Surficial Geology and Geomorphology of the Lake Tapps Quadrangle Washington

GEOLOGICAL SURVEY PROFESSIONAL PAPER 388-A

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By DWIGHT R. CRANDELL

GEOLOGIC STUDIES IN THE PUGET SOUND LOWLAND, WASHINGTON

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A study of glacial, interglacial, and postglacial deposits in part of the Puget Sound lowland and in the foothills of the adjacent Cascade Range

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SURFICIAL GEOLOGY AND GEOMORPHOLOGY OF THE LAKE TAPPS QUADRANGLE, WASHINGTON

By Dwight R. Crandell

ABSTRACT

The Lake Tapps quadrangle lies partly within the Puget Sound lowland and partly on the northwestern flank of the Cascade Range in western Washington. The quadrangle is drained by the White, Carbon, and Puyallup Rivers, each of which heads at glaciers on Mount Rainier, a volcanic cone about 15 miles southeast of the quadrangle. The principal physiographic subdivisions of the quadrangle are the Vashon drift plain in the northern part of the quadrangle, the Osceola mudflow plain in the northeastern part, the Puyallup and Duwamish Valleys along the western edge, and the foothills of the Cascade Range in the southern third of the quadrangle.

Surficial deposits include the sediments of three lithologically dissimilar source areas: Mount Rainer, the Cascade Range east and southeast of the quadrangle, and the northern Cascade Range of Washington and Coast Ranges of southwestern Canada. The Pleistocene history of the quadrangle is one of repeated invasions by the Puget glacial lobe of the Cordilleran ice sheet, originating mainly in the mountains of southwestern Canada. Several of these glaciations were separated by times when the climate was comparable to that of today, during which the lowland was locally alluviated by streams draining the Cascade Range and Mount Rainier. Eruptive activity of Mount Rainier during the Pleistocene is inferred from volcanic mudflows and volcanic ash found in the interglacial sediments, and the contemporary climates are inferred from pollen found in peat beds intercalated with the alluvial and mudflow deposits.

The oldest surficial deposit in the quadrangle is the Orting drift, which includes basal gravel deposited in piedmont alluvial fans along the mountain front during early Pleistocene time, and later drift laid down during the first invasion of the lowland by the Puget glacial lobe. The basal gravel is inferred to have been deposited in part by the ancestral Mowich River, a stream that headed in the Cascade Range near the present cone of Mount Rainier before the appearance of that volcano. The ancestral Mowich Valley trended northward through the foothills along a course approximately coincident with the modern valley of Voight Creek, a tributary of the Carbon River. During the interglacial period that followed the Orting glaciation, the ancestral Mowich Valley was nearly filled with mudflows and alluvium of Mount Rainier derivation, differentiated here as part of the Lily Creek formation. The mudflow and alluvial deposits of a plain built out into the Puget Sound lowland at this time constitute the Alderton formation. Alluviation of this plain was halted by a second glaciation of the lowland, during which the Stuck drift was deposited. This drift includes a single layer of till in most places, overlain and underlain by outwash sand and gravel. The outwash is overlain by fine lacustrine sediments, consisting partly of glacial debris and partly of volcanic ash. Upon withdrawal of the glacier, sedimentation in the lowland was dominated by a river or rivers draining Mount Rainier which deposited the Puyallup formation. Contemporaneously part of the Lily Creek formation was being deposited in the foothills along the course of the ancestral Puyallup River, which trended westward from Mount Rainier, and then turned northward at the west front of the Cascade Range and entered the quadrangle. The Puyallup formation includes many mudflows interbedded with stream gravel and sand and layers of peat.

A period of erosion and weathering occurred after deposition of the Puyallup formation, and a valley at least 100 feet deep was eroded in the vicinity of Sumner. This period terminated with the deposition of the Salmon Springs drift by the Puget glacial lobe. The Salmon Springs drift includes till and outwash sand and gravel deposited during two glacial advances, locally separated by thin nonglacial deposits. Between the Salmon Springs and Vashon glaciations, the drainage pattern of the lowland assumed roughly its present shape, and scouring by the Vashon glacier probably deepened the valleys substantially. In late Pleistocene, pre-Vashon time, the Cascade Range was covered by an icecap that deposited the Wingate Hill drift in the southeastern part of the quadrangle.

During an early phase of the Vashon glaciation, an alpine glacier entered the southeastern corner of the quadrangle along the Carbon River valley, where it deposited the Evans Creek drift. This drift includes a moraine in the vicinity of Upper Fairfax and coarse outwash gravel found in terrace deposits along the Carbon River downstream from the moraine. By the time the Puget lobe of Vashon age reached its farthest southeastward extent in the foothills of the Cascade Range, the Evans Creek glacier had retreated from the quadrangle, and fine sediments were deposited in a Vashon glacial lake in the Carbon River valley. The Vashon glacier left widespread deposits of till that form ground moraine over broad areas. During retreat of the glacier, extensive kame terraces were formed by melt-water streams flowing adjacent to the ice front along the foothills of the Cascade Range and within valleys in the lowland.

As ice melted out of the Puyallup Valley, the valley was occupied by glacial Lake Puyallup, which discharged westward through lower and lower channels as the receding ice margin uncovered successively lower outlets through the ground moraine. Sand and gravel deltas were built into the lake at the

mouth of Fennel Creek by melt water from the glacier margin in the northern part of the quadrangle. Subsequent disappearance of ice from the lowland allowed marine water to enter the glacially scoured stream valleys, and the Puyallup Valley was probably temporarily occupied by Puget Sound at this time.

About 4,800 years ago, the Osceola mudflow originated at Mount Rainier and flowed down the valley of the White River to the lowland, where it spread widely on the low-relief Vashon drift surface and covered some 65 square miles to depths of as much as 75 feet. A large volume of mud flowed down the old valley of the White River (present valley of South Prairie Creek), although the main mass of the mudflow poured out to the west and northwest across the drift plain.

The Osceola mudflow reached the Puyallup Valley near Alderton by way of Fennel Creek and may have extended into an arm of Puget Sound near Sumner. Cutting of the new valley of the White River was instrumental in alluviating the floor of the Puyallup Valley above sea level.

About 500 years ago the Electron mudflow originated at Mount Rainier and flowed down the Puyallup River nearly to Sumner, leaving a blanket of mud and rock over the valley floor. By blocking a tributary valley located where the Puyallup River emerges from the foothills, just south of the Lake Tapps quadrangle, the mudflow formed Lake Kapowsin.

Pre-Salmon Springs formations decrease in altitude northward, but this is inferred to be due largely to the stream gradients on which the interglacial sediments were deposited rather than to a downwarping of the central part of the lowland. Faults are found or inferred in the surficial deposits at a few places. The fact that the Pleistocene sediments in and north of the quadrangle are nearly level suggests that the fill of unconsolidated sediments that extends as much as 2,000 feet below sea level in parts of the lowland is in part of pre-Pleistocene age. There is no record of marine conditions in the lowland until Vashon time, although during or after the Vashon glaciation the lowland may have dropped in relation to sea level, perhaps as much as 500 feet.

The chief economic resources of the quadrangle found in the surficial deposits are sand and gravel and clay. Foundation conditions are good except in parts of the Puyallup Valley floor. The Osceola mudflow provides sufficient bearing strength for types of construction that do not demand footings below a depth of 8 or 10 feet. Below this depth, however, the bearing strength of the mudflow is very low, especially where the deposit is saturated. Damage from a major earthquake in 1949 was extensive in communities on the Puyallup Valley floor, probably as a result of large differential movement in the unconsolidated water-soaked sediments below the valley floor. Communities built on the Osceola mudflow received little damage, despite the fact that the mudflow is unconsolidated below a depth of about 10 feet. Apparently a surficial cemented layer in the mudflow permits structures built upon it to respond as single units during earth movement.

INTRODUCTION

LOCATION, CULTURE, AND ACCESSIBILITY

The Lake Tapps 15-minute quadrangle is in Pierce and King Counties in western Washington (fig. 1). This quadrangle includes four 7½-minute quadrangles that serve as the base for the geologic map (pl. 1) and that are named, clockwise from the northwest corner: Sumner, Buckley, Wilkeson, and Orting. The northwestern corner of the Lake Tapps quadrangle is about 18 miles south of the city limits of Seattle.

The largest communities in the quadrangle are Sumner (population 3,156), Orting (population 1,520), and Buckley (population 3,538), and the northeastern part of the quadrangle includes the outskirts of Enumclaw. Smaller communities are Wilkeson, Carbonado, and South Prairie. The central and western parts of the quadrangle are crossed by the Chicago, Milwaukee, St. Paul and Pacific Railroad, Great Northern Railway, Northern Pacific Railway and Union Pacific Railroad. The principal east-west road is U.S. Highway 410, and the north-south roads are State highways that follow the valleys of the Puyallup and Carbon Rivers.

Access to most of the northern half of the quadrangle is good, the principal exception being the valley of the White River, crossed only by U.S. Highway 410 northeast of Buckley. The most remote part of the area lies in the foothills of the Cascade Range, where only a few public roads give access. In the area west of the Carbon River, however, every section is crossed or bordered by at least one well-maintained private logging and fire-protection road.

PURPOSE AND SCOPE

The Lake Tapps quadrangle was mapped as part of a more extensive geologic investigation of the metropolitan area between Seattle and Tacoma. The purpose of this investigation is to provide basic geologic data that will be useful in planning for future metropolitan and industrial growth. Mapping of the surficial deposits of the Lake Tapps quadrangle was undertaken primarily to provide a stratigraphic framework for mapping and understanding the Pleistocene and Recent deposits that occur throughout the metropolitan area.

The present report describes the post-Miocene unconsolidated formations and the geomorphic evolution of the area, and discusses deposits of possible economic importance found in these formations. A companion report currently being prepared by L. M. Gard, Jr., describes the bedrock and pre-Pleistocene unconsolidated deposits and the fuel resources they contain.

A brief preliminary report on both the bedrock and surficial deposits of the Buckley quadrangle has previously been published (Crandell and Gard, 1959), as have short articles in geologic journals on specific aspects of the work (Crandell and Waldron, 1956; Mullineaux, Gard, and Crandell, 1959; and Crandell, Mullineaux, and Waldron, 1958).

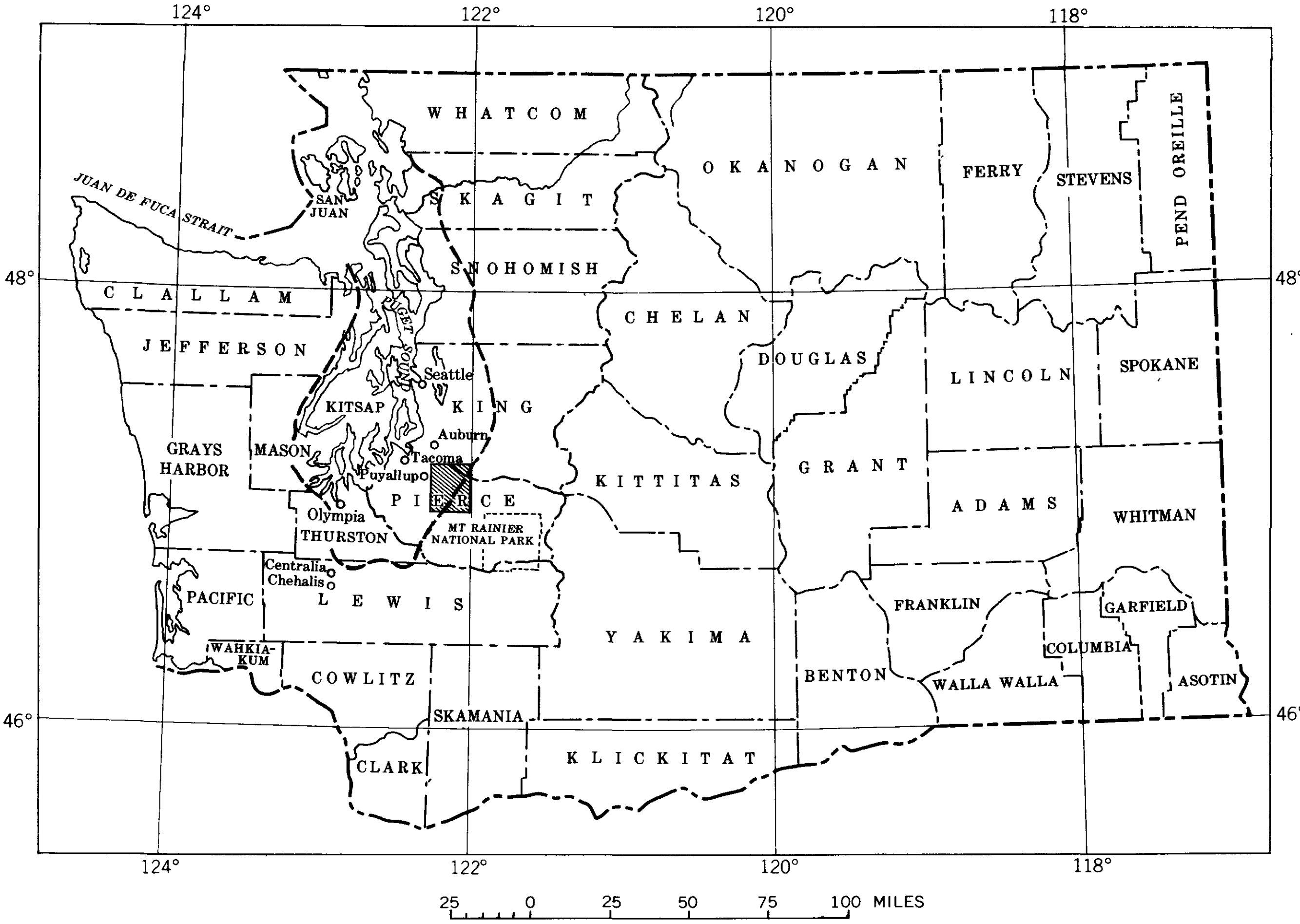

FIGURE 1.—Index map of Washington showing location of the Lake Tapps quadrangle (crosshatched), and approximate boundary of Puget Sound lowland (heavy dashed line).

FIELDWORK AND ACKNOWLEDGMENTS

Geologic mapping was done during the summer and fall of 1953 to 1957. The writer was assisted by L. A. Palmer in 1953 and 1956, by D. C. Kapphahn in 1955, and by Denis LeMoine and P. L. Platt in 1957.

The writer wishes to acknowledge the interest of J. Hoover Mackin, who participated in several field conferences in the area and made many helpful suggestions; Mackin's familiarity with the Pleistocene stratigraphy of the Puget Sound lowland led to selection of the Lake Tapps quadrangle as one in which certain stratigraphic problems might best be solved. Appreciation also is expressed to the staff of the Puyallup office of the Soil Conservation Service, U.S. Department of Agriculture, for help in understanding existing soils on the surficial deposits. R. S. Fiske, C. A. Hopson, and A. C. Waters of The Johns Hopkins University have provided information regarding the lithology and distribution of bedrock formations in Mount Rainier National Park.

Pleistocene and Recent pollen were studied by Estella B. Leopold, and fossil-wood determinations were made by Richard A. Scott, both of the U.S. Geological Survey. Unless otherwise specified, radiocarbon age determinations were made in the low-level radiation laboratory of the Geological Survey under the supervision of Meyer Rubin, and X-ray determinations of silt and clay fractions of certain deposits were made under the supervision of A. J. Gude, 3d, and Dorothy Carroll, U. S. Geological Survey.

The western third of the Lake Tapps quadrangle was mapped geologically in 1939–42 by J. W. Robinson and A. M. Piper of the Geological Survey in cooperation with the city of Tacoma as part of an investigation of the ground-water resources of the Tacoma area. The present writer had access to their manuscript report during the period of his investigation. Although the stratigraphy and geologic history described by Robinson and Piper differ in some respects from that of the present report, the writer wishes to acknowledge the usefulness of the manuscript by Robinson and Piper

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in pointing out specific problems in the Pleistocene stratigraphy of the area.

The discovery that certain heavy minerals indicate three different provenances of Pleistocene sediments in the Puget Sound lowland was made by D. R. Mullineaux, U.S. Geological Survey, whose study of the geology of three 7½-minute quadrangles directly north of the Lake Tapps quadrangle will result in a separate report.

EARLIER STUDIES

The pioneer work on Pleistocene stratigraphy of this part of the Puget Sound lowland was done by Willis (1898) who recognized two glaciations of the lowland, which he named Admiralty and Vashon, and an interglacial interval, which he named Puyallup. With few exceptions, this general sequence has been used ever since by geologists in northwestern Washington (Bretz, 1913; Hansen and Mackin, 1940; Hansen, 1938; Newcomb, 1952; Sceva, 1957). As long ago as 1913, however, Bretz (p. 15, 177) inferred that an even older drift probably exists in the lowland. In addition to his work on pre-Vashon stratigraphy, Bretz (1913) made an outstanding contribution in his study of melt-water channels and lakes formed during the recession of the Vashon glacier.

The first well-documented description of more than one pre-Vashon glaciation in the lowland was presented by Hansen and Mackin and was based on outcrops at Everett and Possession Point north of Seattle, where two pre-Vashon till sheets were found; these till sheets are separated from each other by pollen-bearing sediments that indicate "an interglacial stage of significant magnitude, rather than a temporary retreat of a minor stage" (Hansen and Mackin, 1949, p. 855).

N. R. Anderson (1950) investigated the geology at the site of Mud Mountain Dam on the White River east of Buckley; there he found early Pleistocene deposits that include two till sheets, separated by a zone of decomposition on the lower till. He stated that these tills are overlain by tills of Illinoian (?) and Wisconsin age, with interbedded peat and fluvial and lacustrine deposits. According to Anderson, all the tills at this locality were formed by Cascade glaciers that descended the White River valley.

GENERAL SETTING

DRAINAGE AND RELIEF

The master streams of the area are the Puyallup River and its two main tributaries, the Carbon and White Rivers, each of which heads in the glaciers of Mount Rainier, a volcanic cone about 15 miles southeast of the quadrangle. The east-central part of the quadrangle is drained by South Prairie Creek and its tributary, Wilkeson Creek, both of which head on the slopes of the Cascade Range. The south-central part of the quadrangle is drained by Voight and Frame Creeks which originate on the north slope of the divide between the Carbon and Puyallup Rivers.

Smaller streams in the area are Fennel Creek, which drains part of the drift plain south of Lake Tapps, and Newaukum Creek, which is the only sizable stream on the Osceola mudflow plain. Newaukum Creek flows northward and joins the Green River about 2.5 miles north of the quadrangle.

Waterfalls are found at several places where some of the smaller streams cross bedrock or a resistant stratum in the Pleistocene deposits. Falls and rapids occur at four places on Voight Creek, in the NE¼ sec. 3, and in secs. 2, 12, and 13. At each of these places the stream has been superposed from kame-terrace deposits onto outcrops of volcanic breccia. Lily Creek forms a waterfall in sec. 5 where it spills into the Carbon Gorge over outcrops of sandstone, and low falls and rapids occur at several places along the course of Wilkeson Creek in secs. 27 and 34 upstream from Wilkeson. The only perennial stream in the lowland that forms a waterfall is Fennel Creek. At Victor Falls east of McMillin, the creek plunges about 60 feet from a caprock consisting of a well-indurated mudflow deposit in the Puyallup formation (see measured section 11, p. 79).

The largest body of water in the quadrangle is Lake Tapps, created by raising the level of four small preexisting lakes—Church, Kirtley, Tapps, and Crawford (see Tacoma 30-minute quadrangle, edition of 1900)—by the construction of 13 embankments around the drainage basin (Engineering News, 1912; Henshaw and Parker, 1913). Printz, Dingle, and Wickersham Basins are artificial settling basins created to remove bedload from water taken from the White River east of Buckley and diverted to Lake Tapps via canals and flumes. This water is taken from Lake Tapps, dropped through penstocks over the adjacent valley wall, and passed through a hydroelectric plant at Dieringer. All the other lakes in the area either lie within depressions in the ground moraine (Orting, Morgan, Rhode, and Bonney Lakes) or in kettles in stratified drift (Sunset, Snell, and Forest Lakes). In 1959 a small artificial lake was created in a valley near the center of sec. 28 northeast of Bonney Lake, in connection with a new residential development in the adjacent area.

Total relief is about 2,400 feet; the highest point is the crest of the knoll in the south-central part of the area, on which the Electron fire lookout is situated, at an altitude of 2,435 feet. The lowest point is west of Sumner where the Puyallup River flows from the quadrangle at an altitude of a little less than 40 feet.

The quadrangle is divided into two principal physiographic parts: a broad rolling lowland area, at an altitude of 50 to 1,100 feet, that is part of the Puget Sound lowland, and an upland area, at an altitude of 1,100 to about 2,400 feet, that forms the foothills of the Cascade Range (also referred to as "Cascade foothills" in this report). The lowland area, in turn, consists of several smaller physiographic subdivisions: drift plain, Osceola mudflow plain, and several large valleys (fig. 2). The drift plain consists of ground moraine and outwash channels and continues southwestward beyond the Lake Tapps quadrangle to the Nisqually River and westward

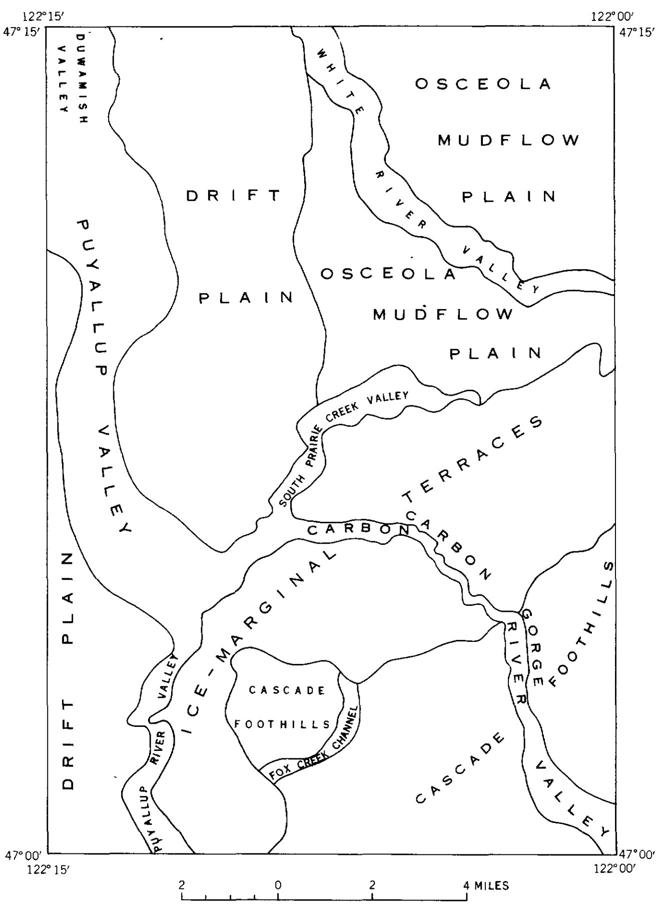

Figure 2.—Physiographic subdivisions of the Lake Tapps quadrangle.

to an arm of Puget Sound southwest of Tacoma. The drift plain gradually increases in altitude to the southeast and, along the front of the foothills, is bordered by a series of broad terraces that represent the courses of ice-marginal melt-water streams formed during the last glaciation. These terraces are bounded on the southeast by an abrupt scarp, several hundred feet high, above which is older drift. The drift plain is bounded on the east by the Osceola mudflow plain, a broad, nearly flat depositional surface of a Recent mudflow from Mount Rainier that continues eastward beyond the edge of the quadrangle to the base of the Cascade foothills.

The largest valley in the quadrangle is occupied by the Puyallup River; this valley is a flat-bottomed trench, 1 to 2 miles wide, incised 300 to 600 feet below the adjacent drift plain. The landform known locally as the Puyallup Valley extends from a point about 1 mile south of Orting, north and west to Commencement Bay at Tacoma. This valley, however, splits at Sumner, one part extending northward to Renton, where it narrows and trends northwestward to Elliot Bay on Puget Sound. The part of this valley system that lies between Elliot Bay and Sumner is referred to as the Duwamish Valley. A segment of this valley north of Sumner is occupied by the Stuck River, which is the name given to the downstream part of the White River.

The White River flows northwestward in a steep-walled, flat-floored trench, ½ to 1 mile wide, that gradually deepens downstream from about 75 feet at Buckley to 200 feet where it leaves the quadrangle. Prior to a particularly high and destructive flood in 1906, the White River split into two branches southeast of Auburn (see Tacoma quadrangle, edition of 1900). The main branch flowed north toward Elliot Bay and the smaller southern branch formed the Stuck River which entered the Puyallup at Sumner. During the 1906 flood, an accumulation of trees and other debris forced the White River from its channel and into the channel of the Stuck. The resulting flood washed out highway and railroad bridges and farm buildings north of Sumner. Subsequently, the White has been kept in the old Stuck River channel by a diversion dam and debris barrier designed to keep the river from returning to its previous northward course near the point of the 1906 diversion (Roberts, W. J., 1916). In this report, the name Stuck River will be used exclusively for the river north of Sumner prior to the 1906 flood, and the present downstream segment of the White between Sumner and Auburn will be referred to henceforth as the White River.

Areas between the major valleys of the lowland are characterized by youthful topography; an integrated drainage pattern has not developed either on the drift plain or the Osceola mudflow plain, and in many places the major valleys can be approached to within a few hundred yards before they are visible.

The deepest valley that cuts through the Cascade foothills is the Carbon River valley. Where it enters the southeastern corner of the quadrangle, the valley is about a mile wide and is nearly 1,000 feet deep. A few miles downstream the valley narrows, because the river cuts through more resistant bedrock, and forms the Carbon Gorge. At Fairfax Bridge, the gorge is more than 800 feet deep and only a little more than 1,000 feet wide. The sides of this gorge form some of the most precipitous slopes in the area (fig. 22); in some places between Fairfax Bridge and Carbonado the valley walls are vertical to overhanging. About 3 miles downstream from Carbonado, the river emerges from the gorge and occupies a wider valley. East of Orting, the Carbon is joined by South Prairie Creek, and then enters the Puyallup Valley, where it is joined by Voight Creek. The Carbon River takes a northward course along the east edge of the Puyallup Valley for nearly 4 miles before joining the Puyallup River.

The other principal valleys in the foothills are those of Gale and Voight Creeks. The valley of Gale Creek is V-shaped and narrow throughout its course in the quadrangle, but the upper 4-mile segment of the Voight Creek valley in the Lake Tapps quadrangle is U-shaped and broad, although occupied by a stream of roughly the same size as Gale Creek. After crossing the margin of the foothills, Voight Creek follows a wandering course across the drift surface and then, after plunging over a waterfall, becomes deeply entrenched below this surface about 3 miles upstream from its confluence with the Carbon River.

Fox Creek channel is a narrow steep-sided gorge between Spar Pole Hill and Cowling Ridge. This large channel is occupied partly by a tributary of Voight Creek and partly by Fox Creek. A similar but narrower and shallower channel in bedrock occurs in secs. 10 and 15 northwest of Spar Pole Hill.

CLIMATE AND VEGETATION

The Puget Sound lowland has a marine climate, modified somewhat by its distance from the Pacific Ocean and by the intervening mountains; summers are cool and dry, and winters are moist and mild. Prevailing winds are off the Pacific Ocean and bring moist air inland. Precipitation in the Lake Tapps quadrangle falls principally as rain and increases with an increase in altitude from the northwest to the southeast (table 1). About 65 percent of the yearly precipitation at Buckley falls during the 6-month period from October to March (table 2).

The lowland part of the quadrangle is primarily agricultural; highly productive soils on the floor of the Puyallup Valley are used for berry crops and truck gardening, and the area around Enumclaw and Buckley is widely used for pasture and hay crops for dairy herds.

TABLE 1.—*Precipitation and annual temperature records, showing increase in precipitation and decrease in temperature with increase in altitude*

[Records for locations in Mount Rainier National Park are included to indicate probable rainfall and temperature of higher portions of the Lake Tapps quadrangle]

Location	Altitude (feet)	Average annual precipitation, (inches)	Years of record	Average annual temperature (°F)	Years of record	Source (U.S. Weather Bureau)
Puyallup	50	40.27	43	50.9	43	1959
Buckley	726	49.07	46	50.2	46	Do.
Carbon River entrance, Mount Rainier National Park	1,716	66.94	24	46.4	19	1953
Longmire, Mount Rainier National Park	2,762	76.91	41	44.6	41	1954

TABLE 2.—*Average monthly precipitation and temperature at Buckley, Wash., for 46 years of record*

[U.S. Weather Bureau, 1959]

	Precipitation (inches)	Temperature (°F)
January	5.55	37.6
February	4.82	40.4
March	4.90	43.9
April	3.87	49.0
May	3.08	54.4
June	3.36	58.6
July	1.39	62.9
August	1.34	62.7
September	2.68	58.3
October	5.13	50.8
November	5.95	43.2
December	7.00	40.0
Annual average	49.07	50.2

The Lake Tapps quadrangle lies in the Humid Transition vegetation zone (Rigg, 1926, p. 169), which is characterized by luxuriant Douglas fir (*Pseudotsuga taxifolia*) and western hemlock (*Tsuga heterophylla*) forests. The virgin forests of the area described by Willis and Smith (1899) have been logged off, and much of the Cascade foothills now is covered with second-growth timber. The last extensive stand of virgin forest, which was in the headwaters area of Frame Creek, was logged in 1951–56. Much of the area between the Puyallup and Carbon Rivers is now a tree farm.

In the lowland, uncleared parts of valley floors are characterized by cottonwood trees (*Populus trichocarpa*) and dense underbrush. Most valley walls are thickly covered with second-growth coniferous trees, mainly Douglas fir and western hemlock, and vine maple (*Acer macrophyllum*), blackberry (*Rubus* sp.), Oregon grape (*Berberis nervosa*), and salal (*Gaultheria shallon*). Nearly all open uncultivated areas are thickly overgrown with bracken fern (*Pteridium aquilinum*). Abandoned logging roads and railroads are densely overgrown with red alder (*Alnus oregona*).

BEDROCK

Consolidated bedrock of the area consists of Tertiary sedimentary and volcanic rocks that are intruded locally by andesite, basalt, and diorite dikes and sills. Most of the area between the Carbon and Puyallup Rivers is underlain by volcanic rocks in the Puget group of Eocene age. The valley walls of the Carbon River and the foothills east of the Carbon are mostly made up of sandstone, shale, and coal beds of the Puget group, and a small area along the east edge of the quadrangle is underlain by sedimentary rocks of volcanic origin in the Keechelus andesitic series of Eocene to Miocene age.

Small areas in the valleys of South Prairie Creek and Voight Creek are underlain by unconsolidated or poorly consolidated sedimentary rocks of late Miocene age (Mullineaux, Gard, and Crandell, 1959).

PHYSICAL GEOLOGY OF SURFICIAL DEPOSITS

REGIONAL GEOLOGIC SETTING

Most of the Lake Tapps quadrangle lies within the Puget Sound lowland, a topographic and structural basin that extends from the Cascade Range on the east to the Olympic Mountains on the west. The southeastern part of the lowland is underlain by sedimentary and volcanic rocks of Eocene to Miocene age. These rocks crop out in and adjacent to the cities of Seattle and Renton and in a belt, 10 to 15 miles wide, along the western flank of the Cascade Range. In this belt they consist principally of folded and faulted rocks of the Puget group. The lowland itself is a broad undulating plain of glacial drift, deeply entrenched by wide stream valleys, some of which are occupied by arms of Puget Sound. The drift plain is underlain by a thick fill of unconsolidated deposits. Entrenched valleys do not reach the base of the fill, which in some places extends to depths of as much as 2,000 feet below sea level (Sceva and others, 1955, p. 168). Depth to firm bedrock below this fill is known in only a few places.

Unconsolidated deposits of late Miocene age crop out locally along the east margin of this fill, where the Pleistocene formations abut the Cascade foothills. It seems likely that the Miocene sediments continue westward and thicken, and a considerable thickness of the unconsolidated fill beneath the lowland thus may be of pre-Pleistocene age.

The Cascade Range consists of a mountainous area, 50 to 75 miles wide, east of the Lake Tapps quadrangle, ranging in altitude from 1,500 to 8,000 feet. The dominant rock unit exposed in the range is the Keechelus andesitic series of Eocene to Miocene age, and includes the Fifes Peak andesite. The lower Keechelus is predominantly altered and indurated massive tuff, breccia, and porphyry of andesitic composition (Coombs, 1936). Subordinate rock units consist of andesite flows, felsite, basalt, hornfels, and sediments. Overlying the typically altered rocks of the lower Keechelus is a series of lava flows of pre-late Miocene age, 300 feet or more thick, named the Fifes Peak andesite (Warren, 1941). The lower Keechelus is more strongly folded than the overlying flows of the Fifes Peak andesite, which are either horizontal or have been warped into low undulating folds (Coombs, 1936, p. 199–200).

The Keechelus has been intruded by a batholith or batholiths of Snoqualmie granodiorite of Miocene age. Most outcrops of this rock in the Cascade Range southeast of the Lake Tapps quadrangle occur in the lower parts of valley walls (Coombs, 1936, pl. 1).

The structure of the Cascade Range, itself, appears to be a broad synclinorium, upon which many smaller folds are superimposed. The height of the mountain range is a result of post-late Miocene uplift.

The dominating feature of the landscape is the majestic cone of the stratovolcano Mount Rainier, whose summit lies about 15 miles southeast of the quadrangle. The cone is a product of volcanic activity during much of Pleistocene time, and perhaps in small part of Recent time. The summit is an altitude of 14,410 feet, and the base of the volcano rests on the Cascade Range at an altitude of about 6,000 feet. The cone thus towers nearly 9,000 feet above the mountains upon which it was built. The rocks of the volcano cover an area of about 100 square miles, and lava flows extend for as much as 9 miles beyond the base of the volcano, although Coombs (1936, p. 173) pointed out that most extend less than 6 miles from the central vent.

