M. Colman, written commun., 1983) suggest that these terraces may represent outwash from an early Wisconsin advance in an upstream area subsequently overridden by the Evans Creek advance.

The three principal Hayden Creek terraces grade to different areas of the broad Hayden Creek morainal belt (see Erdmann and Bateman, 1951). The map pattern of the late Hayden Creek terrace suggests that the glacial Cowlitz River flowed close to its modern course, whereas the early and middle Hayden Creek terraces were probably fed by meltwater flowing through gaps in the hills east and northeast of Salkum. The late Hayden Creek outwash deposits are generally 5 to 10 m thick whereas the early deposits consist of 10 to 15 m (35 m near Salkum) of gravel; deposits beneath the middle terrace are at least 16 m thick near Salkum. Caps of weathered silt 1 to 3 m thick cover each of the gravel deposits. Oxidation depths are about 1.5, 2.0, and 3.0 m in late, middle, and early Hayden Creek outwash, respectively. The early terrace surface is slightly more dissected than the middle and the late Hayden Creek surfaces.

Topographic position, weathering-rind thickness, and depth of oxidation indicate that the Hayden Creek deposits are of similar age to pre-Wisconsin drift in the southern Puget lowland (Colman and Pierce, 1984). Isotopic ages at best give minimum ages for Hayden Creek deposits. Radiocarbon ages and climatic interpretations from Davis Lake (fig. 1), which lies in a depression last occupied by ice during the time when Hayden Creek Drift was deposited, span the period from about 26 ka to the present (Barnosky, 1983, 1984). The Hayden Creek deposits are thus older than 26 ka in the Cowlitz basin. Crandell and Miller (1974) dated organic matter from units overlying Hayden Creek till in the vicinity of Mount Rainier, but both ^{14}C ages were infinite and thus older than about 40 ka. Glaciers of Hayden Creek age also advanced west along the Lewis River drainage south of Mount St. Helens (D.R. Crandell, written commun., 1980). A log collected from outwash deposits of the penultimate glaciation (probably equivalent to late Hayden Creek time) some 70 km south of Mossyrock gave a radiocarbon age of greater than 60 ka (Dethier and Bethel, 1981). In the same area, weathered till of the penultimate glaciation underlies the 38-ka Mount St. Helens tephra of Mullineaux and others (1975). The buried Hayden Creek till is oxidized to a greater depth than surface deposits of Evans Creek age, which suggests that deposits of the penultimate glaciation are older than about 60 ka, and perhaps considerably older in the Mount St. Helens area. However, the late Quaternary history of glaciation in the Cascades near Mount St. Helens has not been described in detail (M. Mundorff, unpublished data), and correlation with the Cowlitz sequence is uncertain.

If the late Hayden Creek terrace is pre-Wisconsin, its age is probably about 150 ka (table 3). The depth of weathering in the early Hayden Creek terrace suggests it is considerably older, perhaps 300 to 250 ka (table 2). The middle Hayden Creek surface probably represents a recessional stand during ice retreat from the early Hayden Creek glacial maximum or a pause in trenching of the older deposits following deglaciation. However, it is possible that the middle surface represents a separate glaciation of intermediate age.

Outwash Deposits of the Wingate Hill Drift

Wingate Hill outwash is exposed beneath a broad terrace that extends westward from outcrops of deeply weathered till near Salkum (fig. 3). Local relief on the surface is as much as 10 m, and stream dissection is more extensive than on the early Hayden Creek terrace. Weathered silt deposits 1 to 3 m thick overlie gravel thicker than 30 m near Salkum and of unknown thickness elsewhere. Oxidation commonly extends to a depth of 5 to 10 m, and stones in the upper 2 m of the deposits are completely weathered to clay in many exposures.

Weathered Wingate Hill Drift overlies deeply weathered Logan Hill(?) till at several localities in the vicinity of Salkum (Crandell and Miller, 1974) and underlies Hayden Creek Drift in the hills between Salkum and Silver Creek. The depth and degree of oxidation in surface deposits of Wingate Hill Drift are comparable to that in the underlying Logan Hill Formation where the two are superposed (Crandell and Miller, 1974). This suggests that the Logan Hill Formation near Salkum weathered subaerially for as many years as the age of the Wingate Hill Drift. Oxidation of Hayden Creek till exposed at the surface west of Silver Creek is similar to that in underlying Wingate Hill till (Crandell and Miller, 1984), suggesting that the Wingate Hill till weathered for 150,000 to 300,000 years before burial by the Hayden Creek glacier (assuming the Hayden Creek is of pre-Wisconsin age). However, at measured section 5 of Crandell and Miller (1974, p. 25), Wingate Hill(?) Drift is more deeply weathered than overlying Hayden Creek deposits.

Colman and Pierce (1981) demonstrated that weathering-rind thickness in the western United States can be approximated as a function of the square root of time. Because weathering rinds on Wingate Hill clasts are about twice as thick as those formed on Hayden Creek cobbles, the ages of these deposits likely differ by a factor of more than two (Colman and Pierce, 1981, 1984). Wingate Hill rinds are about half as thick as Logan Hill rinds, although many Logan Hill clasts are completely altered, making the comparison tenuous. On the basis of these observations, I suggest that the Wingate Hill Drift is less than half as old as the Logan Hill Formation. Unfortunately, absolute ages are not available for either unit. Because most of the Hayden Creek Drift is probably at least 140,000 years old, Wingate Hill Drift is probably at least 300,000 years old, and perhaps as old as 300,000 to 600,000 years (Colman and Pierce, 1981, 1984).

Logan Hill Formation

The deeply weathered gravel of the Logan Hill Formation underlies an extensive, rolling surface best developed near Marys Corner (fig. 3). Weathered silt and clay 2 to 4 m thick overlies more than 40 m of gravel east of Marys Corner, but deposits south of the Cowlitz River (Roberts, 1958) are thinner. At many exposures, oxidation extends to depths of more than 10 m, and the original texture of the upper 2 to 3 m of the Logan Hill is commonly obscured by weathering. Below that depth the Logan Hill is saprolite which appears to be gravel, but all the "clasts" can be cut and smeared with a trenching tool.

Along the Cowlitz River south of Silver Creek, gravel of the Logan Hill Formation unconformably overlies the Miocene Wilkes Formation (fig. 3). Deeply weathered Wingate Hill Drift overlies deposits of the Logan Hill Formation in the hills northeast and northwest of Silver Creek and at other locations (Crandell and Miller, 1974). The Logan Hill Formation includes diamictons, and exposures of deeply weathered till have been mapped east of the Logan Hill surface (Crandell and Miller, 1974), but the unit may not be of glacial origin. Sedimentary structures are similar to those in the younger outwash sequences and suggest a braided stream environment, but a tectonic origin for the gravel is also possible. Snavely and others (1958) and Crandell and Miller (1974) tentatively assigned the Logan Hill to the early Pleistocene on the basis of topographic position and deep weathering. Rates of saprolite formation (Washington Public Power Supply System, 1974;

Table 3. Selected field parameters in soils of different age (see supplementary table 1)

Designation	Approximate age (ka)	Depth to unweathered material (m)	Maximum hue in B horizon	Finest texture in B horizon
Late Holocene	0.25	0.25	10YR3/3 moist	sandy loam[1]
Latest Pleistocene(?)	10.0-12.0	2.0	10YR6/5 dry	sandy loam
Late Evans Creek	14.0	0.7	10YR4/4[1] moist	loam[1]
Early Evans Creek (site 1)	24.0	0.9 (1.0)[2]	7.5YR5/6 moist	loam
Early Evans Creek (site 2)	24.0	1.3	5YR4/6 moist	loam
Pre-Evans Creek(?)	40-70	1.45	5YR4/5 moist	silty loam
Late Hayden Creek	65-170	2.50 (1.8)[2]	10YR7/5 dry	silty clay loam
Middle Hayden Creek	130-280	3.80	5YR4/4 moist	silty clay loam
Early Hayden Creek	240-340	>3.00 (3.0)[2]	2.5YR4/6 moist	silty loam
Wingate Hill	300-600	>3.00 (5.0)[2]	5YR5/8 moist	silty clay
Logan Hill	630-1,600	>2.40 (7.0)[2]	2.5YR3/8 moist	silty clay

[1]Maximum in profile, where B horizon is not present.
[2]Values in parentheses from Crandell and Miller (1974).

Woodward-Clyde, 1978) suggest that the Logan Hill is older than about 630 ka and that it may be as much as 1 to 1.5 Ma. The oldest drift on the Cascade crest at the head of the Cowlitz River (G.A. Clayton, written commun., 1983) is at least 1.7 Ma, but it cannot be directly related to the Logan Hill Formation. If the Logan Hill is about twice as old as Wingate Hill outwash, as suggested by weathering thickness where the deposits are superposed, the Logan Hill is at least 600 ka and perhaps as old as 1,700 ka.

SAMPLING METHODS AND SOIL DESCRIPTIONS

Field description and collection procedures were designed to obtain a comprehensive sample from the soil typical of each terrace. Soils were sampled at 11 locations on 10 different geomorphic surfaces between Toledo and Salkum during August and September 1978. Locations of sampling sites are shown on figure 3. Supplementary table 1 summarizes descriptions of the sample locations and sampling methods used at each site. Sampling sites on level, undisturbed areas on terraces were chosen after completion of geologic mapping, examination of soil maps (Soil Conservation Service, 1987), and studies of natural soil exposures.

Terrace deposits younger than the early Evans Creek surfaces were generally sampled by excavating back into roadcuts or the edges of gravel pits. After careful examination for disturbance of the surface soil in these areas, we cut exposed faces back 50 to 120 cm, then described and sampled the soils. Older terraces were sampled in backhoe trenches as deep as about 3 m. Two sites (CW 4 and 5) were excavated on the early Evans Creek surface to test the variability of soil properties at different locations on the same age surface. One backhoe site, CW 1 (not shown), was abandoned because it appeared to be partly disturbed and a shallow water table made soil sampling dangerous. The soil at CW 12 (early Hayden Creek outwash) appeared to have an overthickened A horizon and a more weakly developed B_t when compared to nearby exposures in the same deposit. However, soils exposed in the backhoe pits generally resembled the upper parts of weathering profiles examined in nearby roadcuts and cutbanks. Complete samples were not collected from the three oldest terraces because soil profiles extended deeper than 3 m (the maximum depth for backhoe sampling), and natural exposures were disturbed or otherwise unsuitable for sampling.

Soil horizons and subhorizons exposed in backhoe pits and fresh natural exposures were carefully described and boundaries marked with pegs before excavation of 2-kg channel samples within about 100 cm of the peg line. Profile thickness and boundaries between horizons and subhorizons were relatively uniform in the area sampled (see supplemental table 1) and, except for the sites noted above, comparable to nearby natural exposures. Soil samples are representative of the sample site, and are considered typical of a terrace. Assessment of the range and variability of soil properties on a geomorphic surface was beyond the scope of this study, and poses formidable sampling problems (Birkeland, 1984). However, data presented in Singer and Janitsky (1986) suggest that soil chemistry from carefully chosen sites is reproducible, and that soils separated on the basis of field properties and geologic relations can be distinguished using a variety of chemical properties at a highly significant level of probability.

Soils developed on late Holocene alluvium are classified as mesic Fluventic Haploxerolls and belong to the Puyallup series, whereas the soil on the latest Pleistocene(?) surface is included in the Olequa soil series and classified as a mesic Ultic Haploxeralf (Soil Conservation Service, 1987). Soils on the Evans Creek surfaces belong to the Winston soil series and are classified as mesic Andic Xerocrepts. The soils found on the Logan Hill, Wingate Hill and Hayden Creek terraces are mapped as the Salkum soil series and described as mesic Xeric Haplohumults by the Soil Conservation Service (1987).

Extractive analyses, total X-ray fluorescence (<2-mm and fine fraction), and instrumental neutron activation (fine fraction) analyses were performed on soil samples to aid interpretation of changes in soil chemical properties with time. Results of these analyses, soil field descriptions, and soil mineralogic data are listed in the supplementary tables. Analyses listed in supplementary tables 2, 3, and 4 were performed at the University of Washington's Forest Soils Laboratory. Additional physical, mineralogic, and chemical data were presented by Bethel (1982). The data analysis presented below focuses on physical, mineralogic, and chemical changes in soils with time. This focus and procedures for data reduction limited use of the analyses in the supplementary tables. Inspection of the X-ray fluorescence data, for instance, suggested that similar time-related trends were present in the fine and <2-mm analyses. The latter values are used below to aid comparison with literature analyses, many of which are reported for the <2-mm fraction. Although chemical trends are apparent in some of the neutron-activation results (supplementary table 7), many elements repeat patterns of the X-ray fluorescence data, and some show little change with soil age. Time-related changes in soil chemistry presented below are thus calculated mainly from data in supplementary tables 1, 2, 3, 4, and 6.

DATA REDUCTION

Analysis of time-related trends in Cowlitz soil chemistry required several preliminary steps to reduce the data to a common base. Data reduction consisted of correction for missing analyses, normalization procedures using zirconium (Zr) concentrations, and correction of chemical mass values to unit soil thickness. Chemical data listed in the supplementary tables are incomplete because not all sampled subhorizons were analyzed for each soil and because the deepest horizons of the older soils were not sampled. Where multiple divisions of a horizon (B11, B12, B13, for instance) were sampled, in some cases only the one or two best developed, thickest subhorizons were submitted for analysis. In calculations I assumed that unanalyzed subhorizons had the same chemical compositions and bulk density as adjacent, analyzed samples of the same horizon. If two samples from the horizon had been analyzed, I assumed that missing subhorizons had the bulk density and chemical composition of the more weakly developed subhorizon. In most cases, chemical data from multiple subhorizons were consistent within 5 to 10 percent, but densities varied by as much as 15 percent within some horizons. Such variations are only slightly larger than uncertainty in the analytical techniques (Singer and Janitsky, 1986). Interpolation of values for unanalyzed subhorizons may slightly overestimate the contribution of that horizon to profile gains or losses, but the unanalyzed layers were generally thin. Thus errors introduced by correction for missing data probably have a minimal effect on the substantial calculated changes in soil chemistry.

Chemical analyses from all profiles were normalized to constant Zr values, assuming that total Zr in soil profiles did not change with time (Birkeland, 1984; Harden, 1987). Soil parent material was assumed to have a Zr concentration of 177 ppm and a bulk density of 1.3 g cm^{-3} (supplementary tables 2 and 6), giving a Zr mass of 0.23 mg cm^{-3} of soil. Soils developed on deposits older than late Holocene alluvium contained the lowest Zr concentrations in least altered horizons (C, C_{ox}, or B_3), whereas the highest concentrations occurred in the most leached zones (A horizons) or in the B horizon. Variations in profile Zr concentrations probably result from pedogenic processes and slight variations in parent material. Concentrations of Zr generally increase with increasing soil age and reach a peak value of over 280 ppm in the Logan Hill Formation. Relatively low Zr concentrations and low bulk density give the soil on early Hayden Creek outwash (supplementary table 6) an anomalously low mass of Zr, and the soil on the middle Hayden Creek outwash contains "excess" Zr. However, the general pattern of increase is well defined. Other oxides such as TiO_2, Fe_2O_3, and Al_2O_3 were also relatively immobile in Cowlitz soil profiles (see below). I chose to use Zr because of good analytical precision (± 10 percent) and because it is the least mobile of the elements noted in acidic soils (Birkeland, 1984). The normalization procedure minimizes the effects of apparent changes in oxide concentration that result from leaching and variations in parent material, but obscures some information about pedogenic processes.

The average oxide concentration (in grams per centimeter) in the soil profile provides a basis for analyzing time-related changes in Cowlitz soil chemistry for profiles containing _n_ horizons:

$$C_{i,p} = \sum_{n=1}^{k} C_{i,n} \cdot (t_n/T) \cdot e_n \cdot cm^2$$

where $C_{i,p}$ = horizon concentration of oxide i (percent),
t = thickness of horizon (cm),
e = horizon bulk density (g cm^{-3}),
k = all horizons in profile, and
T = total profile thickness (cm).

I chose oxide mass/profile thickness, rather than oxide mass, as the basis for comparison of different soils because it was difficult to estimate total mass values for older soils, where soil pits did not reach unaltered C material. Observation of nearby natural exposures showed that oxidation extended at least 2 m below the base of trenches on the early Hayden Creek, Wingate Hill, and Logan Hill surfaces. Use of oxide mass/depth, calculated from horizons actually sampled, provides a basis for comparison of all the Cowlitz soils, but assumes that the horizons sampled are representative of the entire weathering profile, a reasonable approximation for older profiles. In those soils, calculated chemical values are dominated by thick, strongly altered B and C_{ox}(BC) horizons that resemble unsampled parts of the soil.

DISCUSSION OF THE SOIL CHRONOSEQUENCE

Parent Material

Soils of the Cowlitz River chronosequence are developed from remarkably similar sediment with respect to both depositional environment and mineralogy. Mineralogic studies of the soil samples suggest that they are derived almost exclusively from volcanic rock: late Tertiary andesite and basalt, and Quaternary andesite and dacite (Bethel, 1982). Addition of substantial amounts of tephra to the Cowlitz basin can be documented from at least Hayden Creek time to the present, and tephra deposition probably occurred periodically throughout Quaternary time. Resistant clasts of andesite and basalt dominate the gravel fraction of all the terrace units, whereas loess caps on the gravel contain tephra as well as volcanic silt and fine sand. Superimposed loess mantles have been recognized at only a few places in the Cowlitz River area, but it is likely that some windblown material was added to all existing terrace surfaces during each glaciation. No systematic variation in the thickness or texture of eolian layers can be demonstrated in the Cowlitz River area. However, periodic additions of dacitic tephra and windblown material probably influenced soil formation on all terrace surfaces. For long time intervals, the influx of tephra can be viewed as constant, except for the fine-grained layer on Evans Creek surfaces, which is particularly rich in glassy, dacitic debris (Bethel, 1982).

Field Properties

The age control for Cowlitz River terraces provides a framework for studying changes in soil development with time. In addition, if other factors such as climate and vegetation were similar for the different terraces, rates of soil development can be inferred from soil-age plots (Harden, 1982a; Harden and Taylor, 1983). These rates, however, are subject to uncertainties in the age estimates.

Soils on the Cowlitz terraces display striking variations in thickness and degree of development. The depth to unweathered material in the soil profile (fig. 5) increases quite regularly with time, except for the anomalously thick and oxidized zone on the middle Hayden Creek surface. Other simple field measurements such as the strongest hue and finest texture in the B horizon show a general trend with increasing age: hues become redder and the amount of clay increases (fig. 5, table 3).

The degree of soil development in the Cowlitz sequence can be quantified using a number of field properties (Harden, 1982a). Field properties that change most systematically with age are the best indices for the degree of soil development, and these properties include pH lowering, clay films, rubification (development of hue and chroma), total texture (texture and wet consistence), and the index that combines soil properties (fig. 6). Field properties that were not good indices of soil development include soil structure, melanization (darkening of the topsoil), and moist consistence.

Field properties can be plotted against linear, log, or ranked (young to old) time to compare rates at which these properties develop. Most field properties develop rapidly at the young end of the time scale. This suggests that rates of soil development are initially rapid and appear to decline after a few hundred thousand years (fig. 7B). When properties are plotted against log time, the curves appear to be straight, suggesting that over long periods of time, soils develop at decreasing exponential rates (fig. 7C). The ages of the Cowlitz soils and deposits are not well defined, therefore observations of curve shape are subject to considerable uncertainty.