The cone and radiating lava flows of Mount Rainier are mostly hypersthene and pyroxene andesite, although basalt also has been recognized (Coombs, 1936, p. 174). Pebbles of Mount Rainier rocks collected by the writer from surficial deposits of Pleistocene and Recent age in the Lake Tapps quadrangle are various shades of red and gray andesite with hypersthene, hornblende, or both minerals occurring as the principal ferromagnesian silicates. Chemical analyses of rocks found in the oldest and youngest surficial deposits of Mount Rainier provenance show close similarity in composition (table 3). Samples A and B are both hornblende-hypersthene andesites from boulders in a mudflow that probably dates back to the earliest recognized interglacial stage (from unit 4 in measured section 1, p. 77), and sample C is from a fresh scoriaceous hypersthene andesite abundant in a mudflow (Electron) from Mount Rainier that is about 500 years old.

TABLE 3.—*Rapid chemical analyses of Mount Rainier rocks from mudflow deposits in the Lake Tapps quadrangle*

[Analyses made under the supervision of W. W. Brannock, U.S. Geological Survey, by methods similar to those described by Shapiro and Brannock (1956)]

	Sample A	Sample B	Sample C
SiO_2	60.5	60.6	59.8
Al_2O_3	17.5	18.0	17.8
Fe_2O_3	2.1	1.9	4.2
FeO	3.9	3.6	.06
MgO	2.7	2.4	1.9
CaO	5.8	5.8	4.8
Na_2O	4.1	4.1	4.2
K_2O	1.6	1.6	1.6
H_2O	.77	.63	1.4
TiO_2	.94	.91	.58
P_2O_5	.26	.24	.18
MnO	.10	.10	.08
CO_2	.05	.05	.05

The earliest depositional record of Mount Rainier in the Lake Tapps quadrangle appears in stream gravels and mudflows deposited during the first interglacial stage. The fact that pebbles of Mount Rainier provenance were found neither in the till and outwash of the earliest recorded glaciation nor in stream gravels derived from the Cascade Range that are believed to be older than this glaciation, suggests that the volcano appeared at some time during or immediately after the first glaciation. It is noteworthy that Mount Baker, a similar andesite stratovolcano in the northern Cascade Range (Coombs, 1938), is believed to have appeared just after the first glaciation of that area (Stearns and Coombs, 1959; Stearns, H. T., oral communication).

DEPOSITIONAL ENVIRONMENTS AND PROVENANCE OF SEDIMENTS

The Pleistocene and Recent sedimentation history of this part of the Puget Sound lowland is one of alternate glacial and nonglacial deposition (table 4). During each major glacial episode, a glacier of northern origin advanced into the area, where a part of its margin terminated against or adjacent to the foothills of the Cascade Range. These northern glaciers each left deposits of till and stratified drift remarkably similar in general appearance. Sediments of northern provenance, or derivation, are characterized by the appreciable content of stones and minerals derived from the regionally metamorphosed rocks of the northern Cascade Range in Washington and the Coast Ranges of British Columbia. The stones are composed of gneiss, schist, marble, and quartzite, and the distinctive mineral present in the heavy fraction [1] of the sand-size material is garnet (D. R. Mullineaux, oral communication).

By analogy with the source and size of the last glacier to occupy the Puget Sound lowland, each of these northern glaciers represents a small southward lobation of the Cordilleran ice sheet, which, according to Dawson (1890, p. 27), mantled the region in Canada south of the 63d parallel. In accordance with the usage of previous writers (Mackin, 1938, 1941; and Bretz, 1913), the term "Puget glacial lobe" is used to refer to the part of the Cordilleran glacier that repeatedly pushed down into the Puget Sound lowland during the Pleistocene.

A second major source of sediments in the Lake Tapps quadrangle is the central part of the Cascade Range in Washington. Sediments derived from this part of the range are referred to as being of central Cascade provenance. This provenance is best typified by alluvial sand and gravel deposited by streams that drained the Cascade Range southeast of the quadrangle before the first advance of the Puget glacial lobe and before the appearance of Mount Rainier. This alluvium contains dark-gray to dark-greenish-gray andesitic and basaltic volcanic rocks derived from the lower Keechelus andesitic series and Fifes Peak andesite, and it includes granodiorite and diorite derived from the Snoqualmie granodiorite and other smaller intrusive igneous bodies. The characteristic heavy-mineral suite found in the sand-size fraction of the alluvium consists of magnetite, ilmenite, and epidote. Younger deposits chiefly of central Cascade provenance contain, in addition, hypersthene and hornblende that probably have been reworked from the alluvial, mudflow, and pyroclastic deposits of Mount Rainier originally deposited in the Cascade foothills.

Sediments of Mount Rainier provenance are characterized by an abundance of hypersthene and hornblende in the heavy-mineral fraction and by light-gray to black, reddish-gray, and pale-red to grayish-red pebbles of hypersthene and hornblende andesite.

In summary, the three distinctly different source areas for the surficial deposits of the Lake Tapps quadrangle are as follows: northern source area, referring to the Cascade Range north of Snoqualmie Pass and the Coast Ranges of southwestern Canada; central Cascade, referring to the Cascade Range south of Snoqualmie Pass and, in particular, to the part of the range that lies east and southeast of the quadrangle; and Mount Rainier, the only volcano of Quaternary age known to be within the drainage basin that includes the Lake Tapps quadrangle.

During intervals between glaciations, the Puget Sound lowland was free of ice, and sedimentation occurred in valleys and in lakes left on the drift surfaces. Substantial thicknesses of sedimentary deposits that accumulated in this part of the lowland during nonglacial intervals were derived in large part from Mount Rainier.

[1] Heavy minerals were initially separated from sediments by use of a gold pan and then by bromoform.

TABLE 4.—*Summary of stratigraphy and Quaternary history in the Puget Sound lowland south and southeast of Seattle, Wash. Age of Wingate Hill glaciation relative to Salmon Springs glaciation is uncertain*

[Prepared in 1960 by D. R. Crandell, D. R. Mullineaux, and H. H. Waldron]

Time			Approximate age from radiocarbon determinations (years)	Deposit		Event	Inferred climate
Recent						Local lacustrine sedimentation in closed depressions. Fluvial and mudflow aggradation in parts of lowland.	As present.
			520		Electron mudflow		Maximum warmth and dryness.
					Alluvium		Increasing warmth and dryness.
			4,800		Osceola mudflow		
					and lacustrine sediments		Cool, moist.
Middle(?) and late Pleistocene	Vashon glaciation	Late				Invasion of Puyallup and Duwamish Valleys by Puget Sound.	Glacial.
			15,000	Vashon drift	Recessional outwash	Retreat of Puget lobe.	
		Middle			Till	Maximum of Puget lobe.	
					Advance outwash	Advance of Puget lobe.	
		Early	25,000		Evans Creek drift	Advance and retreat of valley glaciers in Cascade Range.	
	Wingate Hill glaciation				Wingate Hill drift	Icecap glaciation of Cascade Range.	Glacial
				Salmon Springs drift	Fluvial gravel from central Cascade Range and Mount Rainier.	Re-establishment of northwest-flowing streams.	Nonglacial.
	Salmon Springs glaciation				Till and outwash gravel.	Advance and recession of Puget lobe.	Glacial.
					Fluvial gravel from central Cascade Range and Mount Rainer.	Re-establishment of northwest-flowing streams.	Nonglacial.
			>38,000		Lacustrine sediments and volcanic ash.	Minor recession of Puget lobe.	Cool, moist.
					Till and outwash gravel.	Advance of Puget lobe.	Glacial.
						Weathering and erosion.	
Early(?) and middle Pleistocene	Puyallup interglacial				Puyallup formation and other alluvial and lacustrine deposits of Puyallup age, including part of the Lily Creek formation.	Lacustrine sedimentation in parts of lowland. Fluvial and mudflow alluviation in parts of lowland and in Cascade foothills adjacent to Mount Rainier. Re-establishment of northwest-flowing streams. Lacustrine sedimentation in parts of lowland.	Comparable to present. Increasing warmth. Cool, moist.
	Stuck glaciation			Stuck drift	Lacustrine sediments. Till.	Advance and recession of Puget lobe.	Glacial.
					Fluvial and lacustrine sediments.	Re-establishment of northwest-flowing streams. Minor recession of Puget lobe.	Nonglacial.
					Till.	Advance of Puget lobe.	Glacial.
	Alderton interglacial				Alderton formation and other deposits of Alderton age, including part of the Lily Creek formation.	Fluvial and mudflow alluviation of parts of lowland and in Cascade foothills adjacent to Mount Rainier. Re-establishment of northwest-flowing streams.	Comparable to present. Increasing warmth. Cool, moist.
	Orting glaciation			Orting drift	Till.	Advance and recession of Puget lobe.	Glacial.
					Lacustrine and fluvial sedimentation	Minor recession of Puget lobe.	
					Till and outwash gravel	Advance of Puget lobe.	
					Cascade stream gravel	Fluvial aggradation in parts of lowland.	Nonglacial.

Predominance of sediments of Mount Rainier derivation probably was caused by the availability of loose fragmental material on the slopes of the volcano in quantities so great as to cause alluviation throughout the downstream courses of the valleys heading at the volcano. At times, this material far surpassed in volume the load being contributed to streams by other sources in the drainage basin, with the result that sand and gravel almost wholly of Mount Rainier provenance was deposited far out into the Puget Sound lowland. The effect of alluviation by material most readily available probably creates a false impression of the intensity and importance of volcanism during the Pleistocene. During most of a given interval, streams of the Cascade Range might not have been aggrading as indicated by the lack of stream sediments. Intense volcanic activity during a small fraction of this same interval, however, might have made available a large volume of fragmental material, resulting in aggradation of streams heading on the volcano. In this way, a relatively short-lived episode of volcanism could have resulted in deposition of a far greater volume of sediment than a much longer period of stream erosion in rocks of the central part of the Cascade Range.

Deposition of sediments from Mount Rainier that might have occurred during glacial episodes was not recorded in this area, owing to drainage changes at each glacial maximum. At these times the rivers that normally flow northward through the quadrangle were diverted southwestward owing to the presence of glacial ice in the lowland. Presumably, if streams of the Cascade Range did carry large amounts of volcanic detritus during these glacial maximums, their depositional record should be preserved somewhere along the drainage diversions. Because of these temporary drainage diversions, the growth of Mount Rainier probably is not completely recorded in the Lake Tapps quadrangle. The fact that sediments of Mount Rainier provenance are limited to the formations deposited during nonglacial intervals thus does not necessarily imply that the volcano was more active then than during the glacial intervals.

Volcanic mudflows are perhaps the most interesting nonglacial deposits in the quadrangle. These mudflows are all of Mount Rainier origin, as indicated by their lithologic character and by the fact that no other Pleistocene and Recent volcano occurs within the drainage area of the streams that cross this part of the lowland. The mudflows are unsorted and unstratified mixtures of rock fragments, as large as 10 feet in diameter, in a matrix of clay, silt, and sand. Most of the mudflows contain at least 50 percent material of sand size and smaller, although some might more properly be called debris flows because of a predominance of material coarser than sand size (Varnes, 1958, p. 37).

Inasmuch as mudflows are commonly interstratified with till in the Lake Tapps quadrangle, the characteristics used here to distinguish between the two kinds of deposits are as follows:

1. Mudflows are of Mount Rainier provenance, although some contain abundant stones of central Cascade provenance. Heavy-mineral grains are principally hypersthene and hornblende, and many grains have a film of volcanic glass adhering to them. In contrast, the tills of the Puget lobe contain a significant content of stones and minerals of northern derivation and few or no stones of Mount Rainier provenance.
2. All mudflows in this quadrangle are characterized by vertical grading, which is a continuous upward decrease in size of component stones from base to top, regardless of thickness of the deposit.
3. The typical unoxidized color of mudflows and tills is gray, but most mudflows have a purplish or pinkish cast, whereas till does not.
4. Pebbles in mudflows are generally much more angular than those in till.
5. The depositional upper surface of mudflows is almost horizontal, that of tills is commonly irregular.

The implication is not intended that each characteristic is in itself an absolute criterion of origin or that these characteristics, even as a group, can be used to distinguish all mudflows from all tills. The features noted, however, are useful in differentiating the mudflows and tills of the Lake Tapps quadrangle.

Although mudflows of different ages and derivations have many features in common, they differ in others. A major distinction is one of lithology: some deposits consist virtually of a single rock type (monolithologic) and others contain a variety of rock types (heterolithologic). Some monolithologic mudflows have traveled as much as 50 miles from their place of origin without significant contamination. This might have been due to a fully loaded condition of the mudflow from time of origin to time of deposition, or to the fact that the mudflow was passing over stream deposits almost wholly of Mount Rainier provenance. Whereas most stones in the monolithologic mudflows are subangular, pebbles not of Mount Rainier derivation in heterolithologic mudflows are rounded; this evidence suggests that the mudflows were contaminated by gravel picked up from alluvium over which they moved.

Mudflows and debris flows of small volume that result from saturation of loose glacial drift by rainfall and melting snow are abundant in the upper parts of valleys that head on Mount Rainier. Such flowage deposits have been seen in the headwaters of the White, Puyallup, and Nisqually Rivers, and, presumably, they owe their origin to the alpine and glacial conditions that prevail on the upper slopes of Mount Rainier and are not directly related to volcanism. In contrast to these relatively small flows, mudflows of the volume required to enter and pass through the Lake Tapps quadrangle, with lengths of 50 or 60 miles, probably originate during eruptions, because of the availability then of very large volumes of unconsolidated and unstable material on the flanks of the volcano. In addition, some mudflows may originate during an eruption as a result of the sudden draining or forceful ejection of a crater lake, phreatic explosions that deposit large quantities of altered rock on the slopes of the volcano, avalanches of hot volcanic debris onto glaciers and snow fields, and other volcanic phenomena.

Mudflows of great length and volume in the Puget Sound lowland probably represent volcanic eruptions, as do the great volcanic mudflows of historic time in Japan, Java, Guatemala, the Philippines and elsewhere. If the thesis is correct that mudflows represent individual eruptions, or, in general, times of greatest volcanic activity, then it seems likely that intervals after these eruptions should be characterized by reworking of mudflow deposits by streams, and by the transport of this debris to the lowland in the form of normal bedload and suspended load. Mudflows might also be formed at this time from precipitation on unconsolidated volcanic ejecta on the slopes of the volcano, but these mudflows probably would not have the volume necessary to reach the lowland. During a subsequent period of volcanic quiescence, with no change in the discharge of streams but with a substantial decrease in load readily available at the volcano, streams would cut down toward their former gradients, and the fill of mudflow and alluvial sediments previously deposited would be eroded until the next eruptive phase began.

Sequences of cutting and filling are seen in the nonglacial formations of Pleistocene age in the Lake Tapps quadrangle, and they probably occurred in this part of the Puget Sound lowland throughout the Quaternary. These sequences are inferred to have little if any climatic significance but are probably for the most part due directly to volcanic activity, or lack thereof, rather than to variations in precipitation or vertical movements of the land.

It was suggested previously that nonglacial sand and gravel deposits of central Cascade provenance in the lowland are likely to be far surpassed in volume and apparent importance by sediments of volcanic origin. Most alluvium derived from the Cascade Range is, moreover, of doubtful value to environmental interpretation owing to the fact that the outwash facies of drift of the Puget lobe is, itself, predominantly of central Cascade provenance; stones of northern provenance compose 15 percent or less of the till and outwash of this lobe. The predominance of stones of central Cascade provenance apparently is due to the incorporation by the glacier of large amounts of locally derived alluvium. The absence of northern material in a given deposit of sand and gravel, however, almost certainly indicates that the deposit was not laid down by melt water from the Puget lobe and that the lowland was at least sufficiently clear of ice at the time of deposition to permit the presence of a Cascade Range stream.

Other than mudflow and alluvial deposits, the most abundant nonglacial sediments are those of lacustrine origin. These sediments consist mostly of silt, sand, and peat formed in swales in the underlying drift or in depressions probably created by disruption of drainage by mudflows. Of these sediments, peat is by far the most helpful for interpreting environment, for climatic conditions during its deposition may be inferred by analysis of pollen preserved in the peat. In this way, periods of nonglacial deposition are inferred from evidence that suggests the climate was probably too warm for a glacier to exist anywhere in the lowland.

The geologic history and depositional environments of the Lake Tapps quadrangle during the last 15,000 years or so are remarkably parallel to earlier glacial and nonglacial environments. The last glacier to invade the quadrangle advanced to a maximum and started to retreat sometime prior to 15,000 years ago. This represented a major advance of the Puget glacial lobe of the Cordilleran glacier, which left deposits of till and gravel widely distributed in the lowland. As the glacier receded, streams draining the Cascade Range and Mount Rainier reoccupied the major valleys of the area, depositing alluvium derived from these source areas. Pollen in peat formed in depressions on the glacial drift suggests first a climatic warming and then minor oscillations to the present.

During the past 5,000 years volcanic mudflows originating at Mount Rainier twice have entered the Puget Sound lowland, one by way of the White River and the other by way of the Puyallup River valley. These deposits bulk large by comparison with any other deposit of Recent age, yet their formation probably occupied only a few days of Recent time.

The resulting glacial and nonglacial deposits of late Pleistocene and Recent age have counterparts in the several drift and nonglacial formations of earlier Pleistocene time, and interpretation of the depositional

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environments of the older deposits is based in large part on analogy.

CRITERIA USED TO ESTABLISH STRATIGRAPHY

PROVENANCE

In a general way, lithology of sediments suggests not only their provenance but also their environment of deposition. Sediments predominantly of Mount Rainier provenance in the lowland indicate that this part of the lowland was free of ice, as does also the presence of alluvium wholly of central Cascade origin. On the other hand, sediments of northern derivation prove the presence of the Puget lobe, for no source other than glacial exists for these sediments. It might be argued that reworking of older drift sheets by nonglacial streams provides a possible alternate source of northern materials, but owing to the already low proportion of northern rock types in the original deposits, it seems unlikely that they can be reworked and still form an appreciable percentage of the resulting nonglacial deposit. By determining provenance of interbedded deposits, therefore, recurring episodes of glaciation separated by times when the lowland was free of glacial ice can be determined.

PALYNOLOGY

The value of pollen analysis to stratigraphy of Pleistocene deposits of the Puget Sound lowland was pointed out by Hansen and Mackin (1949, p. 834–835), who showed that pollen could be used to interpret the nature of depositional environments in an area whose climate alternated between glacial and interglacial conditions.

Paleoclimatic interpretations presented in this report are the result of studies by Estella B. Leopold (written communication), based on a comparison of Pleistocene pollen spectra with modern pollen from bogs at various altitudes on the west slope of the Cascade Range. The Puget Sound lowland and the west slope of the Cascade Range at the latitude of Mount Rainier are divided into four vegetational zones, three of which are of principal concern: Humid Transition, Canadian, and Hudsonian. Here the Humid-Transition zone lies below 1,500 feet and includes most of the Puget Sound lowland proper. The arboreal pollen fallout in this zone is dominated by Douglas fir (*Pseudotsuga taxifolia*) and western hemlock (*Tsuga heterophylla*). The average annual temperature and precipitation at two localities in this zone are shown in table 1. The Canadian zone in the Mount Rainier area extends from about 1,500 to 5,000 feet; the distinctive trees of the lower part of this zone are western hemlock and mountain hemlock (*Tsuga mertensiana*), and the upper part is characterized by a predominance of Engelmann spruce (*Picea engelmanni*), alpine fir (*Abies lasiocarpa*), and Cascade fir (*A. amabilis*). The precipitation and average annual temperature at two localities in Mount Rainier National Park that fall within this zone are shown in table 1. The Hudsonian vegetation zone in the vicinity of Mount Rainier extends from about 5,000 feet to 7,000 feet and is characterized by a predominance of whitebark pine (*Pinus albicaulis*). The average annual precipitation at Paradise Inn in Mount Rainier National Park at an altitude of 5,557 feet is 98.20 inches and the average annual temperature 38.4°F (U.S. Weather Bureau, 1957).

Fossil pollen of a forest assemblage comparable to that existing today in the Puget Sound lowland (predominance of Douglas fir and western hemlock) suggests comparable climatic conditions at the time the pollen-bearing sediments or peat were deposited. The discovery of sediments containing such a pollen assemblage between glacial deposits permits recognition of separate drift sheets that represent distinctly different glacial stages or substages.

WEATHERING

The general lack of deep and intense weathering profiles on interbedded Pleistocene deposits of different ages makes it impossible to correlate these deposits with a reasonable degree of certainty from area to area on the basis of weathering.

Weathering in deposits of the last glacial stage (Vashon) consists mainly of oxidation even to within a few inches of the present land surface, and most included stones have not been visibly altered by weathering. Weathering on drift of the next older glaciation (Wingate Hill) is characterized by oxidation to depths of as much as 15 feet and by alteration of the outer rim of individual rock fragments in the upper few feet of the drift to iron oxides.

The most conspicuous difference in appearance between Vashon drift and older drifts of the Puget lobe is in degree of oxidation; the older drifts typically are oxidized throughout. This oxidation is in part a function of permeability, however, as indicated by layers of unoxidized till commonly found enclosed in deeply oxidized sand and gravel. Oxidation also seems to depend somewhat on lithology, because where sediments of northern and central Cascade provenance are oxidized, adjacent sediments of Mount Rainier provenance typically are light gray regardless of texture. This color is due to the abundance of white plagioclase and to the presence of devitrified white volcanic glass adhering to darker mineral grains.

Depth and intensity of oxidation therefore are not dependable guides in differentiating deposits older than the last glaciation, although these features are useful for distinguishing these deposits from the younger glacial deposits.

ABSOLUTE AGE DETERMINATIONS

Radiocarbon analysis of organic material provides a reliable means for dating prehistoric events in absolute years (for discussion of method see Flint, 1957, p. 298–300). The method, however, is accurate only on carbonaceous materials not older than 30,000 or 40,000 years; thus, events of much the greater part of Pleistocene time are beyond the range of analysis. Radiocarbon dating has been useful in determining the age of the most recent glaciation in the Lake Tapps quadrangle and the age of some events since that glaciation. Radiocarbon determinations have indicated that the age of older sediments below the drift is greater than 37,000 years and have thus demonstrated that these sediments are older than the "classical" Wisconsin drift (Flint, 1957, p. 341–342) of the midwestern United States.

DESCRIPTION OF SURFICIAL DEPOSITS

ORTING DRIFT

The oldest glacial deposit recognized in the Lake Tapp quadrangle is the Orting drift; because of its stratigraphic position and lithology, the drift probably represents the earliest glaciation of the southeastern part of the Puget Sound lowland. The Orting drift of this report includes the Orting gravel of Willis (1898), which was named after the town of Orting in the Puyallup Valley. Willis believed that the Orting gravel was deposited during a time characterized by recession of a glacier from the Puget Sound lowland and by a warming climate. Because of the presence of till sheets in the gravel, however, the name Orting drift has replaced the Orting gravel of Willis (Crandell, Mullineaux, and Waldron, 1958). The formation includes a thick basal gravel of central Cascade provenance and overlying till and gravel deposited by the Puget lobe. Because no unconformity has been recognized between these two major units, both are included here in the Orting drift.

DESCRIPTION

Willis (1898, p. 158) designated as the type section of the Orting gravel an exposure on the "East side of the Puyallup Valley at Orting; section observed along the road grade." His description of the Orting at this locality is 140 feet of "Coarse gravels, boulders, gravel, and sand, orange colored, heterogeneously mingled, firmly cemented, granite boulders occasionally decomposed." Overlying the gravel, according to Willis, is 200 feet of sand containing a few layers of gravel, which is, in turn, overlain by Vashon drift consisting principally of gravel.

Till occurs at several horizons in the Orting drift, but evidently there is no continuous sheet of till over broad areas at any one horizon. The till, typically, is a very compact unsorted and unstratified mixture of subangular pebbles, cobbles, and boulders in a sandy silt matrix; its color ranges from yellowish gray[2] where unoxidized to yellowish-brown where oxidized. Where the till is oxidized, joint surfaces and stone surfaces are coated with iron oxides. The abundance of stones varies from outcrop to outcrop, although most till in the Orting drift is very stony. About 10 to 15 percent of the stones typically consist of rocks of northern provenance in the pebble-size fraction, and the remainder consists of rocks of central Cascade provenance (table 5). Sand-size material in the till generally includes 5 to 15 percent garnet in the heavy-mineral fraction.

X-ray analysis of a sample of till in the Orting from the valley of Coplar Creek, in the SE¼NE¼ sec. 4 southeast of Orting, showed a predominance of montmorillonite in the clay-size fraction and trace amounts of chlorite, quartz, and feldspar.

An easily accessible outcrop of till in the Orting is at stream level at the mouth of Kapowsin Creek (SW¼ sec. 20, T. 18 N., R 5 E.) where about 13 feet of oxidized and very stony till is exposed under sand and gravel (fig. 3). Adjacent to Kapowsin Creek, 0.3 mile southwest of this outcrop (in the southeast corner of sec. 19), a layer of till at a somewhat higher horizon in the Orting drift is equally well oxidized but contains only scattered stones in a sand and silt matrix.

Stratified sediments in the Orting drift consist principally of pebble and cobble gravel and sand. At many places the gravel is poorly sorted and rather closely resembles stony till except for a lack of fine sediment and large boulders. The gravel commonly is closely packed in a matrix of yellowish-brown fine to medium sand, but locally there are beds and lenses of openwork gravel several feet thick. In some of these beds of openwork gravel, voids between adjacent stones are partly filled with grayish-yellow plastic clay. The overall color of gravel outcrops is light yellowish brown, although some outcrops are considerably darker brown than others and some have a distinct reddish-brown "rusty" appearance.

[2] Colors of the deposits are based on the "Rock-Color Chart" (Goddard and others, 1948).

TABLE 5.—*Lithology of geologic map units as determined by identification of 100 or more pebbles*

	Geologic map unit	Andesitic rocks from Mount Rainier	Central Cascade rock types			Northern rock types				Not identified
			Keechelus andesitic series including Fifes Peak andesite	Snoqualmie granodiorite	Total	Gneiss	Quartzite	Other	Total	
1	Carbon River alluvium	32	54	14	68					
2	South Prairie Creek alluvium		97	3	100					
3	Electron mudflow	41	59		59					
4	Osceola mudflow	36	60	4	64					
5	Vashon drift—till	2	75	18	93	2		3	5	
6	do				90	5		5	10	
7	do		81	1	82	3	2	13	18	
8	do				85	6		9	15	
9	do				85	2		13	15	
10	do				84	3	3	10	16	
11	Evans Creek drift—till	2	85	13	98					
12	Terrace gravel of Carbon River	26	54	20	74					
13	do	17	70	8	78					5
14	Wingate Hill drift—till	25	62	9	71					
15	do	17	71	9	80					
16	do	60	30		30					
17	do	14	77	7	84					
18	Wingate Hill drift—till(?)	2	91	2						5
19	Lower Salmon Springs drift—gravel		86	2	88	2		10	12	
20	Upper Salmon Springs drift—gravel	15	78	1	79	2		4	6	
21	do	1	70	6	76	10	1	6	17	6
22	Salmon Springs drift—gravel		84	2	86	5	1	8	14	
23	do	2	80	7	87	2	2	7	11	
24	do	5	86	2	88	1	2	4	7	
25	do	2	82	6	88	2	1	7	10	
26	Puyallup formation—mudflow	89			4					4
27	do	80			20					
28	Puyallup formation—gravel	20			75					5
29	do	45	45	5	50					5
30	Stuck drift—gravel		86	3	89	1	3	7	11	
31	do		75	8	83	4		13	17	
32	Stuck drift—till	2			90				8	
33	do		90	6	90			4	4	
34	do	8	72	3	75	2	10	2	14	
35	Alderton formation—mudflow	84	10	2	12					4
36	do	68	24	2	26					6
37	Lily Creek formation—gravel	47	53		53					5
38	do	87	12	1	13					5
39	Lily Creek formation—mudflow	45	52	4	56					4
40	do	95	5	2	5					6
41	Orting drift—till		81	6	87	4	1	5	10	3
42	do		78		78	5		9	14	8
43	do				81	12		2	14	5
44	do		79	4	83	2		8	10	7
45	Orting drift—gravel				94			1	1	
46	do		89	4	93	1		6	7	
47	do		83	4	97					3
48	do				100					
49	do		94	4	100					2

LOCATION OF SAMPLES

1. NW¼NE¼ sec. 35, T. 18 N., R. 6 E.
2. SE¼ sec 5, T. 18 N., R. 7 E.
3. Average of five samples from different localities.
4. Average of 10 samples from different localities.
5. SE¼ sec. 18, T. 20 N., R. 6 E.
6. NE¼NW¼ sec. 2, T. 19 N., R. 5 E.
7. NE¼SW¼ sec. 34, T. 20 N., R. 6 E.
8. NE¼SW¼ sec. 16, T. 19 N., R. 6 E.
9. SE¼ sec 4, T. 20 N., R. 5 E.
10. NE¼ sec. 9, T. 20 N., R. 6 E.
11. SW¼NE¼ sec. 35, T. 18 N., R. 6 E.
12. NW¼NE¼ sec. 16, T. 18 N., R. 6 E.
13. SW¼NE¼ sec. 35, T. 18 N., R. 6 E.
14. NE¼ sec 17, T. 18 N., R. 6 E.
15. SE¼SE¼ sec. 17, T. 18 N., R. 6 E.
16. NE¼ sec. 4, T. 17 N., R. 6 E.
17. SE¼NE¼ sec. 8, T. 18 N., R. 6 E.
18. SE¼SE¼ sec. 33, T. 20 N., R. 6 E. (till of Cascade piedmont glacier in lowland).
19. SW¼SE¼ sec. 18, T. 20 N., R. 5 E.
20. Same as 19; sample from base of gravel.
21. Same as 19; sample from top of gravel.
22. NW¼SE¼ sec. 1, T. 19 N., R. 4 E.
23. Bluff at northwest edge city of Sumner (sec. 49).
24. NE¼SW¼ sec. 29, T. 20 N., R. 5 E.
25. 0.4 mile northwest of Stuck River bridge in city of Sumner; outcrop on west valley wall.
26. Victor Falls; cap rock.
27. SE¼SW¼ sec. 20 T. 20 N., R. 5 E.
28. Victor Falls; gravel beneath cap rock.
29. Same as 22.
30. NE¼NW¼ sec. 36. T. 20 N., R. 4 E.
31. Same as 23.
32. Same as 30.
33. Same as 23.
34. Same as 22.
35. NE¼NW¼ sec. 12, T. 19 N., R. 4 E.
36. SE¼SE¼ sec. 7, T. 19 N., R. 6 E.
37. NE¼ sec. 8, T. 18 N., R. 6 E.; gravel from near top of formation.
38. Same as 37; gravel from near base of formation.
39. Same as 37; top of thick mudflow near base of formation.
40. Same as 37; from lowest mudflow in formation.
41. SE¼SE¼ sec. 7, T. 19 N., R. 6 E.
42. SE¼NE¼ sec. 4, T. 18 N., R 5 E.
43. NW¼SW¼ sec. 20, T. 18 N., R 5 E.
44. SE¼SE¼ sec. 19, T. 18 N., R. 5 E.
45. NW¼SW¼ sec. 16, T. 19 N., R. 6 E.; from near top of gravel.
46. Same as 45; near base of gravel.
47. SE¼SE¼ sec. 29, T. 19 N., R. 5 E.; from near base of gravel.
48. Same as 47; from near middle of gravel.
49. Same as 47; from near top of gravel.

FIGURE 3.—Outcrop of till in the Orting drift at confluence of Kapowsin Creek and Puyallup River. Till is overlain by oxidized sand and gravel; bedrock crops out at stream level about 100 feet to the right of the photograph.

Much of the stratified sediment in the Orting drift is predominantly or exclusively of central Cascade provenance. The gravel exposed in the east valley wall of the Carbon River at Orting is wholly of central Cascade provenance in both the pebble and the sand fractions. Gravel of northern derivation, however, is particularly abundant adjacent to till sheets.

Bedding in the stratified sediments generally is not well defined, although cut-and-fill stratification occurs at many horizons. Along the north wall of the Carbon River valley, near the east edge of sec. 26, T. 19 N., R. 5 E., gravel in the Orting drift displays long sweeping deltaic forset beds, which dip southwestward.

Although sand and gravel in the Orting drift typically is intensely oxidized, unoxidized stratified sediments have been noted at a few localities. One is an outcrop in the bank of the Puyallup River in NE¼SE¼ sec. 18, T. 18 N., R. 5 E., where 4 to 8 feet of laminated greenish-gray sand and silt is overlain by about 20 feet of horizontally bedded and crossbedded moderate-yellowish-brown sand. All these sediments are of northern provenance.

Along the north wall of the Carbon River valley, in secs. 25 and 30 northwest of Carbonado, the Orting drift is as much as 200 feet thick and consists chiefly of gravel. Near the west edge of sec. 30, however, an unoxidized sand and silt bed of northern provenance, as much as 30 feet thick, is interbedded with the gravel. This sand locally contains abundant wood fragments. The sand and the enclosing gravel are vertically offset as much as 50 feet in places by normal faults, and in one place the beds are found in a jumbled mass of blocks of gravel, sand, and till. This deformation suggests that the beds were deposited upon or against ice whose subsequent melting caused collapse, faulting, and jumbling of the deposits.