Given the uncertainty of age estimates, the best way to test the significance of soil development increasing over time is by using rank regression. For this method, the soil property is ranked from lowest to highest for all soils of the chronosequence; similarly, the ages of the soils are ranked from low (young) to high (old). The ranked soil property is then plotted against ranked age (for example, the oldest soil in figure 7C has the tenth highest index of soil development, thus the x,y coordinates are 10, 11). Linear regression is then applied to the ranked data, and the regression coefficient (Spearman's rho coefficient) is then a test for significance. The Spearman's rho coefficients greater than about 0.55 are significant at the 90 percent confidence level. Coefficients for field data are as follows: total texture (0.71); rubification (0.77); clay films (0.83); structure (0.58); moist consistence (0.52); melanization (0.36); pH lowering (0.89) and index (0.90). The index was calculated from total texture, rubification, clay films, and moist consistence, because these were properties used by Harden and Taylor (1983). If pH lowering were substituted for moist consistence, the regression coefficient would improve.

The systematic increase of texture, clay films, rubification, and pH lowering are probably the result of various soil-forming processes. Total texture and clay films reflect the formation and orientation of clays; the mineralogy section below demonstrates that kaolinite is probably the predominant pedogenic clay forming in these soils. This is consistent with the decreasing pH of these heavily leached soils. Increasing rubification with time represents increasing color hue and chroma; iron oxides are forming in the soils (see below), although the data do not indicate how rapidly oxidation states of the iron change with time.

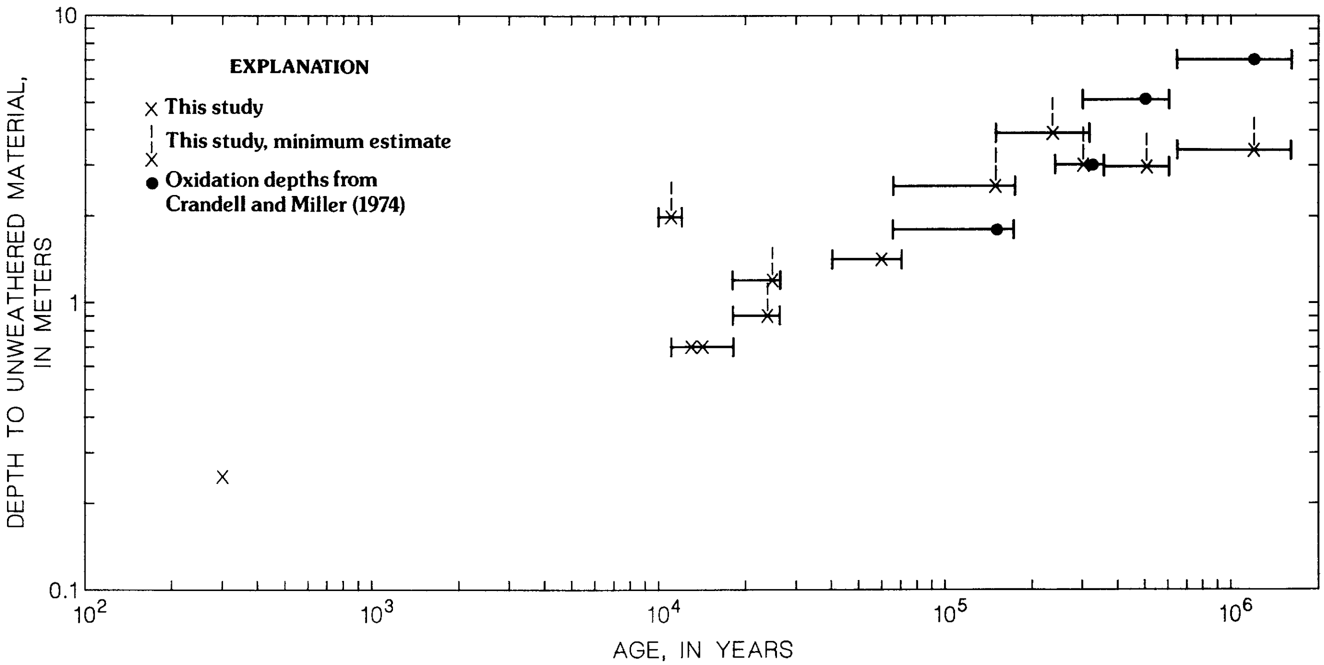


Figure 5. Relation between soil-profile age and depth to unweathered material, Cowlitz River soils, Washington. Age estimates and uncertainty (error bars) from table 2.

Mineralogic Changes in the Sand and Clay Fraction

Bethel (1982) documented systematic and nonsystematic changes with time in heavy minerals (sand fraction) and in clay (<1 μm) mineralogy from the deepest horizon (C, C_{ox}, or B_3) of nine soils presented in this study. With the exception of the opaque fraction, the percentage of heavy minerals decreases with time, concurrent with increases in the degree of inosilicate etching. Changes in clay mineralogy with time are less dramatic, but they suggest that clay in deposits older than about 25 ka is in equilibrium with the weathering environment, whereas fine clay in younger deposits reflects both inherited mineralogy and weathering effects (Bethel, 1982). However, several problems confound this analysis. Sand-size grains are present in the matrix of the outwash deposits, but with increasing time such grains are also derived from the weathering of clasts, providing a source of fresher material. Weathered grains and clay from older deposits and the Wilkes Formation probably contributed to the sand and fine fraction of younger outwash deposits as well. Because the C horizons of younger soils are not appreciably altered, analysis of mineral alteration in C horizons might have provided better comparisons, but our data are insufficient.

The change in so-called heavy grain content (ferromagnesian silicates, opaque minerals, and aggregates of heavy minerals) of Cowlitz deposits gives clear general trends over time (fig. 8) and scatter probably related to periodic additions of fallout tephra (Bethel, 1982). Ferromagnesian silicates (pyroxene, amphibole, and olivine) decreased from about 50 percent of the heavy grains in Holocene deposits to less than about 15 percent in pre-Wisconsin deposits. No ferromagnesian minerals were present in the Logan Hill deposits, which contained 60 percent opaques such as magnetite and ilmenite. These minerals formed less than 20 percent of the late Pleistocene heavy-mineral fraction. Olivine composed 5 to 45 percent of the total ferromagnesian fraction in Evans Creek and younger deposits, which Bethel (1982) attributed to eruption of olivine-bearing tephra at Mount St. Helens or Mount Rainier. However, the persistence of small amounts of olivine 2 m below the present land surface in Wingate Hill deposits is surprising, given the instability of this mineral in laboratory (Grandstaff, 1986) and field (Birkeland, 1984) settings.

The abundance of ferromagnesian and opaque minerals can be used as a general guide to the age of Cowlitz River deposits, but the degree of mineral etching should be a more reliable age indicator because it is less dependent on slight variations in the composition of parent material. The degree of hornblende weathering, or etching (fig. 9) increases with age, and the etching of pyroxenes (orthopyroxene and clinopyroxene) shows a similar trend (Bethel, 1982). Because hornblende grains were absent in several samples, and relative abundance of the two

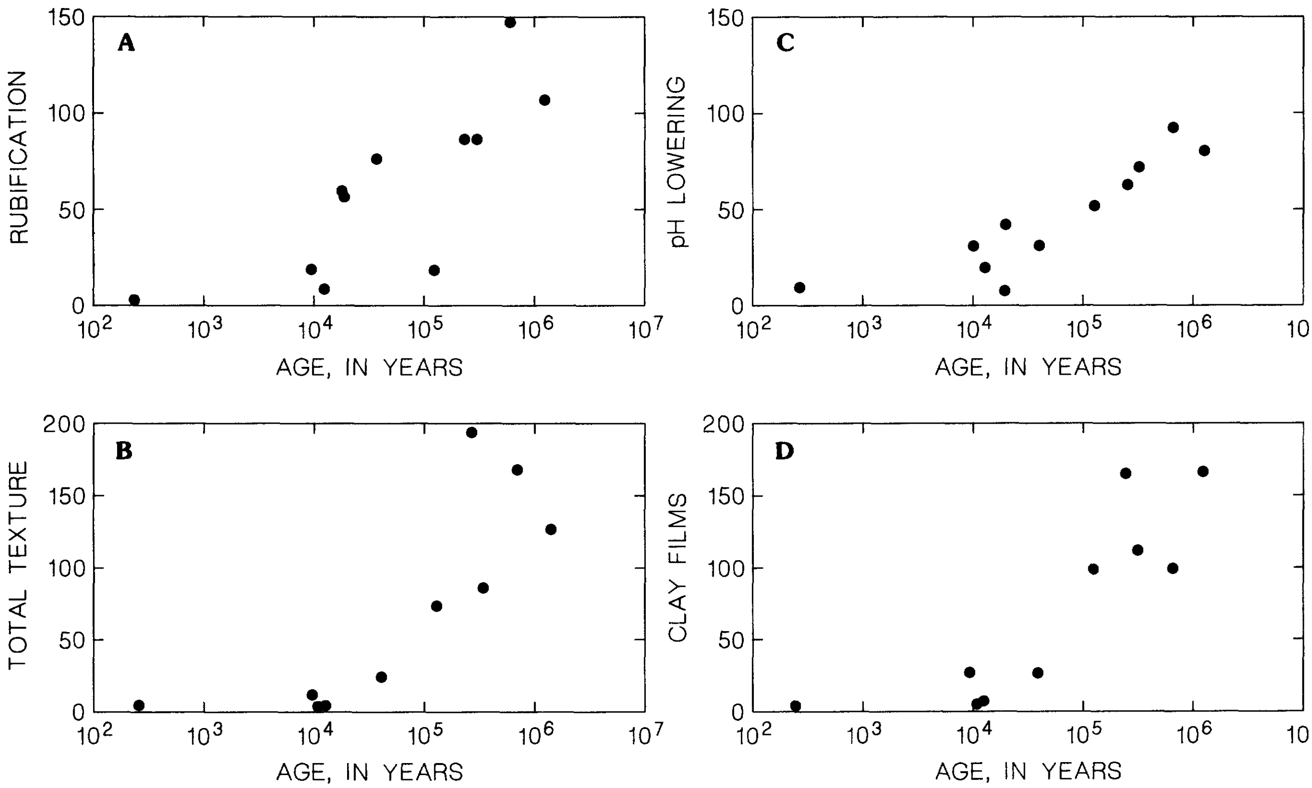


Figure 6. Profile properties versus log time for rubification (A), total texture (B), pH lowering (C), and clay films (D). Calculated after Harden (1982a).

pyroxenes varied, there is some uncertainty in age-etching relations. Nonsystematic changes in mineral abundance suggest that periodic additions of ferromagnesian minerals in tephra complicate a simple model of mineral etching in the Cowlitz area.

Kaolinite (or metahalloysite) dominates the 1-μm fraction of most samples from the Cowlitz sequence, but a chloritized 2:1 mineral (vermiculite?) and smectite are important components of some soils (supplementary table 4). Soils younger than about 25 ka have abundances of kaolinite (K) > smectite (S) > vermiculite (V) > illite (I)=chlorite (C), whereas the three oldest soils showed K > V ≫ S=C=I. Smectite is uncommon in deposits older than Evans Creek outwash, whereas vermiculite(?) is most abundant in deposits of Hayden Creek age and older, probably as sesquioxides

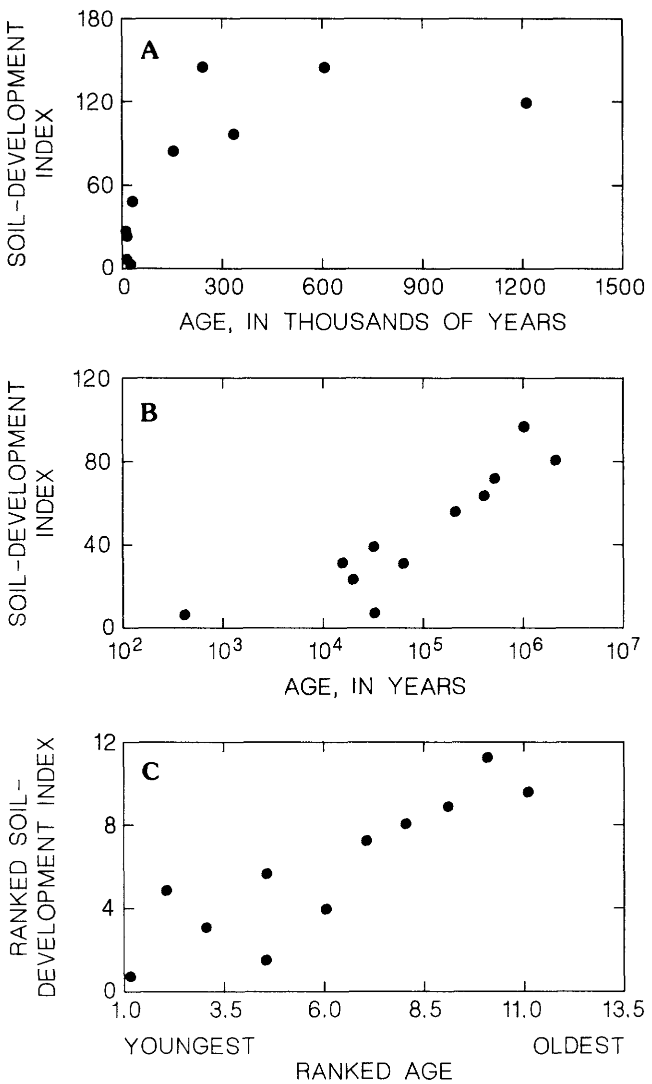


Figure 7. Soil-development index versus age (A), log age (B), and ranked age (C). Soil development index (Harden, 1982a) calculated from four properties: total texture, rubification, clay films, and moist consistence.

filled the interlayer position. In X-ray analyses, the 7 angstrom basal reflection increased in height and decreased in width with increasing age, suggesting progressive crystallization of kaolinite and (or) an increase in the size and crystallinity of metahalloysite (Bethel, 1982). These trends suggest that a kaolin phase is stable and smectite is unstable in Cowlitz soil environments. More detailed work is required to assess the significance of the 2:1 interlayer clay, but the increase in extractable Fe and Al (Fe_d and Al_d, respectively) in older soil horizons likely correlates with the abundance of these oxyhydroxides in interlayer positions. Holocene and late Wisconsin soils contain kaolinite, 2:1 interlayer clay, and minor illite and smectite in all horizons, whereas the early Hayden Creek, Wingate Hill, and Logan Hill soils contain the same mineral suite, but smectite is less abundant. Because kaolinite is abundant in the parent material for each soil, the decrease in smectite and increase in the 2:1 interlayer clay may be the most significant trends in clay mineralogy with time.

Time-Related Changes in Soil Chemical Properties

Changes in the bulk chemical composition of Cowlitz soils reflect progressive losses of alkaline earth metals, SiO_2, and Al_2O_3, and relative accumulation of TiO_2, Fe_2O_3, and Zr with time. The degree of chemical change can be analyzed from relative elemental mobility (Harden and others, 1986), from mass-balance calculations corrected using a stable element such as Zr (Harden and Taylor, 1983, Birkeland, 1984, Harden, 1987), or using a variety of techniques reviewed by Birkeland (1984). Supplemental tables 3, 5, and 6 list extractive and oxide analyses for the <47-μm and <2-mm fractions of the Cowlitz soils; supplemental table 7 lists selected trace-metal analyses for the <47-μm fraction that were not corrected for the mass of gravel in samples. Relative elemental mobility has been used widely to compare environments of chemical weathering (Birkeland, 1984). I calculated a simple index of elemental mobility (<2-mm fraction) for the Cowlitz soil sequence by comparing the Zr-normalized ratio of oxide mass (in soil CW6) to oxide mass soil for each oxide. Calculations showed the following ranking of mobilities:

Ca, Na, Mg>K>Si>Al>Fe, Ti, Zr
mobile-----------------immobile

Elements that had similar ratios of mobility (within a factor of 2) are separated by commas. For instance, Ca and Na had ratios of 56 and 30, respectively, whereas the K ratio was about 5.5 and Si about 1.7. Iron and titanium were relatively immobile. Harden (1987) and Harden and others (1986) reported similar overall mobility patterns from a complex analysis of elemental mobility throughout chronosequence development. Elemental mobility in the <47-μm fraction of Cowlitz soils is similar to values listed above for the <2-mm fraction, except Si is nearly as immobile as Al.

Because Zr is immobile in weathering profiles and Cowlitz parent material is nearly constant, depletion of less stable components should produce increases in the apparent Zr concentration with time. Loss (or gain) of elements relative to Zr is thus a measure of mobility. Mobility trends can be evaluated using dimensionless values for the oxides of interest. Figure 10 shows such a plot for the oxides TiO_2, Al_2O_3, Fe_2O_3, and SiO_2 versus Zr, where all values are made dimensionless by normalizing them against soil CW6, the parent material. The plot scatters about the line x=y for TiO_2 and Fe_2O_3, but SiO_2 losses are highly significant ($p<0.01$) and Al losses are significant ($p<0.10$). General trends in figure 10 show that TiO_2 and Fe_2O_3 are conserved as the Zr ratio (or soil age) increases and that SiO_2 and Al_2O_3 are somewhat mobile. Scatter in each of the oxide trends (for instance, in soils CW4, CW5, and CW12) probably results from slight differences in the mineralogy or texture of parent material.

The relative mobility of soil oxides with time reflects the chemical composition of parent material and acidic weathering solutions typical of humid regions. Titanium and Zr oxides are nearly insoluble in mildly acidic soil waters (Birkeland, 1984). Losses of SiO_2 and Al_2O_3 relative to Zr during soil formation were probably enhanced by the abundance of easily weathered glassy material and the mobility of silica and aluminum complexes at soil pH values below 5.5. The stability of iron in weathering profiles results from the immobility of oxidized Fe in well-drained material. Formation and accumulation of extractable iron (Fe_d) (supplementary table 3) corresponds to the oxidation of Fe in ferromagnesian minerals during weathering, and strong sorption of iron oxyhydroxides at low soil pH (McFadden and Hendricks, 1985). The immobility of Zr, Ti, and Fe over time suggests that any of these elements could be used in studies of humid weathering.