THICKNESS

The greatest known thickness of Orting drift is about 260 feet; by far the largest part of the total consists of gravel. At many localities gravel makes up uninterrupted thicknesses of as much as 200 feet (fig. 4), and nearly vertical outcrops of gravel, as much as 100 feet

FIGURE 4.—Outcrop of gravel in Orting drift on north bank of Carbon River in sec. 33, southeast of Orting. This gravel is inferred to have been deposited by the preglacial ancestral Mowich River before the appearance of Mount Rainier.

thick, are common along the walls of the lower part of the Carbon River valley. Till sheets in the gravel are thin and lenticular. In an outcrop adjacent to the Carbon River north of Orting, a till sheet at an altitude of about 370 feet ranges in thickness from 2 to more than 20 feet in a lateral distance of only a few hundred yards; at the type section of the Orting gravel of Willis, only half a mile to the south, the till is missing. The greatest known thickness of any single layer of till in the Orting drift is 25 feet.

DISTRIBUTION

The Orting drift crops out in a belt about 3 miles wide along the foothills of the Cascade Range. A few outcrops of drift, probably of Orting age, have been found in the foothills at altitudes of as high as 1,400 feet. A short distance north of Orting and South Prairie, the drift disappears beneath a cover of younger formations and does not reappear within the quadrangle. Along the Puyallup Valley, the drift is exposed as far north as the NW¼ sec. 12, northwest of McMillin.

The most extensive outcrops of the formation are along the valley walls of the Carbon River and South Prairie Creek; here the drift seems to be a single widespread sheet of gravel resting upon an eroded bedrock surface. A pre-Orting drainage pattern that is different from the present one, cannot be reconstructed in this area, owing to the fact that some of the Orting itself is of ice-marginal origin and was deposited by streams flowing generally parallel to the mountain front.

Along South Prairie Creek and the Carbon River, the surficial deposits of pre-Vashon age seem to consist of a single major drift unit without important stratigraphic breaks within it. Because this unit can be traced along the valley walls to the type section of the Orting gravel of Willis at Orting, the drift is here all included in the Orting. This usage implies either that no post-Orting, pre-Vashon glacier extended as far south as the valley of South Prairie Creek, or, if one did, that no deposits of this glacier now remain. Because of the lack of any stratigraphic evidence of a post-Orting, pre-Vashon glaciation south of the valley of South Prairie Creek, all pre-Vashon drift of northern derivation in the Cascade foothills in the quadrangle is assigned to the Orting.

WEATHERING

Nowhere in the lowland has a zone of deep and intense weathering been found in deposits known to be of Orting age, although the gravels typically are oxidized throughout and many of the component stones readily disintegrate under a gentle blow of a pick.

The apparent absence of a widespread zone of deep weathering on the Orting drift probably is best explained by quick burial by nonglacial sediments soon after glacial retreat and by local stripping of weathering zones by subsequent glaciers.

ORIGIN

Because of the presence of till at several horizons, it is inferred that the Orting was deposited during a general glaciation of the Puget Sound lowland. Without exception, till of Orting age is of northern provenance; most of the gravel in the Orting not closely adjacent to a till sheet, however, is of central Cascade derivation. This suggests that the gravel was deposited by a stream or streams originating in the Cascade Range to the southwest, and a likely source would have been the ancestral Mowich River (p. 19). In the few places where till of Orting age is seen in contact with this gravel, the till invariably occurs near the top of the gravel, and overlying gravel is of northern provenance. This relation indicates that the gravel of central Cascade derivation is of early Orting age or possibly is even somewhat older than the Orting glaciation.

Deltaic forest beds in gravel along the Carbon River suggest deposition in a lake formed between the ice front and the foothills of the Cascade Range. This situation, however, was evidently only temporary because gravel beds above and below these foreset beds suggest west-flowing streams. It appears that the Orting here was largely of ice-marginal origin, having been deposited, as it were, in a gutter formed between ice on the north and bedrock hills on the south.

STRATIGRAPHIC RELATIONS AND AGE

The Orting drift is the oldest known glacial deposit in the Lake Tapps quadrangle; the youngest deposit beneath it consists of sediments of probable late Miocene age in the walls of Voight Creek and South Prairie Creek valleys (Crandell and Gard, 1959; Mullineaux, Gard, and Crandell, 1959). The drift is inferred to be older than the Lily Creek formation, although this cannot be proved owing to the uncertainties involved in correlating pre-Vashon drift deposits.

LILY CREEK FORMATION

The Lily Creek formation has not been recognized previously. It is here defined as interbedded stream gravel and mudflows principally of Mount Rainier provenance, probably ranging in age from early to middle Pleistocene. It is inferred to be correlative with the Alderton and Puyallup formations of Crandell, Mullineaux, and Waldron (1958). The name is taken from Lily Creek, a minor tributary of the Carbon River, adjacent to which the formation is typically exposed (measured section 1, p. 76). The known distribution of the formation is limited to the Cascade foothills adjacent to the valleys of the Carbon and Puyallup Rivers, but deposits of comparable age and origin probably exist in other valleys whose drainage basins include Mount Rainier. If, as suggested on page 22, the formation was deposited during at least two interglacial ages, it seems likely that somewhere near the base of Mount Rainier the formation includes drift deposited during the glacial interval between the two interglacial ages.

DESCRIPTION

The overall lithology of the Lily Creek formation indicates that it was derived chiefly from the lavas and pyroclastic rocks of Mount Rainier, although some gravel units within the formation contain about equal percentages of Mount Rainier and central Cascade rock types (table 5).

The heavy-mineral suite of sand-size material in the formation is characterized by an abundance of hypersthene and lesser amounts of magnetite, hornblende, and augite. Some sand and gravel beds contain as much as 5 percent epidote in the sand-size heavy-mineral fraction. In the basal sand beds of the formation in measured section 1 (p. 76), a few zircon crystals were found in the heavy-mineral fraction; these probably were derived from sandstone in the Puget group.

Mudflows seem to make up the greatest bulk of the Lily Creek formation; in the drainage basin of Frame Creek in the Wilkeson quadrangle, through a vertical range of at least 700 feet, nearly every outcrop of the formation consists of a mudflow deposit. On the other hand, the basal part of the formation contains an equal amount if not a predominance of fluvial gravel, as in measured section 1 (p. 76). Mudflows in the formation are monolithologic and heterolithologic; in general, rock fragments of the mudflows that consist of mostly one kind of andesite from Mount Rainier are more angular than stones in the heterolithologic mudflows. One monolithologic mudflow, exposed at an altitude of 1,500 feet in the SE¼ sec. 4 southeast of Carbonado, is unusual in that both the included rock fragments and the unconsolidated matrix are greenish gray and have the same texture. This mudflow overlies a heterolithologic mudflow consisting of rounded pink and gray andesite stones in a pinkish-brown matrix.

The various depositional units within the Lily Creek formation typically consist of lenticular fills resting within channels cut into older units of the formation. At measured section 1, three or more mudflows (unit 5) lie in a valley, at least 70 feet deep, cut in sand and gravel. In the southwest corner sec. 24, at the north end of Cowling Ridge, a roadcut exposes a coarse mudflow deposit in the formation. A channel cut into this deposit is filled with a sequence, at least 17 feet thick, of sand beds as much as 3 feet thick, alternating with layers as much as 9 inches thick of very poorly sorted angular rock fragments in a coarse sand matrix. Some of these individual beds have cut-and-fill stratification on a small scale. The beds in the outcrop are cut by small reverse faults and drag folds that suggest deformation while the strata were in a semifluid condition.

Mudflows are interbedded with laminated ash-bearing silt in the scarp southwest and about 50 feet higher than this roadcut. The sequence at the top of the scarp is as follows:

	Thickness (feet)
Mudflow	3
Silt and very fine sand, contains laminae of fine white pumice 1 to 4 mm thick	4
Mudflow	10
Laminated silt and very fine sand	4
Mudflow	>15

The deposits exposed in the roadcut and scarp are only a few hundred feet east of the eastward-sloping contact between bedrock and the Lily Creek formation and are near the top of the formation in this vicinity. They appear to lie within a narrow steep-sided valley in bedrock at least 200 feet deep. The valley is inferred to have headed a short distance to the northwest in sec. 24 and to have trended eastward or southeastward. The deposits at this locality are interpreted as back fills by the ancestral Mowich River into this tributary valley.

The only fossils found in the formation are pollen in clay and silty clay (unit 5 in measured section 2, p. 77) at one locality. In one sample of clay, very small amounts of pine, Douglas fir, and Englemann spruce pollen were found, and a sample from higher in the bed contained a small amount of *Picea* and *Abies* pollen. E. B. Leopold (written communication) suggests that this assemblage does not justify conclusions regarding the age of the Lily Creek formation or the environmental conditions under which the clay was deposited.

THICKNESS

The greatest known thickness of the Lily Creek formation is in measured section 1 where about 273 feet is exposed. A substantially greater thickness can be inferred from the difference in altitude of the top and bottom of the formation in the NE¼ sec. 13, T. 18 N., R. 5 E., in the valley of Voight Creek. The base of the formation lies at an altitude of about 1,160 feet, and the formation extends up on the west valley wall to at least 1,480 feet, a vertical range of 320 feet. About a mile south of this locality, the formation is exposed at an altitude of 2,000 feet, and it seems certain that the entire formation once extended up to this general level; the probable original total thickness thus may well be as much as 800 or 900 feet.

WEATHERING

The formation is deeply weathered over broad areas, and at some localities weathering has been so intense, even at depths of 20 to 25 feet, that stones as large as 4 inches in diameter can be easily cut through with a knife (fig. 5). In general, stones derived from the

FIGURE 5.—Deeply weathered mudflow in Lily Creek formation exposed near the top of the scarp in SW¼ sec. 22, southwest of Spar Pole Hill. Stones and matrix are largely converted to the clay mineral halloysite and are so soft that most stones can be cut with a knife. The dark spots and streaks are pellets of iron oxides, some of which have been crushed and streaked by the pick.

lower Keechelus andesitic series and Fifes Peak andesite are denser and are more resistant than are the stones of Mount Rainier provenance, and they are less deeply weathered at a given horizon. The characteristic clay material produced by the deep weathering is halloysite.

Original structural features, stone shapes, and textures typically have been preserved during weathering without apparent change in volume, a relation noted in deeply weathered parts of the Logan Hill formation in the vicinity of Chehalis, Wash. (Allen and Nichols, 1946). This relation also was noted by D. E. Trimble of the U.S. Geological Survey (oral communication) in gravel deposits of the Gresham formation of probable middle Pleistocene age east of Portland, Oreg. Trimble found these gravel deposits to be almost entirely decomposed to depths of as much as 35 feet, although most of the boulders and larger cobbles in the lower part of the weathering profile still have hard cores. Trimble also describes an older piedmont alluvial plain deposit of probable early Pleistocene age, on which there is a profile of weathering, as much as 75 feet thick, which includes a red soil, as much as 20 feet thick. The red soil is homogeneous and lacks the original structural features and textures of the parent materials. A similar red soil has been seen in the Lake Tapps quadrangle on the Lily Creek formation in the NE¼ sec. 30, T. 18 N., R. 5 E.; X-ray analysis of this soil shows that the predominant clay mineral is halloysite. Red soils have also been seen in the upper part of the formation in the SE¼SW¼ sec. 7, northwest of Brooks Hill and in a roadcut in the NW¼ sec. 30, 0.6 mile north of the Electron lookout and 0.1 mile east of Bear Creek. Thick red soils probably once were much more widespread on the Lily Creek formation but have been largely removed by erosion.

DISTRIBUTION

The Lily Creek formation is widely distributed in a sector-shaped area roughly bounded on the south by Twenty-five Mile Creek and on the east by Gleason Hill (fig. 6). The formation underlies a gently rolling surface of relatively low relief at an altitude of about 1,600 to about 2,700 feet and is bounded on the south and east sides by bedrock of Tertiary age, which forms the foothills of the Cascade Range at altitudes of about 2,000 to more than 4,000 feet.

Within the sector, the formation consists of a broad sheet of alluvial and mudflow deposits, that overlies a bedrock surface with a local relief of probably as much as 1,000 feet. A major relief feature of this bedrock surface is a ridge that extends southward from Spar Pole Hill to and beyond Cowling Ridge; this ridge is here informally named the Cowling Ridge divide (fig. 6).

Cowling Ridge divide splits the Lily Creek formation into northeastern and southwestern areas, each of which represents the location of a major valley that headed on Mount Rainier during Lily Creek time and that is now filled with the Lily Creek formation. The northeastern area will henceforth be referred to as the ancestral Mowich Valley and the other as the ancestral Puyallup Valley. Although the part of the formation in the ancestral Puyallup Valley is now truncated on the west by a scarp cut by glacial melt water, it seems certain that the formation once extended to the west beyond the Cascade Range front. The upper surface of the formation in the ancestral Puyallup Valley has a maximum altitude of nearly 1,900 feet in the vicinity of a broad, low-relief surface, 2 miles east of Lake Kapowsin. The ancestral Mowich Valley in the Lake Tapps quadrangle is bounded on the west by Cowling Ridge and on the east by high bedrock along the east side of Gleason Hill. The lowest exposed part of this ancestral valley is in the valley of Voight Creek in the NE¼ sec. 13, T. 18 N., R. 5 E., where the base of the Lily Creek formation rests on bedrock at an altitude of about 1,160 feet. Within the Lake Tapps quadrangle the formation rises to a maximum altitude of about 2,350 feet on the east side of Cowling Ridge. South of the quadrangle the eroded top of the formation rises to the south and southeast to a maximum altitude of at least 2,640 feet on the divide between the Mowich River and Voight Creek.

The Lily Creek formation in the ancestral Mowich Valley is abruptly truncated on the north by a scarp cut by glacial melt water. The surface of the formation probably once formed a broad northwestward-sloping alluvial plain adjacent to and beyond the mountain front in this area, with tongues extending up into the mountain front along the ancestral Mowich and Puyallup Valleys.

The Lily Creek formation apparently once nearly covered the bedrock throughout the entire sector, as indicated by outcrops of the formation near the crest of Cowling Ridge at an altitude of more than 2,300 feet. The great discrepancy in altitude of the top of the formation on Cowling Ridge and in the area to the west and south, however, implies that the formation did not extend entirely across the top of Cowling Ridge and out to the west. The strong asymmetry of Cowling Ridge suggests that since deposition of the Lily Creek the crest of the ridge has been lowered somewhat and shifted eastward. At the time the formation was deposited in the ancestral Mowich Valley, Cowling

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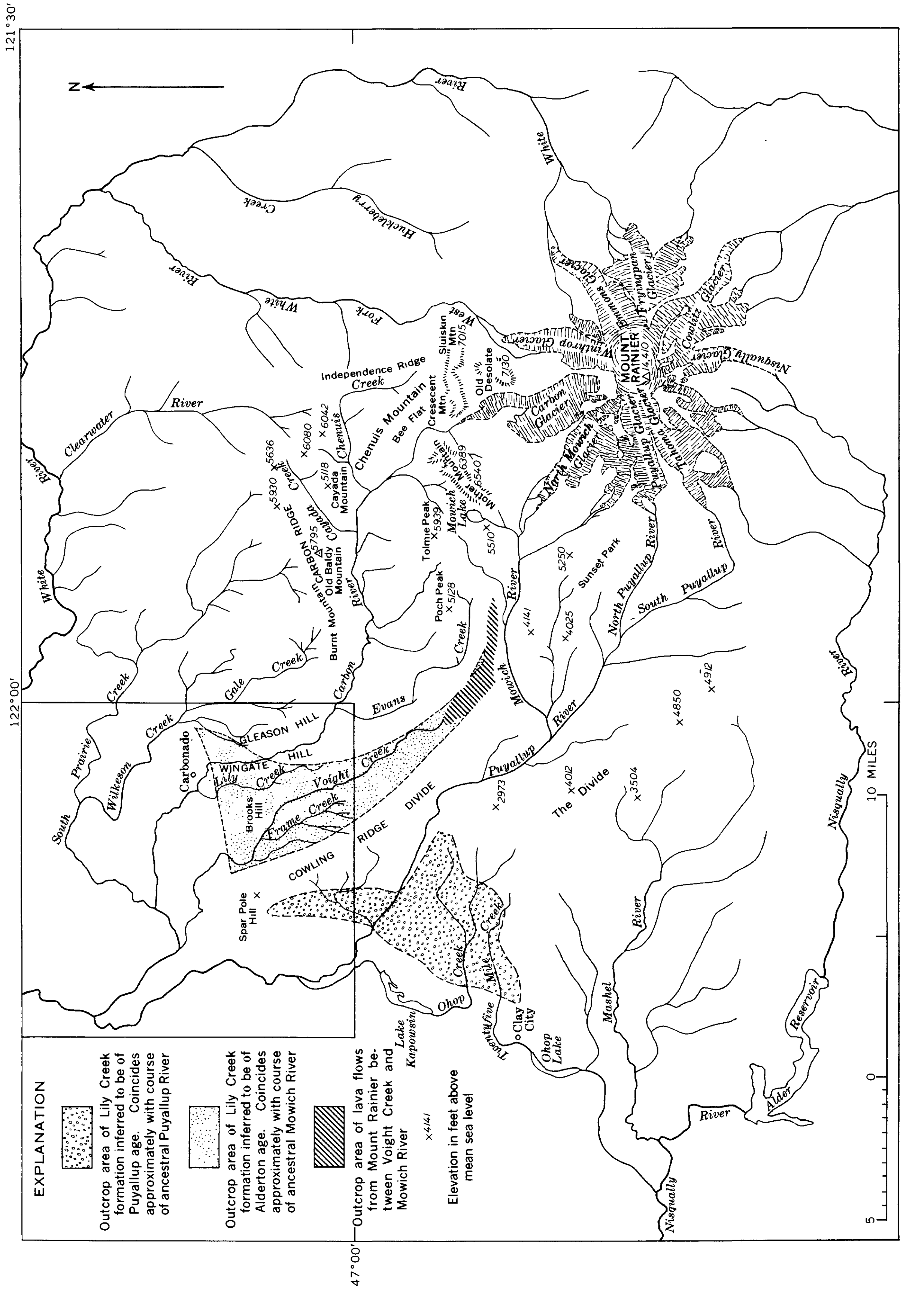

FIGURE 6.—Index map of the southern part of the Lake Tapps quadrangle (outlined at upper left), the adjacent Cascade Range, and Mount Rainier, showing the distribution of the Lily Creek formation.

Ridge probably was a low ridge of bedrock that prevented deposition of the formation west of the divide.

The difference in altitude of the top of the formation in the ancestral Mowich Valley and in the ancestral Puyallup Valley may be explained by differences in age of different parts of the formation in the two valleys. When the Lily Creek was deposited in the ancestral Mowich, a divide probably separated this drainage from that of the ancestral Puyallup. Subsequently, the ancestral Mowich was diverted to the position of the present Mowich River valley, and joined the Puyallup to flow westward. The later deposits of the combined Mowich and Puyallup Rivers in the ancestral Puyallup Valley represent a somewhat younger part of the Lily Creek formation than do the deposits in the ancestral Mowich Valley.

Superposed lava flows of hypersthene olivine andesite from Mount Rainer crop out in and adjacent to the valley of Voight Creek (secs. 23, 24, 25, 26, T. 17 N., R. 6 E.) south of the Lake Tapps quadrangle, within the limits of the broad ancestral Mowich Valley filled with Lily Creek formation (fig. 6). This lava probably is younger than the Lily Creek formation in the ancestral Mowich Valley. Although the contact between the lava and the Lily Creek has not been seen, distribution of the lava flows indicates that the flows lie within a valley cut into the Puget group, and the presence of outcrops of the Lily Creek formation at a lower altitude just north of the northern end of the flows suggests also that the flows are lying within a valley cut into the Lily Creek. This relation implies that with the flows in their present position, the Lily Creek formation could not have been deposited in the ancestral Mowich Valley to the north after the flows occurred. These flows probably occupied the ancestral Mowich Valley and blocked off its downstream part, diverting the ancestral Mowich River into the ancestral Puyallup River drainage system.

In summary, the Lily Creek formation fills valleys cut into the Tertiary bedrock of the Cascade foothills; these valleys coincide only locally with valleys of the present master stream system draining Mount Rainier and this part of the Cascade Range. It is inferred that the present northern and western limits of outcrop of the formation coincide approximately with the former position of the Cascade Range front and that north and west of these limits of outcrop the formation once formed broad piedmont alluvial plains extending out into the Puget Sound lowland.

STRATIGRAPHIC RELATIONS AND AGE[3]

The stratigraphic relations of the Lily Creek formation to most other Pleistocene deposits of the area cannot be unequivocally demonstrated; thus, the age of the formation is in doubt. The youngest deposit that the Lily Creek overlies is bedrock of late Eocene age, which locally is weathered to clay beneath the formation. The best weathering profile generally is found in areas that were adjacent to but not within the deepest valleys of pre-Lily Creek time. For example, sedimentary rock of volcanic origin that has been almost completely altered to clay is exposed in the SW¼NW¼ sec. 23, T. 18 N., R. 5 E., in a roadcut adjacent to Beane Creek. This rock lies directly beneath the Lily Creek formation. The weathered zone here has been protected by burial beneath the Lily Creek formation, whereas the zone has been largely removed by erosion on the higher slopes of Spar Pole Hill. A similar example of burial of deeply weathered bedrock by the Lily Creek is found in the valley of Kings Creek in the SW¼NE¼ sec. 34, T. 18 N., R. 5 E.

Nowhere is the Lily Creek formation in contact with drift known to be of Orting age; the stratigraphic relation of these two formations must thus be inferred from other evidence. Much of the gravel in the Orting drift is of central Cascade provenance, especially the part inferred to lie beneath the drift and to be of early Orting age (p. 17). This gravel probably was deposited by streams draining the Cascade foothills south and southeast of Orting, an area now extensively underlain by the Lily Creek formation. The absence of rocks and minerals of Mount Rainier provenance in the gravel almost certainly precludes the possibility that the Lily Creek formation had been deposited in the foothill area by Orting time.

The presence of two post-Orting formations, the Alderton and Puyallup, which resemble the Lily Creek formation in nearly every way, suggests a possible correlation. The Alderton and Puyallup formations were

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[3] Since completion of this report, C. A. Hopson (written communication, July 31, 1960) has suggested to the writer that the Lily Creek formation is of Pliocene age, and pre-dates the building of Mount Rainier. This suggestion is based partly on the presence of hornblende-hypersthene andesite and dacite pebbles in the Lily Creek. These rocks, according to Hopson, are petrographically similar to intrusive rocks and lavas thought to be of Pliocene age in the vicinity of Mount Rainier and along the crest of the Cascade Range, but are unlike the pyroxene and olivine andesites exposed in the flanks of Mount Rainier and in flows around its base. It seems more likely to the writer that the hornblende-hypersthene andesite in the Lily Creek, Alderton, and Puyallup formations was derived from an ancestral Mount Rainier of early to middle Pleistocene age, which has been buried by the lithologically dissimilar rocks of the modern cone.

deposited during the first and second interglacial intervals, respectively. A similar twofold subdivision of the Lily Creek formation was proposed previously on the basis of distribution and altitude. The Lily Creek formation provides the only possible southeastward correlative of the Puyallup and Alderton formations. Other than the ancestral valleys of the Mowich and Puyallup, no other routes exist by which these formations could have been transported to the lowland.

The proposed equivalence of the older part of the Lily Creek formation (in the ancestral Mowich Valley) to the Alderton formation in the lowland, and younger part of the Lily Creek (in the ancestral Puyallup Valley) to the Puyallup formation is hypothetical, but with the evidence now at hand, it seems to be the most likely correlation. Because the evidence is inconclusive, however, a distinction is made in this report between the three formations.

ORIGIN

The Lily Creek originated as thick valley fills of alluvium and mudflows in response to the contribution of a great volume of volcanic material to certain master streams that had their headwaters at or near Mount Rainier or an ancestor of this volcano. The great quantity of loose fragmental material, intermittently made available to these drainage systems, was not in proportion to the volume of load contributed during normal weathering in the Cascade Range and was not in proportion to the normal load of the major streams. The result of this volcanism was alternate aggradation of valleys heading on Mount Rainier and degradation when streams cut downward in attempts to reach their former gradients. Because the ancestral Mowich Valley was blocked after deposition of part of the Lily Creek formation, a segment of a great composite valley fill of mudflows and alluvium is preserved here virtually intact.

ALDERTON FORMATION

The Alderton formation consists of a succession of nonglacial sediments of Mount Rainier provenance deposited during the interval after the Orting glaciation (Crandell, Mullineaux, and Waldron, 1958). The formation is typically exposed in the west wall of the Puyallup Valley near Alderton (measured sections 5 and 6, p. 78–79), where it consists predominantly of mudflows and alluvium at least 100 feet thick.

DESCRIPTION

The prevailing lithology of the Alderton formation indicates that it was derived almost wholly from Mount Rainier. Rock fragments in mudflows in the formation consist principally of hornblende and hornblende-hypersthene andesite derived from Mount Rainier lavas, and the sand-size fractions of stream deposits in the formation have a heavy-mineral suite dominated by hypersthene and hornblende.

The most prominent beds in the formation along the west wall of the Puyallup Valley are the two mudflows exposed in measured sections 5 and 6. The mudflows consist of angular to subrounded pebble- to boulder-size andesite fragments in a very compact matrix of sandy clay. The heavy-mineral component of the sand-size fraction consists of hypersthene and hornblende. Although the base of the upper mudflow is irregular (fig. 7), the upper surface is nearly flat. Because of

FIGURE 7.—Upper mudflow in the Alderton formation in the NE¼ sec. 12, northwest of McMillin (measured section 6). Mudflow here is 4 to 8 feet thick; 125 feet to the north (right) it thickens to at least 25 feet although the top remains nearly horizontal.

the irregular base, the mudflow ranges in thickness from about 3 feet to more than 25 feet. Vertical grading is very conspicuous in the thicker parts of the mudflow and also is present where the mudflow is only a few feet thick.

In the south wall of Fennel Creek valley, 1.5 miles east of the outcrops previously described, the uppermost 60 feet of the Alderton formation consists of sand and pebble to boulder gravel, and mudflows are not exposed.

One of the most distinctive beds in the Alderton formation is the pumice tuff (bed 5) near the top of the formation at measured section 5; it has been recognized nowhere else. The tuff is not conspicuously bedded, but long axes of the elongate pumice pebbles tend to lie horizontally, and at some horizons there are concentrations of elongate pumice pebbles in horizontal layers. The pumice contains dark phenocrysts of hypersthene and hornblende in a ratio of about 3 to 1; the matrix consists of pinkish-gray crystal ash of fine-sand size. In addition to the ash and pumice pebbles, the tuff contains a few angular rock fragments, as long as 6 mm, and small carbonized wood fragments.

DISTRIBUTION

Outcrops of the Alderton formation are limited mostly to the walls of the Puyallup Valley south of Alderton; north of this community the top of the formation disappears beneath the valley floor. At measured section 5 the top of the formation is at an altitude of about 230 feet, and in the valley of Fennel Creek it is at about 265 feet. The base of the formation in this vicinity is seen only at measured section 6, where it overlies the Orting drift at an altitude of about 160 feet. East of Orting, in the walls of South Prairie Creek valley in secs. 26 and 27, the base of the formation lies at 475 to 520 feet.

Outcrops of the formation are not known to be present in the walls of South Prairie Creek valley or the Carbon River valley east of secs. 26 and 27; but the presence of the Alderton overlying the Orting drift in these two sections suggests the possibility that the formation might once have extended even farther east.

The Alderton formation is not present and sediments of Alderton age are not known to exist in the walls of the White and Green River valleys (D. R. Mullineaux, oral communication); thus, the east depositional boundary of the formation probably was originally along or west of a line that trends northwestward through Buckley.

ORIGIN AND ENVIRONMENT OF DEPOSITION

The Alderton formation represents mudflow and stream alluviation of parts of the lowland by the ancestral Mowich River. The ancestral Mowich probably discharged to the Pacific Ocean through the Puget Sound lowland and the area now occupied by the Strait of Juan de Fuca. The abundance of volcanic materials in the formation represents sedimentation related to volcanism of Mount Rainier.

The climate of part of Alderton time has been determined from a peat and silty peat bed (bed 6 of measured section 6). Pollen in the base of this bed contains a dominance of Englemann spruce, representing the Canadian vegetation zone. The upper part of the bed contains as much as 40 percent Douglas fir and 50 percent alder (probably *Alnus oregona*), both of which are members of the flora of the Humid Transition zone. The climate during this part of the interval after the Orting glaciation thus probably was comparable to that of the present in this area.

STRATIGRAPHIC RELATIONS

A small erosional unconformity separates the Alderton formation from the overlying Stuck glacial drift, but no evidence has been found of deep valley cutting during or after Alderton time and prior to the Stuck glaciation. A weathered zone has not been recognized in or on the Alderton formation, although weathering probably accompanied the erosion interval that ensued between cessation of Alderton deposition and the advance of the Stuck glacier.

STUCK DRIFT

The Stuck drift was first recognized and named by Crandell, Mullineaux, and Waldron (1958); it represents the second glaciation of this part of the lowland by the Puget lobe of the Cordilleran ice sheet. The maximum extent of the Stuck glacier is not known.

DESCRIPTION

The Stuck drift is typically exposed southwest of Alderton at measured section 5 where it consists of 5 feet of till overlain and underlain by glacial sand and gravel. The drift is also well exposed northwest of McMillin at measured section 6 and at the bluff in the northwestern part of the town of Sumner (measured section 8). Other than in the walls of the Puyallup and Duwamish Valleys, the only exposures of the Stuck drift are in the valley of the White River (measured section 9).

In the Puyallup and Duwamish Valleys, till in the Stuck drift typically is oxidized but otherwise unweathered except for disintegration of granitic stones in it. About 10 to 15 percent of the pebbles in the till consists of rocks of northern provenance, and the remainder consists chiefly of rocks of central Cascade provenance (p. 14). At measured section 8, the upper part of the till in the Stuck drift is faintly stratified, and some beds, several inches thick, are somewhat better sorted than those above or below. This poorly stratified till is inferred to have originated by mudflowage.

In the Puyallup Valley the till ranges in thickness from 5 to 20 feet and generally is stony. In the valley of the White River the till is as much as 28 feet thick, and as much as 38 percent of the stones in the till consists of rocks of northern provenance. Of particular note at measured section 9 in the White River valley is a high content of quartz (15 percent) and marble pebbles (5 percent) in the till, and the matrix, itself, is calcareous. These pebbles are very conspicuous owing to their white color. Marble pebbles have not been observed in any other till, and quartz pebbles are nowhere so abundant as here. Whether this till is an exact time correlative of one in the Stuck drift in the Puyallup Valley is not known.

X-ray analysis of a sample of till from an outcrop of Stuck drift in the NW¼NW¼ sec. 36 in the south wall of the Puyallup Valley south of Sumner showed a predominance of montmorillonite in the clay fraction, chlorite as a minor constituent, and quartz and feldspar in trace amounts.

Sand and gravel and till in the Stuck drift typically are oxidized, but in the White River valley the till characteristically is unoxidized. In the Puyallup Valley, as much as 10 percent of the gravel above the till in the Stuck drift is of northern provenance, and the remainder is of central Cascade provenance. This gravel is inferred to represent recessional outwash deposited during retreat of the Stuck glacier. Sand and gravel beneath the till contains materials of all three provenances. A bed 15 inches thick and 10 feet below the base of the till in the Stuck at one locality contains stones of which 25 percent are of northern provenance, although less than 10 percent of the pebbles in the adjacent gravel are of northern provenance. At this same locality, sand lenses of Mount Rainier provenance are interbedded with gravel of central Cascade and northern provenance.

The Stuck drift in the Puyallup Valley is almost everywhere represented by till in addition to sand and gravel. In the valley of Fennel Creek, however, the drift consists only of a single bed of sand and gravel of northern and central Cascade provenance, 10 to 15 feet thick, which lies between the Alderton and Puyallup formations.

Near Sumner, the Stuck drift nearly everywhere consists of lacustrine sediments in its upper part, or is overlain by lacustrine deposits in the Puyallup formation. In the bluff south of Sumner in the NW¼NW¼ sec. 36, 40 feet of laminated silt and fine sand rest directly on till in the Stuck. These beds contain scattered boulders, as large as 2 feet in diameter, and lenses of sand and till-like material. In one outcrop in this vicinity, the laminated sediments dip about 20° and are cut by steeply inclined normal faults on which there has been less than 1 inch of displacement. The laminated beds near the base of the unit consist of alternate fine sand and silt, ranging in thickness from 0.25 to 1 inch; near the top the beds are as much as 1.5 inches thick. Owing to their content of glacial erratics and to other features, these beds are inferred to be of glaciolacustrine origin. At measured section 5 southwest of Alderton, lacustrine deposits that lie at the same stratigraphic horizon consist principally of very fine volcanic ash. It may be that they are only slightly younger than the glaciolacustrine beds in sec. 36 in the bluff south of Sumner and were deposited in the same body of water after the Stuck glacier had retreated farther to the north.

In the valley walls of the White River, the Stuck drift also contains lacustrine deposits (measured section 9), but here they lie below rather than on the till. The beds probably represent deposits of a proglacial lake formed during advance of the Stuck glacier or perhaps, during a temporary retreat.

DISTRIBUTION

Outcrops of drift known to be of Stuck age are limited to the walls of the Puyallup and Duwamish Valleys in the northwestern quarter of the Lake Tapps quadrangle. To the south, lack of adequate exposures prevents distinction of this drift from the other drift formations. The position of the southern margin of th drift is not known. At measured section 5, the Stuck drift is at an altitude of 230 feet, or about 130 feet above the flood plain, and from there northward its altitude decreases. At the bluff northwest of Sumner the base of the drift is below the flood-plain surface, and the drift completely disappears in both valley walls less than 1 mile north of Sumner.

Drift assigned to the Stuck glaciation in the White River valley is correlated principally by stratigraphic position and by lateral tracing along the valley walls by D. R. Mullineaux.

WEATHERING

The Stuck drift is nowhere known to contain a well-developed soil profile or a zone of weathering. In the Puyallup and Duwamish Valleys the lack of weathering at the top of the formation is believed to be due to immediate burial of the drift sheet by lacustrine and alluvial deposits of the Puyallup formation. At measured section 9 in the White River valley, the uppermost 4 inches of the till at the top of the drift is humified; this humified zone probably is partly correlative in age with a sequence of peat beds and lacustrine sediments in a nearby exposure (measured section 12), which are probably of Puyallup age.