Changes in normalized oxide content can be calculated for each soil relative to parent material, or plotted as functions of time. Depletion of a soil oxide in 1 million years of weathering, for instance, can be calculated from its concentration in a million-year-old soil and in soil CW6, where CW6 is assumed to have approximately the same composition as the parent material. The Logan Hill soil, of roughly 1 m.y. age, contains about 80 percent, 58 percent, 17.7 percent, 3.3 percent, and 1.8 percent, respectively, of the Al_2O_3, SiO_2, K_2O, Na_2O, and CaO originally present in the parent material. Elemental losses of most constituents are correlated with log time in the Cowlitz soils. Soil depletion of SiO_2 (fig. 11) is a significant ($p<0.01$) linear function of log time, but the data could also be fit by two different line segments with a break near 140 ka. Losses of Al_2O_3 and Fe_2O_3 are not significant functions of time at the 95-percent confidence level, but at least some unexplained variance results from an apparent change in slope that corresponds with middle Hayden Creek time. Alkaline earths are lost more rapidly than losses of SiO_2, Al_2O_3, and Fe_2O_3, and individual patterns of K, Na, and Ca depletion with time are different (fig. 12). Soil potassium concentrations, for instance, can be plotted

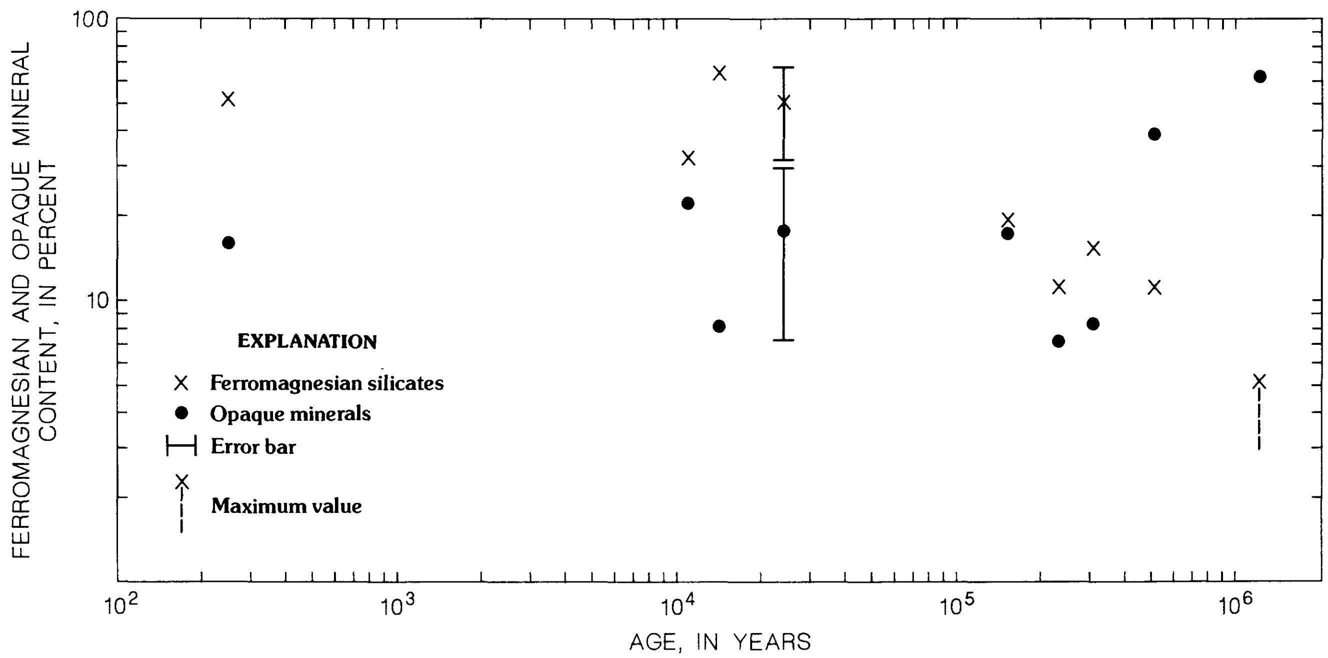


Figure 8. Percent ferromagnesian and opaque minerals in heavy (>2.89 g cm^{-3}) mineral fraction of sand versus time in C, C_{ox}, and B_3 horizons of Cowlitz soils (modified from Bethel, 1982). Error bars for older Evans Creek soil show the range of samples from three sites; Logan Hill Formation ferromagnesian value is upper limit.

against log time as two linear segments with a break between about 60 and 150 ka (log-log or log-linear), or as a linear function of log time. Sodium depletion can be explained as a linear function of log time, but could also be fit by two linear segments with a break between 60 ka and 150 ka. Calcium losses are a linear and highly significant function of log time.

The apparent change in weathering rate of some soil components near 130 ka may be related to parent material or to climate change. Heavy-mineral composition and abundance suggest that the pre-Evans Creek(?) and the late Hayden Creek deposits contained similar mixtures of minerals (Bethel, 1982). The pre-Evans Creek(?) and younger soils are mainly developed in loess caps, whereas parent material for Hayden Creek and older deposits includes both loess and the underlying gravel. The break in slope displayed by the K and Na loss rates, and suggested by the SiO_2, Al_2O_3, and Fe_2O_3 data, indicates more rapid oxide depletion in soils developed before about 130 ka. The relative abundance of clay minerals, particularly kaolinite and vermiculite (supplementary table 4), also shifted at about this time. Soil weathering may have occurred at different rates in the two textures of parent material, or the data may suggest an unrecognized influx of loess at about 130 ka. Greater effective moisture could also have produced more rapid leaching rates and mineral alteration for soils older than about 130 ka. This inference cannot be checked, however, as well-documented reconstructions of climate are available only for the late Pleistocene of the Pacific Northwest.

Accumulation of pedogenic clay, Fe_d, and Al_d with time produces soil changes apparent in both field and laboratory properties. Soil rubification and textural changes (fig. 6) are correlated with soil age and are directly related to the laboratory measurements of Fe_d and 1-µm clay. Clay-rich, strongly oxidized soils developed in pre-Wisconsin deposits contain 2 to 4 times more 1-µm clay and Fe_d than the late Wisconsin soils, and B-horizons on the Wingate Hill and Logan Hill surfaces contain 45 to 60 percent clay. Log-soil age accounts for 94 and 80 percent of the variance in log Fe_d and clay content, respectively, in the Cowlitz soils (fig. 13). After Fe is released from ferromagnesian minerals during weathering, it should accumulate as Fe oxyhydroxides,

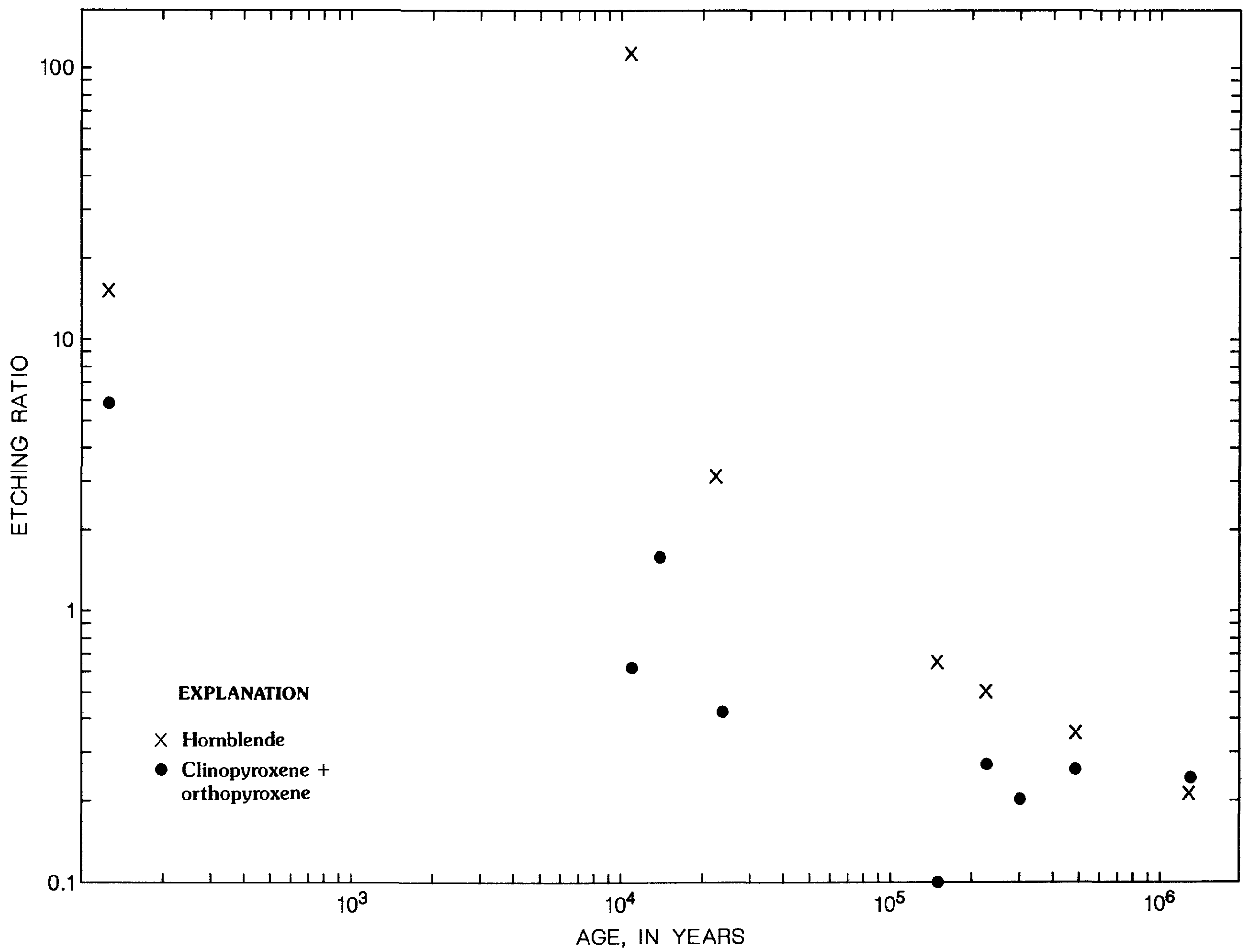


Figure 9. Etching ratio for hornblende and clinopyroxene + orthopyroxene from Cowlitz soils. Ratio is percent of unetched and slightly etched grains divided by percent of grains with moderate or greater etching.

which are included in Fe analyses. If such newly formed Fe-compounds are not converted to crystalline species such as hematite, the ratio Fe_d/Fe_2O_3 should increase with time. The ratio Fe_d/Fe_2O_3 is about 0.1 in the youngest Cowlitz soils and about 0.35 in the three oldest soils, but changes with time are not linear, which suggests some incorporation of Fe_d into mineral lattices. Extractable Al varies considerably with soil age, but the correlation is significant at the 95-percent confidence level. Slight depletion of total soil Al (fig. 11) with time and the variance in Al_d shows that some Al freed by mineral and glass weathering is leached from the soil. Some fraction of the mobile Al is incorporated in fine-grained clays such as halloysite. Latest Pleistocene(?) and late Evans Creek soils contain considerably more clay and almost as much Fe_d and Al_d as the older Evans Creek soils. This pattern is probably related to the addition and rapid weathering of substantial quantities of fine-grained siliceous tephra in the Cowlitz Basin between about 14 ka and 10 ka (Barnosky, 1984; Bethel, 1982).

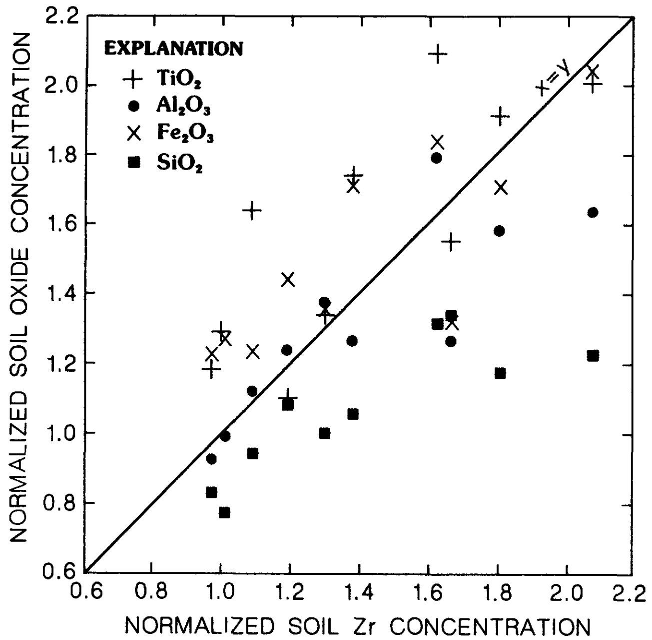


Figure 10. Concentrations of TiO_2, Al_2O_3, Fe_2O_3, and SiO_2 in Cowlitz soils normalized to parent material (late Holocene alluvium, CW6), versus Zr normalized to same material.

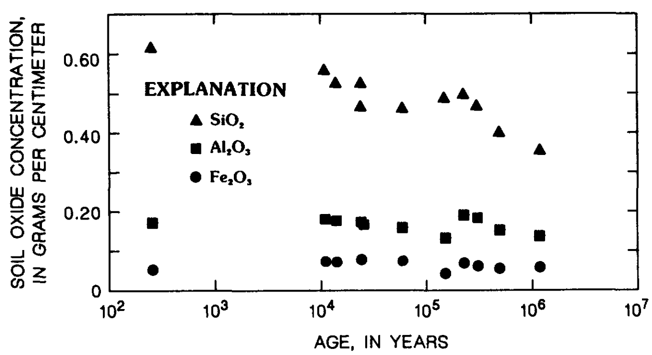


Figure 11. Concentration of SiO_2, Al_2O_3, and Fe_2O_3 versus time for 11 Cowlitz soils.

Estimation of Soil Age from Soil Chemical Parameters

Field measurements, several soil indices calculated from field measurements (figs. 6, 7), and some bulk and extractive-chemical parameters permit relative age separation of many Cowlitz soils. Soil indices demonstrate that there is a considerable age difference between late Hayden Creek and Logan Hill soils, supporting the geologic age estimates. Age estimates for the Wisconsin age deposits are also consistent with most soil data. Calculated soil indices and chemical data, however, do not clearly separate pre-Evans Creek(?) outwash and late Hayden Creek outwash. Several soil indices, including profile pH lowering and the ranked soil development index, are

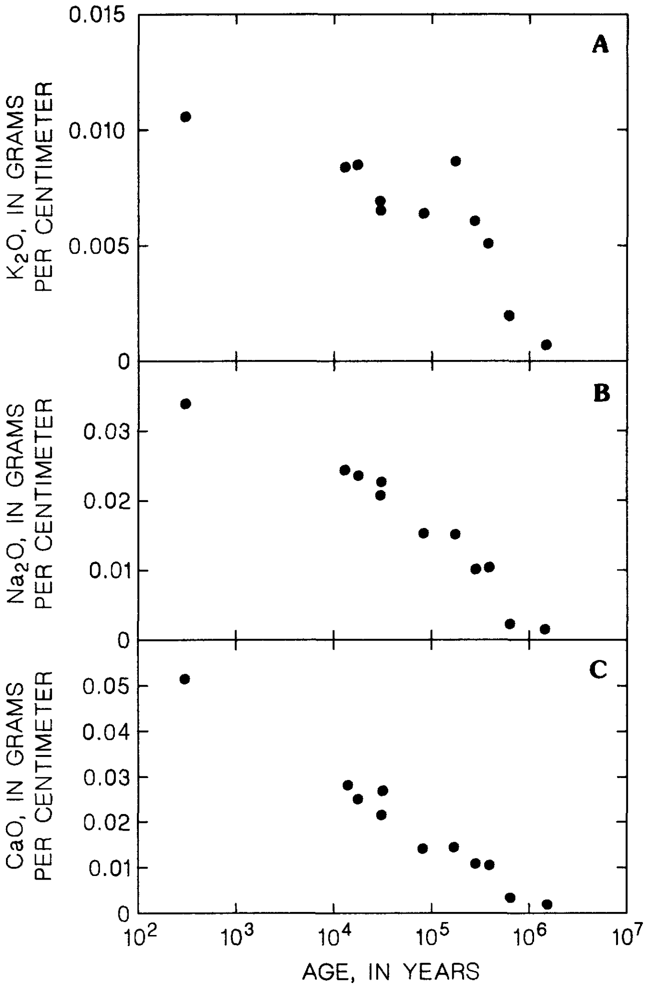


Figure 12. Concentration of K_2O (A), Na_2O (B), and CaO (C) versus time for 11 Cowlitz soils.

strongly correlated with log age, but losses of Ca and Na from weathering profiles and accumulation of Fe_d are most highly correlated (highest r^2 values) with soil age.

Strong correlations between estimated deposit age, soil field measurements, and chemical parameters suggest that physical and chemical data from the Cowlitz soils could be used to predict soil age and thus deposit age. The 95-percent confidence limits on calculated least-squares regression lines provide an instructive test of the value of soil-chemical parameters in estimating deposit age. Two related measures of reliability can be calculated for the regression line: the 95-percent confidence interval for the regression ordinate, and the 95-percent prediction interval for individual observations. For relations of deposit age and soil chemistry, the former interval corresponds to how closely mean deposit age can be predicted from a soil-chemical parameter. The latter measures how closely an individual value for deposit age is predicted by a chemical measurement such as Fe_d. The 95-percent confidence band is narrower for prediction of mean deposit age. As I illustrate below, prediction reliability is hampered by the limited number of observations (11) that define the regression line. However, the range of ages estimated from certain soil-chemical properties is in reasonable agreement with the geologic age estimates used to calibrate the regression relationships.

Soil chemistry cannot provide independent age estimates for Cowlitz outwash deposits, but figures 14A and 14B illustrate the precision of ages calculated using the strongest correlations from the Cowlitz data. Depletion of soil Ca and gain of Fe_d, normalized by Zr values and expressed as g cm^{-1}, are the two closest predictors of deposit age for the Cowlitz sequence. Calcium levels in the soil account for almost 97 percent of the variance in log age (fig. 14A), whereas about 94 percent of the variance in log age is explained by Fe_d (fig. 14B). Predictions about mean deposit age from Ca values give the most precise age estimates. In table 4, I compare the age estimated from geologic relations (table 2) to age ranges calculated from soil chemistry. Despite the high r^2 values, predicted age ranges are quite wide because of the limited number of soils. Calcium values, however, show significant age separation between (1) latest Pleistocene(?) and late Evans Creek deposits; (2) Evans

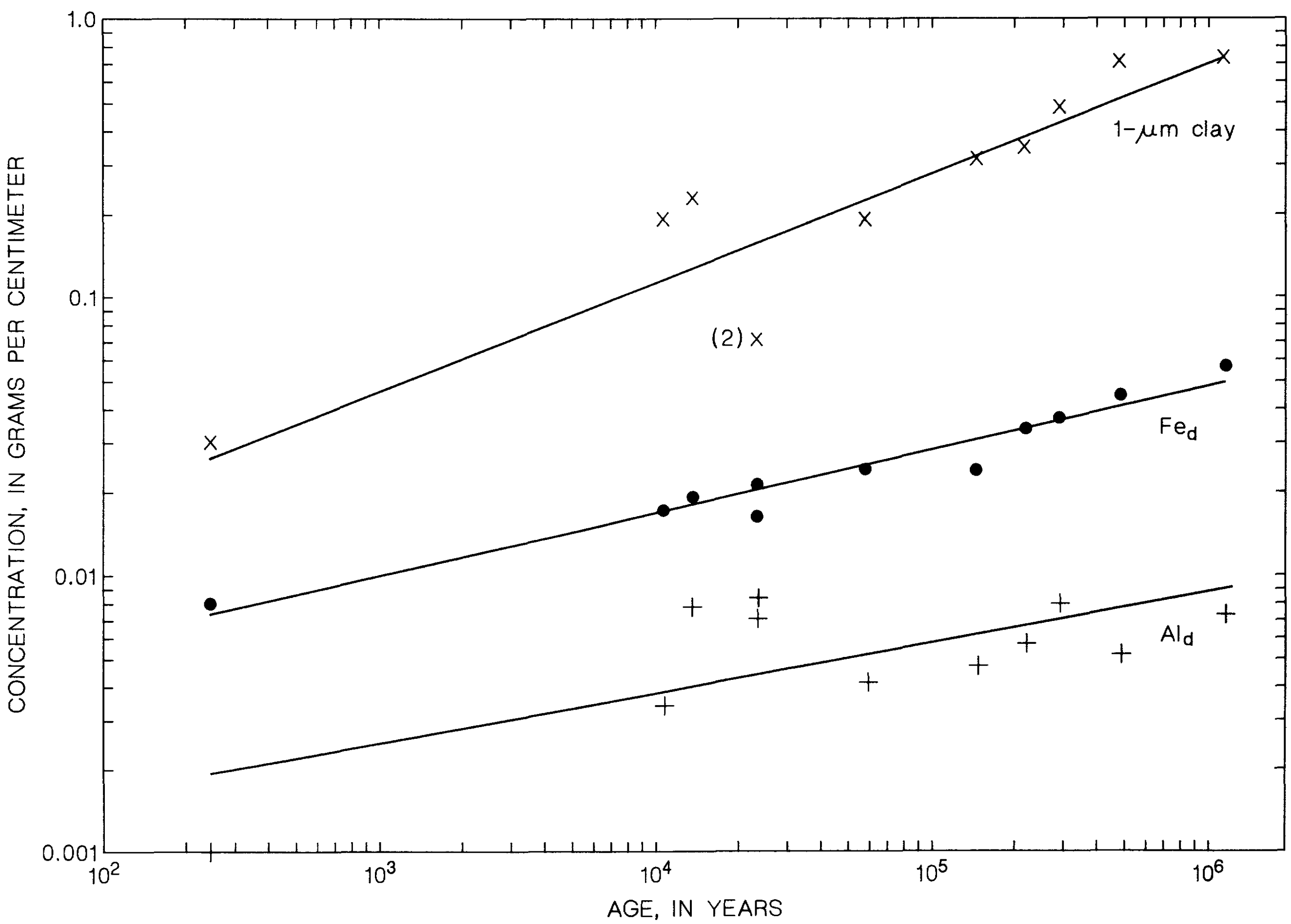


Figure 13. Log concentration plot of 1-μm clay (r^2=0.94), Fe_d (r^2=0.94) and Al_d (r^2=0.45) versus log soil age, where r^2 is the proportion of the total sum of squares explained by the regression line, Fe_d is dithionite-extractable iron, and Al_d is dithionite-extractable aluminum.

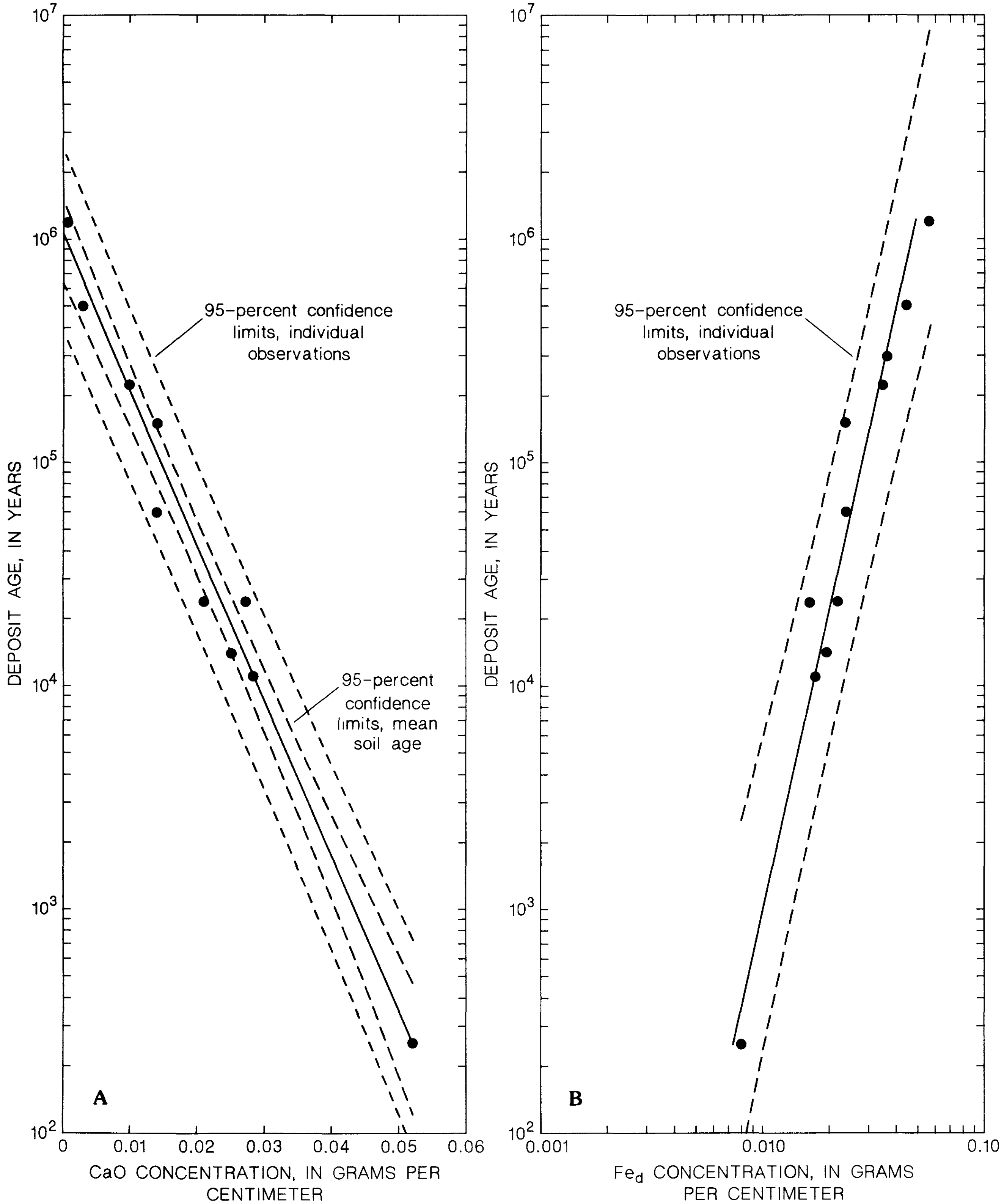


Figure 14. Deposit ages estimated from analysis of Cowlitz soil chemistry. A, CaO versus age. The 95-percent confidence limits for individual observations and for mean soil age are shown as dashed lines. B, Fe_d concentration versus age. The 95-percent confidence limits for individual observations are shown as dashed lines.

Creek and pre-Evans Creek(?) deposits; (3) late and middle Hayden Creek deposits; and (4) Hayden Creek and Wingate Hill deposits. Deposit ages predicted from the Ca or Fe_d content of early Evans Creek soils could be distinguished from ages predicted by latest Pleistocene(?) and late Evans Creek soils only by averaging values for the two early Evans Creek soils. The pre-Evans Creek(?) deposits cannot be distinguished from the late Hayden Creek deposit by these calculations. Age predictions from Ca values do not clearly separate Wingate Hill deposits from the Logan Hill Formation, but there are significant (90-percent confidence level) differences in Fe_d and other soil parameters (figs. 5, 6, 12A) for soils on these deposits.

Table 4 and figure 12B suggest age equivalence of pre-Evans Creek(?) and late Hayden Creek soils, as well as a significant discontinuity between these soils and those developed on middle and early Hayden Creek surfaces. Potassium depletion (fig. 12A), plots of SiO_2, Al_2O_3, and Fe_2O_3 with log time (fig. 11), soil physical properties (fig. 6), and development indices (fig. 7), however, show strong discontinuities at about 100 ka and suggest that pre-Evans Creek(?) and late Hayden Creek soils are of different age. The pattern of fine clay accumulation also displays distinct breaks between the pre-Evans Creek(?) and late Hayden Creek soils. Geologic evidence suggests that the pre-Evans Creek(?) deposit is of early Wisconsin age and that the late Hayden Creek surface is pre-Wisconsin (table 2) in age. Most physical and chemical properties of soils on these surfaces reflect a time break between the two deposits. There is some possibility, however, that the late Hayden Creek soils are about 65 ka old, some 85 ka younger than estimates in table 2; in that case, the age of the Wingate Hill deposits could be 50 to 100 ka less than the 500 ka suggested by weathering-rind data. Radiometric dating and paleomagnetic studies of the Wingate Hill and Logan Hill deposits would help refine trends in physical and chemical development for older soils in the Cowlitz sequence.

Comparison to Other Soil Chronosequences

Chemical weathering rates in southwestern Washington should reflect the influence of two primary soil-forming factors: easily weathered andesite materials and a cool, moist climate. Lithology and moisture regime in the soil sequence along the Cowlitz River might be expected to promote more rapid weathering than in most chronosequences in the Western United States (Harden and Taylor, 1983; Harden, 1982a; Busacca, 1982; Harden, 1987; Harden and others, 1986). However, at least some physical and chemical soil properties are broadly comparable in their development to those reported from other areas. Soil profile characteristics such as the thickness of the argillic B horizon, structure, and depth of oxidation are similar to those of the Merced (California) and Susquehanna River Valley (Pennsylvania) chronosequences (Harden and Taylor, 1983). Soil rubification (Harden, 1982a) is stronger at sites in central and southern California (Harden, 1982a; McFadden and Hendricks, 1985; Harden, 1987) than in southwestern Washington. Cowlitz soils formed in a cooler climate and are more extensively leached than soils of the California chronosequences noted above but not more than those of the Pennsylvania sequence. The generally cool temperatures and absence of an extended dry period during the summer probably slow development of soil structure and rubification (Birkeland, 1984). In addition, the outwash gravel beneath Cowlitz silt caps is coarse, and the textural contrast and clast size may influence soil development and thus calculated soil indices.

The etching of heavy minerals is apparently slower in Cowlitz soils than it is in the Merced soils described by Harden (1987), and clay mineralogy does not show the strong time-related trends that Harden reported. In the Cowlitz area, heavy-mineral etching and clay mineralogy were probably influenced by weathered heavy minerals and clays inherited from the underlying Wilkes Formation and fresh heavy minerals

Table 4. Comparison of predicted soil ages for Cowlitz deposits to the age range predicted from soil chemistry, in thousands of years

Predicted from geologic relations	Predicted from soil chemistry		
	Ca[1]	Ca[2]	Fe_d[2]
0.25	0.1-0.5	0.1-0.7	0.0-2.5
11	8.4-15.7	4.7-28.0	2.5-51.0
14	14.0-24.6	7.6-45.0	5.0-84.0
24	9.9-18.2	5.5-33.2	2.5-43.0
24	27.3-46.0	14.5-86.5	7.9-129
60	83.7-148	45.0-300	11.5-190
150	83.7-148	45.0-300	11.5-190
225	154-283	85-515	54-920
500	438-953	255-1,640	160-3,100
1,200	594-1,370	350-2,360	400-8,600

[1]95-percent confidence interval for mean soil age.
[2]95-percent confidence interval for individual soil age.

contributed by periodic volcanic eruptions. Despite these variations in parent material, it is somewhat surprising that heavy minerals in Cowlitz soils are not more deeply etched.

Clay and Fe_d accumulation are significant time-related parameters common to most soil chronosequences in humid regions (Birkeland, 1984). I calculated the soil-profile masses of 1-μm clay and Fe_d formed in 500,000 years by multiplying soil concentrations (fig. 13) by the sampled thickness (300 cm) of the Wingate Hill profile minus the mass of these constituents in 300 cm of parent material (soil CW6). The Cowlitz values reported in table 5 are minimum estimates because Wingate Hill weathering profiles extend deeper than 3 m (table 3); the red color and fine texture of a Wingate Hill soil exposed 4 m below the surface in roadcuts north of Salkum suggest that estimates in table 5 could be low by as much as 15 percent. Accumulation rates for Fe_d in the Cowlitz sequence are higher than the other rates listed in table 5. Abundant moisture, low soil pH, and high levels of Fe_2O_3 in parent material probably contribute to the rapid accumulation of Fe_d.

The rapid accumulation rate (table 5) and high percentage of clay in Cowlitz subsurface horizons likely reflect pedogenic generation of fine material at rates substantially faster than those at warmer, drier sites. The deeply weathered Wingate Hill deposits and remarkable gravel saprolite of the Logan Hill Formation contain 35 to 55 percent fine clay, much of which likely formed in place. Clasts that are 90 percent clay preserve their original morphology perfectly and show no evidence of cracking or other mechanical disruption, demonstrating that the clay formed in place. Some of the clay in the upper horizons of the Logan Hill and Wingate Hill soils doubtless originated as eolian debris. However, the rate of eolian transport to Cowlitz soils is probably lower than eolian contributions measured or calculated for California chronosequences (for instance, in Ventura; Harden and others, 1986), where climate is drier and vegetative cover is lower.

CONCLUSIONS

Soils developed on terrace surfaces along the Cowlitz River range from a youthful A/C profile in the modern flood plain to clay-rich, deeply oxidized profiles on the early or middle Pleistocene Logan Hill Formation. Terraces formed on outwash gravel capped with windblown material derived from nearby channels and Cascade stratovolcanoes. The gravel is composed of Tertiary and Quaternary andesitic and basaltic lava, breccia, tuff, and minor amounts of late Quaternary dacitic tephra. Four principal terrace groups, each including one or more surfaces, were recognized in the field by topographic position and elevation. They are late Wisconsin Evans Creek Drift, pre-Wisconsin Hayden Creek Drift, middle Pleistocene Wingate Hill Drift, and the early or middle Pleistocene Logan Hill Formation.

Soil profiles on the terrace surfaces show systematic changes with time. The depth to unweathered parent material, texture, soil rubification, pH lowering, clay films, and soil-development indices (Harden and Taylor, 1983) change systematically with estimated age in the sampled soil profiles and at other nearby exposures. Heavy-mineral content in deeper soil horizons decreases as the degree of mineral etching increases, and the percentage of well-ordered kaolinite increases with time. The strongest time-related trends are the loss of CaO and Na_2O, and the gain of Fe_d and 1-μm clay. Soil depletion of CaO, for instance, could be used to predict deposit ages. However, there are anomalies in soil development. The latest Pleistocene(?) soil is as well developed as early Evans Creek soils, and the early Hayden Creek soil has an overthickened A horizon, lacks a strong textural B horizon, and is not as well developed as the soil from nearby exposures on the same surface. The chemistry of the pre-Evans Creek soil and the late Hayden Creek soil are similar, and a number of chemical trends show changes in slope between about 60 and 150 ka. Because rock type and climate fluctuations are similar for all surfaces,

Table 5. Accumulation rate for dithionite-extractable Fe and clay for Cowlitz and other soil sequences, Western United States

Locality	Annual precipitation (mm)	Parent material	Accumulation in 500,000 yr (g/cm^2) Fe_d	Clay
Cowlitz[1]	1,375	Andesitic outwash	11.1	201
Merced[2]	300	Granitic	2.8-3.5	50-65
Transverse Ranges[3]	400-780	Lithic, arkosic alluvium	8.7	74
Ventura[4]	360	Sedimentary alluvium	3.6	90

[1]This report, Wingate Hill soil (CW2).
[2]Harden (1987).
[3]McFadden and Hendricks (1985, p. 192, 198).
[4]Values interpolated to 500 ka from late Pleistocene rates calculated by Harden and others (1986).

differences in texture in the glaciofluvial material, thickness variations in the loess mantle, or postdepositional modification of the terrace surface most likely account for the anomalies in profile development. Overall trends indicate that soils developed on Cowlitz River terraces formed systematically in andesitic parent materials under cool, moist conditions during most of Quaternary time.

REFERENCES CITED

Barnosky, C. W., 1981, A record of the late Quaternary vegetation from Davis Lake, southern Puget lowland, Washington: Quaternary Research, v. 16, no. 2, p. 221-239.

____1983, Late-Pleistocene vegetation and climate of lowlands in southwestern Washington: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 429.

____1984, Late Pleistocene and early Holocene environmental history of southwestern Washington, U.S.A.: Canadian Journal of Earth Sciences, v. 21, no. 6, p. 619-629.

Beget, J.E., 1983, Radiocarbon-dated evidence of worldwide early Holocene climate change: Geology, v. 11, no. 7, p. 389-393.

Bethel, J.P., 1982, An investigation of the primary and secondary mineralogy of a sequence of glacial outwash terraces along the Cowlitz River, Lewis County, Washington: Seattle, University of Washington, M.S. thesis, 90 p.

Birkeland, P.W., 1984, Soils and geomorphology: New York, Oxford University Press, 372 p.

Burbank, D. W., 1979, Late Holocene glacier fluctuations on Mount Rainier and their relationships to the historical climate record: Seattle, University of Washington, M.S. thesis, 85 p.

Burke, R.M, and Birkeland, P.W., 1979, Reevaluation of multiparameter relative dating techniques and their application to the glacial sequence along the eastern escarpment of the Sierra Nevada, California: Quaternary Research, v. 11, no. 1, p. 21-51.

Busacca, A.J., 1982, Geologic history and soil development, northeastern Sacramento Valley, California: Davis, University of California, Ph.D. thesis, 348 p.

Busacca, A.J., Aniku, J.R., and Singer, M.J., 1984, Dispersion of soils by an ultrasonic method that eliminates probe contact: Soil Science Society of America Journal, v. 48, no. 5, p. 1125-1129.

Carson, R.J., III, 1970, Quaternary geology of the south-central Olympic Peninsula, Washington: Seattle, University of Washington, Ph.D. thesis, 67 p.

Colman, S.M., and Pierce, K.L., 1981, Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, Western United States: U.S. Geological Survey Professional Paper 1210, 56 p.

____1984, Correlation of Quaternary glacial sequences in the Western United States based on weathering rinds and related studies, in Mahaney, W.C., ed., Correlation of Quaternary chronologies: Norwich, England, Geo Books, p. 437-453.

Crandell, D.R., 1969, Surficial geology of Mount Rainier National Park, Washington: U.S. Geological Survey Bulletin 1288, 41 p.

Crandell, D.R., and Miller, R.D., 1974, Quaternary stratigraphy and extent of glaciation in the Mount Rainier region, Washington: U.S. Geological Survey Professional Paper 847, 59 p.

Crandell, D.R., Mullineaux, D.R., and Waldron, H.H., 1958, Pleistocene sequence in southeastern part of the Puget Sound lowland, Washington: American Journal of Science, v. 256, no. 1, p. 384-397.

Deming, W.E., 1943, Statistical treatment of data: New York, John Wiley, 261 p.

Dethier, D.P., and Bethel, J.P., 1981, Surficial deposits along the Cowlitz River near Toledo, Lewis County, Washington: U.S. Geological Survey Open-File Report 81-1043, 10 p.

Easterbrook, D.J., Blunt, David, and Rutter, N.W., 1982, Pleistocene glacial and interglacial chronology in western Washington: Geological Society of America Abstracts with Programs, v. 14, no. 4, p. 161.

Easterbrook, D.J., Briggs, N.D., Westgate, J.A., and Gorton, M.P., 1981, Age of the Salmon Springs Glaciation in Washington: Geology, v. 9, no. 2, p. 87-93.

Easterbrook, D.J., Crandell, D.R., and Leopold, E.B., 1967, Pre-Olympia Pleistocene stratigraphy and chronology in the central Puget Lowland, Washington: Geological Society of America Bulletin, v. 78, no. 1, p. 13-20.

Easterbrook, D.J., and Rutter, N.W., 1982, Amino acid analyses of wood and shells in development and correlation of Pleistocene sediments in the Puget lowland, Washington: Geological Society of America Abstracts with Program v. 14, no. 7, p. 480.

Easterbrook, D.J., Westgate, J.A., and Naeser, N.B., 1985, Pre-Wisconsin fission-track, paleomagnetic, amino-acid, and tephra chronology in the Puget lowland and Columbia Plateau, Washington: Geological Society of America Abstracts with Programs v. 7, no. 6, p. 353.

Erdmann, C.E., and Bateman, A.F., Jr., 1951, Geology of damsites in southwestern Washington, pt. II: U.S. Geological Survey Open-File Report, 314 p.

Fiske, R.A., Hopson, C.A., and Waters, A.C., 1963, Geology of Mount Rainier National Park: U.S. Geological Survey Professional Paper 444, 93 p.

Franklin, J.F., and Dyrness, C.T., 1973, Natural vegetation of Oregon and Washington: U.S. Department of Agriculture Forest Service General Technical Report PNW-8, 417 p.

Grandstaff, D.E., 1986, The dissolution rate of forsteritic olivine from Hawaiian beach sand, in Colman, S.M., and Dethier, D.P., eds., Rates of chemical weathering of rocks and minerals: New York, Academic Press, p. 41- 60.

Hammond, P.E., 1980, Reconnaissance geologic map and cross-sections of southern Washington Cascade Range, latitude 45°30'-47°15'N, longitude 120°45'-122°22.5'W: Portland State University Department of Earth Sciences, 31 p.

Harden, J.W., 1982a, A quantitative index of soil development from field descriptions: examples from a chronosequence in central California: Geoderma, v. 28, no.1, p. 1-28.