STRATIGRAPHIC RELATIONS AND AGE

The Stuck drift rests on the Alderton formation with a slight erosional unconformity, but the magnitude of this unconformity elsewhere cannot be determined, owing to sparse exposures of the contact and to altitude variations of the contact, apparently caused by warping or faulting. The age of the Stuck drift is known only in relation to the local sequence of glacial and nonglacial intervals; because it falls in the approximate middle of this sequence, it is inferred to be at least as old as middle Pleistocene.

PUYALLUP FORMATION

The Puyallup formation of this report includes the Puyallup sand of Willis, which is typically exposed in the west wall of the Puyallup Valley near Alderton (Willis, 1898, p. 147). Willis defined the stratigraphic position of the Puyallup sand as between Vashon drift and Orting gravel; in this, he was correct, but subsequent work has shown the sand to be part of a thicker formation lying between the Stuck drift and the Salmon Springs drift (Crandell, Mullineaux, and Waldron, 1958). Because Willis did not recognize the presence of these additional drift sheets, he assigned all post-Orting, pre-Vashon sand deposits in the Puyallup and Carbon River valleys to the Puyallup, and at least one sand deposit of Vashon age (p. 42) as well. Most of these sand units are not correlative with the sand at Willis' type locality, and mapping has shown that sand units of several ages lie in the stratigraphic interval between the Orting and Vashon.

DESCRIPTION

The Puyallup formation consists of about 135 feet of alluvial and lacustrine sand, alluvial gravel, mudflows (fig. 8), volcanic ash, and peat (fig. 9). The formation is typically exposed at measured section 5, southwest of Alderton, where the lowest unit is 9 to 16 feet of horizontally laminated pinkish-gray silt alternating with gray fine sand. Individual beds in this deposit range in thickness from 1/32 inch to 5 inches. This unit, intepreted to be of lacustrine origin, grades up into light-gray medium to coarse sand, about 70 feet thick. This sand contains lenses of granule gravel and very coarse sand-size yellowish-gray pumice, as well as scattered pebbles of light-gray andesite. Much of the sand is horizontally bedded, but some beds show cut-and-fill stratification. This thick deposit of sand, as well as other sand beds of Mount Rainier provenance, is light gray in contrast to yellowish-brown oxidized sands of pre-Vashon age of northern or central Cascade provenance. The gray color of the sand beds is due to the presence on many of the grains of a thin coating of devitrified white glass.

A second area in which the formation is well exposed is in the south valley wall of Fennel Creek in sec. 8 (measured section 10) and at Victor Falls (measured section 11), where Fennel Creek crosses a resistant mudflow. In the Fennel Creek area, nearly the entire formation consists of coarse-grained deposits above basal lacustrine beds only 3 feet thick. The lower 85 feet of the formation in this area consists of five mudflows separated by thin sand beds; the same stratigraphic interval is mostly sand on the west wall of the Puyallup Valley near Alderton. This relation suggests that these two sections represent different parts of an aggrading flood plain; the mudflows were deposited along the central part of the valley, and the sand represents nearly contemporaneous low-gradient stream deposits. This facies relationship was only temporary, however, as indicated by the presence of mudflows and coarse alluvium in the upper part of the Puyallup formation west of Alderton at measured section 5.

FIGURE 8.—Outcrop of mudflow in Puyallup formation on north wall of Fennel Creek valley in the W½ sec. 8. Mudflow here is about 18 feet thick and is interbedded with sand. Black lines show the base and top of the mudflow.

Gravel in the formation typically consists of about equal amounts of stones derived from Mount Rainier and from the central Cascade Range. Most of the mudflows, however, are monolithologic, and as much as 95 percent of their rock fragments is derived from Mount Rainier. Most of the mudflows are relatively thin; the thickest known is a heterolithologic mudflow, 21 feet thick, in the upper part of the formation at measured section 5.

Beds of peat are common in the formation. The beds generally are from 2 to 12 inches thick and are very compact. Typically the peat is associated with laminated clay, silt, and sand inferred to be of lacustrine origin, and in several places the peat is associated with diatomaceous earth.

The mineralogy of a typical mudflow in the formation, the uppermost of the two exposed at Victor Falls, consists of hypersthene (90 to 95 percent) and hornblende in the heavy-mineral fraction of the sand-size material; the light fraction consists of plagioclase feldspar with the approximate composition of labradorite, quartz, and glass. The silt-size fraction contains plagioclase and alpha cristobalite in an estimated ratio of approximately 7 to 2, as determined by X-ray diffraction patterns; the clay fraction contains montmorillonite, plagioclase, and alpha cristobalite in the approximate proportions of 4:4:1.

The only deposit of Puyallup age in the lowland part of the quadrangle other than along the walls of the Puyallup Valley is in the east valley wall of the White River (measured section 12). About 20 feet of lacustrine sand, silt, and peat beds are found here between the Stuck and Salmon Springs drifts. The sediments probably were deposited in a depression on the Stuck glacial drift. These nonglacial deposits are not differentiated on the geologic map, owing to their thinness and limited area of outcrop.

FIGURE 9.—Interbedded sand, peat, and mudflow in the Puyallup formation in a gully near the center sec. 36, northwest of Alderton. The upper peat bed is 8 to 12 inches thick, and the lower bed is 9 inches thick; both are very compact.

DISTRIBUTION

Outcrops of the Puyallup formation in the quadrangle are mostly in the walls of the Puyallup Valley, although the formation has been identified nearly as far north as Des Moines (Crandell, Mullineaux, and Waldron, 1958). The greatest known thickness occurs near Alderton; northward the formation thins rapidly and is represented in the bluff in the northwestern part of Sumner by only about 20 feet of gravel and sand. North of Sumner the formation is 30 to 50 feet thick. The thinning of the formation north of Alderton apparently is the result of erosion before the next glacial interval; possibly this erosion was localized along some valley ancestral to the present drainage system.

The Puyallup formation has not been seen in the valley of White River, and it seems unlikely that the formation ever extended that far east. The distribution of the formation west of the Puyallup Valley is not known, but the writer has recognized the formation as far west as sec. 10, T. 20 N., R. 3 E. in the eastern part of the city of Tacoma.

WEATHERING

Near Alderton the top of the Puyallup formation locally is weathered to a depth of about 10 inches; in this zone, the matrix and many of the andesitic rock fragments of a fine-grained mudflow consist of halloysite. The only clay mineral in the unweathered part of this mudflow is montmorillonite. Montmorillonite is found in the matrix of unweathered mudflows of several ages in the Lake Tapps quadrangle, and this mineral has probably originated from the alteration of glass and perhaps other materials at the source volcano rather than from subaerial weathering after the mudflow came to rest. The halloysite, however, evidently is a product of subaerial weathering (Allen and Nichols, 1946).

ENVIRONMENT OF DEPOSITION

The Puyallup formation represents an interval of volcanic sedimentation in the area now occupied in part by the Puyallup Valley, and its deposition is analogous to that of the Alderton formation. Sediments of the Puyallup are believed to have been transported to the lowland by way of the ancestral Puyallup Valley. According to this interpretation, the part of the Lily Creek formation lying southwest of the Cowling Ridge divide (fig. 6) is the upstream equivalent of the Puyallup formation.

The depositional environment of the formation in the lowland probably was a broad plain whose east side lay in the area now occupied by the interfluve between the White River and the Puyallup River. Peat and lacustrine sediments in the east valley wall of the White

River that are inferred to be of Puyallup age probably were deposited in a depression in the Stuck drift on an upland area east of this broad plain.

The Puyallup formation began to accumulate during the withdrawal of the Stuck glacier from the Lake Tapps quadrangle; at only one locality (measured section 8) is there evidence of erosion between the Stuck drift and Puyallup formation (fig. 10). This erosion, however, probably occurred during Puyallup time. Both north and south of this locality, the basal beds of the Puyallup consist of lacustrine deposits that lie directly on the Stuck drift; at measured section 8, gravels of the Puyallup formation occupy this stratigraphic position and the lacustrine beds are missing. Stream erosion in early Puyallup time probably cut through some of the lacustrine deposits and down into the Stuck drift, and these sediments were replaced by alluvial sand and gravel.

Climatic conditions during depositions of the Puyallup formation are inferred from pollen obtained from beds of peat and fine-grained sediments at three localities. At the first of these localities, on the west valley wall of the Puyallup River, 0.8 mile south of measured section 5, beds of silt and peat immediately overlie unoxidized Stuck till. Pollen from these beds is dominated by pine and small amounts of Engelmann spruce, suggestive of the forests of the upper Canadian vegetation zone. On the basis of the superposition of these silt and peat beds on till in the Stuck drift, the cool and moist conditions of early postglacial time can probably be inferred from the pollen.

At a second pollen locality, about 1.1 miles north of measured section 5, along the same valley wall, three beds of peat lie at a stratigraphic horizon between units 11 and 12 of measured section 5. The lowest of these peat beds contains predominantly pine and non-tree pollen, and the middle bed shows a rise in prominence of Englemann spruce and *Abies*. Near the top of the upper peat bed, *Abies* is predominant, but is accompanied by spruce, pine, western and mountain hemlock, and Douglas fir. These pollen assemblages suggest a climatic warming and an environment similar to that of the middle Canadian vegetation zone during the warmest phase.

A third locality is in the east wall of the White River valley (measured section 12). In the sediments of Puyallup age that rest on unweathered till of Stuck age, herb and shrub pollen predominate at the base, above which there is first a maximum of *Populus* and then pine (probably whitebark pine). Above this zone, concurrent with a gradual decrease of pine and a corresponding increase of Engelmann spruce, mountain hemlock and fir (*Abies* sp.) make their first appearance, followed by a predominance of fir in association with mountain hemlock, western hemlock, pine, and spruce. Finally, at the top, there is a decrease in fir and an increase in both hemlocks, especially the western species. This succession probably represents a gradual warming and drying from early postglacial conditions to a climate similar but somewhat cooler and moister than that of today in the upland part of the Lake Tapps quadrangle (Leopold and Crandell, 1957). The pollen-

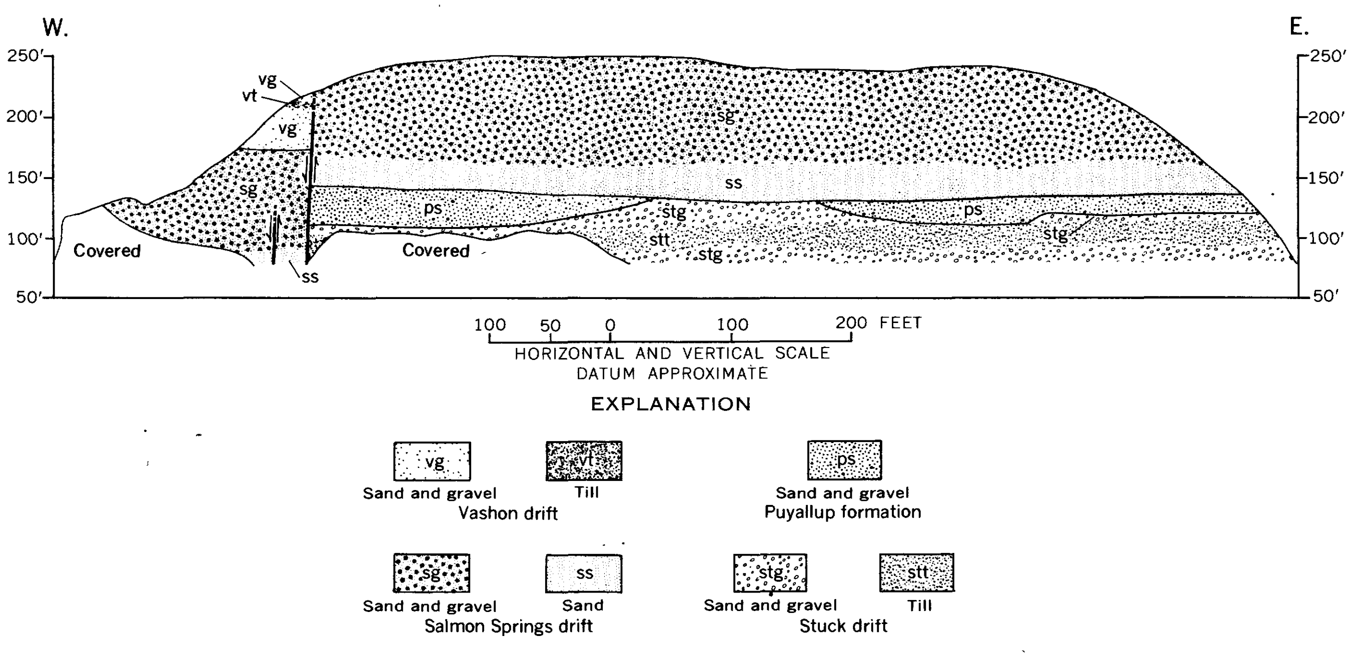

FIGURE 10.—Exposure at bluff at the northwest outskirts of Sumner, showing the relations between Stuck drift, Puyallup formation, and Salmon Springs and Vashon drifts. Vashon drift occurs on the hillside above and north of the bluff. The beds are displaced about 80 feet on the large fault at the left and about 6 feet on the smaller fault.

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bearing beds are truncated by an erosional unconformity, and possible later stages in a climatic trend are not recorded.

A still warmer climate in the lowland in Puyallup time is indicated by pollen in fine sediments and peat exposed in cliffs adjacent to Puget Sound between Seattle and Tacoma (Crandell, Mullineaux, and Waldron, 1958). The basal beds of the pollen-bearing sediments overlie a mudflow of Mount Rainier provenance, and contain pollen of Douglas fir, western hemlock, and alder, reflecting a vegetation and climate comparable to today. The only difference between the assemblage in this zone and modern pollen fallout in the lowland is the presence of small additional amounts of fir and pine, which perhaps are coastal fir (*Abies grandis*) and beach pine (*Pinus contorta*). Above this zone is a pollen zone dominated by fir, but all of the Humid Transition forms such as Douglas fir, western hemlock, and alder still are present. Mountain hemlock increases in this zone. The overlying sediments contain a predominance of Englemann spruce pollen, and forms that are representative of the Humid Transition zone are absent. Above this zone is one of pine (perhaps whitebark pine) and *Populus*, succeeded by a final assemblage of pine and cold-loving plants. The entire sequence suggests a slow cooling of the regional climate during deposition of this part of the Puyallup formation.

In the cliffs adjacent to Puget Sound, the Puyallup formation is separated from the overlying Salmon Spring drift by an erosional unconformity (H. H. Waldron, oral communication), and it is not known whether this regional cooling sequence records the approaching end of the nonglacial interval or whether it is merely a climatic fluctuation within the interval.

STRATIGRAPHIC RELATIONS AND AGE

The Puyallup formation is separated from the underlying Stuck drift by a minor unconformity, probably representing, in part, constructional topography on the Stuck drift surface. In outcrops in the walls of the Puyallup Valley near Sumner, late-glacial lacustrine deposits of Stuck age grade upward into early postglacial lacustrine deposits of Puyallup age, indicating that the drift here was buried soon after retreat of the Stuck glacier.

Before the next glaciation, the Puyallup formation was eroded by streams and a broad valley at least 100 feet deep was formed near Sumner. During and possibly after this erosion, the formation was being weathered elsewhere.

Pollen in the Puyallup formation indicates a trend from an early postglacial climate to a climate like that of the present in the lowland and a subsequent reversal to a colder climate. Nonglacial climates continued after deposition of the formation, as suggested by weathering on top of the formation and by erosion. Evidence in the Puyallup formation itself thus reveals only a part, perhaps a small part, of the nonglacial interval between the Stuck and Salmon Springs glaciations.

SALMON SPRINGS DRIFT

At many localities in the Puyallup and Duwamish Valleys the Puyallup formation is overlain by till of pre-Vashon age and pebble to boulder gravel of northern and central Cascade provenance. In most places these sediments appear to represent a single drift unit. In exposures near Sumner, however, the presence of nonglacial sediments between two deposits of drift in this stratigraphic interval indicates that two glaciations or two advances of a single major glaciation are represented. The Salmon Springs drift includes both of these post-Puyallup, pre-Vashon glacial deposits, and, in addition, nonglacial deposits in the same stratigraphic interval (Crandell, Mullineaux, and Waldron, 1958).

DESCRIPTION

Northeast of Sumner (measured section 13) the Salmon Springs drift includes two gravel and till units separated by about 4 feet of volcanic ash, silt, and peat. The sediments below the volcanic ash consist of 10 to at least 27 feet of oxidized pebble to boulder gravel of central Cascade and northern provenance. At one exposure in the vicinity of Salmon Springs, the basal part of this unit contains a layer of till at least 5 feet thick.

The volcanic ash bed that is exposed in the vicinity of Salmon Springs in the middle of the drift is 6 to 12 inches thick. Heavy minerals in the ash are principally hornblende and hypersthene, in a ratio of about 3 to 1, and small amounts of biotite and magnetite. The light fraction consists chiefly of plagioclase and glass.

The part of the formation above the peat and ash consists of 37 to 55 feet or more of gravel, sand, and till. There is a wide range of provenance in these deposits; although they are predominantly of central Cascade derivation, the base of the gravel in the vicinity of Salmon Springs contains as much as 15 percent pebbles of Mount Rainier derivation, in contrast to only 6 percent of northern derivation. The upper part of this gravel contains 1 percent pebbles of Mount Rainier provenance and 26 percent pebbles of northern provenance. The heavy minerals of the sand fraction of this deposit show a similar vertical change: the basal beds are predominantly hypersthene and small amounts of hornblende, magnetite, and ilmenite, but contain no garnet, whereas the upper beds contain as much as 15 percent garnet and only about 10 percent hypersthene.

At the bluff exposure (fig. 10) in the northwestern part of Sumner (measured section 8), the Salmon Springs consists of basal sand of northern derivation about 28 feet thick. This is overlain by 75 feet of pebble and cobble gravel. The lower part of this gravel is of northern and Cascade provenance, but upward the gravel becomes increasingly rich in rocks and minerals of Mount Rainier derivation and poor in northern rock types. Although this sand and gravel unit rests directly on the Puyallup formation, its relation to the peat and ash beds of the Salmon Springs area is not known. About 0.3 mile north of the bluff at Sumner, on the west wall of the Duwamish Valley a discontinuous layer of gray till, 10 feet thick, lies immediately above the Puyallup formation. There is a mixed zone, 4 feet thick, along the base of this till, and wedge-shaped masses of till extend 3 to 6 feet down into the Puyallup formation. This till is overlain by more than 25 feet of sand and pebble and cobble gravel in which there is another lens of till as much as 1 foot thick.

In addition to the 2 drift units and the intervening peat and volcanic ash, 2 other sedimentary units occur in the stratigraphic interval between the Puyallup formation and the Vashon drift. These deposits make up much of the Duwamish Valley wall north of Sumner. One unit consists of sand and pebble to cobble gravel predominantly of central Cascade provenance; the other consists chiefly of sand and pebble gravel, mostly of Mount Rainier derivation. The stratigraphic relation of these deposits to the two drift units and to the nonglacial sediments in the vicinity of Salmon Springs is uncertain. The gravel of central Cascade provenance is exposed along the east valley wall in the vicinity and north of Dieringer, and the sediments of Mount Rainier provenance crop out along the west valley wall north of Sumner, northwest of the Lake Tapps quadrangle.

DISTRIBUTION

Salmon Springs drift is best exposed in the vicinity and north of Sumner. South of Sumner the drift is thin, and it has not been recognized south of McMillin. The base of the drift decreases in altitude toward the north, along the erosional unconformity on the Puyallup formation. It has not been recognized in the valley walls of South Prairie Creek or the Carbon River.

Drift of Salmon Springs age has been seen overlying beds of Puyallup age at only one locality in the valley walls of the White River in the north-central part of the quadrangle, although drift inferred to be of Salmon Springs age crops out beneath the Vashon drift along the valley walls as far upstream as sec. 29, T. 20 N., R. 6 E. In the White River valley, till in the Salmon Springs typically is oxidized and appears to be a single layer as much as 25 feet thick; pebble counts show that 5 to 8 percent of the stones are probably of northern derivation and the remainder are of central Cascade provenance. Gravel lies above and below the till in most places. The lower gravel attains a maximum known thickness of more than 75 feet along the west valley wall of the White River in the SE¼ sec. 11, T. 20 N., R. 5 E. The fact that the base of this gravel lies more than 60 feet below the base of the formation on the opposite valley wall suggests that the gravel represents advance outwash which has filled an older valley. The maximum known thickness of gravel above till in the Salmon Springs is in the SE¼SW¼ sec. 19, T. 20 N., R. 6 E., where about 60 feet of oxidized gravel underlies till of Vashon age.

X-ray analysis of the clay-size fraction of till sample taken from an outcrop of Salmon Springs drift in SW¼SE¼ sec. 11, in the north-central part of the quadrangle, shows a predominance of montmorillonite, chlorite and illite as minor constituents, and trace amounts of quartz and feldspar.

STRATIGRAPHIC RELATIONS AND ENVIRONMENT OF DEPOSITION

The Salmon Springs drift rests unconformably upon the eroded and weathered surface of the Puyallup formation, and, in turn, is overlain unconformably by the Vashon drift. Evidence from the Salmon Springs drift indicates two glaciations of the lowland separated by a nonglacial interval. Pollen in the peat bed between the two drifts in measured section 13 is dominated by pine and fir (*Abies*) and contains small additional amounts of spruce (*Picea*), western hemlock, and mountain hemlock. This flora suggests a cool and moist climate and indicates that the early Salmon Springs glacier had retreated far enough to permit a pine and fir forest to grow near Sumner.

Radiocarbon analysis of the peat in measured section 13 gave an age of more than 38,000 years (W–672).

WINGATE HILL DRIFT

A widely distributed till of pre-Vashon age in the Cascade foothills previously has been recogized by J. H. Mackin (oral communication) who informally named it the "rind" till. This till is here included in the Wingate Hill drift, and is defined as a drift sheet that mantles the Cascade foothills in western Washington, and that is characterized by a lack of constructional topography and the presence of weathered rims, as much as one-fourth inch thick, on constituent stones in the uppermost few feet. The name is taken from Wingate Hill south of Carbonado, on the west side of which till in the drift is typically exposed (measured section 1). In addition to the till, the map unit locally includes several types of material too thin or discontinuous to be differentiated from the Wingate Hill drift on the geologic map. These materials include silt, clay, and volcanic ash, and glaciolacustrine sediments of Vashon age.

DESCRIPTION

Most till of the Wingate Hill drift is brown and stony, and is very compact except where modified by weathering or frost heaving. The sand fraction is characterized by a heavy-mineral suite consisting principally of magnetite, ilmenite, and epidote, and pebbles in the till are of central Cascade and Mount Rainier provenance. On Gleason Hill the till is predominantly of central Cascade provenance, and in areas underlain by the Lily Creek formation, the till is rich in Mount Rainier rocks. The thickest exposed sections of the till are along the Mowich Lake Road near and just south of the south edge of the Lake Tapps quadrangle, where the till is as much as 30 feet thick (fig. 11). In secs. 30 and 31, east of Cowling Ridge, many exposures along logging roads indicate a range in thickness from 3 to 15 feet. The pre-Wingate Hill surface of this area, formed almost wholly in the Lily Creek formation, is closely similar to the drift surface of today, and the till merely veneers this surface.

In many places the till is covered by poorly consolidated dark-yellowish-orange to moderate-yellowish-brown silt and clay containing scattered stones; this material contains abundant hornblende or hypersthene, or both minerals in addition to minerals derived from the underlying till. On Gleason Hill a deposit of as much as 16 feet of silt and clay and few or no stones overlies the till. In an auger hole near the northeast corner of sec. 22, 16 feet of light-yellowish-gray plastic sandy silt and clay was found oxidized to a depth of about 3 feet. A sample of this material 2 feet below the surface contains nearly 90 percent hornblende in the heavy-mineral fraction and both hornblende and hypersthene at a depth of about 15 feet. Fragments of carbonized wood were found at a depth of 13 feet. Sandy silt containing stones found at the bottom of the hole, 16 feet below the ground surface, is inferred to represent till of the Wingate Hill drift. Abundant hornblende and hypersthene euhedra in the 16 feet of silt and clay suggest that the sediments are chiefly weathered volcanic ash in which the glass has devitrified. Oxidation revealed in another auger hole in this material, in the NW¼SE¼ sec. 15, extends to a depth of about 6 feet.

FIGURE 11.—Outcrop of very compact till in the Wingate Hill drift on Mowich Lake Road near the south edge of the Lake Tapps quadrangle. Note lack of sorting and stratification. Pick gives the scale.

Similar fine sediments locally occur both above and below till in sec. 30, east of Cowling Ridge; the older sediments are well exposed along a logging road, 0.45 mile northeast of the lookout tower on Cowling Ridge. On the northeast slope of the ridge at an altitude of 2,000 to 2,200 feet, only compact brown silt and clayey silt is exposed; this material was not seen in contact with till. In a small exposure adjacent to a logging road 0.55 mile southwest of the northeast corner of sec. 31, the till overlies a brownish-gray sandy silt, which contains scattered stones and a humified zone at the top. Although mineralogical determinations were not made of the fine sediments in secs. 30 and 31, it seems likely that they are at least in part weathered volcanic ash.

Here, as elsewhere, the poorly consolidated silt and clay and scattered stones probably represent a mixture of weathered volcanic ash and of stones that were derived from the underlying till by frost heave during deposition of the ash.

At several localities along the margin of the Vashon drift, the Wingate Hill drift, as mapped, includes glaciolacustrine sediments of Vashon age. These deposits are discussed under Vashon drift (p. 42–43).

In an exposure adjacent to a logging road in the valley of Voight Creek in SW¼SE¼ sec. 29, till, a few feet thick, occurs between fine sediments; the upper sediments probably are of Vashon age. The underlying sediments are laminated silt and sand in which the heavy-mineral fraction consists predominantly of hypersthene and hornblende and a little epidote, magnetite, and ilmenite. These sediments may have been deposited in a proglacial lake of Wingate Hill age that subsequently was overridden by the Wingate Hill glacier.

Stratified drift probably of Wingate Hill age has been recognized at the community of Upper Fairfax. Here at least 15 feet of oxidized sand and pebble to boulder gravel underlies 10 to 15 feet of Carbon River terrace gravel. A similar deeply oxidized cobble to boulder gravel crops out in the east bank of Evans Creek a short distance southwest of Upper Fairfax. Here the oxidized gravel lies under the Evans Creek drift.

The absence of sand and gravel of Wingate Hill age elsewhere in the quadrangle is not understood. In the Carbon River valley, the absence of these deposits might be attributed to subsequent erosion by melt-water streams. In the valley of Voight Creek, however, seemingly there has been little removal of material by stream erosion since the Wingate Hill glaciation. Possibly very little outwash originated from the Wingate Hill glacier owing to cold air temperatures during deglaciation; the glacier then would have disappeared largely through evaporation.

DISTRIBUTION

The Wingate Hill drift mantles nearly all the foothills area above an altitude of 1,600 feet; it extends from the tops of the highest ridges down to the valley floor of Voight Creek and down the valley walls of the Carbon River to the edge of the Evans Creek drift; thus, it has a range in altitude of about 1,000 feet. The drift also underlies broad areas south and east of the Lake Tapps quadrangle, where it likewise mantles topography with a relief of 1,000 feet or more. In the quadrangle, the margin of the drift is determined by erosion and by an overlap of younger drift. Because most of its north edge coincides with the top of a steep north-facing scarp, the drift probably once extended northward beyond its present outcrop area. The west edge of the Wingate Hill drift on Cowling Ridge is poorly defined, and the materials mapped as drift may be weathered bedrock and colluvium in places. Residual mantle that has originated from weathering of volcanic breccia on top of Spar Pole Hill resembles till, but the absence of any rock types other than those that occur in the local bedrock suggests that the mantle is not a glacial deposit. Similar mantle is found on the west slope of Cowling Ridge.

WEATHERING

Two distinguishing features of the Wingate Hill drift are its depth of oxidation and the presence of weathering rinds on stones in the upper part of the drift. Oxidation commonly extends to depths of 10 to 15 feet in areas of low relief, and to a depth of at least 5 feet, even on slopes where erosion probably has removed the upper part of the oxidized zone. In areas where the thickness of the till is 20 feet or less, such as in secs. 30 and 31 east of Cowling Ridge, oxidation commonly extends to the base of the drift. The only extensive outcrop of gray, unoxidized till of Wingate Hill age noted is adjacent to the Fairfax Truck Trail where it crosses the valley of South Fork Gale Creek in sec. 23, where overlying thick fine sediments apparently have protected the till from deep oxidation.

Weathering has resulted in the formation of rinds on stones in the upper few feet of the till, beneath surfaces of low relief. These rinds are from 0.1 to 0.2 inches thick and are so characteristic that the drift has become informally known as the "rind" till. The weathered rind from a cobble of dark-gray andesite or basalt from till in the Wingate Hill on the valley floor of Voight Creek near the south edge of the Lake Tapps quadrangle was determined by X-ray analysis to consist predominantly of noncrystalline iron oxide, and lesser amounts of cristobalite, plagioclase feldspar, potash feldspar, and a trace of quartz.

The surface of the drift is typically of low relief, and drainage is mostly well integrated; morainal topography that might once have been present on the drift no longer exists, largely because the drift is thin and veneers a preexisting surface upon which a well-integrated drainage pattern apparently had developed prior to Wingate Hill time. The nature of the drift surface probably is also a reflection of a substantially longer time of exposure to weathering and erosion than either the Vashon or Evans Creek drifts.

ORIGIN

Till in the Wingate Hill drift probably represents an icecap glaciation of this part of the Cascade Range. This inference is based on the wide vertical distribution and central Cascade provenance of the till. It seems likely that the Lake Tapps quadrangle included the northwest margin of the icecap, but it is not known how far beyond the present outcrops of the drift the glacier might have extended.

In the area immediately east of Mount Rainier National Park, Abbott[4] found evidence that " * * * great sheets of ice moved over parts of the crest of the Cascades at an elevation of at least 6,000 feet." Although Abbott did not assign an age to these ice sheets, possibly they were formed during the Wingate Hill glaciation.

STRATIGRAPHIC RELATIONS AND AGE

The youngest unit recognized beneath the Wingate Hill drift is the Lily Creek formation. Deep weathering and erosion on the Lily Creek formation indicate that deposition of the two units was separated by a time interval much longer than the elapsed time between the Wingate Hill glaciation and the present.

The oldest stratigraphically dated deposit that overlies the Wingate Hill drift is the Evans Creek drift. On the basis of differences in the amount of weathering on these two drift sheets, it seems likely that the Wingate Hill-Evans Creek interval was at least as long as the interval between Evans Creek time and the present.

Certain glacial landforms and weathering features in drift in the Puyallup River valley, 5 miles south of the Lake Tapps quadrangle, have suggested to L. A. Palmer (written communication) that a glacial advance occurred between the Wingate Hill and Evans Creek glaciations. This advance is inferred to have reached a point in the Puyallup River valley about 3 miles farther downstream than the terminal moraine of Evans Creek age in the tributary Mowich River valley.

Evidence of a Carbon valley glacier of post-Wingate Hill, pre-Evans Creek age was not found in the Lake Tapps quadrangle. The drift on the valley walls is is somewhat less weathered than is the Wingate Hill drift beneath flat areas of the adjacent interfluves, but this difference probably can be attributed to the slow removal of weathering products on slopes by erosion.

TILL AND GRAVEL OF PRE-VASHON PIEDMONT GLACIER

A light-olive-gray compact till crops out immediately beneath the Vashon drift in a cutbank on the north side of the White River in the SE¼SE¼ sec. 33, one-half mile northwest of Buckley. This till is distinctive in its high content of subangular stones and its exclusively central Cascade and Mount Rainier provenance. This till almost certainly represents the deposit of a piedmont glacier originating in the Cascade Range.

[4] Abbott, A. T., 1953, The geology of the northwest portion of the Mount Aix quadrangle, Washington: Washington Univ., unpublished Ph.D. dissertation, p. 231.

Pre-Vashon deeply oxidized pebble and cobble gravel that crops out in a scarp at the east edge of the quadrangle in sec. 23 north of Enumclaw is of central Cascade provenance, and it may be outwash related to the till exposed in the White River valley near Buckley.

Although both of these deposits are older than the Vashon glaciation, just how much older they may be is not known. In outcrops in the valley walls of the White River downstream from Buckley, the Salmon Springs drift immediately underlies the Vashon and is of northern provenance. The till and gravel of central Cascade provenance in the vicinity of Buckley and Enumclaw probably were deposited by a glacier that extended into the lowland from the White River valley during the Wingate Hill glaciation.

EVANS CREEK DRIFT

The deposits of an alpine glacier that moved down the valley of the Carbon River about to the present position of Fairfax in an early phase of the Vashon glaciation are here named the Evans Creek drift. The drift is typically exposed in the banks of Evans Creek, in the SE¼NW¼ sec. 35, downstream from the Carbon Glacier Road.

DESCRIPTION

The Evans Creek drift consists of till in the vicinity of Fairfax, and of proglacial sand and gravel that forms a valley train in the Carbon River valley downstream from Fairfax. The till is complexly interbedded with poorly sorted sand and gravel, and the resulting mixture of materials is here referred to as drift complex. At the type locality of the Evans Creek drift (fig. 12), the drift complex contains many boulders as large as 5 feet, and the adjacent stream bed is choked with boulders as large as 12 feet that probably were derived from the drift complex. The drift complex is locally at least 50 feet thick, and it has a gently rolling topography that extends a short distance up each valley wall at the southeastern corner of the quadrangle. This topography is interpreted as morainal, and its presence at the downstream terminus of the drift complex suggests that it represents remnants of a terminal moraine of the valley glacier.

The western (downstream) edge of the drift complex lies between the communities of Fairfax and Upper Fairfax on the south side of the Carbon River. From here downstream, the Evans Creek drift consists of outwash pebble to boulder gravel that forms terraces nearly as far downstream as Carbonado. The surface of these terraces is about 130 feet above the Carbon flood plain near Fairfax and about 230 feet above the river

FIGURE 12.—Exposure of Evans Creek drift in a bank of Evans Creek downstream from the highway in the southeast corner of the Lake Tapps quadrangle. The drift consists of a complex of bouldery till and gravel deposited at or near the terminus of a valley glacier in the Carbon River valley.

in sec. 9, south of Carbonado. As far as a mile downstream from Fairfax, the outwash occurs in proglacial fill terraces in the valley and is at least 100 feet thick, but downstream it typically forms a veneer less than 20 feet thick lying on bedrock straths.

PROVENANCE

Pebbles in the Evans Creek drift are almost entirely of central Cascade provenance (table 5); only 2 percent is of Mount Rainier provenance. This percentage contrasts markedly with that of the present alluvium of the Carbon River at Upper Fairfax, which consists in large part of outwash from the Carbon Glacier, 19 miles upstream. About 30 percent of the pebbles in this alluvium is of Mount Rainier derivation, 15 percent is Snoqualmie granodiorite, and 55 percent consists of rocks from the lower Keechelus and Fifes Peak andesite. This difference in percentage of rock types is believed to be related to the effect of a lower snowline in Evans Creek time than now. Today, the only existing glaciers in the headwaters of the Carbon River are on the slopes of Mount Rainier. Rock material contributed to the Carbon by melt-water streams thus is largely derived from the volcano. Downstream, the outwash gravel becomes diluted with Snoqualmie granodiorite and andesite from the Keechelus andesitic series contributed by tributary streams that drain the Cascade Range.

At present, the zone of heaviest snowfall on Mount Rainier is at an altitude of 8,000 to 10,000 feet (Matthes, 1914, p. 21), and the regional snowline has an altitude of about 9,000 feet (Matthes, 1942, p. 380), several thousand feet higher than the highest areas of the Cascade foothills in the Carbon River drainage basin. In this drainage basin, however, there are at least 25 well-defined cirques with floors at altitudes of 4,300 to 5,500 feet (fig. 13); all are in the Keechelus andesitic series or the Snoqualmie granodiorite. If the present snowline were lowered to the altitude of the cirque floors, a very large increase in the glacier accumulation area

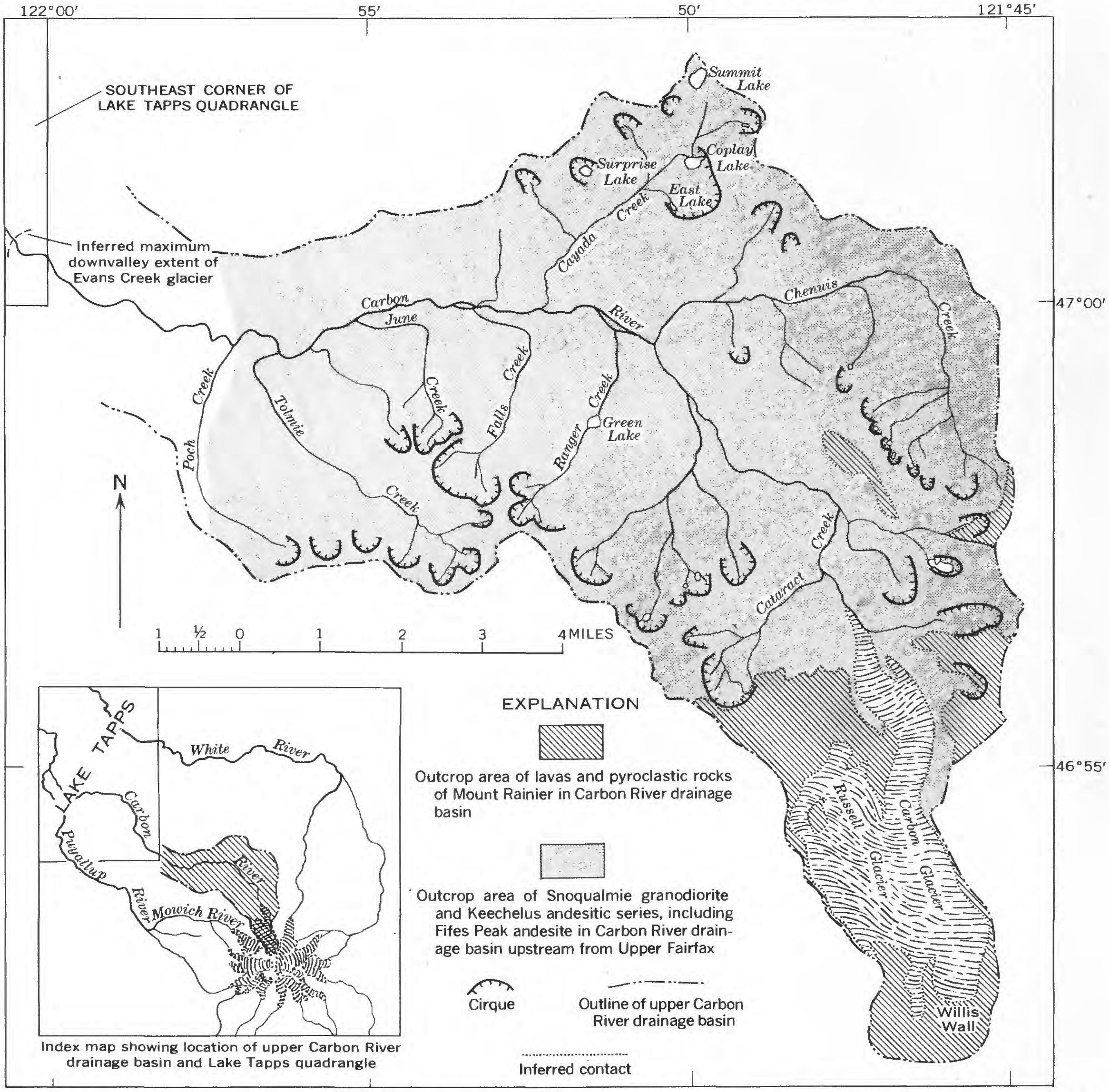

FIGURE 13.—Map of the upper drainage basin of the Carbon River, showing distribution of Mount Rainier volcanic rocks and cirques which probably formed during the Evans Creek glaciation. Distribution of Mount Rainier rocks after an unpublished map by R. S. Fiske, C. A. Hopson, and A. C. Waters.

would result within the Carbon River drainage basin (fig. 13). Because this increased area would lie wholly in rocks other than those of Mount Rainier, the deposits of this broader accumulation area would be expected to consist of sediments principally of central Cascade provenance and only in small part of Mount Rainier provenance.

The relation between altitude of snowline and sources of drift probably explains the predominantly central Cascade provenance of the Evans Creek drift in the Lake Tapps quadrangle. It is assumed, however, that the cirques in the Carbon drainage basin are largely a result of the Evans Creek glaciation. Whereas this has not been proved, the large size of the cirques, the absence of a large number of cirques at other altitudes, and the lack of evidence of long valley glaciers at any time since Evans Creek time suggest that the cirques ranging in altitude from 4,300 to 5,500 feet date from the time when valley glaciers reached their largest extent during an early part of the Vashon glaciation.

STRATIGRAPHIC RELATIONS AND AGE

Several lines of evidence suggest that the Evans Creek and Wingate Hill glaciations were separated by a nonglacial interval of weathering and erosion and that the Evans Creek is not simply a recessional stage of the more widespread Wingate Hill glaciation. The absence of weathering rinds like those of the Wingate Hill drift, on pebbles and cobbles in the surficial few feet of the Evans Creek drift, suggests that the two drifts were separated by an interval at least as long as the elapsed time from Evans Creek deglaciation to the present. Furthermore, there typically is a difference in depth of oxidation of the two drift sheets in comparable topographic positions; for example, at the south edge of the quadrangle, in sec. 35 south of Upper Fairfax, Wingate Hill drift is oxidized to a depth of more than 10 feet, whereas the Evans Creek drift in a nearby outcrop is oxidized to a depth of 4 to 5 feet. The topography of the two drift sheets suggests a difference in time of exposure to erosion; for example, the Evans Creek drift retains constructional topography little modified by erosion; and the Wingate Hill drift in a comparable topographic position is characterized by smoothly graded slopes and erosional topography.

In an outcrop in the east bank of Evans Creek, at the south edge of the quadrangle in the NW¼SW¼ sec. 35, T. 18 N., R. 6 E., 2 to 2.5 feet of silt and peaty silt lies beneath the Evans Creek drift and above oxidized sand and gravel that probably is part of the Wingate Hill drift. The lower part of the silt contains a bed of white pumice granules in a silt matrix. In four samples taken for pollen analysis from the silt bed, pollen density increases from 16 grains per gram at the base to 150 grains at the top. The upper two samples are predominantly *Lycopodium annotinum* spores. According to E. B. Leopold (written communication), this *Lycopodium* species ranges from lowland to alpine environments, but its spores are especially well represented in tundra and alpine sediments, and are generally outnumbered by tree pollen in sediments from forest environments. Tree pollen from the samples compose from 24 to 40 percent of the total pollen content, and the flora is rich in herbaceous types, which further suggests a tundra-type environment. The fact that Englemann spruce is the best-represented tree indicates that the climate at this locality was as cold as that of the uppermost Canadian zone at the time the silt and peaty silt was deposited.

The relation of the Evans Creek drift to the Vashon drift is demonstrated by a mantle of glaciolacustrine sand on outwash and a moraine of Evans Creek age. This sand was deposited in a glacially dammed lake in the Carbon River valley at the maximum of the Vashon glaciation (p. 43). The stratigraphic relation of the sand to the Evans Creek drift is well exposed near the southeastern corner of the quadrangle in an outcrop adjacent to the road leading to Upper Fairfax. Here, in the NE¼NW¼SW¼ sec. 35, the following section is exposed.

	Feet	Inches
8. Silt, dark-yellowish-brown, and disseminated light-yellowish-gray pumice granules	1	2
7. Sand, silt, and clay, light-yellowish-gray; contains scattered pebbles of northern provenance	3	6
6. Sand, yellowish-gray, fine, lenticular		4
5. Silt and fine sand, mottled light-yellowish-gray and dark-yellowish-orange		3
4. Sand, light-olive-gray, medium		5
3. Clay and silt, mottled light-yellowish-gray and dark-yellowish-orange; has bed, 1 in. thick, of coarse sand near middle of unit		11
2. Sand and scattered pebbles, dusky-yellow, medium to very coarse		10
1. Til, light-olive-gray, compact		>15

The fine sediments of this section are chiefly of central Cascade and Mount Rainier provenance and probably represent sedimentation in a glacial lake by the Carbon River. The presence of pebbles of northern provenance, notably fragments of garnet-mica schist, however, demonstrates that the lake was dammed by the Puget lobe.

Samples for pollen analysis were taken from beds 3, 5, and 6; of these, samples from beds 3 and 5 contained no pollen, and in bed 6 the pollen was too sparse to be significant (18 grains per gram).

Although the glaciolacustrine sediments are chiefly sand and silt, at a few localities near Fairfax they contain layers of coarse sand and granule gravel and scattered pebbles, cobbles, and boulders. On the north side of the Carbon River opposite Fairfax, coarse Evans Creek outwash gravel is successively overlain by about 15 feet of sand, 2 to 12 feet of pebble to boulder gravel, and 6 feet of medium sand. Probably only the uppermost sand is of Vashon age and all the underlying sediments are Evans Creek drift, but there is a possibility that the lower sand also is Vashon. If so, the lake at this locality probably was temporarily displaced by deposition of coarse alluvium by the Carbon River. With this possible exception, the predominantly fine glaciolacustrine sediments suggest that at the maximum of the Vashon glaciation the Evans Creek glacier had retreated far up the valley and was not contributing large amounts of coarse outwash to the Carbon River.

This inferred relation is in accord with evidence in the Snoqualmie-Cedar area, about 35 miles northeast of Fairfax along the west front of the Cascade

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Range. Here Mackin (1941, p. 470) found that "local valley glaciers did not occupy the lower parts of these valleys when, at the maximum stand of the Puget Vashon Glacier at their mouths, the valleys were the sites of lacustrine sedimentation." Mackin concluded from this and from other evidence that local valley glaciers were "notably small at the time of maximum extent of the Puget Glacier and that they did not attain large size at any subsequent time." He found that valley glaciers were somewhat larger during an early phase of the Vashon glaciation and tentatively inferred that the time lapse between the maximums of the valley glaciers and the Vashon glacier was short (Mackin, 1941, p. 471–473). The sequence in the Carbon River valley during the Evans Creek and Vashon glaciations is closely similar to that in the Snoqualmie-Cedar area, and it seems likely that Mackin's early Vashon valley-glacier stage is correlative with the Evans Creek glaciation.

VASHON DRIFT

The Vashon drift was deposited by the Puget glacial lobe during the last major glaciation of the Puget Sound lowland. The glacier that deposited this drift originated principally in the coastal mountains of British Columbia as did its predecessors. Along its central part, the glacier extended to a point in Thurston County about 10 miles south of the Lake Tapps quadrangle (fig. 14). In the quadrangle, the Vashon glacier extended to altitudes as high as 1,750 feet along the Cascade foothills, and thus probably was 1,000 to 2,000 feet thick over the rest of the quadrangle to the north.

During the advance and recession of this glacier, two distinctive types of drift were formed: till, deposited at the base of the ice, and stratified drift, deposited by melt water. In the Lake Tapps quadrangle, these two kinds of drift are distributed in large part in two different geographic positions; broad sheets of till are found mainly in the lowland, and stratified drift is most abundant in the lower parts of the Cascade foothills. This general pattern of distribution is caused by the fact that during its maximum extent and early stages of ice recession, the Puget lobe blocked valleys emerging from the Cascade Range and forced their discharge to escape to the southwest along the edge of the ice sheet. Most of the till deposited in this sector thus was reworked by running water. As the glacier margin withdrew northward, melt-water drainage was limited to a few major channels, and large areas of ground moraine were left untouched by stream erosion.

TILL

DESCRIPTION

Till in the Vashon drift is a very compact unsorted and unstratified concretelike mixture of pebbles and cobbles in a matrix of silt and sand; it is gray to within a few feet of the surface. Most of the included stones are of pebble and cobble size; boulders are present but not common. The till ranges in thickness from a few feet to at least 90 feet, but is generally 15 to 30 feet thick in the lowland. In the Cascade foothills it is generally thinner, ranging from 5 to 20 feet. In excavations, 4 to 7 feet deep, for a gas pipeline in sec. 18 northeast of Sumner, till was observed to lie beneath the surface at depths of a few inches to more than 7 feet, and to be overlain by poorly sorted pebble to boulder gravel. This gravel contains lenticular masses of till a few feet to several tens of feet in length and less than 1 to about 3 feet thick. Thin lenses and layers of till have been seen elsewhere in gravel, but in most places the till consists of a single massive layer.

From 75 to 92 percent of the pebbles in the till is of central Cascade derivation (p. 14); nearly all these pebbles seem to have been derived from the Keechelus andesitic series and similar rocks. Only at 1 of the 6 exposures sampled is there a sizable percentage (18 percent) of stones derived from the Snoqualmie granodiorite; this exposure is in a roadcut adjacent to U.S. Highway 410 in sec. 18 west of Enumclaw. At this locality 2 percent of the stones are derived from Mount Rainier; stones of this provenance were not found in the other samples. From 5 to 18 percent of the stones in the till in the lowland part of the quadrangle is of northern derivation. In the foothills, the till commonly contains much material derived from the formations on which it rests. This is most conspicuous in the vicinity of Wilkeson, where the till contains much sandstone reworked from the Puget group.

In most places the till is veneered with 1 to 15 feet of poorly sorted and unstratified pebble and cobble gravel. The thickness of the gravel varies widely within distances of a few hundred feet or less, and its distribution on the till surface suggests that it was deposited as superglacial debris dumped on the till during ablation of the glacier. The contact between the till and overlying gravel typically is very sharp. This gravel is conspicuously different in distribution, thickness, and origin from the various types of proglacial and ice-contact stratified drift in the area; it is not mapped as a separate unit owing to variability in thickness and unpredictability of distribution.

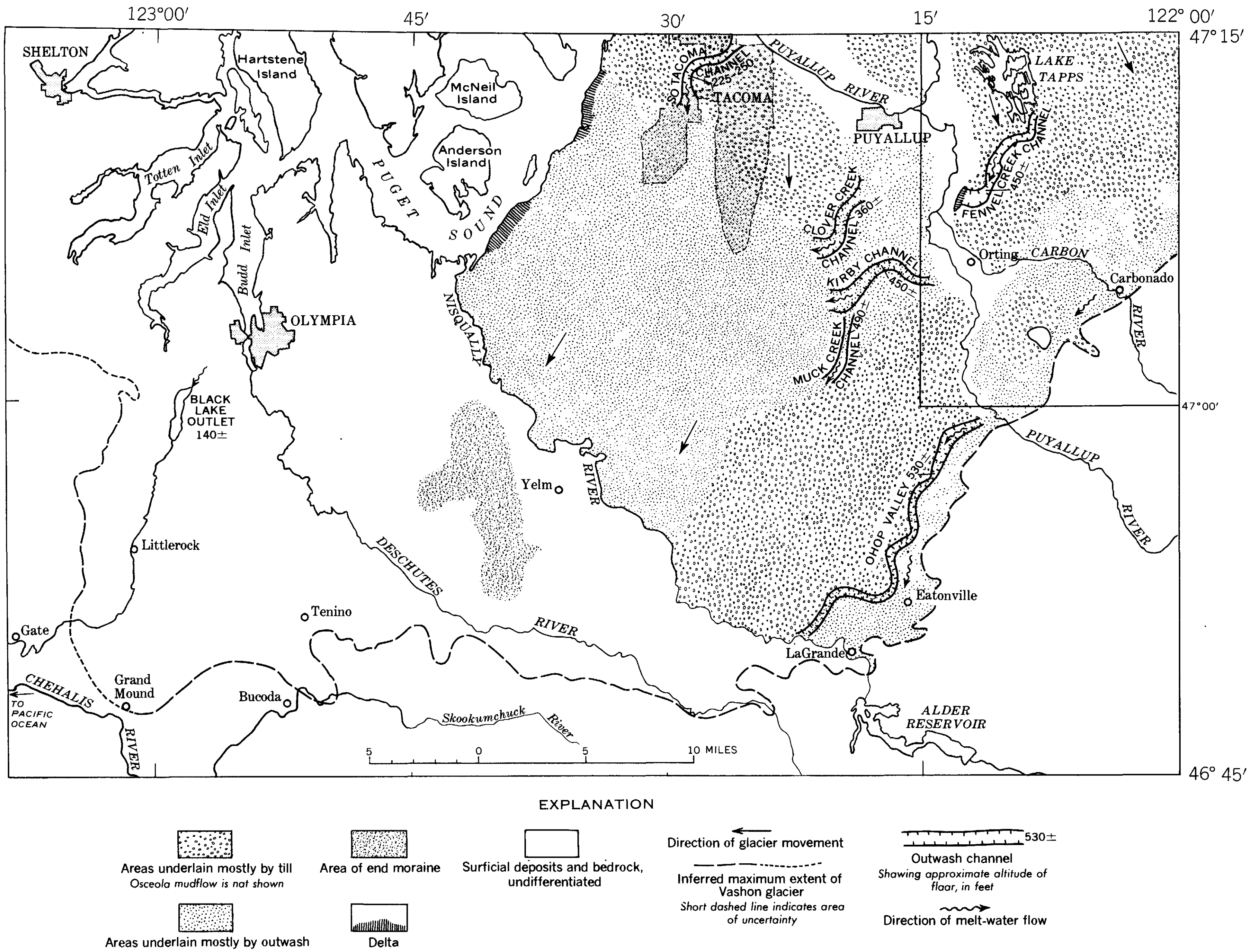

FIGURE 14.—Index map of the southeastern part of the Puget Sound lowland, showing glacial features formed during the Vashon glaciation. The Lake Tapps quadrangle is in the northeast corner. Geologic data on the area outside this quadrangle from Bretz (1913); Mundorff and others (1953); Robinson and Piper (U.S. Geol. Survey unpublished map); Snavely and others (1958); and reconnaissance work by the writer.

DISTRIBUTION

The Puget lobe probably initially left a nearly continuous blanket of till across the entire area up to an altitude of 1,600 to almost 1,800 feet. The till now forms the surface or near-surface deposit across much of the western half of the quadrangle, and crops out in smaller areas within the eastern half. Till probably lies beneath most of the area covered by the Osceola mudflow, although here the till probably is overlain locally by stratified drift. Along the margin of the foothills, till is mostly limited to the tops and sides of bedrock hills, and the intervening depressions are occupied by stratified drift. The southward limit of the till is roughly defined by a scarp, 250 to 500 feet high, that trends southwestward from a point southeast of Sunset Lake to the valley of Voight Creek. The scarp is interrupted by Spar Pole Hill, where till is found up to a maximum altitude of nearly 1,800 feet on the northwestern slope. To the south, the till is found up to an altitude of about 1,600 feet along the west slope of Cowling Ridge. The only major lobation of the till margin occurs in the valley of Voight Creek in secs. 18 and 19 just west of Brooks Hill, where the Puget lobe extended southward up the valley of Voight Creek and left till on the valley floor and on the lower slopes of the valley walls.

TOPOGRAPHY

Owing to its youth, till of Vashon age retains much of its original constructional topography. This topography is of two general types: ground moraine and drumlinized ground moraine. Only along steep valley walls and hillsides has the till surface been appreciably altered by erosion and mass wasting. End moraines are not present in the Vashon drift in this quadrangle, and except for an end moraine in the Yelm area (fig. 14) this absence seems to characterize the drift of the entire Puget lobe (Bretz, 1913). Stillstands of the ice margin at various places can be determined fairly closely in the quadrangle, but these are marked by ice-marginal outwash channels rather than by end moraines.

Ground moraine is characterized by an undulatory surface without a regular pattern or lineation; it generally has a local relief of 10 to 100 feet, although much greater relief is found on the till surface in the foothills where the till veneers bedrock hills of high relief. Areas mapped as ground moraine are immediately underlain by till, locally mantled with a thin veneer of sand and gravel. In a few places, the area mapped as ground moraine includes areas of outwash sand and gravel too small or topographically indistinct to be differentiated.

Much of the ground moraine consists of elliptical mounds of till separated by swales; these mounds are drumlins formed by depositional and erosional processes at the base of the glacier. Individual drumlins range in length from 0.2 mile to nearly 1 mile and in width from 100 yards to 0.2 mile. The most conspicuous area of drumlinized ground moraine in the quadrangle is in the north-central part. The outline of the drumlins here is emphasized by partial submergence of the drift surface, caused east of the White River by the Osceola mudflow, and west of the river by Lake Tapps.

WEATHERING

A brown podzolic soil profile has formed on the till of the Vashon drift, and oxidation commonly extends 2 to 3 feet below the ground surface. In the soil profile most stones are fresh and do not have weathering rinds, but they are commonly coated with a film of iron oxides.

DRIFT BORDER

At its maximum extent in Vashon time, the Puget glacial lobe lay along a southwest-trending line across the southeastern part of the Lake Tapps quadrangle; this line coincides with an escarpment cut into bedrock and the Lily Creek formation (fig. 22). The glacier did not surmount this escarpment except locally; thus, this major topographic feature coincides generally with the boundary between Vashon drift on the northwest and Wingate Hill drift on the south.

The upward limit of Vashon drift on this scarp is difficult to locate accurately, owing, in part, to extensive reworking of older unconsolidated formations and weathered bedrock by the Vashon ice. On the upland in sec. 35 southeast of Wilkeson, within a few hundred yards of this escarpment, drift is found that consists almost wholly of Cascade provenance, but the presence of garnets in the heavy-mineral fraction suggests reworking of Wingate Hill drift by the Vashon glacier. The close resemblance of this drift to Wingate Hill drift, just to the south, indicates that reworking was not extensive and that there was not a large contribution of northern drift. On the northwestern part of Gleason Hill southeast of Carbonado the contact of Vashon drift and Wingate Hill drift is gradational in a zone perhaps 500 to 1,000 feet wide.

In addition to these small variations in the drift margin, small lobes of the Vashon glacier evidently extended into the valleys of the Carbon River and Voight Creek. It is of interest to note, however, that the larger lobe of the two seems to have extended into the smaller valley, that of Voight Creek. The smaller lobe in the Carbon may be only apparent, owing to steeper valley walls there that would have made preservation of till remnants more difficult. If the few outcrops of drift accurately represent the actual size of the lobe, its smallness might be due to calving of the glacier terminus into a proglacial lake in the Carbon Gorge that prevented extensive flowage up the valley. A similar proglacial lake did exist in the valley of Voight Creek, but it seems to have been shallower and possibly was of shorter duration.

Spar Pole Hill forms a northward bend in the trend of the Vashon drift margin. The presence of drift on the northeast side of the hill at nearly 1,600 feet, on the northwest side at about 1,800 feet, and on the south side at about 1,500 feet indicates that the upper slopes and crest of the hill were entirely surrounded by the Puget glacial lobe at its maximum extent.

No evidence was found that any Puget lobe of pre-Vashon age extended higher or reached farther south than the glacier in Vashon time.

ADVANCE STRATIFIED DRIFT

During the advance of the Puget lobe across the Lake Tapps quadrangle, melt-water streams deposited sand and gravel in front of the ice sheet; most of this material was laid down either as proglacial outwash or as deltas and glaciolacustrine sediments deposited in lakes formed in front of the glacier. This stratified drift ranges widely in thickness, owing to the fact that in many areas it filled depressions eroded during the Salmon Springs-Vashon interval. The proglacial gravel is not well exposed because the glacier advanced across it and buried it under a thick mantle of till. Identification of sand and gravel deposited during the advance of the glacier is complicated by the difficulty of interpreting whether a lens or thin sheet of till in gravel represents the main advance or whether it was deposited during glacier recession as a till mudflow. Advance stratified drift may exist at many places where it has been mapped inadvertently as part of the recessional stratified drift.

Advance stratified drift consists principally of sand, pebble and cobble gravel, and scattered boulders, although locally it includes fine laminated sediments and layers of boulder gravel; no intercalated lenses or layers of till have been seen in it.

One of the best exposures of the drift is in cuts adjacent to U.S. Highway 410 on the east wall of the Puyallup Valley west of Bonney Lake in the southern part of sec. 29, where gravel in the Vashon overlies an eroded surface on gravel of Salmon Springs age. In one outcrop, a V-shaped gully at least 20 feet deep in the Salmon Springs drift that drained southwestward is filled with advance gravel of Vashon age. In the next roadcut north of this exposure, the base of the advance gravel is below the road grade, and at the highway curve on the south edge of sec. 29, the gravel is overlain by till of Vashon age. About 50 feet of pebble and cobble gravel is exposed in a roadcut east of the community of Bonney Lake in the SW¼ sec. 33. At the northwest end of this cut, the gravel is overlain by a few feet of till of Vashon age. The advance outwash here probably extends downward at least as far as the valley floor of Fennel Creek, and probably is part of the same body of advance gravel as that exposed along the highway west of Bonney Lake.

The gravel pit in the SE¼ sec. 20, east of Sumner, is in a deposit of deltaic sand and gravel characterized by long sweeping foreset beds that slope westward; the gravel is overlain near the top of the pit by about 18 feet of till belonging to the Vashon. Farther north, in the vicinity of Salmon Springs, Vashon advance gravel crops out continuously for about a mile along the valley wall, where it overlies the eroded surface of the Salmon Springs drift. The till is not seen here in contact with the gravel, but the topographic position of the gravel suggests that it is of advance origin. Many springs issue here from the basal part of the gravel, which is underlain by beds of peat or silt and clay.

The distribution of the advance stratified drift does not suggest a major drainage pattern different from that of the present, although a few minor drainage elements that do not now exist can be inferred. The delta in the wall of the Puyallup Valley east of Sumner suggests that when the valley was ponded by the advancing Puget lobe, a melt-water stream entered the valley from the east at this point. This implies the presence of a stream draining a part of the upland in the vicinity of Lake Tapps at that time. The base of the advance gravel in the vicinity of Salmon Springs is about 200 feet above the present valley floor, so it seems unlikely that this gravel marks the position of a major pre-Vashon valley entering the Puyallup Valley from the east.

Advance sand and gravel, more than 20 feet thick, in sec. 37 (29) west of Osceola in the northeastern part of the quadrangle, may extend downward to the level of the White River flood plain. These deposits indicate the presence here of a pre-Vashon valley cut into the underlying drift, but neither the maximum depth nor trend of this supposed valley is known. Another gravel-filled valley is exposed in cross section in the north wall of the Carbon River valley in the SE¼SE¼ sec. 25, T. 19 N., R. 5 E, where a channel, at least 100 feet deep, cut in Orting drift and filled with advance gravel of Vashon age extends nearly to the altitude of the present Carbon River flood plain.

Fine lacustrine sediments deposited during the advance of the Vashon glacier are exposed in the east side of a gully occupied by Beane Creek in sec. 23 on the south side of Spar Pole Hill, at an altitude of about 1,150 feet. These sediments consist of 10 to 20 feet of laminated silt and sand and a few layers of granule gravel; they are overlain by 3 feet of till of Vashon age.

In the SE¼ sec. 23, till in the Vashon lies upon poorly exposed laminated silt and sand. The lacustrine sediments here, as well as those at Beane Creek, were deposited just before the Puget lobe reached its maximum height and represent local ponding between the glacier margin and the western slope of the foothills. Elsewhere similar sediments are not overlain by till, and evidently these were deposited at the time of maximum extent or during glacier recession; these deposits are discussed under recessional stratified drift.

RECESSIONAL STRATIFIED DRIFT

Sand and gravel deposited during northward retreat of the margin of the Puget lobe is termed recessional stratified drift and is subdivided into two principal groups; deposits formed on or against the glacier are referred to as "ice-contact deposits" and those formed beyond the limits of the glacier are termed "proglacial". In the following discussion of the recessional deposits, each of these groups is further subdivided according to the way in which individual deposits originated.

ICE-CONTACT STRATIFIED DRIFT

KAME AND KAME-FIELD GRAVEL

A deposit of sand and gravel deposited in ice-walled depressions, and ultimately left in an irregular mound or group of mounds on the ground-moraine surface, is here distinguished as a "kame" or "kame field." The only kame field is in the northeast corner of the quadrangle, where it is characterized by a hummocky surface and an irregular outline. The kame-field deposit consists of poorly sorted pebble and cobble gravel and scattered boulders, as large as 8 feet in diameter; bedding is poorly defined and consists mostly of torrential stream foreset beds, dipping in random directions (fig. 15). The southeastern part of the kame field is made up mostly of sand and granule gravel, as are also the two nearby individual kames in the NE¼ sec. 11.

A kame in sec. 14 between Lake Tapps and the White River consists predominantly of pebble and cobble gravel, and the central part of the kame is overlain by several feet of medium to fine sand. The kame consists of two irregular mounds or group of mounds, connected by a low ridge. At the north end, the west side of the kame is steep and probably represents an ice-contact face, whereas the east side of the hill slopes

FIGURE 15.—Kame-field deposit exposed in gravel pit in sec. 2 in northeast corner of the quadrangle. Poor sorting and wide range of sizes in the deposit are typical of ice-contact stratified drift.

gently eastward at about the same angle as that of the bedding of the kame deposit. This part of the kame is interpreted as having originated as a delta built into a lake in an ice-walled depression. The sand on the lower part of the kame, as well as the sand in the small outcrop just east of the kame, probably was deposited in a lake in the same depression simultaneously or a little later than the formation of the delta.

A kame on the west side of sec. 13, southwest of McMillin, consists of a mound of sand and pebble and cobble gravel with deltaic foresetting toward the south. This kame and another kame, 0.2 mile to the south probably were formed while ice still occupied the Puyallup Valley.

The two kames on the valley floor of South Prairie Creek probably are related to the extensive collapsed kame-terrace deposists on the adjacent valley walls, and were formed during melting of a mass of stagnant ice in the valley.

KAME-TERRACE GRAVEL

Kame-terrace gravel consists of stratified drift deposited by melt water between the ice margin and an adjacent sloping ground surface. The highest of these deposits in the Lake Tapps quadrangle were formed when the Puget lobe lay against the northwestern slope of the Cascade foothills, and the lower ones, which are confined within preexisting valleys, were formed between the ice margin and the adjacent valley wall. The north or west sides of many of the kame terraces have irregular outlines that roughly duplicate the shape of the contemporaneous ice front; the term "ice-contact zone" is used here to refer to these parts of the deposits.

The kame-terrace deposits typically are sand and pebble to cobble gravel containing scattered boulders. The gravel is generally well sorted, except in ice-contact zones, where it commonly contains lenses of till and more boulders than do contemporary deposits formed farther from the ice front. The kame-terrace deposits are characterized by cut-and-fill stratification (fig. 16), and, at some horizons, by torrential foreset bedding with prevailing dips toward the west or south. Thickness depends in large part upon the relief of the underlying topography; along the mountain front the deposits range in thickness from a few feet to as much as 100 feet, and within the valleys they are at least 200 feet thick in places.

The surfaces of the kame-terrace deposits take several forms; against the mountain front some kame terraces have ice-contact zones as much as 0.5 mile wide that are characterized by many kettles, kames, and crevasse fillings. These features generally become less abundant in a direction away from the ice margin, and merge into a smooth, sloping surface broken only by a few kettles. This relation is particularly well shown in secs. 19 and 30 west of Wilkeson. Elsewhere, streams flowing on an adjacent, lower kame terrace have trimmed back the ice-contact zone of the higher terrace, leaving a smooth scarp, as in secs. 27 and 34 in the southern part of the quadrangle between Fox and Kings Creeks.