___1982b, A study of soil development using the geochronology of Merced River deposits: Berkeley, University of California, Ph.D. thesis, 237 p.

___1987, Soils developed in granitic alluvium near Merced, California: U.S. Geological Survey Bulletin 1590-A, 65 p.

Harden, J.W., and Marchand, D.E., 1977, The soil chronosequence of the Merced River area, in Singer, M.J., ed., Soil development, geomorphology, and Cenozoic history of the northeastern San Joaquin Valley and adjacent areas, California: Soil Science Society of America-Geological Society of America joint field session, 1977, guidebook, p. 22-38.

___1980, Quaternary stratigraphy and interpretation of soil data from the Auburn, Oroville, and Sonora areas along the Foothills fault system, western Sierra Nevada, California: U.S. Geological Survey Open-File Report 80-30, 57 p.

Harden, J.W., Sarna-Wojcicki, A., and Dembroff, G., 1986, Soil development on coastal terraces near Ventura, California: U.S. Geological Survey Bulletin 1590-B, 34 p.

Harden, J.W., and Taylor, E.T., 1987, A quantitative comparison of soil development in four climatic regimes: Quaternary Research, v. 20, no. 3, p. 342-359.

Heusser, C.J., 1977, Quaternary palynology of the Pacific slope of Washington: Quaternary Research, v. 8, no. 1, p. 282-306.

Heusser, C.J., and Heusser, L.E., 1980, Sequence of pumiceous tephra layers and the late Quaternary environmental record near Mount St. Helens: Science, v. 210, no. 4473, p. 1007-1009.

___1981, Palynology and paleotemperature analysis of the Whidbey Formation, Puget lowland, Washington: Canadian Journal of Earth Sciences, v. 18, no. 1, p. 136-149.

Lea, P.D., 1983, Glacial history of the southern margin of the Puget lowland, Washington: Geological Society of America Abstracts with Programs, v. 15, no. 5, p. 430.

Machette, M.N., 1983, Geologic map of the southwest quarter of the Beaver County, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1444, scale 1:24,000.

Machette, M.N., and Steven, T.A., 1983, Geologic map of the northwest quarter of the Beaver quadrangle, Beaver County: U.S. Geological Survey Miscellaneous Investigations Series Map I-1445, scale 1:24,000.

Machette, M.N., Steven, T.A., Cunningham, C.G., and Anderson, J.J., 1984, Geologic map of the Beaver quadrangle, Beaver and Piute Counties, Utah: U.S. Geological Survey Miscellaneous Investigations Series Map I-1520, scale 1:50,000.

Marchand, D.E., and Allwardt, Alan, 1981, Late Cenozoic stratigraphic units in northeastern San Joaquin Valley, California: U.S. Geological Survey Bulletin 1470, 70 p.

McFadden, L.D., and Hendricks, D.M., 1985, Changes in the content and composition of pedogenic iron oxyhydroxides in a chronosequence of soils in southern California: Quaternary Research, v. 23, no.2, p. 189-204.

Meixner, R.E., and Singer, M.J., 1981, Use of a field morphology rating system to evaluate soil formation and discontinuities: Soil Science, v. 131, no. 2, p. 114-123.

Mullineaux, D.R., Hyde, J.H., and Rubin, Meyer, 1975, Widespread late glacial and postglacial tephra deposits from Mount St. Helens volcano, Washington: U.S. Geological Survey Journal of Research, v. 3, no. 3, p. 329-335.

Porter, S.C. 1977, Present and past glaciation threshold in the Cascade Range, Washington, U.S.A.: Topographic and climatic controls, and paleoclimatic implications: Journal of Glaciology, v. 18, p. 101-116.

Porter, S.C., and Clayton, G.A., 1982, Pleistocene glaciation and volcanism in the Washington Cascades: Geological Society of American Abstracts with Programs, v. 14, no. 4, p. 225.

Reheis, M.C., 1984, Chronologic and climatic control on soil development, northeastern Bighorn Basin, Wyoming and Montana: Boulder, University of Colorado, Ph.D. thesis, 293 p.

Roberts, A.E., 1958, Geology and coal resources of the Toledo-Castle Rock District, Cowlitz and Lewis Counties, Washington: U.S. Geological Survey Bulletin 1062, 71 p.

Singer, M.J., and Janitsky, Peter, 1986, Field and laboratory procedures used in a soil chronosequence study: U.S. Geological Survey Bulletin 1648, 49 p.

Soil Conservation Service, 1987, Soils of Survey Lewis County area, Washington: Washington, D.C., U.S. Government Printing Office, 466 p.

Snavely, P.W., Jr., Brown, R.D., Jr., Roberts, A.E., and Rau, W.W., 1958, Geology and coal resources of the Centralia-Chehalis district, Washington: U.S. Geological Survey Bulletin 1053, 159 p.

U.S. Weather Bureau, 1965, Mean annual precipitation, 1930-57, State of Washington: Portland, Oregon, U.S. Soil Conservation Service, map M-4430.

Waitt, R.B., Jr., and Thorson, R.M., 1983, The Cordilleran ice sheet in Washington, Idaho, and Montana, in Wright, H.E., Jr., ed., Late-Quaternary Environments of the United States: Minneapolis, University of Minnesota Press, p. 53-70.

Waitt, R.B., Jr., Yount, J.C., and Davis, P.T., 1982, Regional significance of an early Holocene moraine in Enchantment Lakes Basin, North Cascade Range, Washington: Quaternary Research, v. 17, no. 2, p. 191-210.

Washington Public Power Supply System, 1974, WNP 3 and 5 Preliminary Safety Analysis Report, Section 2.5, Geology and Seismology: Seattle, Washington Public Power Supply System.

Weigle, J.M., and Foxworthy, B.L., 1962, Geology and ground-water resources of west-central Lewis County, Washington: Washington Department of Water Resources Water-Supply Bulletin 17, 248 p.

Woodward-Clyde Consultants, 1978, Evaluation of faults and landslides, Washington Public Power Supply System Nuclear Projects Nos. 3 and 5, Grays Harbor County, Washington: Unpublished report prepared for Ebasco Services, Inc.

SUPPLEMENTARY TABLES

KEY[1]

SOIL STRUCTURE

Grade	Size	Type
m, massive	vf, very fine (v thin)	gr, granular
sg, single grained	f, fine (thin)	pl, platey
1, weak	m, medium	pr, prismatic
2, moderate	c, coarse (thick)	cpr, columnar
3, strong	vc, very coarse (v thick)	abk, angular blocky
		sbk, subangular blocky

If two structures-listed as primary and secondary

SOIL TEXTURE

co, coarse	S, sand	SCL, sandy-clay loam
f, fine	LS, loamy sand	CL, clay loam
vf, very fine	SL, sandy loam	SiCL, silty-clay loam
gr - granular	L, loam	SC, sandy clay
vgr - very granular	SiL, silt loam	C, clay
	Si, silt	SiC, silty clay

SOIL CONSISTENCE

Dry	Moist	Wet	
lo, loose	lo, loose	so, nonsticky	po, nonplastic
so, soft	vfr, very friable	ss, slightly sticky	ps, slightly plastic
sh, slightly hard	fr, friable	s, sticky	p, plastic
h, hard	fi, firm	vs, very sticky	vp, very plastic
vh, very hard	vf, very firm		
eh, extremely hard	efi, extremely firm		

HORIZON BOUNDARIES

Distinctness	Topography
va, very abrupt	s, smooth
a, abrupt	w, wavy
c, clear	i, irregular
g, gradual	b, broken
d, diffuse	

ROOTS AND PORES

Size	Abundance	Pore Shape
vf, very fine	1 few	tub, tubular
f, fine	2 common	ir, irregular
m, medium	3 many	v, vesicular
co, coarse		

CLAY FILMS

Frequency	Thickness	Morphology
vf, very few	n, thin	pf, ped face coatings
1, few	mk, moderately thick	br, bridging grains
2, common		po, pore linings
3, many	k, thick	(w, occurs as waves or lamellae)
4, continuous		co, coats on clasts

[1] For more detailed information, see Soil Survey Staff 1951 and 1975.

Supplementary table 1, part 1. Site location data for soils of the Cowlitz chronosequence

Site	Geologic unit	Elevation (ft)	Modern vegetation	Parent texture	Location Mt. Diablo Base Meridian
CW6	late Holocene alluvium	130	mixed forest	SL	SW/4, SW/4, Sec 3, T11N, R1E
CW8	latest Pleistocene(?) outwash	170	Doug. Fir, grasses and mixed forest	SL	SW/4, SW/4, Sec 32, T12N, R1E
CW3	late Evans Creek outwash	350	mixed forest	SL	NW/4, SW/4, Sec 23, T12N, R1E
CW4	early Evans Creek outwash	310	mixed forest	SL	SW/4, NE/4, Sec 23, T12N, R1E
CW5	early Evans Creek outwash (#2)	360	alders, Doug. Fir	SL	NW/4, NE/4, Sec 23, T12N, R1E
CW7	pre-Evans Creek outwash (?)	320	fir, hemlock alder	SL	SW/4, NE/4, Sec 29, T12N, R1E
CW9	late Hayden Creek outwash	280	Doug. Fir and mixed forest	SL	SW/4, SW/4, Sec 11, T11N, R1W
CW10	middle Hayden Creek outwash	540	mixed forest	SL	NE/4, NE/4, Sec 13, T12N, R1E
CW12	early Hayden Creek outwash	480	Doug Fir and mixed forest	SL	SW/4, SW/4, Sec 13, T12N, R1E
CW2	Wingate Hill outwash	520	Doug. Fir and mixed forest	SL	SE/4, SE/4, Sec 17, T12N, R1E
CW11	Logan Hill Formation	590	Doug. Fir and mixed forest	SL	center, NE/4, Sec 10, T12N, R1W

Supplementary table 1, part 2. Field descriptions

[Analyst: J.W. Harden, U.S. Geological Survey; and others]

No.	Sample	Horizon	Basal depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Consistence			Roots	Pores	Clay films	pH	Assumed Parent material	
									Dry	Moist	Wet					Texture	Wet consistence
								late Holocene alluvium, .25 ka									
1	CW6	A11	10	c,w	10YR3/2	10YR5/2	SL	2 m gr	--	vfr	so,po	3f	2mtub,	0	6.2	SL	so,po
2		A12	25	c,w	10YR3/3	10YR6/2	SL	m, 1 m gr	--	vfr	so,po	2f,m	1ftub	0	6.0	SL	so,po
3		2Cn	50	--	10YR4/2	10YR6/2	LS	m-sg	--	vfr	so,po	2co, 1m,1f	--	0	6.4	LS	so,po
								latest Pleistocene(?) outwash, 11 ka									
4	CW8	A11p	18	c,w	--	10YR5/2	L	2 m gr	--	fr	ss,ps	3f, vfm	1mtub	0	--	L	ss,ps
5		A12p	31	c,w	--	10YR5/2	L	2 m-c gr	--	fr	ss,ps	2m,2f	2ftub	0	--	L	ss,ps
6		A+B	50	g,w	--	10YR6/3	L	m, 1-2 m shk	--	fr	ss,ps	--	2f, 1mtub	0	--	L	ss,ps
7		2B21t	70	g,w	--	10YR6/4	SL/L	m, 2 m sbk	--	fi	ss,ps	1m	3f, 1mtub	2nbr	--	SL	ss,ps
8		2B22t	94	c,s-w	--	10YR6/5	SL	m, 2 m shk	--	fi	ss,ps	1co	2-3f tub	2nbr, 1mkbr	--	SL	s,ps
9		3B3	127	c,s-w	--	10YR7/4	L	m, 2 m shk	--	fi	s,p	1co	2f, 1-2mtub	2-3nbr	--	(S)L	ss,ps
10		4C1ox	140	g,w	--	10YR7/2 7.5YR4/4	SL	--	--	fi	so,po	--	1mtub	1nbr	--	SL	so,po
11		5C2ox	200	--	--	10YR6/3	LS	--	--	lo	so,po	--	--	0	--	LS	so,po
								late Evans Creek outwash, 14 ka									
12	CW3	A11	23	c,s	10YR2/2	--	L	3 m-c gr	--	--	so,po	3m,3f, 3co	3mtub	0	--	L	so,po
13		A12	48	g,w	10YR3/2	--	L	2 c gr	--	--	so,po	3m	3mtub	0	--	L	so,po
14		2C1ox	66	d,w	10YR4/4	10YR6/4	L	m, m shk	--	--	so,po	1-2m	1f, 1mtub	0	--	L	so,po
15		3C2	100	--	10YR4/4	10YR7/3	LS	m, m abk	--	--	so,po	1m	1-2m, 1-2ftub	0	--	LS	so,po

early Evans Creek outwash, 24 ka																
16	CW4	A	15	--	10YR2/2	7.5YR4/3	SL	3 f cr	--	vfr	so,po	3f,3m	--	0	--	SL	so,po
17		B	72	--	7.5YR4/6	10-7.5YR 5/6	SL	1-2 m sbk	--	--	so,po	2f,2m	1vf,1f, 1mtub	0	--	SL	so,po
18		2C1ox	90	--	7.5YR4/4	10YR5/6	ext cob SL	sg	--	vfr	so,po	3m,3f	1ftub	0	--	SL	so,po
19		3C2n	200	--	--	2.5Y6/2	gr SL	sg	--	lo	so,po	--	--	0	--	SiL	so,po
20	CW5	A	14	c,w	10YR2/2	10YR3/3	L	3 c gr	--	--	so,po	3co,3m, 3f	3mtub	0	--	L	so,po
21		B	60	c,w	5YR4/6	7.5YR5/6	SL	2 c gr, 1 m sbk	--	--	so,po	3co,3m, 3f	2mtub, 2m int	0	--	L	so,po
22		2C1ox	92	g,w	7.5YR4/4	10YR5/6	gr L	m, c abk	--	--	so,po	3m	2-3f tub	0	--	SL	so,po
23		3Cox	130	a,w	7.5YR4/4	10YR5/6	v gr SL	m, c abk	--	vfr	so,po	2m	2ftub	0	--	SL	so,po
24		4C3	200	--	7.5-10YR 3/3	--	gr S	sg	--	--	--	--	--	0	--	S	so,po
pre-Evans Creek outwash(?), 60 ka(?)																
25	CW7	A1	26	--	7.5YR3/2	10YR6/4	gr SiL	2 f gr	--	fr	ss,ps	3co,2m, 2vf	--	0	--	SiL	ss,ps
26		B11	38	--	7.5YR 3-4/4	10YR6/4	gr SiL	2 f gr	--	fr	ss,ps	2co,2m, 2vf	--	0	--	SiL	ss,ps
27		B12	56	--	7.5YR4/4	10YR6/4	gr Si/L	m, 2 c abk	--	fr	ss,ps	1vfm, vfco	--	1nbr	--	L	so,po
28		B21t	70	--	7.5YR4/4	7.5YR6/4	gr L	2 f-c sbk	--	fi	s,p	2m,1co	1m,2f tub	1-2nbr, vfnpo, 2nco	--	L	so,po
29		B22t	101	--	5YR4/5	7.5YR6/4	gr L	m	--	fi	s,ps	2m,1co	3ftub	2nbr,1npo	--	L	so,po
30		2B31	111	--	--	10YR5/4	gr L	1 m sbk	--	--	s,ps	0	2m,1co	1npo	--	L	so,po
31		2B32	145	--	10YR5/7	10YR5/6	vgr LS	m, 1 m abk	--	fi	ss, ps-po	0	2ftub	2nco	--	LS	so,po
32		3C	250	--	2.5YR4/7 10YR3/2	10YR6/4 10YR6/4	vgr LS/S	m-sg	--	fr	so,po	1f,1m	--	0	--	LS/S	ss,po
late Hayden Creek outwash, 150 ka(?)																
33	CW9	A11	5	c,w	--	10YR5/3	gr SiL	3 m gr	--	vfr	ss,ps	2m,1co, 1f	--	0	--	SiL	ss,ps
34		A12	17	c,w	--	10YR6/2	gr SiL	2 c gr	--	fr-fi	ss,ps	2m,2co, 1f	--	0	--	Si	ss,ps
35		B1	26	c,w	--	10YR6/3	gr SiL	2 f sbk	--	fi	ss,ps	1m,1co	1ftub	0	--	SiL	ss,ps
36		B21t	38	g,w	--	10YR7/3	gr SiCL	2 m-c sbk	--	fi	s,p	2co	1f, 1mtub	1nbr	--	SiL	ss,ps
37		B22t	75	a,s	--	10YR7/4	gr SiCL	2-3 vc abk 2-3 vc sbk	--	vfi	vs, p-pv	1co,1m	3f, 1cotub	3nbr, 2mkbr	--	SiL	ss,ps
38		2B31	92	g,w	--	10YR7/5	vgr C	m	--	fi	sv,pv	1vf	2f, 1mtub	4nco	--	SiL	ss,ps
39		3B32	196	d,w	--	10YR7/4	vgr SCL	m	--	fi	s,p	--	2mtub	4nco	--	SL	ss,ps
40		3C1ox	250	--	--	10YR7/3	vgr SL	m	--	fi	s,p	--	--	3nco	--	SL	ss,ps

Supplementary table 1, part 2. Field descriptions--Continued

No.	Sample	Horizon	Basal depth (cm)	Lower boundary	Moist color	Dry color	Texture	Structure	Consistence: Dry	Consistence: Moist	Consistence: Wet	Roots	Pores	Clay films	pH	Assumed Parent material: Texture	Assumed Parent material: Wet consistence
							late Hayden Creek outwash, 150 Ka(?)										
41	CW1	A	20	c,i	10YR3/2	--	SiL	2 m gr	so	--	ss,ps	3co,2m,1f	2mtub	0	6.8	--	--
42		B11	50	c,w	7.5YR4/4	--	SiL	m	so	--	ss,ps	3co,1m	vftub	0	6.0	--	--
43		B12	65	d,s	7.5YR4/4	--	SiL	m, m abk	--	--	ss,ps	3co,1m	2ftub	0	5.4	--	--
44		B21 buried?	88	g,w	5Y 7/1 5-7.5YR 5/6 7.5YR 5/4	--	Sil	1 m sbk	--	--	s,p	co,m,vf	2-3ftub	2n-mkbr	5.3	--	--
45		B22 buried?	135	a,i	5Y 7/1 5YR4/4 5YR4/6	--	SiCL	2 m pr	--	--	--	--	3ftub	2 n-mkpo 3mkbr 3mkpo	5.3	--	--
46		2C buried	150	--	5YR5/6 2.5YR 4.6	--	S	--	--	--	--	--	--	0	5.3	--	--
							middle Hayden Creek outwash, 225 Ka(?)										
47	CW10	A	10	c,w	7.5YR3/2	10YR5/3	SiL	3 f gr	--	fr	ss,po	3f,2m	cotub	0	--	SiL	ss,po
48		B11	30	g,w	7.5YR3/4	7.5YR5/4	SiCL	2 f-m sbk	--	fr	s,ps	3c,2m 2f	2co, 2ftub	0	--	SiL	ss,po
49		B12	54	--	5YR4/4	7.5YR5/4	SiCL	2 c sbk	--	fi	s,p	--	2f,2m tub	2nbr	--	SiL	ss,po
50		B2t	100	--	5YR4/4	10YR6/4	C	2 c-vc sbk	--	fi	s,p	1m	2f,2m 2kbr	3n-mkbr	--	SiL	ss,po
51		2B3t	260	d,w	--	10YR6/4	ext grSL	m	--	fi	s,pv	--	2ftub	1kco, 2mkco	--	SL	ss,po
52		3Cox	380	--	--	10YR8/4	SCL	m	--	--	vs,pv	--	3nco 2-3f	2n-mkco	--	SL	ss,po
							early Hayden Creek outwash, 300 Ka(?)										
53	CW12	A11	32	g,w	7.5YR3/2	10YR4/3	SiCL	1 c sbk, c gr	--	fi	s,p	1m,1c	1m,1co tub	0	--	SiCL	ss,po
54		A12	53	c,w	7.5YR4/2	10YR5/3	SiCL	1 c abk, 1 c gr	--	fi	s,p	1m,1c	1c	0	--	SiCL	ss,po