FIGURE 16.—Kame-terrace deposit north of Kings Creek in sec. 34 at the south edge of the quadrangle. Note the coarseness of the deposit and cut-and-fill bedding typical of melt-water stream deposits.

The kame terraces in the valleys of the Puyallup and Carbon Rivers and South Prairie Creek have three forms. Where ice-marginal melt-water streams cut straths on glacial drift or on bedrock in the valley wall, the kame terrace has an almost flat surface, broken by few kettles. In other areas, sand and gravel was deposited on and against blocks of ice that, upon melting, caused extensive collapse of the sand and gravel, as in the kame terrace in secs. 28 and 33 north of the Puyallup Fish Hatchery. Finally, in some places, collapse has been so complete as to destroy the form of the original terrace. The relation of two such kinds of topography can be seen in the deposits of a single kame terrace in secs. 34, 35, and 36 east of Crocker. The gravel in sec. 36 was deposited upon till of Vashon age, Orting drift, and bedrock, and there are only a few kettles in the kame terrace. In sec. 34, however, the gravel was deposited on a mass of ice that remained in the valley of the Carbon River; subsequent melting caused so much subsidence that the terrace form is no longer recognizable. Here, and in the valley of South Prairie Creek, irregular topography formed in this way is markedly similar to that produced by some kinds of landslides.

ICE-CONTACT LACUSTRINE SAND

Sand deposited in lakes enclosed by ice is here differentiated as being of ice-contact origin. The sand is generally distinguished by the fact that it is not now limited to closed depressions, thus the presence of ice is required to explain its areal distribution. The sand commonly shows chaotic bedding and faults of small displacement. These features indicate that the deposit collapsed owing to the melting of supporting ice. The proximity of ice also is suggested by local lenses of till and gravel within the sand.

As much as 30 feet of fine to medium sand overlies hummocky ground moraine in two areas just north of the valley of South Prairie Creek. A pit in the deposit in sec. 11, T. 19 N., R. 5 E., exposes about 20 feet of horizontally bedded sand and scattered pebbles, cobbles, and boulders.

A deposit of lacustrine sand west of Enumclaw in secs. 10 and 15, that was formed in an ice-walled depression on top of ground moraine, is at least 12 feet thick. The deposit contains some granule gravel, and, at the north end of the outcrop, pebble and cobble gravel.

Northeast of Wilkeson, ice-contact glaciolacustrine sand mantles drift topography with a relief of more than 300 feet. Where Spiketon Road is crossed by the transmission line in sec. 22, the sand contains lenses of till, and elsewhere it includes layers of pebble gravel. In secs. 1 and 6 west of Carbonado, as much as 20 feet of sand overlies irregular topography in the ice-contact zone of a kame terrace. The sand here includes layers of gravel and thin lenses of till; typical inclusions are exposed in the walls of a small borrow pit in the NE¼SW¼ sec. 6.

North of Cowling Ridge, in the NE¼ sec. 24, mottled gray and brown silty clay mantles the flat upland area between Bear Creek and the edge of Fox Creek channel. Mineralogic examination indicates that this material is principally volcanic ash and slopewash from Wingate Hill drift, but the presence of scattered pebbles of northern provenance implies that the fine sediments accumulated in a temporary ice-marginal lake when the Puget lobe lay in the Fox Creek channel. This glaciolacustrine sediment is not differentiated from the Wingate Hill drift on the map.

Ice-contact lakes existed within the Puyallup Valley at several places prior to complete withdrawal of the Puget lobe and creation of proglacial Lake Puyallup (p. 43). The highest of the ice-contact lake deposits consists of more than 5 feet of clayey silt and fine sand containing scattered pebbles and cobbles, and is exposed in the NW¼SE¼ sec. 35, west of Cowling Ridge, at an altitude of about 1,550 feet. Heavy minerals in this sediment are mostly hornblende euhedra, and include only a very few garnets; the hornblende probably was drived from a contemporaneous volcanic ash fall.

An ice-contact lake deposit on the west wall of the Puyallup Valley extends from the south edge of the Orting quadrangle northward into sec. 20. This sand mantles the drift surface from the valley floor up to a maximum altitude of about 630 feet. Beneath the transmission line at the west side of sec. 32, these sediments are very fine to medium sand and silt more than 15 feet thick.

Extensive sand deposits flank both sides of the Puyallup Valley near Orting; the deposits on the west valley wall may include some sand deposited in proglacial Lake Puyallup, but the absence of sand at lower altitudes on the terrace just south of the deposit suggests that the sand is mostly of ice-contact origin. The deposit consists of as much as 30 feet of horizontally bedded and locally faulted silt and medium to fine sand containing scattered pebbles, cobbles, and boulders and some layers of granule gravel. The sand on the east valley wall is exposed along a road in sec. 29 that leads to the Carbon River flood plain. As seen in exposures along this road, the glaciolacustrine sand forms a mantle across the top and down the face of a kame-terrace deposit that consists of 220 feet of interbedded gravel and sand. The glaciolacustrine sand and the kame-terrace deposit were described by Willis (1898, p. 158), and tentatively correlated with part or all of his Puyallup sand.

PROGLACIAL LACUSTRINE SAND

Glacial lakes formed in several valleys of the quadrangle when the Puget lobe was at its farthest southward extent, and during recession of the glacier margin. Although these lakes owed their existence to ice dams, their deposits are here distinguished from those of smaller ice-contact lakes formed in depressions surrounded by ice. Proglacial lacustrine sand rarely contains collapse structures, nor does it commonly include lenses of till and coarse gravel as do the ice-contact lacustrine sediments.

Three proglacial lakes were formed; the earliest occupied the valleys of the Carbon River and Voight Creek when these valleys were blocked by the glacier; later, during glacier recession, an even larger lake formed in the Puyallup Valley.

CARBON RIVER VALLEY

When the Puget lobe abutted the foothills, a small ice lobe that projected southward into the Carbon River valley reached nearly as far upstream as the center of sec. 9 south of Carbonado. This ice lobe ponded water upstream beyond the east edge of the quadrangle, and sediments deposited in the lake have been found near the community of Upper Fairfax at a maximum altitude of about 1,520 feet. The sediments are sand and silt composed predominantly of material contributed to the lake by the Carbon River and its tributaries; the sediments thus are mainly of central Cascade and Mount Rainier provenance (p. 35). At many localities, however, stones of northern provenance, notably fragments of garnet-mica schist, occur in the sand. These have been seen as far upstream as the east edge of the quadrangle, a distance of about 4.5 miles from the inferred terminus of the Puget lobe, and must have been transported by ice rafting. The sediments range in thickness from a few feet to 33 feet and commonly mantle terrace deposits of outwash sand and gravel of Evans Creek age.

The spillway of this glacial lake is at the north end of Wingate Hill, where the lake discharged across a bedrock threshold at an altitude of about 1,150 feet. Ice-marginal channels have not been seen along the top of Wingate Hill above this spillway, so it is inferred that the Carbon River initially was ponded to an altitude of about 1,520 feet and the lake then spilled out to the west along the northern scarp of Wingate Hill. The absence of ice-marginal channels on the scarp suggests that the melt water rapidly cut downward and northward through the margin of the glacier until it reached the approximate position of the present bedrock threshold. This threshold at the edge of the Carbon Gorge is bare sandstohe for a width of 100 to 400 feet, probably because the lake water was relatively free of sediment and did not obtain a load of sand and gravel until after crossing the edge of the valley wall.

VOIGHT CREEK VALLEY

The part of the Puget lobe that extended up the valley of Voight Creek produced a temporary lake in which sand, silt, and clay of central Cascade and Mount Rainier provenance were deposited; these sediments mantle the valley floor and sides up to an altitude of about 1,620 feet. They appear to have been derived entirely from the Wingate Hill drift and older formations that crop out in the valley walls; ice-rafted stones of northern provenance were not found. These sediments in exposures adjacent to the logging road along the valley floor of Voight Creek are as much as 5 feet thick. Owing to their thinness and undistinctive mineralogy, and to unusually poor exposures in this area, the lacustrine sediments are not differentiated from the Wingate Hill drift on the map.

GLACIAL LAKE PUYALLUP

The proglacial lake that occupied the Puyallup Valley during retreat of the Vashon glacier was named Lake Puyallup by Bretz (1913, p. 126). This lake gradually lengthened northward, discharging through successively lower spillways as they were uncovered by the retreating ice margin. The sequence of lake levels and discharge routes is discussed on pages 65–67.

Most of the sand along the walls of the Puyallup Valley was deposited in ice-contact lakes, but a deposit in secs. 18 and 19 southeast of McMillin probably was laid down in Lake Puyallup at a time when melt water was discharging into the lake directly from the ice front and via the Fennel Creek channel (pl. 2), and when the lake was draining westward through a spillway west of Orting. The deposit in secs. 18 and 19 consists of two parts: a deeply dissected deposit, whose surface extends from 380 to 420 feet, and a lower practically undissected deposit, whose surface is at about 300 feet. As far as could be determined, the upper deposit consists entirely of silt and fine to medium sand, possibly as much as 120 feet thick. Deep gullies in the sediment are not now occupied by streams, nor are there alluvial fans where the gullies debouch on the surface of the lower sand deposit. The gullies probably were excavated by small streams and mass wasting while the lake dropped from an altitude of about 420 feet to about 300 feet; this erosion might have been greatly intensified by withdrawal of hydrostatic support from the saturated sand of the upper deposit. The sand from the gullies probably was an important source of material for the formation of the lower sand deposit.

The lower deposit consists of fine to medium sand and is as much as 25 feet thick; it mantles the surface and locally extends down across the face of the underlying kame-terrace deposit.

The deposition of these lacustrine sediments was contemporaneous with the building of the sand and gravel delta at the mouth of the Fennel Creek channel, and the thickness of the sand deposits probably is explained by their proximity to the delta.

DELTA

Most of the outwash deposits of deltaic origin in the Lake Tapps quadrangle lie at the mouth of Fennel Creek. The delta here consists of sand and pebble to cobble gravel and scattered boulders; its internal structure is nowhere well exposed, but, by analogy with other deltas of this kind, probably consists of foreset beds dipping about 20°W. There are three distinct flat surfaces in the delta at altitudes of about 460 feet, 400 feet and 360 feet. Because the upper surface of a delta closely approximates the level of the lake into which it is built, these three surfaces mark three successive levels of glacial Lake Puyallup, controlled by the altitudes of the lowest available spillways during the life of the lake. Leading to each of the delta surfaces is a valley train in the valley of Fennel Creek that headed in the Puget lobe some miles to the northeast. The extensive sand and gravel deposit north of Fennel Creek is deeply kettled, particularly on its northern side, and is probably a partly collapsed kame-terrace deposit, formed contemporaneously with the 400-foot delta surface.

PROGLACIAL MELT-WATER STREAM DEPOSITS

Proglacial melt-water stream deposits consist of sand and gravel laid down in the form of valley trains, outwash plains, and channel deposits in spillways of glacial lakes. Each of these deposits is distinguished by the fact that it was formed beyond the glacier margin and as a result is, on the whole, better sorted than are deposits of ice-contact origin. Moreover, the surface of proglacial deposits typically is smooth, unbroken by the kettles and kames that distinguish ice-contact deposits. Owing to the nature of the topography in the Lake Tapps quadrangle, however, deglaciation resulted mostly in the accumulation of ice-contact stratified drift, rather than in the formation of extensive proglacial sand and gravel deposits.

The longest valley-train deposits in the area are those in the valley of Fennel Creek; when they were laid down, the ice margin probably was a short distance north of Connells Prairie. Valley-train deposits are found at several heights above the floor of this valley, the highest being preserved in secs. 4, 33, and 34 in the vicinity of U.S. Highway 410. This deposit consists mostly of sand and pebble to boulder gravel at least 20 feet thick, although a strip along the western part of the deposit in the vicinity of the highway consists of medium sand at least 20 feet thick. The lowest valley train is represented by a remnant near the center of sec. 8 on the south side of Fennel Creek. This deposit consists of pebble and cobble gravel and sand, and it is about 55 feet thick. It rests on a stream-cut surface on the Puyallup formation.

Most valley-train deposits in the northeastern part of the quadrangle are mantled with Osceola mudflow. In sec. 7 near the northwest corner of the quadrangle there are remnants of a valley train that subsequently was cut into by later melt water, leaving the earlier deposits as a terrace. The channel here is floored with mudflow, but presumably it overlies sand and gravel of the later melt-water stream.

Another valley train lies within a channel that trends southwestward from sec. 18 southeast of South Prairie to the Carbon River valley in secs. 25 and 26 east of Crocker. The channel floor hangs in relation to modern valleys at both ends. At the north end of the channel, the valley-train deposit is at least 50 feet thick, and at its south end, about 200 feet thick.

During and immediately after the maximum stand of the Puget lobe, melt water flowed through a deep, narrow channel cut into bedrock southeast of Spar Pole Hill; this channel is now occupied by Fox Creek in part and will be referred to as the Fox Creek channel. Two kame-terrace deposits lead into the mouth of the channel at its northeastern end, and there are other kame-terrace deposits at the southwestern end. Gravel deposits within the channel are mostly veneers, a few feet thick, of pebble to boulder gravel, with individual boulders, as large as 15 feet in diameter, resting on scoured bedrock surfaces. The thickest deposit of gravel in the channel is in the NW¼ sec. 24 southeast of Spar Pole Hill, and pebble and cobble gravel is exposed in pits a short distance northwest of road junction 1137. The gravel is overlain by earthflow material except where exposed in excavations.

The floor of the Fox Creek channel probably is underlain by gravel deposits at most places, but these are mantled by alluvium and colluvium of Recent age.

An extensive mass of proglacial sand and gravel lies beneath a broad west-trending depression west of Orting (pl. 1). This outwash between an altitude of about 640 feet at the south and 500 feet at the north probably was deposited by melt water originating from an ice lobe in the Puyallup Valley, although ice probably still occupied the northern part of the depression while gravel in the higher southern part was being deposited. The outwash consists mostly of sand and pebble to cobble gravel; its maximum exposed thickness is only 10 feet adjacent to a trail in the SW¼ sec. 36 but, locally, probably is considerably greater. At the north side of the broad depression there is a narrower, deeper channel whose floor is at about 445 feet. The deposit in this channel consists of sand and pebble gravel of undetermined thickness. This channel was cut and the outwash deposited by overflow from glacial Lake Puyallup when the highest delta surface was being built at the mouth of Fennel Creek. The channel follows a winding course for about 7 miles to the west of the quadrangle and is truncated in the vicinity of the community of Frederickson by a later and lower discharge channel.

The largest outwash plain of the area lies on the upland west of the Puyallup Valley (pl. 1). At and beyond the west edge of the quadrangle, the plain is a broad, gently west-sloping surface broken only by a few kettles and underlain by pebble and cobble gravel. In a belt adjacent to the edge of the Puyallup Valley the plain is extensively kettled, the westward slope increases, the surface is dotted with large boulders, and, in a zone immediately adjacent to the valley wall, the plain grades eastward into very rough kame-and-kettle topography. These relations imply that while the plain was being built the upland to the west was free of ice, but a remnant of the glacier still occupied part of the Puyallup Valley. Melt water from this remnant must have built the outwash plain just prior to the cutting of the narrow channel west of Orting by overflow of Lake Puyallup.

TERRACE GRAVEL ALONG CARBON RIVER

DESCRIPTION

Upstream from Carbonado the Carbon River valley contains terrace deposits of gravel. Most of these deposits consist of 5 to 40 feet of cobble and boulder gravel that overlies a strath cut on bedrock or older drift.

The terrace deposit farthest upstream in the quadrangle occurs on the south side of the valley at Upper Fairfax, where it consists of cobble and boulder gravel, 10 to 15 feet thick. The top of the terrace deposit is about 50 feet higher than the adjacent flood plain. This deposit rests directly on an oxidized sand and pebble to boulder gravel of Wingate Hill age. The next terrace remnant downstream is on the north side of the valley opposite Fairfax. This deposit consists of cobble and boulder gravel that overlies sandstone about 10 feet above the flood plain; the top of the terrace is about 50 feet above the flood plain. Additional small remnants of gravel, less than 20 feet thick, veneer sandstone straths on both sides of the valley in secs. 21 and 22. Downstream from Fairfax Bridge, the best-preserved terrace is at the north edge of sec. 16; the top of this terrace is 150 to 175 feet above the bottom of the Carbon Gorge, and the underlying deposit consists of 20 to 25 feet of poorly sorted boulder and cobble gravel. A pebble count of this material shows about 75 percent central Cascade rock types and 25 percent Mount Rainier rock types (table 5).

ORIGIN

Terrace gravel in the Carbon River valley underlies paired terraces that form a smoothly sloping longitudinal profile in the valley south of Carbonado. This longitudinal profile apparently represents a distinct interruption in the sequence of downcutting in the valley. The profile has a lower gradient than does the present valley floor, but the gravel is substantially coarser than the recent alluvium. This evidence and the thickening of the gravel upstream suggest the possibility that the gravel represents outwash of a valley glacier that terminated upstream from the Lake Tapps quadrangle.

STRATIGRAPHIC RELATIONS AND AGE

Terrace gravel in the Carbon River valley is not mantled with glaciolacustrine sediments of Vashon age, as is the adjacent outwash of Evans Creek age; the terrace gravel thus is younger than the maximum of the Vashon glaciation. The base of the terrace gravel is as much as 50 feet below the top of the outwash of Evans Creek age, indicating some downcutting in the valley between the Evans Creek maximum and deposition of the terrace gravel. Only a small amount of this downcutting occurred in rock. Downstream from Fairfax Bridge, the gravel is preserved on narrow bedrock straths adjacent to an inner gorge, 200 to 300 feet deep, cut in bedrock. It is inferred that this 200 feet or so of downcutting represents erosion after deposition of the terrace gravel, but it is possible that the inner gorge had been cut previously and was simply re-excavated.

The terrace gravel probably represents outwash of late Vashon age derived from glaciers in the headwaters of the Carbon River, graded to an ice-marginal channel at the front of the retreating Puget lobe. Possibly this gravel was deposited during a retreatal stand of the Puget lobe, as indicated by the Sallal moraine east of Seattle (Mackin, 1941), and by an end moraine in the Yelm area (fig. 14, this report; Mundorff, Weigle, and Holmberg, 1953), both of which postdate the maximum advance of the glacier in Vashon time.

OSCEOLA MUDFLOW

The Osceola mudflow was originally named Osceola till by Willis (1898) and was interpreted as the deposit of a piedmont glacier that originated in the Cascade Range east of the Lake Tapps quadrangle. Willis (1898, p. 143) inferred from its topographic relation to drumlins northwest of Enumclaw that the Osceola is overlain by Vashon drift, but that the two drifts represent only one episode of glaciation. He suggested that the piedmont ice reached the area before the Vashon ice, but that eventually the two ice masses merged.

A study of the Osceola by the writer established that it overlies and is separated from the Vashon drift by a soil profile. The distribution and lithology of the Osceola indicate that it was deposited as a mudflow of volcanic origin, and lateral tracing up the valley of the White River established its source on the northeast side of Mount Rainier (Crandell and Waldron, 1956).

DESCRIPTION

The Osceola mudflow is an unsorted and unstratified mixture of subround to subangular stones in a purplish-gray plastic clayey-sand matrix. The lower part of the deposit typically contains abundant cobbles and boulders (fig. 17), whereas stones in the upper part are fewer in number and generally include only pebbles and cobbles.

FIGURE 17.—Basal part of the Osceola mudflow in a gully in sec. 29 west of Osceola. Wood fragments are indicated by arrow. Note lack of bedding and sorting and large size of stones in the deposit. Pick at right gives the scale.

Very large boulders are widely scattered on the surface of the mudflow; they are all of Mount Rainier provenance and presumably were transported to the lowland by the mudflow. The largest is a 30- by 40-foot block of breccia whose top stands 20 feet above the mudflow surface in the SW¼ sec. 18, T. 20 N., R. 6 E. Some boulders have disintegrated into piles of angular rubble, probably because of frost action. One such pile in the SW¼ sec. 11, T. 20 N., R. 6 E., has dimensions of 20 by 20 feet and extends 15 feet above the mudflow surface.

Stones in the mudflow are principally of central Cascade and Mount Rainier provenance; a few consist of Snoqualmie granodiorite. The proportion of the several rock types as determined by counting a total of 900 pebbles, collected from 10 localities in the lowland, is as follows:

	Percent
Lower Keechelus andesitic series, Fifes Peak andesite, and related intrusive rocks	60
Mount Rainier rocks	36
Snoqualmie granodiorite	4

In the sand-size material of the matrix, rock fragments, glass, plagioclase feldspar, and a little quartz and biotite occur in the light fraction, and hypersthene makes up 95 percent of the heavy fraction. X-ray analysis shows that the silt fraction consists mostly of plagioclase but includes a little montmorillonite, alpha cristobalite, and a trace of quartz. The clay fraction is predominantly montmorillonite, small amounts of plagioclase and alpha cristobalite, and a trace of kaolinite.

Wood fragments are very abundant in the mudflow; they range from logs, several feet in diameter and at least 10 feet long, to macerated vegetal matter. Most of the wood fragments are fresh, although a few are decayed or are partly carbonized. No stumps or roots in the position of growth have been seen at the base of the mudflow.

In the northeast corner of SE¼SW¼ sec. 11 in the northeast part of the quadrangle, a hard dark-brown layer, as much as 2 feet thick, occurs at the surface of the mudflow. This crust appears to consist of an aggregate of fused and cemented pellets; X-ray analysis indicates that it consists of amorphous iron oxides. A similar layer—1 to 5 inches thick, at a depth of 4 to 14 inches, in the Osceola just south of Printz Basin—is described as hardpan by Anderson, Ness, and Anderson (1955, p. 27).

THICKNESS AND VOLUME

The observed thickness of the Osceola mudflow in the quadrangle ranges from 75 feet to a featheredge. Between the east edge of the quadrangle and Osceola a thickness of 50 feet or more is exposed in the valley walls of the White River; farther downstream, the mudflow is generally less than 35 feet thick and is of variable thickness, owing to irregularities in the underlying drift surface. Its average thickness probably is not less than 20 feet.

In the lowland west of the mountain front the reconstructed area of the mudflow is about 65 square miles, including the area now occupied by the White River valley, but not including any part of the Puyallup River or Green River valleys. If an average thickness of 20 feet is assumed, the original volume of the mudflow in the lowland alone would be about 1.3 billion cubic yards.

DISTRIBUTION, AND SURFACE FEATURES

The main body of the Osceola mudflow forms a broad plain that extends from the valley of South Prairie Creek northward to the Green River (figs. 18, 19). This plain is bounded for the most part by low hills of glacial drift and also is broken by knobs and ridges of drift. Long lobes of the mudflow extend several miles beyond the main body. The most prominent of these are in the valleys of South Prairie Creek and Fennel Creek. The lobe in the South Prairie Creek valley was fed mainly through the gap between hills of bedrock in sec. 11 southeast of Buckley, supplemented by material coming into the valley in at least three other localities (pl. 1). The lobe once extended entirely across the valley floor of South Prairie Creek, at least down to its confluence with the Carbon River, but has been extensively removed by erosion or buried by younger alluvium.

FIGURE 18.—Aerial view of the Osceola mudflow plain from near Buckley. The White River valley is shown in the foreground and also crossing the middle ground from left to right. Note the smoothness of the mudflow surface and lack of stream dissection even adjacent to the White River. Exposures in the wall of the White River valley show mudflow overlying Vashon drift.

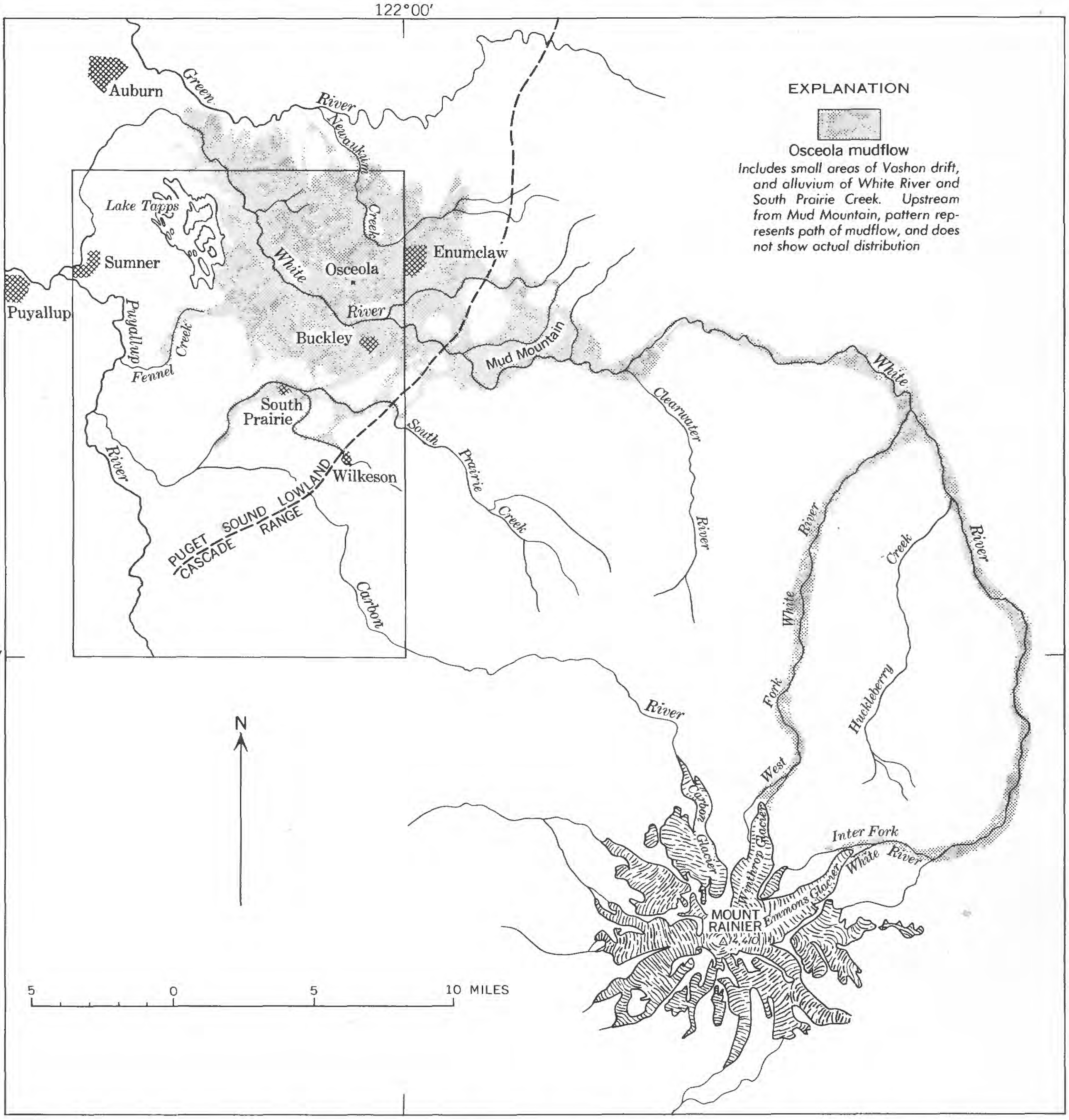

FIGURE 19.—General-distribution map of the Osceola mudflow, showing location of the Lake Tapps quadrangle. After Crandell and Waldron (1956).

The mudflow lobe in the valley of Fennel Creek occupies the floor of a Vashon melt-water channel down to Victor Falls. No mudflow was found on the floor of Fennel Creek below Victor Falls, but a large mass is inferred to have flowed down this deep and narrow valley and to have spread on the Puyallup Valley floor. This inference is based on several small outcrops of the mudflow in banks of the Puyallup River, just upstream and downstream from the crossing of State Route 5E north of Alderton. These exposures are isolated; a search of the flood plain north and south of Sumner failed to reveal any additional outcrops of the deposit. No large mass of the mudflow is known to have reached the floor of the Duwamish Valley north of Sumner via the Green River (D. R. Mullineaux, oral communication) and the only possible alternative source of the deposit north of Alderton is the lobe that flowed down South Prairie Creek. The possibility that this lobe was the source of the mudflow on the Puyallup Valley floor cannot be disproved, but it seems less likely as a source than does Fennel Creek.

The mudflow lobe in the valley of Fennel Creek has not been dissected by stream erosion, because the creek has a small drainage area and a small discharge. The surface of the deposit in this lobe has a gradient of about 24 feet per mile.

Mud flowing through the gap in sec. 11 southeast of Buckley was restricted by the steep-sided and narrow strike valley in sandstone just east of Burnett. Owing to this constriction, and also to the fact that this strike valley makes a right-angle turn to the north and thus forms a further impediment to flowage, the mudflow was ponded here to a depth of 150 to 200 feet. While ponded, a lobe spilled out south of Burnett along a melt-water channel and reached the valley of Wilkeson Creek. From here, it flowed down Wilkeson Creek and rejoined the main body of the mudflow, but part of the mudflow backed up Wilkeson Creek valley to the town of Wilkeson where it apparently formed a low dam in the SE¼ sec. 28. Peat deposits have accumulated in the resulting shallow basin in the melt-water channel east of Wilkeson.

The surface of the Osceola mudflow in the vicinity of Buckley and Enumclaw is remarkably flat over broad areas, although there are minor swells and swales and some larger topographic features on its surface. These surface features probably are related to irregularities on the underlying Vashon drift. Broad expanses of the mudflow have a local relief of less than 5 feet, and its surface has a general northwestward gradient of 25 to 40 feet per mile. Most areas of the mudflow are very poorly drained, owing to its fine-grained, nearly impermeable matrix and to its nearly flat upper surface; shallow ditches have been excavated in many areas in order to improve surface drainage.

Typically the mudflow abuts but does not rise appreciably on the sides of hills of glacial drift and bedrock; however, low drumlins of till adjacent to the White River valley are partly or wholly covered by a mantle of mudflow. This mantle is inferred to be generally less than 10 feet thick, and it could have originated from mudflow carried across the top of the drumlin by momentum or by the lowering of a once-higher mudflow surface while the mud was still fluid.

AGE

In much of the Lake Tapps quadrangle the Osceola mudflow overlies Vashon drift that typically has a brown podzolic soil profile at its top. At one locality, in the SE¼ sec. 11, T. 20 N., R. 5 E., the mudflow rests on peat and lacustrine or bog sediments that overlie till of Vashon age (fig. 20). Pollen analysis indicates that this peat was deposited during the cool and moist climate of early postglacial time, and thus the peat apparently represents a bog that had been filled long before the mudflow covered it.

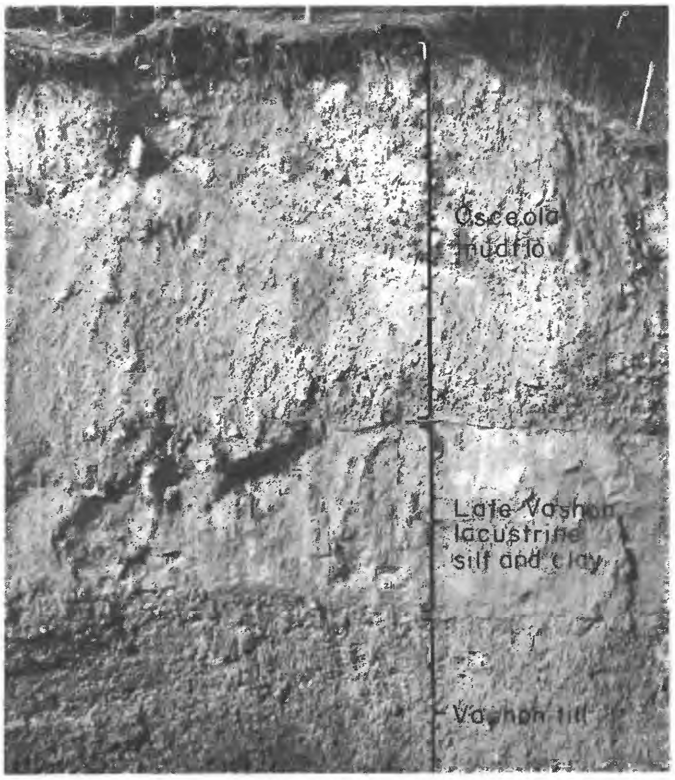

FIGURE 20.—Osceola mudflow, about 35 feet thick, overlying Vashon drift in the side of a gully in the SE¼ sec 11 east of Lake Tapps. The gully was cut by water from a drainage ditch. A peat bed, 2 to 3 inches thick, at the top of the silt and clay has not been appreciably eroded by the mudflow.

Three samples of wood from the Osceola mudflow have been analyzed for their radiocarbon age. One was from an undecayed log in the vicinity of Mud Mountain Dam, about 4 miles east of Buckley; it has a radiocarbon age of 4,800 ±300 years (L–233A [4]). A sample from a partly decayed log in a roadcut of U.S. Highway 410 through the mudflow just southwest of Boise has an age of 4,950 ±300 years (L–223B [5]). A third wood sample, taken from a log embedded in the deposit on the northeast bank of the Puyallup River in the SE¼ sec. 25, T. 20 N., R. 4 E., has an age of 4,700±250 years (W–564).

[4] Radiocarbon age determination by J. L. Kulp, Lamont Geological Observatory, Columbia University.