55		B1	66	c,w	5YR3/3 5YR4/4	10YR5/4	SiC	1 c sbk, 1 c gr	--	fi	s,p	--	2c,2m tub	1nhrw	--	SiCL	ss,po
56		B2 buried?	137	-,w	7.5YR5/6 2.5YR4/6	10YR5/6	C	m, 1 c sbk	--	fi	s,p	--	2co,2m, 2ftub	3mkbr, 3mkhr, 1k	--	SiCL	ss,po
57		2B31 buried	250	g,s	7.5YR5/4 5YR4/6	10YR6/5	SiC	m, 1 c sbk	--	fi	ss,ps	--	2m,2f tub	3n-mk, 3n-mkhr, 1k-mkbr, 1k-mkpo	--	SiCL	ss,po
58		2B32 buried?	270	--	7.5YR4/6	2.5YR7/4	L/CL	m	--	fr	ss,ps	--	3f,2m tub	2n-mkco	--	SL	ss,po
59		3C1 buried?	300	--	--	10YR7/3	vgrSL	--	--	--	--	--	--	0	--	SL	ss,po
							Wingate Hill outwash, 500 Ka(?)										
60	CW2	A	20	c,s	10YR3/2	10YR5/3	CL	3 m gr	so	--	so,po	3f,2m, 2c	2mtub	0	6.5	CL	so,po
61		A3	35	g,s	5YR4/2 5YR4/4	10YR6/4	SiC	1 f sbk	sh	fi	ss,ps	2f,1c	2-3ftub, 2-3fint	0	6.5	CL	so,po
62		B21t	66	g,s	5YR4/3 5YR4/6	7.5YR5/6	SiC	2 m sbk	h	vfi	s,p	2m	2f, 1mtub	2n-mk hrw	6.0	CL	so,po
63		2B22t	94	c,w	5YR5/6 5YR5/8	7.5YR6/6	grC	m, 1 m abk	--	vfi	s,p	--	2ftub	3mkbrw, 3mkpo	5.4	CL	so,po
64		2B23t	245	d,w	5YR4/6 5YR5/8 5YR4/4	10YR5/6	C	m	--	--	s,p	--	1ftub	3mkhr	5.2	CL	so,po
65		2B3	300	--	5YR4/4 5YR4/8	10YR6/8 10YR7/3	grC	m	--	--	--	--	--	0	--	CL	so,po
							Logan Hill Formation, 1,200 Ka(?)										
66	CW11	A	12	c,w	10YR3/2.5	10YR5/3	SiCL	3 m gr	--	fr	s,p	2m,2c	--	0	--	SiCL	ss,po
67		B1t	40	c,w	5YR4/6 5YR3/4	10-7.5 YR5/4	Sic	2 f sbk	--	fi	s,p	2m,2c	2ftub	3nhr, 2npo	--	SiCL	ss,po
68		B21t	64	g,w	7.5YR4/4	10-7.5 YR5/4	C	2 m-c sbk	--	fi	vs,pv	2m,2c	3f,2m tub	3nhr, 3npo	--	SiCL	ss,po
69		B22t	94	c,s	7.5YR4/6	10YR5/7	C	2 c sbk	--	fi	vs,pv	--	2f,1c	4mkbr, 2khr,pf	--	SiCL	ss,po
70		2B23t	106	c,w	7.5YR5/6	10YR6/5	grC	m, 2 c sbk	--	fi	vs,pv	--	2c	4kco, 4mkbr	--	SiCL	ss,po
71		3B24t	150	g,w	7.5YR4/6 2.5YR3/6 2.5YR3/8 10YR6/8	10YR5/6	grC	m, 2 c sbk	--	fi	vs,pv	--	2c,2f	4kco, 4mkbr	--	CL	ss,po
72		3B3t	240	--	7.5YR 4-5/4	5YR5/8 2.5Y7/6	grC	m	--	fi	s,p	--	--	4mk-kco, 4mkbr	--	CL	ss,po

Supplementary table 2. Physical properties

[Analysts: J.P. Bethel under F.C. Ugolini, University of Washington, Seattle]

No.	Sample	Horizon	Basal depth (cm)	>2 mm	Percentage of <2-mm fraction: Total sand	vco sand	co sand	m sand	fi+vfi sand	Silt	<2-μ clay	<1-μ clay	Bulk density (g/cm³)
late Holocene alluvium, 0.25 ka													
1	CW6	A11	10	--	47.9	0.48	0.96	0.96	35.50	45.6	6.5	5.4	--
2	CW6	A12	25	--	51.1	0.00	0.00	0.51	50.59	46.0	2.9	0.8	1.16
3	CW6	Cn	--	--	81.2	--	--	--	--	18.4	0.4	0.0	--
latest Pleistocene(?) outwash, 11 ka													
4	CW8	A11p	18	--	39.1	0.00	0.39	2.54	36.36	40.4	20.6	14.5	1.23
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	1.23
6	CW8	A+B	50	--	48.0	0.00	0.48	2.88	45.12	33.3	18.8	20.0	1.32
7	CW8	B21t	70	--	52.5	0.00	1.05	7.88	44.10	32.2	15.3	14.0	1.32
8	CW8	B22t	94	--	66.1	0.00	1.98	11.90	52.22	18.3	15.5	12.8	1.33
9	CW8	2B3	127	--	33.4	0.00	0.33	3.01	29.72	47.2	19.4	16.8	1.32
10	CW8	3C1ox	140	--	71.7	0.72	6.45	22.23	42.30	20.3	8.0	5.5	1.37
11	CW8	3C2ox	--	--	35.0	5.25	12.60	11.20	6.30	12.5	2.5	3.0	1.41
late Evans Creek outwash, 14 ka													
12	CW3	A11	23	--	35.4	--	--	--	--	43.3	21.3	16.1	--
13	CW3	A12	48	--	23.1	0.00	1.15	3.00	18.95	33.7	23.1	21.1	--
14	CW3	C1ox	66	--	36.9	0.00	1.84	5.17	29.89	41.8	21.2	19.2	1.19
15	CW3	C2	--	--	83.6	32.60	36.78	9.20	5.01	16.4	0.0	0.0	1.27
early Evans Creek outwash, 24 ka													
16	CW4	A	15	--	56.3	5.63	7.32	15.76	28.15	38.3	5.4	3.8	--
17	CW4	B	72	--	56.1	7.29	8.98	10.10	29.17	33.4	10.5	8.5	0.98
18	CW4	2C1ox	90	--	62.0	3.72	8.68	11.78	37.20	34.2	3.8	2.5	1.04
19	CW4	2C2n	--	--	35.8	0.00	0.72	2.51	32.58	53.1	11.0	9.0	--
20	CW5	A	14	--	48.3	2.90	5.80	6.28	33.33	42.7	9.0	9.3	0.78
21	CW5	B	60	--	47.2	4.26	6.62	6.15	30.75	36.6	16.1	11.7	--
22	CW5	2C1ox	92	--	53.8	5.38	8.07	6.46	33.36	41.2	5.0	3.8	0.99
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	1.07
24	CW5	4C3	--	--	87.3	--	--	--	--	12.5	0.2	1.3	--
pre-Evans Creek outwash(?), 60 ka(?)													
25	CW7	A1	26	--	31.8	1.27	3.82	5.09	21.94	44.5	23.9	20.7	1.19
26	CW7	B11	38	--	31.3	5.01	7.82	7.51	10.95	45.2	23.5	19.5	1.40
27	CW7	B12	56	--	31.4	2.20	5.65	6.28	17.27	43.3	25.4	24.0	--
28	CW7	B21/B22	101	--	48.3	5.31	9.18	8.21	25.60	33.6	18.1	15.8	1.14
29	CW7	B31	111	--	47.7	2.86	7.63	7.63	29.58	33.6	18.8	18.8	--
30	CW7	2B32	145	--	86.1	37.02	33.58	7.75	7.75	10.2	3.8	3.8	1.61
31	CW7	2C	--	--	86.7	22.51	10.75	12.14	11.27	9.8	3.4	2.9	1.79

Supplementary table 2. Physical properties--Continued

late Hayden Creek outwash, 150 ka(?)													
33	CW9	A11	5	--	19.6	0.59	1.18	2.16	15.48	56.6	23.8	19.3	--
34	CW9	A12	17	--	17.5	0.18	0.88	1.75	14.70	58.3	24.1	18.4	1.23
35	CW9	B1	26	--	19.9	0.20	1.00	1.99	16.51	54.7	25.4	20.6	--
36	CW9	B21t	38	--	18.6	0.19	0.93	1.86	15.44	49.4	32.0	29.8	--
37	CW9	B22t	75	--	15.4	0.15	0.77	1.54	12.93	47.1	37.4	34.1	1.44
38	CW9	2B31	92	--	19.9	0.80	1.59	2.59	14.92	35.9	44.2	39.4	--
39	CW9	2B32	196	--	53.8	4.84	11.30	11.84	25.82	27.8	19.2	15.4	--
40	CW9	2C1ox	--	--	61.2	20.20	15.91	6.12	18.36	24.7	14.0	13.5	--
middle Hayden Creek outwash, 225 ka(?)													
47	CW10	A	10	--	19.2	0.38	1.73	2.69	14.40	53.8	27.0	23.3	1.20
48	CW10	B11	30	--	20.4	0.41	2.04	3.47	14.48	49.5	32.0	29.3	--
49	CW10	B12	54	--	19.0	0.38	2.09	3.23	13.30	48.2	32.8	27.4	1.42
50	CW10	B2t	100	--	16.0	0.16	0.64	2.08	13.12	29.7	54.3	49.3	1.48
51	CW10	B3t	260	--	63.1	21.45	18.93	6.94	15.77	24.1	12.5	11.5	1.68
52	CW10	Cox	380	--	52.6	12.62	17.36	6.84	15.26	19.2	28.2	27.2	--
early Hayden Creek outwash, 300 ka(?)													
53	CW12	A11	32	--	11.4	--	--	--	--	52.3	36.2	32.0	1.30
54	CW12	A12	53	--	12.9	0.13	0.52	0.90	11.22	52.3	34.9	35.3	1.31
55	CW12	B1	66	--	11.9	0.48	1.07	1.31	9.05	46.7	41.3	37.0	1.19
56	CW12	2B2b?	137	--	15.5	0.31	0.77	1.24	13.02	35.8	48.8	50.0	1.30
57	CW12	2B31b?	250	--	11.9	0.24	0.83	1.19	9.64	43.3	44.8	37.5	1.18
58	CW12	3B32b?	270	--	36.2	3.26	7.24	5.43	20.63	37.1	26.7	16.9	1.22
59	CW12	3C1b?	--	--	73.1	19.74	29.97	9.50	13.89	20.4	6.5	7.0	1.37
Wingate Hill outwash, 500 ka(?)													
60	CW2	A	20	--	14.1	0.28	0.70	1.13	11.99	54.4	31.5	26.4	1.01
61	CW2	A3	35	--	6.7	0.54	0.94	0.80	4.36	52.4	40.9	38.0	1.50
62	CW2	B21t	66	--	10.6	0.53	1.38	1.27	7.31	54.8	34.5	31.8	1.54
63	CW2	2B22t	94	--	7.1	0.36	0.71	0.85	5.18	31.6	61.3	61.3	1.46
64	CW2	2B23t	245	--	13.6	0.82	1.63	1.63	9.52	29.4	57.0	55.0	1.47
65	CW2	2B3	300	--	18.9	2.84	5.67	3.97	6.43	36.2	44.9	44.0	1.32
Logan Hill Formation, 1,200 ka(?)													
66	CW11	A	12	--	14.7	4.12	2.65	1.91	6.03	50.3	35.0	30.5	--
67	CW11	B1t	40	--	10.0	0.30	1.00	1.20	7.40	48.3	41.7	39.8	--
68	CW11	B21t	64	--	11.1	0.22	0.78	1.55	8.55	37.7	51.3	52.0	--
69	CW11	B22t	94	--	12.9	0.13	0.90	1.81	10.06	31.6	55.5	55.3	--
70	CW11	2B23t	106	--	16.0	0.48	2.88	3.36	9.28	26.0	58.0	56.5	--
71	CW11	2B24t	150	--	18.0	0.90	3.24	3.06	10.80	28.2	53.8	55.0	--
72	CW11	2B3t	240	--	20.5	0.41	1.23	2.05	16.98	35.3	44.2	43.5	--

Note: CW1 has been described but not analyzed

Supplementary table 3. Extractive chemical analyses

[CEC, cation exchange capacity. Analysts: J.P. Bethel under F.C. Ugolini, University of Washington, Seattle]

No.	Sample	Horizon	Basal Depth (cm)	Percentage of <2-mm		meq/100g soil						pH	pH	pH	Percentage of <2-mm	
				Total N	Organic C	Exchange Na	Exchange K	Exchange Ca	Exchange Mg	Exchange H	CEC	$1:1H_2O$	1:1KCl	Saturated	Fe_d	Al_d
						late Holocene alluvium, 0.25 ka										
1	CW6	A11	10	0.15	3.13	--	0.52	7.52	2.19	9.8	25.8	5.70	4.40	5.60	0.68	0.060
2	CW6	A12	25	0.08	1.28	--	0.48	7.86	1.66	6.8	17.1	5.90	4.80	6.10	0.69	0.11
3	CW6	Cn	--	--	--	--	0.44	5.06	1.02	3.4	16.6	5.90	4.50	6.00	0.56	0.085
						latest Pleistocene(?) outwash, 11 ka										
4	CW8	A11p	18	0.17	3.59	--	1.07	11.49	2.84	21.2	37.1	5.80	4.60	5.70	1.34	0.38
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	--	--	1.34	--
6	CW8	A+B	50	0.07	1.07	--	0.99	8.49	2.54	13.6	27.3	5.90	4.40	5.90	1.24	0.34
7	CW8	B21t	70	--	--	--	0.80	9.17	3.57	10.8	19.6	5.80	4.20	5.53	1.53	0.26
8	CW8	B22t	94	--	--	--	0.71	8.44	3.48	10.2	24.2	5.50	4.10	5.50	1.35	0.18
9	CW8	2B3	127	--	--	--	0.65	10.22	--	11.0	23.3	5.60	4.20	5.50	1.42	0.21
10	CW8	3C1ox	140	--	--	--	0.41	8.22	3.91	7.6	20.1	5.60	4.10	5.90	1.00	0.20
11	CW8	3C2ox	--	--	--	--	0.24	6.31	2.79	7.2	15.2	5.70	4.00	5.90	0.69	0.11
						late Evans Creek outwash, 14 ka										
12	CW3	A11	23	0.31	5.08	--	1.09	8.08	1.74	24.6	39.5	5.30	4.20	5.30	1.67	0.71
13	CW3	A12	48	0.17	2.41	--	1.0	7.60	1.52	18.0	33.5	5.30	4.40	5.60	1.60	0.50
14	CW3	C1ox	66	0.06	0.80	--	1.08	7.14	2.18	12.4	28.0	5.50	4.20	5.60	1.63	0.78
15	CW3	C2	--	--	--	--	0.19	6.21	1.56	4.0	14.2	6.00	4.20	6.10	0.49	0.12
						early Evans Creek outwash, 24 ka										
16	CW4	A	15	0.38	5.58	--	0.41	8.24	1.87	24.6	43.9	5.70	4.90	5.80	1.48	1.1
17	CW4	B	72	0.10	1.54	--	0.16	1.38	0.30	18.0	18.8	6.10	5.20	6.10	1.57	0.89
18	CW4	2C1ox	90	--	--	--	0.14	1.16	0.39	19.1	19.4	5.80	5.20	6.00	1.73	0.71
19	CW4	2C2n	--	--	--	--	0.47	--	--	10.2	30.3	5.50	3.90	5.40	1.62	0.20
20	CW5	A	14	0.32	6.04	--	0.61	14.32	3.42	29.0	34.3	6.10	5.00	5.80	1.79	1.1
21	CW5	B	60	0.13	1.78	--	0.04	1.46	0.37	20.2	25.7	6.14	5.04	6.11	1.94	0.74
22	CW5	2C1ox	92	--	--	--	0.03	1.64	0.13	18.0	22.5	6.20	5.20	6.50	2.28	0.60
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	--	--	2.28	--
24	CW5	4C3	--	--	--	--	0.07	4.97	1.44	7.8	12.6	6.20	4.20	6.20	1.36	0.27
						pre-Evans Creek outwash(?), 60 ka(?)										
25	CW7	A1	26	0.12	2.14	--	0.44	6.12	1.64	15.0	25.9	6.00	4.70	5.90	1.83	0.48
26	CW7	B11	38	0.05	0.44	--	0.28	--	--	12.8	22.7	5.60	4.30	5.30	2.05	0.30
27	CW7	B12	56	0.04	0.53	--	0.34	5.82	2.78	10.6	25.0	5.50	4.30	5.70	2.06	0.30
28	CW7	B21/B22	101	--	--	--	0.50	6.66	3.52	12.2	25.0	5.70	4.30	5.80	2.08	0.28
29	CW7	B31	111	--	--	--	0.30	7.29	3.65	11.8	24.9	5.70	4.20	5.40	2.02	0.27

30	CW7	2B32	145	--	--	--	0.31	4.90	1.83	9.4	17.1	6.00	4.30	6.10	1.17	0.21
31	CW7	2C	--	--	--	--	0.26	5.62	1.76	10.2	12.9	6.10	4.20	5.90	0.96	0.19
							late Hayden Creek outwash, 150 ka(?)									
33	CW9	A11	5	0.24	6.04	--	0.53	7.56	1.38	29.2	40.1	5.50	4.20	5.60	1.20	0.52
34	CW9	A12	17	0.12	2.01	--	0.45	5.02	1.03	20.0	24.9	5.80	4.40	5.80	1.39	0.43
35	CW9	B1	26	0.10	1.55	--	0.43	5.10	0.82	18.6	25.8	5.60	4.20	5.60	1.58	0.39
36	CW9	B21t	38	--	--	--	0.43	5.20	0.93	15.4	24.9	--	--	--	1.79	0.33
37	CW9	B22t	75	--	--	--	0.62	5.62	2.27	13.6	21.3	--	--	--	2.05	0.26
38	CW9	2B31	92	--	--	--	0.60	6.02	2.84	16.6	27.3	5.20	4.00	4.90	2.16	0.31
39	CW9	2B32	196	--	--	--	0.35	9.37	3.13	14.0	26.0	5.40	4.10	5.40	1.43	0.32
40	CW9	2C1ox	--	--	--	--	0.35	9.32	2.90	9.8	20.7	5.60	4.00	5.70	1.15	0.080
							middle Hayden Creek outwash, 225 ka(?)									
47	CW10	A	10	0.17	3.09	--	0.16	5.0	0.89	21.9	--	5.82	4.38	5.62	2.22	0.59
48	CW10	B11	30	0.08	1.07	--	0.22	1.29	0.65	19.4	17.3	5.21	3.92	5.11	2.27	0.57
49	CW10	B12	54	0.05	0.57	--	--	--	--	18.0	19.8	5.42	3.80	5.29	2.11	0.37
50	CW10	B2t	100	--	--	--	0.14	4.40	2.54	18.4	23.5	5.71	3.64	5.20	2.40	0.32
51	CW10	B3t	260	--	--	--	0.28	7.36	3.34	17.7	25.0	6.21	4.14	5.92	2.31	0.39
52	CW10	Cox	380	--	--	--	0.35	9.01	4.41	11.0	26.2	5.48	3.84	6.26	1.44	0.23
							early Hayden Creek outwash, 300 ka(?)									
53	CW12	A11	32	0.11	2.90	--	0.78	6.26	1.79	23.8	20.9	5.20	4.00	5.10	2.35	0.46
54	CW12	A12	53	0.15	1.72	--	0.53	4.13	1.35	20.2	27.0	5.30	4.00	5.30	2.44	0.53
55	CW12	B1	66	0.19	1.07	--	0.60	4.10	1.46	20.8	25.9	5.20	3.90	5.30	2.45	0.64
56	CW12	2B2b?	137	--	0.57	--	0.64	5.65	1.89	19.4	30.4	5.48	4.06	5.51	--	0.57
57	CW12	2B31b?	250	--	--	--	0.76	4.95	1.61	21.9	28.4	5.70	4.20	5.70	3.00	0.68
58	CW12	3B32b?	270	--	--	--	0.42	6.22	2.30	20.0	30.6	5.60	4.20	5.80	2.78	0.79
59	CW12	3C1b?	--	--	--	--	0.46	7.50	2.64	15.6	26.0	5.90	4.40	6.00	1.06	0.54
							Wingate Hill outwash, 500 ka(?)									
60	CW2	A	20	0.19	3.55	--	0.49	10.38	1.33	16.8	29.5	5.80	4.90	6.00	1.67	0.68
61	CW2	A3	35	0.10	1.30	--	0.26	7.14	0.46	13.4	21.2	5.60	4.50	5.60	1.94	0.51
62	CW2	B21t	66	--	--	--	0.25	6.96	0.39	12.0	17.2	5.80	4.70	5.70	1.85	0.43
63	CW2	2B22t	94	0.05	--	--	0.55	5.73	2.76	12.0	22.2	5.80	4.70	5.50	3.14	0.31
64	CW2	2B23t	245	--	--	--	0.20	3.96	2.68	12.9	24.4	5.00	3.70	4.70	3.28	0.36
65	CW2	2B3	300	--	--	--	0.12	5.26	3.54	12.1	25.4	5.40	4.10	5.00	3.45	0.32
							Logan Hill Formation, 1,200 ka(?)									
66	CW11	A	12	0.21	--	--	0.53	5.28	0.88	19.8	24.4	5.40	4.70	5.70	1.99	0.63
67	CW11	B1t	40	0.09	1.07	--	0.29	2.65	0.39	15.4	20.9	5.40	4.25	5.40	2.64	0.54
68	CW11	B21t	64	--	--	--	0.22	1.01	0.46	16.1	16.6	5.00	3.70	4.80	3.28	0.47
69	CW11	B22t	94	--	--	--	0.08	0.77	0.63	18.0	19.1	5.10	3.80	4.90	3.79	0.53
70	CW11	2B23t	106	--	--	--	0.10	0.88	0.78	16.8	20.2	5.10	3.50	5.00	4.07	0.57
71	CW11	2B24t	150	--	--	--	0.12	1.49	0.91	16.4	18.4	5.10	3.65	5.20	4.03	0.41
72	CW11	2B3t	240	--	--	--	0.10	2.26	1.75	11.8	14.9	5.20	4.00	5.00	3.92	0.43

Supplementary table 4. Clay mineralogy[1]

(Analysts: J.P. Bethel under F.C. Ugolini, University of Washington, Seattle)

No.	Sample	Horizon	Basal depth (cm)	Kaolinite	Chlorite	Vermiculite	Illite	Smectite
			late Holocene alluvium, 0.25 ka					
1	CW6	A11	10	--	--	--	--	--
2	CW6	A12	25	++	--	++	+	+++
3	CW6	Cn	--	++	+	--	--	+++
			latest Pleistocene(?) outwash, 11 ka					
4	CW8	A11p	18	+++	--	++	--	++
5	CW8	A12p	31	+++	--	++	--	++
6	CW8	A+B	50	+++	--	+++	+	--
7	CW8	B21t	70	--	--	--	--	--
8	CW8	B22t	94	+++	--	+	--	++
9	CW8	2B3	127	--	--	--	--	--
10	CW8	3C1ox	140	--	--	--	--	--
11	CW8	3C2ox	--	+++	--	+	+	++
			late Evans Creek outwash, 14 ka					
12	CW3	A11	23	--	--	--	--	--
13	CW3	A12	48	++	+	+++	+	++
14	CW3	C1ox	66	++	--	++	--	++
15	CW3	C2	--	++	--	+	--	+
			early Evans Creek outwash, 24 ka					
16	CW4	A	15	+	--	+	--	--
17	CW4	B	72	--	--	++	--	--
18	CW4	2C1ox	90	--	--	--	--	--
19	CW4	2C2n	--	+++	--	++	--	++
20	CW5	A	14	+	--	++	--	--
21	CW5	B	60	--	--	+	--	--
22	CW5	2C1ox	92	--	--	--	--	--
23	CW5	3C2ox	130	--	--	--	--	--
24	CW5	4C3	--	+++	--	--	--	--
			pre-Evans Creek outwash(?), 60 ka(?)					
25	CW7	A1	24	+++	--	++	+	+
26	CW7	B11	38	--	--	--	--	--
27	CW7	B12	56	--	--	--	--	--
28	CW7	B21/B22	101	+++	--	++	+	--
29	CW7	B31	111	--	--	--	--	--
30	CW7	2B32	145	--	--	--	--	--
31	CW7	2C	--	+++	--	+	--	--

Supplementary table 4. Clay mineralogy--Continued

late Hayden Creek outwash, 150 ka(?)								
33	CW9	A11	5	+++	+	+++	+	--
34	CW9	A12	17	+++	--	+++	+	+
35	CW9	B1	26	+++	--	+++	+	--
36	CW9	B21t	38	+++	--	+++	+	--
37	CW9	B22t	75	+++	--	+++	+	--
38	CW9	2B31	92	+++	--	+++	+	--
39	CW9	2B32	196	+++	+	++	--	++
40	CW9	2C1ox	--	+++	--	++	--	--
middle Hayden Creek outwash, 225 ka(?)								
47	CW10	A	10	+++	--	+++	+	--
48	CW10	B11	30	--	--	--	--	--
49	CW10	B1	54	--	--	--	--	--
50	CW10	B2t	100	+++	--	++	--	--
51	CW10	B3t	260	--	--	--	--	--
52	CW10	Cox	380	+++	--	++	++	+
early Hayden Creek outwash, 300 ka(?)								
53	CW12	A11	32	--	--	--	--	--
54	CW12	A12	53	+++	--	+++	--	+
55	CW12	B1	66	--	--	--	--	--
56	CW12	2B2b?	137	+++	--	++	--	+
57	CW12	2B31b?	250	--	--	--	--	--
58	CW12	3B32b?	270	+++	--	++	--	--
59	CW12	3C1b?	--	+++	--	++	--	--
Wingate Hill outwash, 500 ka(?)								
60	CW2	A	20	+++	--	++	--	--
61	CW2	A3	35	--	--	--	--	--
62	CW2	B21t	66	--	--	--	--	--
63	CW2	2B22t	94	--	--	--	--	--
64	CW2	2B23t	245	+++	--	++	+	+
65	CW2	2B3	300	+++	--	++	+	--
Logan Hill Formation, 1,200 ka(?)								
66	CW11	A	12	+++	+	++	--	--
67	CW11	B1t	40	+++	+	++	--	--
68	CW11	B21t	64	+++	--	++	--	--
69	CW11	B22t	94	+++	--	++	--	--
70	CW11	2B23t	106	+++	--	++	--	--
71	CW11	2B24t	150	+++	--	++	--	--
72	CW11	2B3t	240	+++	--	++	--	--

1/ +,trace constituent; ++,minor constituent; +++,major constituent; --,not detected

Supplementary table 5. Total chemical analyses of the fine (<47 μm) fraction by X-ray fluorescence

[Zr in parts per million; all others in weight percent. Analysts: J. Baker, J. Budahn, R. Knight, J.Taggart, and J.S. Wahlberg]

No.	Sample	Horizon	Basal depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Zr
late Holocene alluvium, 0.25 ka														
1	CW6	A11	10	53.0	16.2	7.13	2.4	4.52	2.7	1.13	1.13	0.3	0.12	194
2	CW6	A12	25	--	--	--	--	--	--	--	--	--	--	--
3	CW6	Cn	--	54.8	16.8	7.92	2.7	4.78	3.0	1.15	1.28	0.3	0.12	226
latest Pleistocene(?) outwash, 11 ka														
4	CW8	A11p	18	50.2	17.7	7.34	1.6	2.38	2.3	1.01	1.23	0.53	0.17	196
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	--	--
6	CW8	A+B	50	--	--	--	--	--	--	--	--	--	--	--
7	CW8	B21t	70	49.7	21.7	9.11	1.7	1.74	1.7	0.91	1.38	0.1	0.10	212
8	CW8	B22t	94	--	--	--	--	--	--	--	--	--	--	--
9	CW8	2B3	127	--	--	--	--	--	--	--	--	--	--	--
10	CW8	3C1ox	140	49.9	21.2	9.08	1.7	2.11	1.6	0.73	1.30	0.1	0.10	215
11	CW8	3C2ox	--	--	--	--	--	--	--	--	--	--	--	--
late Evans Creek outwash, 14 ka														
12	CW3	A11	23	44.8	17.8	7.80	1.7	2.05	1.9	0.93	1.19	0.5	0.18	202
13	CW3	A12	48	--	--	--	--	--	--	--	--	--	--	--
14	CW3	C1ox	66	50.4	20.2	8.81	2.0	1.84	2.1	1.05	1.38	0.2	0.12	221
15	CW3	C2	--	--	--	--	--	--	--	--	--	--	--	--
early Evans Creek outwash, 24 ka														
16	CW4	A	15	38.5	16.2	7.03	1.6	2.52	1.6	0.70	1.06	1.2	0.24	179
17	CW4	B	72	43.5	20.5	8.34	1.8	2.17	1.8	0.74	1.26	0.94	0.20	230
18	CW4	2C1ox	90	41.8	20.9	8.61	2.0	1.88	1.5	0.71	1.39	0.4	0.11	248
19	CW4	2C2n	--	--	--	--	--	--	--	--	--	--	--	--
20	CW5	A	14	39.0	15.9	7.13	1.2	2.12	1.7	0.70	1.14	0.5	0.21	187
21	CW5	B	60	45.7	19.3	8.64	1.4	1.89	2.0	0.76	1.39	0.3	0.14	228
22	CW5	2C1ox	92	44.3	21.1	9.01	1.4	1.56	1.7	0.72	1.42	0.3	0.07	222
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	--	--
24	CW5	4C3	--	--	--	--	--	--	--	--	--	--	--	--
pre-Evans Creek outwash(?), 60 ka(?)														
25	CW7	A1	26	54.5	17.6	8.33	1.3	1.41	2.1	1.07	1.54	0.3	0.20	239
26	CW7	B11	38	--	--	--	--	--	--	--	--	--	--	--
27	CW7	B12	56	--	--	--	--	--	--	--	--	--	--	--
28	CW7	B21/B22	101	47.7	22.1	9.94	1.5	1.18	1.3	0.75	1.55	0.2	0.09	212
29	CW7	B31	111	--	--	--	--	--	--	--	--	--	--	--
30	CW7	2B32	145	--	--	--	--	--	--	--	--	--	--	--
31	CW7	2C	--	42.4	23.5	10.7	2.5	2.26	1.1	0.41	1.86	0.4	0.12	246

Supplementary table 5. Total chemical analyses of the fine (<47 μm) fraction by X-ray fluorescence--Continued

late Hayden Creek outwash, 150 ka(?)														
33	CW9	A11	5	--	--	--	--	--	--	--	--	--	--	--
34	CW9	A12	17	60.6	15.8	6.08	1.4	1.58	2.0	1.49	1.21	0.4	0.18	247
35	CW9	B1	26	--	--	--	--	--	--	--	--	--	--	--
36	CW9	B21t	38	59.5	16.9	6.63	1.4	1.38	1.9	1.45	1.19	0.2	0.1	235
37	CW9	B22t	75	--	--	--	--	--	--	--	--	--	--	--
38	CW9	2B31	92	--	--	--	--	--	--	--	--	--	--	--
39	CW9	2B32	196	--	--	--	--	--	--	--	--	--	--	--
40	CW9	2C1ox	--	44.9	27.6	7.74	1.3	0.88	0.8	0.59	0.97	0.2	0.15	145
middle Hayden Creek outwash, 225 ka(?)														
47	CW10	A	10	56.4	16.2	7.14	1.1	1.24	1.8	1.08	1.48	0.2	0.18	251
48	CW10	B11	30	--	--	--	--	--	--	--	--	--	--	--
49	CW10	B12	54	--	--	--	--	--	--	--	--	--	--	--
50	CW10	B2t	100	54.9	20.1	7.64	1.3	0.74	1.2	0.89	1.31	0.1	0.08	233
51	CW10	B3t	260	--	--	--	--	--	--	--	--	--	--	--
52	CW10	Cox	380	44.3	28.2	7.80	1.3	0.75	0.9	0.53	1.05	0.2	0.11	147
early Hayden Creek outwash, 300 ka(?)														
53	CW12	A11	32	--	--	--	--	--	--	--	--	--	--	--
54	CW12	A12	53	55.9	17.7	7.25	1.3	1.13	1.8	1.09	1.38	0.3	0.09	243
55	CW12	B1	66	--	--	--	--	--	--	--	--	--	--	--
56	CW12	2B2b?	137	51.0	21.7	7.88	1.3	0.84	1.2	0.82	1.24	0.3	0.10	248
57	CW12	2B31b?	250	--	--	--	--	--	--	--	--	--	--	--
58	CW12	3B32b?	270	--	--	--	--	--	--	--	--	--	--	--
59	CW12	3C1b?	--	39.7	29.1	6.75	1.5	0.89	0.7	0.43	1.00	0.52	0.12	233
Wingate Hill outwash, 500 ka(?)														
60	CW2	A	20	--	--	--	--	--	--	--	--	--	--	--
61	CW2	A3	35	56.3	19.1	7.66	0.85	0.61	0.8	0.68	1.46	0.2	0.1	284
62	CW2	B21t	66	--	--	--	--	--	--	--	--	--	--	--
63	CW2	2B22t	94	--	--	--	--	--	--	--	--	--	--	--
64	CW2	2B23t	245	58.5	17.7	7.08	0.96	0.87	1.0	0.84	1.46	0.2	0.1	275
65	CW2	2B3	300	--	--	--	--	--	--	--	--	--	--	--
Logan Hill Formation, 1,200 ka(?)														
66	CW11	A	12	62.8	13.7	5.68	0.75	0.78	0.7	0.73	1.60	0.2	0.17	352
67	CW11	B1t	40	--	--	--	--	--	--	--	--	--	--	--
68	CW11	B21t	64	--	--	--	--	--	--	--	--	--	--	--
69	CW11	B22t	94	--	--	--	--	--	--	--	--	--	--	--
70	CW11	2B23t	106	54.8	21.0	8.73	0.4	0.08	0.2	0.38	1.47	0.1	0.04	243
71	CW11	2B24t	150	--	--	--	--	--	--	--	--	--	--	--
72	CW11	2B3t	240	--	--	--	--	--	--	--	--	--	--	--

Supplementary table 6. Total chemical analyses of the less-than-2-mm fraction by X-ray fluorescence

[Zr in parts per million; all others in weight percent. Analysts: D. Burgi and R. Johnson]

No.	Sample	Horizon	Basal depth (cm)	SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO	Zr
						late Holocene alluvium, 0.25 ka								
1	CW6	A11	10	54.9	16.2	6.32	2.37	4.73	2.94	1.20	0.96	0.22	0.10	174
2	CW6	A12	25	--	--	--	--	--	--	--	--	--	--	--
3	CW6	Cn	--	58.2	17.1	6.75	2.73	5.21	3.22	1.27	1.05	0.19	0.10	177
						latest Pleistocene(?) outwash, 11 ka								
4	CW8	A11p	18	51.4	16.9	7.16	1.72	2.86	2.30	0.98	1.17	0.48	0.17	171
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	--	--
6	CW8	A+B	50	--	--	--	--	--	--	--	--	--	--	--
7	CW8	B21t	70	54.3	18.9	8.63	1.98	2.42	2.18	1.01	1.32	0.1	0.12	193
8	CW8	B22t	94	--	--	--	--	--	--	--	--	--	--	--
9	CW8	2B3	127	--	--	--	--	--	--	--	--	--	--	--
10	CW8	3C1ox	140	56.9	17.7	7.66	2.05	3.43	2.66	0.98	1.17	0.11	0.10	176
11	CW8	3C2ox	--	--	--	--	--	--	--	--	--	--	--	--
						late Evans Creek outwash, 14 ka								
12	CW3	A11	23	48.1	17.2	7.34	1.85	2.41	2.11	0.98	1.10	0.38	0.18	177
13	CW3	A12	48	--	--	--	--	--	--	--	--	--	--	--
14	CW3	C1ox	66	53.7	18.9	8.16	2.01	2.23	2.23	1.11	1.21	0.17	0.14	199
15	CW3	C2	--	--	--	--	--	--	--	--	--	--	--	--
						early Evans Creek outwash, 24 ka								
16	CW4	A	15	43.4	15.7	7.96	3.08	2.89	1.99	0.84	1.15	0.80	0.21	173
17	CW4	B	72	48.1	17.9	9.15	3.65	2.73	2.20	0.91	1.31	0.55	0.17	202
18	CW4	2C1ox	90	48.0	17.9	9.68	4.08	2.47	2.04	0.93	1.38	0.23	0.13	187
19	CW4	2C2n	--	--	--	--	--	--	--	--	--	--	--	--
20	CW5	A	14	43.7	16.7	7.90	1.98	2.54	1.94	0.81	1.18	0.42	0.21	173
21	CW5	B	60	47.8	19.0	8.94	2.17	2.21	2.06	0.87	1.32	0.28	0.14	198
22	CW5	2C1ox	92	49.7	18.9	9.62	2.79	2.20	2.11	0.93	1.41	0.19	0.1	208
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	--	--
24	CW5	4C3	--	--	--	--	--	--	--	--	--	--	--	--
						pre-Evans Creek outwash(?), 60 ka(?)								
25	CW7	A1	26	55.1	16.3	8.30	2.01	1.66	1.99	1.06	1.42	0.28	0.24	223
26	CW7	B11	38	--	--	--	--	--	--	--	--	--	--	--
27	CW7	B12	56	--	--	--	--	--	--	--	--	--	--	--
28	CW7	B21/B22	101	50.5	19.2	9.83	3.08	1.49	1.58	0.87	1.41	0.16	0.12	211
29	CW7	B31	111	--	--	--	--	--	--	--	--	--	--	--
30	CW7	2B32	145	--	--	--	--	--	--	--	--	--	--	--
31	CW7	2C	--	52.1	16.2	10.1	6.50	2.78	2.07	0.85	1.35	0.22	0.16	196