ORIGIN

The Osceola mudflow has been traced up the valleys of the White River and its tributary, West Fork, to the northeast side of Mount Rainier (Crandell and Waldron, 1956), on whose sides the deposit has been found up to an altitude of nearly 10,000 feet (fig. 19). Consideration of available space and known distribution of the deposit on the sides of the volcano suggests that the mudflow was not derived principally by large-scale sliding or flowage of a deeply weathered mantle of pyroclastics from the flanks of the mountain. The presence of fresh volcanic glass within the mudflow suggests that the montmorillonite was not formed in place from alteration of glass after the mudflow came to rest; the only available source of the large quantity of clay found in the mudflow seems to be within the volcano. The montmorillonite probably was formed by long-continued steaming of wallrock along old vents and fissures within the volcano and may have been ejected along with fragments of unaltered wallrock by a phreatic explosion or by a series of explosions. As soon as this material settled on the flanks of Rainier and on the glaciers, it probably started to flow downslope as near-fluid masses. Moisture content of the mud may have been provided by water vapor associated with the eruption, melting of glacier ice and snow, rainfall, or by a crater lake.

TERRACE ALLUVIUM ALONG WHITE RIVER

Terraces along the White River range from 20 to 100 feet in height above the flood plain, and are underlain by fine and coarse alluvium deposited by the White River shortly after the Osceola mudflow came to rest. The terrace alluvium is 15 to 30 feet thick and generally consists of 5 to 15 feet of medium to very coarse sand underlain by 10 to 15 feet of pebble to boulder gravel. In some terraces the entire deposit is poorly sorted pebble, cobble, and boulder gravel.

Distribution of rock types in sand and gravel of the terrace alluvium closely resembles that of the Osceola mudflow, from which the alluvium was largely derived.

Most of the terraces occur singly, but in a few places they form steps along the valley wall separated by scarps 10 to 40 feet high. The most conspicuous flight of terraces is in the large re-entrant in the southwest valley wall of the White River, about 2 miles northwest of Buckley.

In most places the terrace alluvium rests on straths cut into the Osceola mudflow, although at a few places the alluvium overlies Vashon and older drift. The terraces are unpaired and the alluvium represents veneers left on narrow straths formed by lateral swinging by the White River as it cut downward through the Osceola mudflow.

ELECTRON MUDFLOW

At least 13 square miles of the floor of the Puyallup Valley is underlain by a volcanic mudflow, younger than the Osceola, that originated at Mount Rainier. This deposit is here named the Electron mudflow after exposures in the south bank of the Puyallup River in the SW¼SW¼ sec. 32, T. 18 N., R. 5 E., near the community of Electron, just south of the south edge of the quadrangle.

DESCRIPTION

The Electron mudflow is an unsorted mixture of subangular rock fragments in a matrix of purplish-gray clayey sand. The deposit decreases in grain-size range from south to north along the Puyallup Valley: at the south edge of the quadrangle, boulders as large as 2 feet in diameter are common; in an exposure at the confluence of the Puyallup and Carbon Rivers, the maximum dimension of stones in the deposit is about 1 foot; and at Gardella Road near the northermost extent of the deposit, the mudflow consists of a few inches of clayey sand and granules. A few very large boulders are scattered on the mudflow plain in the vicinity of Orting. The largest boulder seen is in a field about 200 yards east of State Highway 5E in the northwest corner sec. 9 south of Orting; its maximum observable dimension is about 35 feet.

In the pebble-size fraction, about 60 percent of the stones in the mudflow consists of rock types derived from the lower Keechelus andesitic series and Fifes Peak andesite and about 40 percent consists of rocks of Mount Rainier provenance. The most distinctive rock found in the mudflow is a black scoriaceous hypersthene andesite, containing some boulders as large as 5 feet in diameter. The largest boulders in the deposit, however, are of a reddish-brown breccia of Mount Rainier provenance.

In the heavy-mineral fraction of the sand-size material, hypersthene ranges from 80 to 90 percent and the remainder consists mostly of other pyroxenes. The light fraction in the sand-size material consists of rock fragments, volcanic glass, quartz, and plagioclase feldspar with an approximate composition of labradorite. The silt-size fraction consists principally of plagioclase feldspar with some alpha cristobalite and a trace of quartz. The clay-size fraction consists mainly of montmorillonite, lesser amounts of plagioclase feldspar and alpha cristobalite, and a trace of kaolinite.

Wood fragments are found in the mudflow but are not as abundant as in the Osceola mudflow; most of the fragments are splinters, although a few branches several feet in length and as much as 3 inches in diameter have been found.

THICKNESS

The Electron mudflow ranges in thickness from more than 26 feet to a featheredge. The deposit rests on the surface of a former flood plain of the Puyallup River, so it seems likely that the thickness of the deposit varies considerably from place to place, depending on the relief of the buried flood-plain surface.

The maximum known thickness of the mudflow occurs upstream from a constriction in the Puyallup River valley in sec. 17; a power auger penetrated 26 feet of mudflow adjacent to McDonald Road, about 100 yards west of its junction with State Highway 5E, before it was stopped by a large boulder. The Electron mudflow forms an embankment just south of the quadrangle that dammed Ohop Creek to produce Lake Kapowsin. The maximum known depth of this lake is about 30 feet, so the mudflow in the embankment probably is at least 30 feet thick. Nowhere north of the valley constriction just mentioned is the deposit more than 16 feet thick, although a thickness of 15 or 16 feet is typical in the valley south of McMillin. In the vicinity of Alderton the mudflow is nowhere known to be more than 9 feet thick, and, in many places, particularly at the margins of the deposit, it is less than 1 foot thick.

The greater thickness of the deposit upstream from the constriction in the Puyallup valley is attributed to ponding caused by restricted flow. This phenomenon has been noted in the Osceola mudflow at several localities (Crandell and Waldron, 1956, and p. 49 of this report).

The gradient of the Electron mudflow decreases from about 68 feet per mile near the south edge of the quadrangle to about 34 feet per mile in the vicinity of Orting, and the gradient is only 16 feet per mile between McMillin and Alderton. The surface of the mudflow south of the confluence of the Puyallup and Carbon Rivers is slightly convex, and streams on the valley floor tend to follow the margins of the mudflow owing to this convexity.

AGE AND ORIGIN

The Electron mudflow overlies Puyallup and Carbon River alluvium throughout the Puyallup Valley and is overlain only by younger alluvium. The underlying sediments, penetrated in exploratory power-auger holes, range from sand to pebble and cobble gravel. In a streambank at the confluence of the Puyallup and Carbon Rivers, the following section is exposed.

Surface of flood plain.	Feet	Inches
4. Sand, gray, fine	6	3
3. Mudflow, brownish-gray; contains subangular pebbles and cobbles in clayey sand matrix; has faint purplish cast; mottled with light-brown iron ixides	6	6
2. Sand, gray, fine to medium	5	0
1. Gravel and sand to river level	4	0

The relation of the Electron mudflow to the Osceola mudflow is established in scattered exposures along the south bank of the Puyallup River north of Alderton (pl. 1). Here the top of the Osceola is 2 to 3 feet above low-water stage of the Puyallup River, and it is overlain by at least 8 feet of pebble and cobble gravel. The northernmost part of the Electron mudflow, on Gardella Road (pl. 1), lies in a channel cut into the surface of the present flood plain and the base of the mudflow is about 15 feet above the low-water stage of the Puyallup River. At this locality, a power-auger penetrated the mudflow and reached pebble and cobble gravel that stopped the auger. The two mudflows cannot be seen in stratigraphic superposition because of a blanket of riprap along the critical area of the streambank.

Two age determinations were made of wood from the Electron mudflow in the U.S. Geological Survey laboratories. One sample was taken from a log exposed in the side of a drainage ditch in the southwest corner of SE¼NW¼ sec. 4, T. 18 N., R. 5 E. This sample (W–407) has an age of 135 years. This age is inconsistent with the minimum age of the deposit inferred from annual rings of tree stumps on its surface, and it seems likely that the sample was not in place. A second wood sample was obtained from an outcrop in the south bank of the Puyallup River near Electron (in the southeast corner of sec. 32, T. 18 N., R. 5 E.). This sample (W–565) has a radiocarbon age of 530±200 years. This age is consistent with the maximum age of vegetation on the mudflow surface.

South of the quadrangle, at the confluence of the Puyallup and Mowich Rivers, another mudflow is exposed that superficially resembles the Electron mudflow; the mudflow at the confluence of the two rivers, however, contains no black scoria. Furthermore, a log taken from it was determined to have a radiocarbon age of 2,170±200 years (W–566). This mudflow has not been recognized in the Lake Tapps quadrangle.

The source of the Electron mudflow has not been determined, although it is presumed to have originated at Mount Rainier. There is, as yet, no independent evidence of the type of volcanic activity that caused the Electron mudflow.

LACUSTRINE DEPOSITS

Depressions in the Vashon drift, Osceola mudflow, and alluvium locally contain lacustrine deposits made up of peat and mineral sediments. The peat is mostly fibrous and ranges in thickness from about 1 foot to at least 14 feet; the mineral sediments consist of silt, sand, and clay, 1 foot to at least 8 feet thick. A layer of volcanic ash about 1 inch thick is found in the peat bogs on the Vashon drift. In the bog in sec. 5 northwest of Lake Tapps, the ash layer was reached by boring at depths of 4.5 to 5 feet; in the bog fringing Rhode Lake, at a depth of 5 to 7 feet; and in a small bog (not shown on the geologic map) adjacent to the northwest side of Bonney Lake, at a depth of 13 feet. Radiocarbon age of peat just below this ash layer in bogs in the Puget Sound lowland ranges from 5,390±60 (Y–313) to 7,000 ±200 (L–269B) years (Deevey, Gralenski, and Hoffren, 1959).

Lacustrine sediments on the Vashon drift are found mostly in depressions on ground moraine. Some of these depressions are still occupied by small lakes such as Morgan Lake, Rhode Lake, and Orting Lake, and the peat and mineral sediments fringe the lake margin and underlie the lake. Other depressions have been filled to the level of the local water table with organic and inorganic sediments, and standing water is present only during periods of heavy precipitation. Examples of such depresssions are the two small bogs northwest of Lake Tapps, and the three deposits north of Morgan Lake. These depressions are partly filled with peat, silt, sand, and clay. Deposits in the western and middle depressions consist of 1 foot to at least 7 feet of peat overlying clay and silt; the eastern depression, however, contains only clay, silt, and sand. Where peat and mineral sediments are thin or occur in very narrow bands along margins of lakes as at Sunset, Orting, and Bonney Lakes, the deposits are not shown on the geologic map.

The thickest peat deposit in the area was found at the northeastern side of Rhode Lake, where 14 feet of peat on top of till was penetrated by an auger. West of this lake, the peat ranges in thickness from about 1 to 7 feet.

Lacustrine deposits on the floors of the outwash channels in the Cascade foothills consist mostly of silt, sand, and clay. In the south-center of sec. 10, northwest of Spar Pole Hill, 2.5 feet of peaty clay overlies at least 4 feet of silt, sand, and clay.

In areas underlain by the Osceola mudflow, lacustrine deposits occur mostly in shallow depressions in the mudflow surface, but one is in a shallow basin behind a mudflow dam (p. 49), and another is on a gently sloping area just downslope from a group of springs. In the depression in secs. 11, 14, and 15, northwest of Enumclaw, 3 feet of medium sand overlies 1.5 to more than 5 feet of peat, which in turn lies on Osceola mudflow. In the southern part of the outcrop in the valley of Fennel Creek in sec. 35, T. 20 N., R. 5 E., as much as 4 feet of sand overlies peat, ranging in thickness from 1 foot to more than 7 feet. The sand probably was derived from outcrops of Vashon sand on the east side of the depression.

At a few places diatomaceous earth has been found interbedded with the peat and associated sediments. In the SW¼ sec. 11, T. 20 N., R. 6 E., diatomaceous earth, 4 inches thick, lies beneath 3 feet of sand and on top of Osceola mudflow.

Peat locally underlies the floor of the Duwamish Valley. Along both sides of the valley north of Sumner, peat lies in shallow depressions between low natural levees along the banks of the White River and the valley walls (p. 54), where it ranges in thickness from a foot to more than 7 feet and overlies fine sand (see Rigg, 1958, p. 137–138). Thin beds of peat and organic-rich clay are interstratified with overbank alluvium at many places on the floor of the valley, especially along the margins; these deposits are not differentiated from the alluvium because they are neither thick nor areally extensive.

Peat in the quadrange includes a rather wide range of ages; peat on Vashon drift probably has been accumulating continuously since early postglacial time, whereas peat on the Osceola mudflow has accumulated only during the past 4,800 years or so. Peat on the floor of the Duwamish Valley presumably is still younger but just how much is not known.

COLLUVIUM

Colluvium is here subdivided into slumps and earthflow deposits. A colluvial cover that ranges widely in thickness mantles most slopes along valley walls and in the Cascade foothills. The presence of this mantle, in addition to the luxuriant cover of vegetation, makes the location of contacts between formations very difficult. Because the colluvial mantle is so widespread, it is not differentiated as a separate map unit, and only large slumps and earthflows are shown.

SLUMPS

Slumps have been recognized in two areas. One is in secs. 2 and 11 along the west valley wall of the White River at the north edge of the quadrangle. Here, downward movement and rotation of blocks of Vashon and older drift and Osceola mudflow have formed a series of ridges and depressions, bordered on the back side by shallow alcoves in the valley wall. When this area was visited in March 1957, minor sloughing of saturated material from the back scarp of some of the alcoves was producing intermittent mudflows, some of which flowed down gullies through the slump blocks and spread out on the alluvial fans built on the White River flood plain. Some of the slump blocks consist of units that apparently have moved without disturbing their internal structure; others have broken into a group of smaller blocks. Slumps of the same general character are abundant on the west side of the White River valley downstream from the quadrangle (D. R. Mullineaux, oral communication).

A second area inferred to have slumped is in sec. 22, on the east side of the Carbon River valley, south of Fairfax Bridge. Here the valley wall between the Fairfax Truck Trail and another trail, at an altitude of about 1,300 feet, is mantled with Wingate Hill drift. The slope is interrupted by several subparallel ridges whose crestlines slope gently southward. These ridges are 50 to 150 feet wide and locally are bounded on both sides by steep slopes; the uppermost ridge is separated from the adjacent valley wall on the east by a linear depression, 10 to 35 feet deep. Only volcanic ash and Wingate Hill drift were found in pits, 3 feet deep, along the sides and crestlines of the ridges. Bedrock in this area consists of steeply dipping sedimentary rocks of the Puget group, which are exposed along the Truck Trail, but which do not crop out within the slump area. The interpretation of the ridges as being parts of slump blocks is based in part on the absence of any other apparent explanation for their origin. If they were lateral moraines of Wingate Hill age, their crestlines would slope northward, down the valley of the Carbon River, rather than up the valley. Furthermore, the freshness of the ridges and depressions is not consistent with the graded slopes typical of the Wingate Hill drift elsewhere in the area. It is inferred that the slide movement that produced the corrugated topography occurred entirely in the drift.

A small rockfall deposit on the south slope of Fox Creek channel in sec. 23 is shown on the geologic map as a slump. Here, blocks of rock extend from the base of a cliff down to the floor of the channel. The deposit is about 200 feet wide where crossed by a logging and fire-protection road.

EARTHFLOWS

Earthflows are found mostly in the foothills and originate principally in the Lily Creek formation and volcanic breccia (bedrock). The largest earthflow in the breccia originated in a deep re-entrant in the south wall of the Fox Creek channel. Deeply weathered beds of sandstone, conglomerate, and mudflow breccia, consisting of detritus derived from volcanic rocks of intermediate and basic composition, form the source material. The earthflow is exposed along a logging road on the east side of sec. 23, where the material consists of a dark-yellowish-brown sandy clay and scattered rock fragments; it is structureless, plastic, and looks very much like till. The central part of the earthflow has a hummocky surface, and it is drained by gullies at each margin. The deposit extends into the Fox Creek channel and at least 50 feet vertically up the north wall of the channel. This evidence suggests that the earthflow acquired enough momentum during downslope flowage to carry it some distance up the opposite slope and that the flowing mass was quite mobile. A reconstructed longitudinal profile of the Fox Creek channel beneath the earthflow suggests that the deposit may be about 175 feet thick at Road Junction 1137 and the volume of the deposit is estimated to be roughly 35 million cubic yards.

Because the earthflow blocks the Fox Creek channel, it must antedate the maximum of the Vashon glaciation. Deeply weathered bedrock is not seen in the channel below an altitude of about 1,100 feet, so it seems likely that most of the channel above this altitude is of pre-Vashon age and that the part below, cut in fresh rock, represents Vashon melt-water erosion. Deepening by melt-water erosion probably was ultimately responsible for formation of the earthflow by oversteepening the channel walls at this point. In this connection, it is interesting to note that the volume of the depression from which the earthflow originated is at least seven times greater than the estimated volume of the existing earthflow. This implies that a large amount of older earthflow from the same alcove was removed by Vashon melt water.

Earthflows derived from deeply weathered bedrock are also found along the eastern slope of Spar Pole Hill and are exposed in cuts adjacent to the logging road on the west side of Fox Creek channel in sec. 13.

Earthflows also are found downslope from outcrops of deeply weathered Lily Creek formation where erosion by Vashon melt water has oversteepened slopes. The earthflow material consists of a mixture of sand, clay, and scattered rock fragments and, locally, has hummocky topography. These deposits appear to have originated as a succession of small flows and include some slopewash and fan alluvium derived from the scarp above the deposit.

Small earthflows and mudflows found along the bases of many of the valley walls in the area are not differentiated from alluvium. Especially along the west valley wall of the Puyallup River between Orting and Sumner, thin loose mantle develops on steep outcrops of very compact mudflows and till. This mantle periodically becomes saturated and sloughs off with its mat of roots and moves downslope as an earthflow. Most of these earthflows, with their included vegetative debris, are incorporated with alluvial-fan deposits.

FLOOD-PLAIN ALLUVIUM

Flood-plain sediment in the quadrangle is thickest and most widespread along the courses of the four main streams: the Puyallup, Carbon, and White Rivers, and South Prairie Creek. Flood-plain deposits of tributaries are generally thin, discontinuous, and are neither economically nor stratigraphically of much importance.

Alluvial-fan deposits of pebble to boulder gravel are common along the flood plains of each major river at the mouth of gullies in the valley walls, but they are of small areal extent and are not differentiated on the map. Fans rarely are more than 100 yards wide or long, and their apexes generally are but 10 to 15 feet higher than the adjacent flood plain.

The alluvium of the quadrangle has five main ultimate sources, as follows: (1) The sedimentary rocks of the Puget group, (2) basaltic and andesitic volcanic rocks of the lower Keechelus andesitic series and Fifes Peak andesite, (3) hypersthene and hornblende andesite lava flows and pyroclastic rocks of Mount Rainier, (4) the Snoqualmie granodiorite and related intrusive rocks, and (5) the Vashon drift. Rocks and minerals of Mount Rainier provenance predominate over those of all other sources in the alluvium of each major valley to a greater amount than might be expected by comparing the area of outcrop of Mount Rainier rocks with that of other rock types in the drainage basins of streams that flow through the quadrangle. This predominance probably is caused by (1) relatively greater efficiency of mechanical weathering on the high slopes of Mount Rainier than on lower slopes in the Cascade Range, (2) the flood of fine volcanic-rock detritus contributed by melt-water streams from glaciers of Mount Rainier, and (3) the presence on or closely adjacent to valley floors of extensive mudflows of Mount Rainier derivation, which now are being reworked by present tributary streams.

ALLUVIUM OF THE PUYALLUP AND DUWAMISH VALLEYS

Deposits that underlie the flood plain of the Puyallup and Duwamish Valleys include coarse and fine alluvium. peat, and volcanic mudflows. The coarse alluvium is limited mostly to present and former channels of the major rivers and the fine alluvium represents overbank sediments deposited during flood stage. The near-surface sediments of the valley floor have been mapped and are described in considerable detail in the Soil Survey Report for Pierce County (Anderson, Ness, and Anderson, 1955).

Channel deposits characteristically are pebble to cobble gravel and sand that form narrow bars exposed only during low-water stage adjacent to the present river channels. Older channel deposits are inferred to lie under several feet of overbank alluvium along former courses of the Puyallup and Carbon Rivers south of Sumner. Where these older channel deposits are exposed by natural or manmade excavations, they consist chiefly of coarse sand and pebble to cobble gravel with cut-and-fill stratification.

The channel alluvium of the modern Puyallup River becomes coarser upstream, grading from pebble and cobble gravel in the vicinity of Sumner to pebble to boulder size gravel south of Orting. This size gradation probably is caused in part by downstream decrease of gradient and in part by the availability of coarse material in the Electron mudflow. The mudflow, from which many of the larger stones in the channel alluvium were derived, ranges in particle size from a mixture of clay, sand, and pebble- to boulder-sized rock fragments south of Orting to clay, sand, and granules just north of Alderton.

The most widespread alluvial deposit flooring the valley consists of sand and silt. Locally this alluvium forms low, barely perceptible natural levees along the present river channels; the most conspicuous levee is along the east side of the Duwamish Valley south of Dieringer. Here, and along the west side of the valley as well, the swale beneath the valley wall and the levee has been partly filled with peat. The peat west of the river forms a wedge-shaped deposit in cross section that thins toward the center of the valley. Lenses of fine sand and silt, interbedded with the peat, also increase in number and thickness toward the center of the valley and are inferred to be overbank alluvium deposited during flood stages prior to 1906 (p. 5) when the Stuck River received a part of the flood discharge of the White River. Peat underlies and is interbedded with sand and silt elsewhere beneath the valley floor, especially along the margins of the valley.

The quantitative importance of overbank sediments in relation to channel deposits has been questioned by Wolman and Leopold (1957), who conclude that the proportion of overbank alluvium is generally small on most flood plains. In the Puyallup and Duwamish Valleys, overbank deposits seem to be areally large in contrast to the relatively narrow bands of coarse channel alluvium. Insofar as thickness and, thereby, volume is concerned, however, this same proportion cannot be verified, so channel deposits may be much greater volumetrically than their present surface distribution indicates.

The following relations suggest that the fine sediments that directly underlie the Puyallup flood plain are overbank alluvium and not point-bar deposits formed by lateral accretion as the river shifted across the flood plain: (1) Along the excavation for a pipeline between U.S. Highway 410 and the valley wall in the SE¼ sec. 19 east of Sumner, more than 4 feet of peat and peaty clay underlie 5 feet of silt and fine sand. The presence of the peat and peaty clay is not consistent with a hypothesis that the overlying and and silt are a point-bar deposit of a laterally shifting channel because lateral channel migration would have removed the peat and clay. (2) As much as 7 feet of fine to medium sand and silt overlie remnants of the Electron mudflow. The existence of these remnants of the mudflow indicates, with a few exceptions, that the channel of the Puyallup River has been confined to relatively narrow courses on the flood plain during the past 500 years. Inasmuch as the channel has not cut laterally through the mudflow remnants, the fine alluvium that overlies the mudflows must necessarily be of overbank origin.

The presence of overbank alluvium, as much as 7 feet thick, on the Electron mudflow and the lack of evidence of wholesale lateral shifting and point-bar accretion suggest that the veneer of fine sediments on the flood plain is largely, if not wholly, of overbank origin. Streams on the flood plain appear to have shifted their position by abandoning old channels and cutting new ones during flood stage rather than by gradual lateral cutting.

North of Sumner, the Duwamish Valley was occupied only by the Stuck River immediately prior to the 1906 flood on the White River (p. 5). The channel of the Stuck seems to have been fixed in position for a long time, as suggested by the absence of any surface features that might represent old channels and by the presence of thick peat deposits in swales between natural levees and the adjacent valley walls. The old Stuck channel might represent a channel used by the White River when it last occupied a southward course to Sumner prior to 1906.

The channel of the present White River (pl. 1) lies east of the old Stuck River channel (see Tacoma quadrangle, 1900 edition) most of the way from Benroy to the north outskirts of Sumner. This eastward migration probably occurred mostly after 1906 and before 1913, when the diversion of the White River into Lake Tapps and the hydroelectric works at Dieringer were completed (p. 4).

A survey of the effects of the 1906 flood on the White River (Corps of Engineers, U.S. Army, Duwamish-Puyallup Surveys, 1907) shows that the channel of the White in 1906 ranged in altitude from 44 to 50 feet at the present highway bridge at Sumner, and it is inferred that the water surface was about 50 feet above sea level. In comparision, the water surface was at about 32 feet above sea level beneath the bridge on August 18, 1959. These figures are not precise, but they probably indicate a net lowering of the channel of at least 15 feet since the 1906 flood.

The most likely explanation for the eastward migration and subsequent lowering of the channel is that diversion of the White River into the old Stuck channel in 1906 caused alluviation of the channel in response to the large bedload of the White. This permitted lateral migration of the channel until 1913, when most of the discharge of the White was diverted near Buckley and then returned, without bedload, to the valley near Dieringer. The channel downstream from Dieringer was then cut down to its present gradient in response to the new discharge-bedload conditions.

Unconsolidated deposits extend hundreds of feet below sea level in the Puyallup and Duwamish Valleys as shown in logs of drilled wells. Three of these wells in the N½ sec. 24 in the northern part of Sumner are driled in 462, 572, and 575 feet of sand, gravel, and clay (Sceva and others, 1955, p. 239–241). The altitude of the land surface at the wells is about 60 feet. A well drilled in similar materials reached a depth of 408 feet in the vinicity of the school at Dieringer (Sceva and others, p. 246). South of Orting in the SE¼ sec. 32, where the land surface is about 220 feet in altitude, a well was drilled in 250 feet of sand, gravel, and clay (Sceva and others, p. 188); the bottom of the well therefore is at a point slightly below sea level in unconsolidated deposits despite the fact that bedrock crops out to an altitude of as much as 500 feet only 1.5 miles to the southwest. According to a driller's log, a well in sec. 17, in the vicinity of the saw mill on the flood plain south of Orting, reached rock at a depth of 96 feet.

It generally is not possible to distinguish lithologic units from well-log records; the position of the Vashon drift in the sediments that underlie the valley floor thus is not known.

Many drillers' logs of wells in the valley between McMillin and Sumner indicate that the upper 75 or 80 feet of the alluvium consists of sediments of sand-size or smaller that are directly underlain by gravel.

WHITE RIVER VALLEY

Alluvium on the floor of the White River valley consists chiefly of sand and pebble to boulder gravel. Sand found mostly in strips a few hundred feet back from the present channel probably represents overbank sediment deposited during flood stages. Boulders with a maximum dimension of 5 to 8 feet are common in the gravel, and some as large as 12 feet have been seen in the vicinity of the highway and railroad bridges across the White River at Buckley.

The exposed thickness of alluvium on the White River flood plain is less than 10 feet; its maximum thickness probably does not exceed 20 feet.

SOUTH PRAIRIE CREEK VALLEY

Alluvium of South Prairie Creek characteristically consists of pebble and cobble gravel immediately adjacent to the present stream channel and of silt and sand on the adjacent flood plain. The Osceola mudflow on the valley floor has little or no alluvial sediment on it, suggesting that floods that inundate the valley floor do not deposit appreciable amounts of overbank alluvium.

Records of wells drilled on the valley floor indicate that at least 35 to 40 feet of sand and gravel underlie the surface; the age of these deposits is not known.

CARBON RIVER VALLEY

The alluvium of the Carbon River flood plain, near the east edge of the quadrangle, consists of sand and pebble to boulder gravel; the thickness of the alluvium is not known but probably is not greater than 30 feet. Downstream, the Carbon River flows through a deep and narrow bedrock gorge in which the flood plain is narrow or absent. The flood plain widens and is made up of pebble to boulder gravel below the gorge, where the maximum thickness might be much greater than upstream from the gorge, especially immediately downstream from the westernmost outcrops of bedrock.

ARTIFICIAL FILL

Manmade accumulations of earth materials such as mine dumps and highway or railroad fills are shown on the geologic map as artificial fill. In general, only the accumulations that are topographically high or extensive are shown. Mine dumps are found only in the southeastern part of the quadrangle and are near portals of coal mines, now mostly abandoned. A small area at the northwestern outskirts of Sumner is mapped as modified land, owing to extensive cutting and filling of the original land surface there in connection with the construction of a highway, railroad, and several large buildings.

STRUCTURE

The great thickness of unconsolidated sediments beneath parts of the lowland—which extend to depths of at least 1,500 feet below sea level in the northeastern part of Tacoma, only 9 miles west of Sumner (Sceva and others, 1955, p. 209–210)—suggests extensive downwarping of the lowland in post-Oligocene(?) time. The thick unconsolidated fill beneath the lowland, however, probably is mostly of pre-Pleistocene age and downwarping of the fill probably occurred chiefly before Pleistocene time.

Each of the Pleistocene formations of pre-Salmon Springs age decreases in altitude northward or northwestward from the edge of the Cascade foothills toward the center of the Puget Sound lowland. East of Orting, the base of the Alderton formation is at an altitude of about 500 feet; 5 miles northwest, the base of the formation disappears beneath the floor of the Puyallup Valley at an altitude of about 100 feet. In sec. 18 south of Orting (measured section 7) the base of the Puyallup formation is at an altitude of about 600 feet; 7.5 miles to the north, in exposures in the valley walls of Fennel Creek (measured section 10), the base is at about 265 feet. Much of the decrease in altitude is probably due to the effect of stream gradients sloping northwestward during Alderton and Puyallup times. This situation is analogous to the present northward gradient of 20 to 25 feet per mile of the Puyallup Valley floor. The fact that the altitude variations of the Pleistocene formations are not in excess of those expectable of stream gradients implies that these formations have not participated to any large extent in downwarping. The Puyallup formation, for example, lies at an altitude of about 60 feet just north of Sumner and is exposed near sea level in beach cliffs in the vicinity of Des Moines, 14 miles north of Sumner (H. H. Waldron, oral communication).

Locally, there is evidence of faults. In the vicinity of measured section 13 northeast of Sumner, the altitude of the distinctive beds of peat and volcanic ash in the Salmon Springs drift decreases 80 feet from south to north between exposures only 1,000 feet apart. This much variation cannot be explained by stream gradient, because the ash and peat probably were deposited on an almost flat surface and because the underlying Puyallup formation also is displaced in this vicinity. Because of dense vegetation in the critical area, however, the place where the beds are dislocated cannot be seen. North and south of this area, an apparent northward slope of about 40 feet per mile of the peat and ash beds possibly can be interpreted as evidence for local downwarping.

Movement along a northwest striking, nearly vertical slip surface near the west end of the bluff at the northwest outskirts of Sumner has resulted in displacement of about 80 feet in the Vashon drift and older formations (fig. 10). The downthrown block is on the (south) side of the fault nearest the valley wall, so the displacement might possibly have been caused by slumping into the valley.

Several faults are exposed in the valley of Kings Creek in the SW¼NE¼ sec. 34 at the south edge of the quadrangle. Two faults cut mudflows in the basal part of the Lily Creek formation. One strikes N. 60° W. and dips 50° SW., and slickensides along the fault show strike-slip movement with a southeast plunge of 15°. Where this fault is exposed in the bed of Kings Creek, it has a zone of very plastic dark-reddish-brown clay gouge, 6 to 15 inches thick. Downstream about 60 feet, another fault that cuts the Lily Creek formation strikes N. 5° E. and dips 55° W.; a gouge zone along this fault is as much as 2 feet wide. Still farther downstream, below the base of the Lily Creek, outcrops of volcanic breccia are cut by two faults. One fault, which strikes N. 70° E. and dips 85° SE., has brought deeply weathered breccia on the north side against fresh breccia on the south. Fifty yards to the south, another fault, which strikes N. 35° W. and is vertical, has brought weathered rock on the south into contact with fresh rock on the north. Because the Lily Creek formation is not weathered at this place, the underlying bedrock must have been weathered prior to Lily Creek time. Owing to their short distance of outcrop, the traces of these faults are not shown on the surficial geologic map (pl. 1).

GEOLOGIC HISTORY AND GEOMORPHIC DEVELOPMENT

PRE-PLEISTOCENE TIME

The geologic history of this part of western Washington recorded by exposed bedrock formations starts in middle to late Eocene time with the deposition of the Puget group and the Keechelus andesitic series (Crandell and Gard, 1959). At some time between early Oligocene time and middle Miocene time, these sedimentary and volcanic rocks were folded and faulted and locally intruded by sills and dikes of diorite. An erosion surface of low to moderate relief subsequently formed on the bedrock, upon which lacustrine and alluvial sand and gravel were deposited in late Miocene time. The deposition of these sediments was interrupted in at least one area by the deposition of volcanic mudflows, volcanic ash, and pumice gravel that probably had their source in a volcanic area east of the Lake Tapps quadrangle (Mullineaux, Gard, and Crandell, 1959). In Pliocene time the Cascade Range was uplifted to a height probably comparable to that of today, and valleys were eroded in the range that were similar in size to present valleys such as those of the White and Nisqually Rivers. Warren (1941, p. 814) concluded that the uplift of the Cascade Range was completed by the early part of the Pleistocene.

PLEISTOCENE TIME

PRE-ORTING DRAINAGE PATTERN

By early Pleistocene time, the major northwest-trending valley that drained the site of Mount Rainer before birth of the volcano was the valley of the ancestral Mowich River. This valley probably headed in the Cascade Range between the modern valleys of the Carbon and North Puyallup Rivers, in an area now buried by the volcano (fig. 6). The ancestral Mowich Valley trended northwestward athwart the present course of the Mowich River, along what is now a divide, into the Lake Tapps quadrangle. In the southern part of the quadrangle, the ancestral valley is exposed in cross section between Cowling Ridge and Brooks Hill (fig. 6), where it is now mostly filled with sediments of the Lily Creek formation deposited during an early phase of Mount Rainier volcanism. The ancestral valley probably had been eroded to a depth of at least 1,000 feet below the adjacent bedrock upland surface of the Cascade foothills, and between Cowling Ridge and Brooks Hill the valley floor was at least as low as 1,160 feet altitude.

The ancestral Mowich Valley has a rather steep western wall: in the NE¼ sec. 13 northwest of Brooks Hill, the contact between bedrock and the Lily Creek formation slopes eastward from an altitude of at least 1,450 to 1,150 feet in a distance of about 0.4 mile. The east side of this valley is similarly well defined in cross section in the E½SW¼ sec. 16 just northwest of Fairfax Bridge and in sec. 34 east of Carbonado.