Supplementary table 6. Total chemical analyses of the less-than-2-mm fraction by X-ray fluorescence--Continued

late Hayden Creek outwash, 150 ka(?)														
33	CW9	A11	5	--	--	--	--	--	--	--	--	--	--	--
34	CW9	A12	17	59.5	15.5	6.22	1.38	1.86	1.90	1.39	1.15	0.45	0.26	228
35	CW9	B1	26	--	--	--	--	--	--	--	--	--	--	--
36	CW9	B21t	38	59.0	16.9	6.71	1.46	1.68	1.78	1.35	1.16	0.20	0.14	233
37	CW9	B22t	75	--	--	--	--	--	--	--	--	--	--	--
38	CW9	2B31	92	--	--	--	--	--	--	--	--	--	--	--
39	CW9	2B32	196	--	--	--	--	--	--	--	--	--	--	--
40	CW9	2C1ox	--	51.1	22.0	8.29	1.64	1.34	1.38	0.93	1.18	0.15	0.15	184
middle Hayden Creek outwash, 225 ka(?)														
47	CW10	A	10	55.2	15.8	7.47	1.26	1.58	1.78	1.0	1.43	0.22	0.23	240
48	CW10	B11	30	--	--	--	--	--	--	--	--	--	--	--
49	CW10	B12	54	--	--	--	--	--	--	--	--	--	--	--
50	CW10	B2t	100	53.2	20.4	8.20	1.33	0.93	1.03	0.81	1.26	0.10	0.12	219
51	CW10	B3t	260	--	--	--	--	--	--	--	--	--	--	--
52	CW10	Cox	380	49.1	22.4	8.41	1.82	1.23	1.34	0.91	1.27	0.20	0.16	197
early Hayden Creek outwash, 300 ka(?)														
53	CW12	A11	32	--	--	--	--	--	--	--	--	--	--	--
54	CW12	A12	53	55.1	17.3	7.53	1.38	1.40	1.59	1.03	1.33	0.31	0.11	238
55	CW12	B1	66	--	--	--	--	--	--	--	--	--	--	--
56	CW12	2B2b?	137	50.2	21.7	8.05	1.34	0.94	0.96	0.77	1.22	0.26	0.12	201
57	CW12	2B31b?	250	--	--	--	--	--	--	--	--	--	--	--
58	CW12	3B32b?	270	--	--	--	--	--	--	--	--	--	--	--
59	CW12	3C1b?	--	51.0	19.3	8.56	2.62	1.88	1.86	1.07	1.42	0.29	0.14	209
Wingate Hill outwash, 500 ka(?)														
60	CW2	A	20	--	--	--	--	--	--	--	--	--	--	--
61	CW2	A3	35	60.5	16.0	6.69	1.08	1.39	1.30	0.87	1.54	0.18	0.13	288
62	CW2	B21t	66	--	--	--	--	--	--	--	--	--	--	--
63	CW2	2B22t	94	--	--	--	--	--	--	--	--	--	--	--
64	CW2	2B23t	245	51.5	21.6	8.81	0.74	0.31	0.17	0.47	1.42	0.15	0.12	251
65	CW2	2B3	300	--	--	--	--	--	--	--	--	--	--	--
Logan Hill Formation, 1,200 ka(?)														
66	CW11	A	12	60.2	13.8	6.52	0.79	0.88	0.62	0.67	1.64	0.24	0.22	306
67	CW11	B1t	40	--	--	--	--	--	--	--	--	--	--	--
68	CW11	B21t	64	--	--	--	--	--	--	--	--	--	--	--
69	CW11	B22t	94	--	--	--	--	--	--	--	--	--	--	--
70	CW11	2B23t	106	52.7	21.5	10.2	0.43	0.09	0.15	0.35	1.46	0.14	0.06	283
71	CW11	2B24t	150	--	--	--	--	--	--	--	--	--	--	--
72	CW11	2B3t	240	--	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 1. Total chemical analyses of the fine (<47 μm) fraction by instrumental neutron activation

[K and Fe values in weight percent; all others in part per million. Analysts: J. Budahn and R. Knight]

No.	Sample	Horizon	Basal depth (cm)	Ba	Ce	Co	Cr	Cs	Dy	Eu	Fe	Gd	Hf	K	La	Lu	Mn
late Holocene alluvium, 0.25 ka																	
1	CW6	A11	10	329.	37.9	18.2	61.1	2.04	4.01	1.27	4.87	--	4.61	0.940	18.3	0.342	971.
2	CW6	A12	25	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	CW6	Cn	--	308.	44.0	19.2	70.8	2.06	4.19	1.41	5.26	4.65	5.47	0.962	19.5	0.354	933.
latest Pleistocene(?) outwash, 11 ka																	
4	CW8	A11p	18	423.	34.8	19.6	72.5	2.26	3.26	0.995	5.25	2.56	4.78	0.869	19.1	0.260	1320.
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	--	--	--	--	--
6	CW8	A+B	50	--	--	--	--	--	--	--	--	--	--	--	--	--	--
7	CW8	B21t	70	330.	59.3	20.0	80.6	2.05	7.50	2.06	6.44	6.7	5.39	0.76	25.5	0.592	827.
8	CW8	B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
9	CW8	2B3	127	--	--	--	--	--	--	--	--	--	--	--	--	--	--
10	CW8	3C1ox	140	305.	63.2	19.9	79.9	1.99	6.85	1.88	6.64	6.86	5.47	0.697	24.0	0.518	830.
11	CW8	3C2ox	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
late Evans Creek outwash, 14 ka																	
12	CW3	A11	23	461.	49.8	21.8	77.6	2.49	4.94	1.31	5.96	4.74	5.16	0.762	27.6	0.386	1430.
13	CW3	A12	48	--	--	--	--	--	--	--	--	--	--	--	--	--	--
14	CW3	C1ox	66	392.	55.7	22.4	76.5	2.73	6.45	1.55	6.40	6.00	5.50	0.980	23.0	0.465	1060.
15	CW3	C2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
early Evans Creek outwash, 24 ka																	
16	CW4	A	15	428.	64.1	22.1	136.	1.61	4.82	1.47	5.63	4.49	4.61	0.663	29.5	0.375	1930.
17	CW4	B	72	303.	69.8	22.5	136.	1.77	6.28	1.89	5.85	6.87	5.30	0.631	29.5	0.435	1500.
18	CW4	2C1ox	90	242.	76.7	21.1	153.	1.63	6.53	1.94	5.99	6.69	5.49	0.582	22.1	0.476	841.
19	CW4	2C2n	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
20	CW5	A	14	464.	53.7	21.2	135.	1.80	4.23	1.34	5.43	4.37	4.52	0.705	28.3	0.306	1670.
21	CW5	B	60	336.	65.8	24.7	160.	1.83	5.80	1.82	6.19	6.34	5.22	0.643	27.0	0.437	1140.
22	CW5	2C1ox	92	296.	70.2	23.9	168.	1.80	5.96	1.80	6.33	6.76	5.30	0.611	20.0	0.489	592.
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	--	--	--	--	--
24	CW5	4C3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
pre-Evans Creek outwash(?), 60 ka(?)																	
25	CW7	A1	26	486.	41.5	20.0	125.	2.09	3.90	1.03	5.40	2.95	5.60	1.00	21.0	0.302	1450.
26	CW7	B11	38	--	--	--	--	--	--	--	--	--	--	--	--	--	--
27	CW7	B12	56	--	--	--	--	--	--	--	--	--	--	--	--	--	--
28	CW7	B21/B22	101	379.	76.7	22.3	146.	1.84	6.72	1.80	6.78	--	5.47	0.660	23.4	0.474	754.
29	CW7	B31	111	--	--	--	--	--	--	--	--	--	--	--	--	--	--

30	CW7	2B32	145	--	--	--	--	--	--	--	--	--	--	--	--	--	--
31	CW7	2C	--	363.	94.4	20.4	172.	0.987	8.16	2.55	7.71	8.57	6.16	0.50	27.2	0.558	944.
late Hayden Creek outwash, 150 ka(?)																	
33	CW9	A11	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--
34	CW9	A12	17	637.	47.6	13.7	66.2	3.40	3.62	0.924	4.08	--	6.07	1.17	23.6	0.286	1350.
35	CW9	B1	26	--	--	--	--	--	--	--	--	--	--	--	--	--	--
36	CW9	B21t	38	592.	52.4	14.1	70.5	3.83	4.00	1.05	4.71	3.67	6.37	1.28	23.2	0.327	816.
37	CW9	B22t	75	--	--	--	--	--	--	--	--	--	--	--	--	--	--
38	CW9	2B31	92	--	--	--	--	--	--	--	--	--	--	--	--	--	--
39	CW9	2B32	196	--	--	--	--	--	--	--	--	--	--	--	--	--	--
40	CW9	2C1ox	--	303.	101.	17.6	37.0	2.26	5.37	1.40	4.87	6.05	3.32	0.50	22.0	0.357	1090.
middle Hayden Creek outwash, 225 ka(?)																	
47	CW10	A	10	506.	46.2	18.5	83.9	2.43	--	0.861	4.50	2.96	5.73	0.864	23.4	0.302	1380.
48	CW10	B11	30	--	--	--	--	--	--	--	--	--	--	--	--	--	--
49	CW10	B12	64	--	--	--	--	--	--	--	--	--	--	--	--	--	--
50	CW10	B2t	100	375.	53.5	18.0	64.4	2.82	4.07	1.05	4.84	4.10	5.46	0.842	22.5	0.339	670.
51	CW10	B3t	260	--	--	--	--	--	--	--	--	--	--	--	--	--	--
52	CW10	Cox	380	418.	87.2	16.8	41.2	0.951	--	1.29	5.15	4.60	3.41	0.50	19.7	0.358	891.
early Hayden Creek outwash, 300 ka(?)																	
53	CW12	A11	32	--	--	--	--	--	--	--	--	--	--	--	--	--	--
54	CW12	A12	53	416.	48.5	16.0	85.4	2.90	--	1.47	4.61	5.27	5.49	1.04	27.7	0.398	756.
55	CW12	B1	66	--	--	--	--	--	--	--	--	--	--	--	--	--	--
56	CW12	2B2b?	137	547.	55.0	16.9	72.2	2.69	--	1.25	5.09	4.6	5.24	0.736	21.8	0.395	787.
57	CW12	2B31b?	250	--	--	--	--	--	--	--	--	--	--	--	--	--	--
58	CW12	3B32b?	270	--	--	--	--	--	--	--	--	--	--	--	--	--	--
59	CW12	3C1b?	--	686.	103.	21.0	45.5	1.06	5.09	1.27	4.14	4.83	2.74	0.50	16.8	0.341	921.
Wingate Hill outwash, 500 ka(?)																	
60	CW2	A	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--
61	CW2	A3	35	--	--	--	--	--	--	--	--	--	--	--	--	--	--
62	CW2	B21t	66	411.	71.7	23.2	95.7	4.08	4.10	1.13	6.03	4.6	7.88	0.714	27.8	0.399	840.
63	CW2	2B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
64	CW2	2B23t	245	456.	62.1	19.1	94.2	4.42	4.02	1.09	5.61	4.53	7.46	0.695	28.6	0.389	817.
65	CW2	2B3	300	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Logan Hill Formation, 1,200 ka(?)																	
66	CW11	A	12	402.	49.2	11.0	85.7	3.50	3.30	0.716	3.58	3.43	7.84	0.536	23.6	0.330	1270.
67	CW11	B1t	40	--	--	--	--	--	--	--	--	--	--	--	--	--	--
68	CW11	B21t	64	--	--	--	--	--	--	--	--	--	--	--	--	--	--
69	CW11	B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
70	CW11	2B23t	106	184.	44.2	15.1	77.2	3.27	3.70	0.788	5.76	3.38	7.15	0.50	21.6	0.357	380.
71	CW11	2B24t	150	--	--	--	--	--	--	--	--	--	--	--	--	--	--
72	CW11	2B3t	240	--	--	--	--	--	--	--	--	--	--	--	--	--	--

Supplementary table 7, part 2. Total chemical analyses of the fine (<47 μm) fraction by instrumental neutron activation

[Na value in weight percent; all others in part per million. Analysts: J. Budahn and R. Knight]

No.	Sample	Horizon	Basal depth (cm)	Na	Nd	Rb	Sb	Sc	Sm	Sr	Ta	Tb	Th	Tm	U	Yb	Zr
								late Holocene alluvium, 0.25 ka									
1	CW6	A11	10	2.00	18.3	32.9	0.556	17.9	4.54	314.	0.747	0.676	4.02	0.34	1.64	2.09	165.
2	CW6	A12	25	--	--	--	--	--	--	--	--	--	--	--	--	--	--
3	CW6	Cn	--	2.06	19.7	29.9	0.484	19.1	4.20	320.	0.804	0.772	4.39	0.22	1.55	2.17	215.
								latest Pleistocene(?) outwash, 11 ka									
4	CW8	A11p	18	1.74	15.9	35.3	0.416	15.9	3.14	291.	0.909	0.532	3.74	--	1.47	1.50	147.
5	CW8	A12p	31	--	--	--	--	--	--	--	--	--	--	--	--	--	--
6	CW8	A+B	50	--	--	--	--	--	--	--	--	--	--	--	--	--	--
7	CW8	B21t	70	1.25	35.3	33.6	0.45	28.2	7.89	279.	0.979	1.09	4.69	0.650	2.20	3.36	175.
8	CW8	B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
9	CW8	2B3	127	--	--	--	--	--	--	--	--	--	--	--	--	--	--
10	CW8	3C1ox	140	1.24	32.6	28.3	0.426	30.0	7.53	300.	0.979	1.10	4.93	--	1.88	3.17	190.
11	CW8	3C2ox	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
								late Evans Creek outwash, 14 ka									
12	CW3	A11	23	1.53	23.3	36.1	0.564	20.4	4.64	277.	0.926	0.763	4.19	--	1.57	2.35	185.
13	CW3	A12	48	--	--	--	--	--	--	--	--	--	--	--	--	--	--
14	CW3	C1ox	66	1.60	25.3	33.	0.399	25.4	5.76	262.	0.969	1.01	4.46	0.500	1.82	3.04	197.
15	CW3	C2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
								early Evans Creek outwash, 24 ka									
16	CW4	A	15	1.37	29.8	25.6	0.453	20.2	5.70	242.	0.854	0.799	4.64	0.330	1.80	2.24	197.
17	CW4	B	72	1.42	38.0	10.	0.272	23.7	7.60	210.	0.891	1.04	5.26	0.56	1.89	2.71	175.
18	CW4	2C1ox	90	1.20	33.0	22.3	0.320	26.1	7.61	193.	0.970	1.05	5.11	--	1.81	2.89	190.
19	CW4	2C2n	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
20	CW5	A	14	1.37	26.6	31.8	0.335	16.8	5.03	218.	0.879	0.716	4.28	0.35	1.64	1.93	151.
21	CW5	B	60	1.48	33.9	29.2	0.313	23.8	7.02	195.	0.964	0.959	5.00	0.520	1.94	2.75	175.
22	CW5	2C1ox	92	1.29	31.5	28.4	0.382	27.6	6.87	171.	0.931	1.01	5.04	0.417	0.50	3.00	228.
23	CW5	3C2ox	130	--	--	--	--	--	--	--	--	--	--	--	--	--	--
24	CW5	4C3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
								pre-Evans Creek outwash(?), 60 ka(?)									
25	CW7	A1	26	1.59	22.0	38.1	0.488	16.1	3.76	170.	0.978	0.592	4.96	--	1.95	1.94	400.
26	CW7	B11	38	--	--	--	--	--	--	--	--	--	--	--	--	--	--
27	CW7	B12	56	--	--	--	--	--	--	--	--	--	--	--	--	--	--
28	CW7	B21/B22	101	1.02	32.3	29.8	0.379	30.5	7.08	179.	0.962	0.948	4.99	0.26	1.75	2.90	215.
29	CW7	B31	111	--	--	--	--	--	--	--	--	--	--	--	--	--	--

30	CW7	2B32	145	--	--	--	--	--	--	--	--	--	--	--	--	--	--
31	CW7	2C	--	0.699	46.1	14.	0.510	35.4	9.78	403.	1.16	1.18	6.14	0.620	2.03	3.14	253.
late Hayden Creek outwash, 150 ka(?)																	
33	CW9	A11	5	--	--	--	--	--	--	--	--	--	--	--	--	--	--
34	CW9	A12	17	1.49	20.5	61.8	0.569	12.3	3.80	193.	1.08	0.568	6.76	0.28	2.35	1.82	226.
35	CW9	B1	26	--	--	--	--	--	--	--	--	--	--	--	--	--	--
36	CW9	B21t	38	1.41	19.6	64.8	0.691	15.4	4.19	163.	1.13	0.639	7.46	0.310	2.69	2.04	225.
37	CW9	B22t	75	--	--	--	--	--	--	--	--	--	--	--	--	--	--
38	CW9	2B31	92	--	--	--	--	--	--	--	--	--	--	--	--	--	--
39	CW9	2B32	196	--	--	--	--	--	--	--	--	--	--	--	--	--	--
40	CW9	2C1ox	--	0.583	28.8	32.3	0.65	22.1	6.27	220.	0.663	0.850	3.81	0.420	1.21	2.22	134.
middle Hayden Creek outwash, 225 ka(?)																	
47	CW10	A	10	1.39	19.0	44.5	0.599	13.9	3.82	149.	1.16	0.496	5.67	0.312	2.20	1.86	198.
48	CW10	B11	30	--	--	--	--	--	--	--	--	--	--	--	--	--	--
49	CW10	B12	64	--	--	--	--	--	--	--	--	--	--	--	--	--	--
50	CW10	B2t	100	0.877	22.1	44.0	0.546	16.8	4.68	127.	1.13	0.640	5.66	0.370	2.35	2.09	180.
51	CW10	B3t	260	--	--	--	--	--	--	--	--	--	--	--	--	--	--
52	CW10	Cox	380	0.602	23.5	22.5	0.443	24.5	5.63	280.	0.740	0.726	3.07	0.347	1.04	2.19	128.
early Hayden Creek outwash, 300 ka(?)																	
53	CW12	A11	32	--	--	--	--	--	--	--	--	--	--	--	--	--	--
54	CW12	A12	53	1.25	29.6	47.4	0.57	18.1	6.12	190.	1.03	0.840	5.83	0.450	2.45	2.48	208.
55	CW12	B1	66	--	--	--	--	--	--	--	--	--	--	--	--	--	--
56	CW12	2B2b?	137	0.814	24.8	32.4	0.765	19.1	5.31	180.	1.01	0.681	5.88	--	2.45	2.55	182.
57	CW12	2B31b?	250	--	--	--	--	--	--	--	--	--	--	--	--	--	--
58	CW12	3B32b?	270	--	--	--	--	--	--	--	--	--	--	--	--	--	--
59	CW12	3C1b?	--	0.499	21.7	17.2	0.23	23.8	5.40	290.	0.648	0.763	3.05	0.332	1.30	2.24	105.
Wingate Hill outwash, 500 ka(?)																	
60	CW2	A	20	--	--	--	--	--	--	--	--	--	--	--	--	--	--
61	CW2	A3	35	--	--	--	--	--	--	--	--	--	--	--	--	--	--
62	CW2	B21t	66	0.563	24.6	39.0	0.769	19.5	4.58	100.	1.35	0.647	8.44	0.440	3.04	2.41	290.
63	CW2	2B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
64	CW2	2B23t	245	0.828	24.7	49.4	0.611	18.7	4.40	100.	1.39	0.618	8.59	0.410	3.12	2.31	295.
65	CW2	2B3	300	--	--	--	--	--	--	--	--	--	--	--	--	--	--
Logan Hill Formation, 1,200 ka(?)																	
66	CW11	A	12	0.560	20.3	41.5	0.801	12.4	3.85	100.	1.41	0.526	7.54	0.360	3.11	2.22	248.
67	CW11	B1t	40	--	--	--	--	--	--	--	--	--	--	--	--	--	--
68	CW11	B21t	64	--	--	--	--	--	--	--	--	--	--	--	--	--	--
69	CW11	B22t	94	--	--	--	--	--	--	--	--	--	--	--	--	--	--
70	CW11	2B23t	106	0.140	20.9	28.3	0.951	16.3	3.82	--	1.30	0.550	8.12	0.400	3.11	2.22	238.
71	CW11	2B24t	150	--	--	--	--	--	--	--	--	--	--	--	--	--	--
72	CW11	2B3t	240	--	--	--	--	--	--	--	--	--	--	--	--	--	--

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