Two knobs of bedrock, surrounded and partly buried by the Lily Creek formation crop out within the ancestral Mowich Valley; one of these extends northward from Brooks Hill along the east side of secs. 18 and 7 and the other is a smaller knob on the west side of sec. 7 just northwest of Brooks Hill. These two bedrock knobs or ridges do not seem to be parts of a continuous interfluve and do not seem to be bedrock spurs trending northeast from Cowling Ridge; instead they are probably knobs isolated by erosion before deposition of the Lily Creek formation.

The ancestral Mowich Valley was probably part of the drainage system that existed prior to the birth of Mount Rainier (Coombs, 1936, p. 196–198) and that had become established during the Pliocene uplift of the Cascade Range. The ancestral Mowich River presumably extended northwestward into the Puget Sound lowland and ultimately drained into the Pacific Ocean through what is now the Strait of Juan de Fuca.

Other major elements of this drainage pattern of the Cascade Range, south and east of the Lake Tapps quadrangle, have not been identified with certainty, although the valleys of the South Prairie Creek and the Puyallup River probably had become established in the foothills before Mount Rainier appeared. The Carbon River valley, however, seems to postdate, in part, this early stage of valley development.

The only alluvial deposit in the quadrangle that is probably related genetically to the pre-Mount Rainier stage of valley development is gravel of central Cascade provenance in the Orting drift at and east of Orting. The gravel is probably a deposit of the ancestral Mowich River, as its outcrop area coincides with the northwestern trend of the ancestral valley. The gravel, as well as other gravel like it along the front of the Cascade Range, probably formed an alluvial plain built out into the lowland by streams draining the Cascade Range in early Pleistocene time before the appearance of Mount Rainier.

ORTING GLACIATION

The Puget lobe probably advanced over a bedrock surface of low relief and onto the alluvial plain mentioned above. When the glacier abutted the Cascade foothills in the Lake Tapps quadrangle, the ancestral Mowich River probably was temporarily detoured to a southwestward course along the mountain front, similar to the diversion of the White, Carbon, and Puyallup Rivers that occurred at the maximum of the Vashon glaciation. Outwash gravel, probably deposited in ice-marginal channels in Orting time, is exposed in the north wall of the Carbon River valley.

ALDERTON TIME

MOUNT RAINIER VOLCANISM AND THE FILLING OF THE ANCESTRAL MOWICH VALLEY

The depositional history of Alderton time is chiefly a history of Mount Rainier volcanism; because of the nature of the evidence, only the parts of the interglacial age during which Mount Rainier was sufficiently active to cause large-scale stream and mudflow transport of volcanic rock debris to the lowland are well represented. The Alderton and Lily Creek formations may represent only a fraction of the entire nonglacial age that intervened between the Orting and Stuck glaciations.

Retreat of the Orting glacier left a drift plain in the lowland, across which the ancestral Mowich River became re-established in a northwestern course. In early post-Orting time, volcanic rocks and minerals derived from Mount Rainier made their first appearance in sediments deposited in the lowland and in the ancestral Mowich Valley, heralding the birth of the volcano. This activity must have included eruption of vast amounts of volcanic material, for, during Alderton time, streams and mudflows from the volcano very nearly filled the ancestral valley with volcanic sediments, and similar debris was carried out to the lowland where it formed a broad northwest-sloping alluvial plain now represented by the sediments of the Alderton formation.

Several lines of evidence suggest that no important stream coincident with the modern Carbon River drained the north side of Mount Rainier before or during Alderton time:

1. Distribution of volcanic rocks on the north side of Mount Rainier (fig. 6) suggests that the Carbon River valley was not formed before the appearance of Mount Rainier, and, in fact this valley apparently did not drain Mount Rainier until relatively late in the history of the volcano. Recent geologic mapping of Mount Rainier National Park by R. S. Fiske, C. A. Hopson, and A. C. Waters has shown that early in the history of Mount Rainier a hornblende andesite lava flow extended northward from the volcano toward Windy Gap, and then moved northwestward and terminated at Bee Flat (fig. 6). At Bee Flat the flow lies on the floor of a valley that headed at Windy Gap rather than at the volcano (C. A. Hopson, unpublished communication, Oct. 17, 1959). Subsequently, relatively late in the history of the volcano, olivine andesite flows from vents on the northwest side of the volcano crossed the area that is now the upper part of the Carbon River valley and terminated against the base of Old Desolate (fig. 6; C. A. Hopson, unpublished communication, Oct. 17, 1959). The Carbon River valley also appears to postdate the development of the eastern part of the Wingate Hill surface.
2. No alluvial and mudflow fill comparable to the Lily Creek formation has been found that can be related to a valley coinciding with the present Carbon River valley.
3. Geologic mapping in the Lake Tapps quadrangle shows that the southeast edge of the Lily Creek formation trends northeastward across the modern Carbon River valley near Fairfax Bridge. The appearance of the contact between Lily Creek formation and bedrock in this vicinity suggests that the Lily Creek was here banked against a low bedrock hill or scarp, and gives no indication that the Carbon River valley was then present.

The Cascade Range east of the Lake Tapps quadrangle before the appearance of Mount Rainier probably was drained by ancestors of Gale and South Prairie Creeks and possibly by Chenuis and Cayada Creeks and an embryonic Carbon River. These latter three streams probably had not yet grown headward into the area now occupied by Mount Rainier, owing to an intervening high divide of the Cascade Range represented by Mother, Crescent, Sluiskin, and possibly Chenuis Mountains (fig. 6). These streams might have emptied into the ancestral Mowich River, but evidence is lacking. The upper part of the Carbon River seems to have come into existence after deposition of the Lily Creek formation in the ancestral Mowich Valley and might have originated through the headward growth toward the south of a tributary to the Chenuis-Cayada stream system.

CLIMATE

Pollen in sediments of the Alderton formation at one locality (measured section 6) suggest that the climate was comparable to that of today in the Puget Sound lowland. At this locality, interbedded peat and silt that lie about 40 feet above the Orting drift contain a pollen profile representing a forest succession that progresses from Englemann spruce and fir to Douglas fir and alder. According to E. B. Leopold (written communication), the Engelmann spruce and firm record Canadian zone climatic conditions and the Douglas fir and alder represent a Humid Transition zone environment. The duration of this environment is not known. Leopold infers that the initial attainment of the Douglas fir and alder forest represents a vegetation evolution that probably required a period at least as long as that which followed the Vashon deglaciation, and which culminated in a period of maximum warmth and dryness about 8,000 years after withdrawal of the glacier. Owing to the nature of the depositional record of Alderton time, it seems likely that the Alderton formation represents only a small part of the nonglacial interval, and climatic conditions recorded in the sediments are representative of a still smaller fraction of this interval.

STUCK GLACIATION

Events of the Stuck glaciation are imperfectly known from the Lake Tapps quadrangle, although evidence of the advance of a glacial lobe across the Puget Sound lowland and its subsequent recession is present. The southern limit of this advance is not known. A ponding of northward-flowing drainage is demonstrated by glaciolacustrine sediments formed during glacier advance in the area of the White River valley, and a recessional lake is represented by laminated fine-grained sediments in outcrops near Sumner.

The thinness of the Stuck drift in the Puyallup and Duwamish Valleys in comparison with the deposits of the Orting and Vashon glaciations might suggest that the Stuck glaciation here was of short duration. In the valleys of the White River and Green River north of the quadrangle, however, two till sheets, separated by 100 to 200 feet of glacial and nonglacial sediments, are correlated with the Stuck drift (D. R. Mullineaux, oral communication). This relation implies that the Stuck glaciation is not completely represented in the Puyallup Valley.

The Stuck glaciation temporarily disrupted streams in the area now occupied in part by the Puyallup Valley. In Alderton time the drainage of this area was northward or northwestward, but with the advance of the Stuck glacier this drainage must have been temporarily detoured to the southwest. Upon withdrawal of the glacier, northward drainage was re-established.

PUYALLUP TIME

Puyallup time is represented by deposition of the Puyallup formation and part of the Lily Creek formation and by deep weathering and erosion. During the interval, which was probably comparable to an interglacial age in duration, the climate in the lowland was at least temporarily comparable to that of today.

DRAINAGE CHANGES IN THE FOOTHILL AREA

Between Alderton and Puyallup time, a major drainage change seems to have occurred in the Cascade foothills between Mount Rainier and the Lake Tapps quadrangle. The lava flows that blocked the ancestral Mowich Valley (p. 21) may have caused a southward diversion of the upper Mowich drainage into the Puyallup River valley (fig. 6).

The present valley of Voight Creek coincides with the axis of the ancestral Mowich Valley and may be in part a remnant of the valley in the Lily Creek formation that was blocked by the Mount Rainier lava flows mentioned previously. The part of the Voight Creek valley upstream from the SW¼ sec. 14, T. 17 N., R. 6 E., follows the contact between the Puget group on the north and the lava flows on the south. This part of the Voight Creek valley thus seems to have originated in a flow-marginal position, probably at the time the ancestral Mowich was diverted by the flows into the Puyallup drainage.

The Lily Creek formation southwest of the Cowling Ridge divide is not known to lie within a deep, narrow well-defined valley comparable to the axial part of the ancestral Mowich Valley, but instead it seems to occupy a broad shallow valley that is 4 to 5 miles wide, extending from the present Puyallup River southward to Twentyfive Mile Creek.

VOLCANISM AND AGGRADATION IN ANCESTRAL PUYALLUP VALLEY

In very early Puyallup time, a lake occupied the northwestern part of the Lake Tapps quadrangle. In this lake were deposited fine sediments of Mount Rainier derivation, indicating that drainage resumed northward in the Puget Sound lowland immediately upon withdrawal of the Stuck glacier. The deposits of the Puyallup formation exposed in the walls of the Puyallup Valley show that this lake was replaced by an aggrading stream, indicated by a succession of alluvial sediments interbedded with mudflows, all dominated by Mount Rainier rocks and minerals.

The Puyallup formation formed a broad piedmont plain built into the Puget Sound lowland by the ancestral Puyallup River, analogous to the piedmont plain of Alderton age built in the lowland by the ancestral Mowich River. The piedmont plain of Puyallup time rose to the southeast, abutted the Cascade foothills south of Orting, and extended into the foothills along the ancestral Puyallup Valley. During Puyallup time, this valley was filled to a depth of at least several hundred feet with sediments of the Lily Creek formation, analogous to the earlier Lily Creek filling of the ancestral Mowich Valley.

In the lowland adjacent to the alluvial plain, the Stuck drift was exposed to weathering and erosion. Pollen in peat deposited in local depressions in the drift suggests a climatic warming and drying to an environment similar to but somewhat cooler and moister than that of today. A similar climatic trend toward warmth and dryness after the Stuck glaciation is suggested by pollen in peat beds in the Puyallup formation. The fact that the peat beds of the Puyallup record early postglacial climatic conditions suggests that much of the formation accumulated early in the nonglacial interval. Evidence that the climate warmed to conditions comparable to today is found in the Puyallup formation near Des Moines, Wash. (Crandell, Mullineaux, and Waldron, 1958, p. 393), where a more complete sequence is recorded in peat beds. Here, above Stuck drift, pollen in peat beds suggests an initial warming trend from cool and moist conditions of early postglacial time to a climate like that of today at this locality and finally a reversal toward cooler and moister conditions.

DEVELOPMENT OF THE WINGATE HILL SURFACE

One of the most conspicuous physiographic features in the southeastern part of the Lake Tapps quadrangle is a broad, gently sloping upland surface at an altitude of 1,600 to 2,400 feet. South and east of the quadrangle this surface extends up to altitudes of more than 3,000 feet. For convenience of reference, this surface will be referred to as the Wingate Hill surface; the surface is not genetically related to the Wingate Hill drift, although the drift overlies it in most places.

The Wingate Hill surface is cut by the present valleys of the Carbon River, Voight Creek, and Gale Creek but does not appear to be graded to these valleys. The most extensive part of the surface is just south of the quadrangle where the divide between Voight Creek and the Puyallup River forms a broad flat upland 7 miles long and 1 to 2 miles wide (fig. 21).

Although the Wingate Hill surface cuts across several formations, it is best developed in areas underlain by the Lily Creek formation, as on Wingate Hill and the

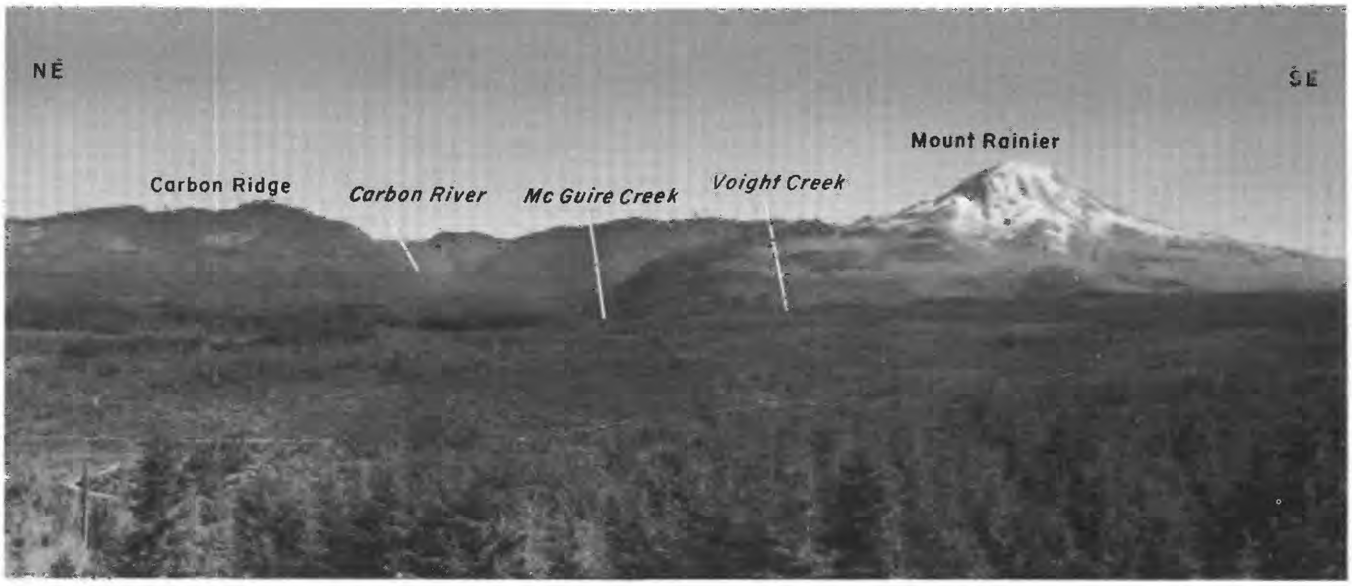

FIGURE 21.—Panorama of Wingate Hill surface veneered with Wingate Hill drift. View east from fire lookout on Cowling Ridge. Note the gradual rise of the surface toward the east and abrupt termination against the Cascade Range. Area in foreground is underlain by Lily Creek formation deposited in the ancestral Mowich Valley. Areas in middle distance northeast of the Carbon River and on east side of Voight Creek are underlain by the Puget group, and mountains in the background are formed by the lower Keechelus andesitic series and Fifes Peak andesite.

northern part of Gleason Hill. Where the surface is underlain by sandstone and shale beds of the Puget group, the surface has somewhat greater relief, as on the southern part of Gleason Hill in secs. 14, 15, 22, and 23. Volcanic rocks in the Puget group also underlie somewhat higher areas of the Wingate Hill surface, such as Brooks Hill and Cowling Ridge. Where the surface abuts the lava flows and well-indurated tuffs and breccias of the Keechelus andesitic series, there is in most places a pronounced topographic break beyond which the Wingate Hill surface can no longer be identified. The western border of mountainous topography in the Cascade Range east of the quadrangle coincides in most places with the western limit of outcrops of the lower Keechelus or Fifes Peak.

Formations that directly underlie the Wingate Hill surface typically are deeply weathered, although the degree of weathering and thickness of the weathered zone are closely related to type of rock and amount of subsequent dissection. The top and upper slopes of Spar Pole Hill and Cowling Ridge are underlain by mudflow breccias of Eocene age that have weathered to a till-like material consisting of boulders of volcanic rock in a plastic clay matrix. The clay probably is a weathering product of the clayey matrix of the original mudflow breccias. Deeply weathered material of this kind is seen in roadcuts on the north side of Cowling Ridge at the south edge of sec. 24. Saturation of the weathered breccias here has been responsible for earthflows that have descended into the Fox Creek channel.

Post-Lily Creek weathering is most conspicuous in the Lily Creek formation; this probably is, in large part, due to the unconsolidated and permeable nature of much of this unit as compared to the local bedrock formations. In some places, weathering has created clayey rinds and has softened pebbles to a depth of 200 feet below the top of the formation.

The presence of deep residual weathering profiles on formations that underlie the Wingate Hill surface suggests that the surface is a product of chemical weathering, colluvial processes, and low-gradient stream erosion over a rather long period of time. Development of the surface probably started with cessation of Lily Creek deposition in the ancestral Mowich Valley in Alderton time, but formation of the parts of the surface underlain by bedrock must have started long before.

Inasmuch as the part of the Lily Creek deposited during Puyallup time is also deeply weathered and is truncated by the Wingate Hill surface, development of the surface probably continued until late Pleistocene time. Deposition of the Wingate Hill drift, however, interrupted further development of the surface.

The Wingate Hill surface apparently is not graded to the valley of the Carbon River but to smaller tributary streams. The reason for this is not clear, but it is thought to mean that the Carbon River did not exist in its present size and importance as a master stream during the formation of the eastern part of the Wingate Hill surface. The present great depth and width of the Carbon River valley, especially upstream from Fairfax Bridge, may be due largely to glacial erosion, rather than to widening and deepening over a long period of time by streams and mass wasting. Similarly, the valley of Voight Creek seems to be a product of glacial erosion of a smaller valley inherited from Lily Creek time. Here, deep scouring during the Wingate Hill glaciation in the relatively nonresistant Lily Creek formation probably was responsible for the present width, depth, and U-shaped cross profile of the valley. The growth of these two valleys, therefore, probably largely postdates the formation of the Wingate Hill surface and is the result of erosion by a different group of processes.

The Wingate Hill surface lies 600 to 1,500 feet above the adjacent Puget Sound lowland. The northwest boundary of the surface is an erosional scarp that marks the maximum southeastward extent of the Puget glacial lobe in the quadrangle. The former northwestern extent of the surface is not known, but the surface probably originally extended into the central part of the lowland, where it merged with the alluvial plains formed by the Alderton and Puyallup formations.

WEATHERING AND EROSION IN THE LOWLAND

Evidence of weathering after deposition of the Puyallup formation in the Puget Sound lowland is limited to outcrops of the formation near Alderton where the top 10 inches locally is kaolinized. Inasmuch as the formation there is directly overlain by outwash gravel of the Salmon Springs drift, it seems probable that this thin weathered zone is but a remnant of a once thicker but now eroded weathering profile, perhaps comparable to that found on the Lily Creek formation.

There is considerable variation in the thickness of the Puyallup formation near Sumner. On the west wall of the Puyallup Valley (measured section 5) and in the valley walls of Fennel Creek (measured sections 10 and 11) the formation is about 135 feet thick, but in the bluff northwest of Sumner (measured section 8) the formation is only 19 feet thick, and northeast of Sumner (measured section 13), 30 feet thick. The eroded surface of the Puyallup formation is overlain by the Salmon Springs drift, but it is not possible to determine how much of the erosion might have occurred prior to Salmon Springs time and how much might be attributed to ice and melt-water stream erosion in Salmon

Springs time. At several places in the walls of the Puyallup Valley near Sumner, however, V-shaped gullies filled with gravel of the Salmon Springs drift have been found. This evidence suggests that at least part of the variation in thickness of the Puyallup was caused by pre-Salmon Springs stream erosion.

SALMON SPRINGS TIME

The Salmon Springs drift is interpreted to be the deposit of a single major glaciation, although the drift includes the deposits of two glacial advances. The initial advance of the glacier resulted in the deposition of outwash gravel and till on the eroded and weathered surface of the Puyallup formation. During retreat of the glacier, an eruption resulted in the deposition of volcanic ash across the Lake Tapps quadrangle, and this ash was preserved in ponds and lakes where silt, clay, and peat were deposited subsequently. The presence of gravel of Mount Rainier provenance just above these lacustrine sediments suggests the possibility that a stream heading at the volcano temporarily flowed across part of the area before the readvance of the Salmon Springs glacier. This readvance formed another mass of till and stratified sediments in the northern part of the quadrangle.

By late Salmon Springs time, the valley system cut into the Puyallup formation had been aggraded by glacial drift and by alluvium of central Cascade and Mount Rainier provenance; gravel of Salmon Springs age in measured section 5 occurs at an altitude of about 400 feet, so it seems likely that the alluvial and glacial fill reached this altitude north of Sumner, although at measured sections 8 and 13, the top of the Salmon Springs drift is a little below 275 feet. In late Salmon Springs time, streams deposited sand and gravel of Mount Rainier and central Cascade provenance as far northwest as Des Moines (H. H. Waldron, oral communication) and as far west as Tacoma. The stream pattern of this time probably was nearly coincident with the pattern of the present major valleys of the lowland.

SALMON SPRINGS-VASHON INTERVAL

In the lowland part of the Lake Tapps quadrangle, the interval between the Salmon Springs and Vashon glaciations is recorded mainly by erosion. Downcutting of streams on the alluvial and drift plain of late Salmon Springs time resulted in the incision of the major valleys of the lowland, some of which now are occupied by arms of Puget Sound and others by master streams heading in the Cascade Range and Mount Rainier.

The Puyallup Valley is 1 of 3 such broad north-trending depressions in the southeastern part of the Puget Sound lowland; the other two are occupied by Colvos Passage and the main arm of Puget Sound. These three depressions are of roughly the same size and orientation and their floors probably reach depths of 400 to 600 feet below sea level, but the Puyallup Valley has now been alluviated to an altitude of as much as 100 feet above sea level.

The origin of the pattern of the major valleys of the Puget Sound lowland is as yet imperfectly understood, although Bretz' (1913) suggestion that the pattern was inherited from a consequent stream drainage pattern that formed on a broad aggradational plain of pre-Vashon drift may be, in part, correct. In its general northward and northwestward trend, however, the Puyallup Valley probably is approximately following a course that existed since before Orting time, although at no previous time did this course coincide with a valley comparable in depth to that of the present.

Bretz (1913, p. 203) proposed that the stream in the Duwamish Valley, north of Sumner, flowed southward and joined the ancestral Puyallup to flow northwestward as a tributary of his "Admiralty River." On the basis of the general northwestward slope of this part of the lowland, however, this course seems anomalous, and it seems more likely that pre-Vashon drainage in the Duwamish Valley was northward. This alternative, however, leaves unexplained the origin of the valley segment between Sumner and Auburn. D. R. Mullineaux (oral communication) has suggested that this valley segment originated as a low divide between the Green and the Puyallup, and was deepened and widened by glacial scour during the Vashon glaciation.

The effect of glacial scour in deepening other parts of the lowland valley system is not known. Bretz suggested that the region was uplifted 1,000 feet in the interglacial period preceding the Vashon glaciation and that the major streams of the area cut valleys to approximately their present depths; after or during the Vashon glaciation the region was lowered to its present depth and marine water inundated the glacially modified stream valleys. The writer and his associates (H. H. Waldron, oral communication, and D. R. Mullineaux, oral communication) have found no compelling evidence for this amount of uplift and subsequent depression but propose that the land surface was about 500 to 600 feet higher throughout most of the Pleistocene before Vashon time. This higher surface would provide sufficient altitude for necessary stream gradients from Orting northward to Admiralty Inlet and the Strait of Juan de Fuca, and moreover would explain the absence of pre-Vashon marine deposits of Pleistocene age in the lowland (H. H. Waldron, oral communication).

In late Pleistocene time before the Vashon glaciation, the Wingate Hill icecap formed in the higher parts of the Cascade Range and extended westward into the foothills of the Lake Tapps quadrangle. This glacier seems to have covered all of the foothills area except Spar Pole Hill and the top and west sides of Cowling Ridge. The valley of Voight Creek was scoured to its present broad U-shaped profile at this time, as probably also was the part of the Carbon River valley upstream from Fairfax Bridge. The glacier probably was thin across the upland part of the area, but must have been more than 1,000 feet thick along the axis of the Carbon River valley. The northwestern extent of the glacier is not known, but probably it was not far north of the present northward limit of the Wingate Hill drift. Along the axes of major valleys of the Cascade Range, however, lobes of the glacier may have extended into the Puget Sound lowland. Such a lobe from the White River valley is thought to have caused a shift in the course of the White River. Sediments of Mount Rainier and central Cascade provenance evidently were deposited at least as far west as Sumner in late Salmon Springs time, probably by the White River. Yet it seems likely that the White River occupied the valley of South Prairie Creek just before Vashon time. The White River may have shifted from a northwestward course to the South Prairie Creek valley during the Wingate Hill glaciation, while the White River valley glacier extended out into the lowland near Buckley. This shift may have resulted from the White following an ice-marginal course along the south edge of the inferred piedmont lobe. The White River remained in the valley of South Prairie Creek, except for temporary diversion during the Vashon, until the Osceola mudflow caused it to shift back to the northwest and cut its present valley.

VASHON GLACIATION

VALLEY GLACIER PHASE

An early phase of the Vashon glaciation was characterized by growth of cirque and valley glaciers in the Cascade Range. At this time, the Evans Creek glacier, which had its source at Mount Rainier and in the higher parts of the Cascade Range southwest of the Lake Tapps quadrangle, advanced down the Carbon River valley to the vicinity of Fairfax. A glacier in the Mowich River valley, which extended about 20 miles downstream from existing glaciers on Mount Rainier (L. A. Palmer, oral communication), probably is of the same age as the Evans Creek glacier, and Mackin (1941, p. 471–474) also described a valley glacier that extended as far as the west front of the Cascade Range in the Snoqualmie-Cedar area at this time.

ADVANCE OF THE PUGET LOBE

During early Vashon time, valley glaciers presumably also were lengthening in the Coast Ranges of British Columbia and the northern Cascade Range. These glaciers merged westward with valley glaciers from Vancouver Island and formed a piedmont glacier that filled the Strait of Georgia (Dawson, 1890, p. 27–29). Southward flowage of this ice down the Puget Sound lowland formed the Puget lobe of Vashon age, which, at its maximum extent, was 85 miles long and 60 miles wide.

Evidence of events during the advance of the Puget lobe in Vashon time is poor in the Lake Tapps quadrangle; only a few small deposits of proglacial stratified drift have been recognized beneath till of Vashon age and they reveal little or nothing about details of the glacial advance.

Evidence of the direction of ice flowage in the Lake Tapps area is provided by the trend of the long axes of drumlins and by striations on bedrock. The drumlins east of the White River in the northwestern part of the Buckley quadrangle bear S. 22°–25° E., those in Lake Tapps bear S. 18°–20° E., and drumlins about 4 to 6 miles west of the Sumner quadrangle on the upland south of the city of Puyallup trend nearly due south (fig. 14). The only striations found on bedrock are on the andesite porphyry exposed in the quarry west of the community of Orting; these strike due south. Evidence has not been found of any deflection of the glacier by topographic features in the quadrangle; the overall fanlike orientation of linear features suggests radial ice flowage outward near the terminus of the glacier.

At its maximum extent, the margin of the Puget lobe lay against the foothills of the Cascade Range and rose to a maximum height of about 1,800 feet on the northern slope of Spar Pole Hill (pl. 2). The glacier was about 200 feet lower in altitude east and south of Spar Pole Hill, probably partly because of constant trimming of the ice margin by melt-water streams and partly because of a steep ice gradient near the glacier's terminus. Spar Pole Hill formed a small nunatak projecting 100 to 300 feet above the surface of the glacier. At its maximum southward extent, the glacier blocked the valleys of the Carbon River and Voight and South Prairie Creeks to form temporary proglacial lakes; the one in the Carbon River valley was at least 4 miles long.

RELATION OF THE PUGET LOBE TO VALLEY GLACIERS

Stratigraphic relations of the Evans Creek drift and the Vashon drift near Fairfax suggest that the valley glacier had retreated up valley by the time the Puget glacial lobe reached its maximum extent, comparable to the relation of Cascade valley ice and Puget lobe ice in the Snoqualmie-Cedar area described by Mackin (1941). The retreat of valley glaciers during advance of the Puget lobe[5] probably is attributable to several factors, each dependent to a large extent on the presence of a glacier in and north of the Puget Sound lowland. Today, storms approach the lowland from a generally western direction during winter months, and it seems likely that they did so in glacial time. Upon meeting the Vashon glacier, however, the weak storms probably were deflected in a southeastern direction along the glacier margin, just as weak cyclonic storms are deflected along the margins of Greenland today (Flint, 1957, p. 38). This inferred deflection in western Washington would have been caused by the topographic barrier formed by the glacier itself, locally more than a mile thick in the Strait of Juan de Fuca (Bretz, 1920), and by the adjacent Olympic Mountains, and it would have been intensified by a barometric high over the Cordilleran icecap to the north. Stronger storms that continued eastward would have lost much of their moisture in crossing the Olympic Mountains and the broad Puget glacial lobe lying in the lowland to the east, owing to an altitude rise of 3,000 to nearly 8,000 feet and to the cold surface of the glacier itself. By the time these storms reached the west slope of the Cascade Range, they probably were greatly depleted of moisture, and the added cooling associated with rising over the 5,000- to 7,000-foot summit of the range probably did not result in enough precipitation to support large valley glaciers contemporaneous with the maximum of the Puget lobe.

ICE-MARGINAL CHANNELS IN CASCADE FOOTHILLS

A remarkable system of channels cut into bedrock is found along the margin of the Cascade foothills in the Lake Tapps quadrangle and in areas to the north and south; they are particularly well displayed on the topographic maps of the Cumberland and Enumclaw 7½-minute quadrangles and the Ohop Valley 15-minute quadrangle. These channels are generally parallel to the trend of the mountain front and intersect the major stream valleys that drain the Cascade Range at right angles. Few of these channels are now occupied by the major streams, although some contain segments of small local streams, such as Gale Creek and Voight Creek, and others contain swamps.

The ice-marginal origin of the channels is demonstrated by the facts that they are underlain by meltwater deposits and that some required the presence of ice for their formation. This requirement is well illustrated by a channel west of Carbonado whose altitude is about 1,200 feet (pl. 1). This channel is confined between bedrock walls west of Waterhole Creek and east of Lily Creek, but between these two creeks, the channel is unconfined on the north side. Clearly the ice front constituted the north side of the channel when meltwater was flowing through the channel. Similarly, ice was required to block the gap between the two bedrock hills on either side of the Carbon River valley at Carbonado and to have formed the north channel wall east of Carbonado.

The blocking of the Carbon River valley at Carbonado implies that the discharge of the Carbon River was added to melt-water drainage along the margin of the ice sheet, augmented by the discharge of each Cascade Range stream dammed by the glacier, such as South Prairie Creek and the White and Green Rivers. During the maximum of the Vashon glaciation, the combined flow of all those sources occupied the channel that lies along the foothills at an altitude of about 1,200 feet and entered the Fox Creek channel (pl. 2).

The Fox Creek channel is the most spectacular of the ice-marginal channels in the Lake Tapps quadrangle owing to its precipitous walls and depth of as much as 700 feet. Near the headwaters of Fox Creek the channel is blocked by a large earthflow, but stream-scoured bedrock surfaces extend to the floor of the channel to the west.

In sec. 23 a broad bench lies at an altitude of a little more than 1,100 feet on the north side of the channel east of Beane Creek. This bench is cut on bedrock and has deeply scoured channels and rock knobs. It is veneered with gravel less than 10 feet thick, locally consisting only of scattered large boulders resting on bedrock. A similar gravel-veneered bench lies at a slightly lower altitude on the south side of the channel south of Beane Creek. These benches give the Fox Creek channel a two-story appearance, suggesting the possibility that the benches approximately mark the floor of a pre-Vashon channel. The bench on the north side of the channel nearly coincides with the contact of resistant volcanic breccias below and less resistant volcanic sediments above; this lithologic difference alone thus could be responsible for the benches, and the pre-Vashon channel floor could have been below them.

[5] This apparent anomaly was first recognized in the Puget Sound area by Cary and Carlston (1937). J. H. Mackin (oral communication) subsequently suggested the general thesis that Cascade Range valley glaciers were starved by being in the "rain shadow" of the Vashon ice sheet.

The general scarcity of extensive gravel deposits within the channel and the extremely coarse boulder veneer on the bench suggest the presence of a melt-water stream of large discharge. The channel probably was suddenly abandoned when the melt water eventually found a lower discharge route north of Spar Pole Hill.

After cessation of melt-water discharge, Voight Creek probably continued to flow through the channel, following its westward gradient to join the Puyallup River near Puyallup River Junction. Owing to the blocking of the channel by the large earthflow in sec. 24, however, the flow of Voight Creek was reversed, and the creek was forced to find a new course to the north. This course wanders across the surface of a broad kame terrace, is superposed on two bedrock outcrops which the creek crosses in waterfalls, and then becomes incised into the Vashon and Orting drifts and sedimentary rocks of Miocene age in a narrow, steep-walled valley. The fact that a comparably deep valley is not found at the west end of the Fox Creek channel probably indicates that Voight Creek was blocked by the earthflow and found its present course soon after the retreat of the Vashon glacier.

A second deep channel cut into bedrock trends southwestward through secs. 10, 11, 15, 16, and 21 north and west of Spar Pole Hill. This channel seems to be analogous with the Fox Creek channel, but the facts that it is nearly everywhere floored with till and is blocked at the east end by a till drumlin indicate that the channel is of pre-Vashon age, or was cut by melt water during the advance of the Vashon glacier. The channel is conspicuously wider east of Coplar Creek than it is to the west. This wider segment, in sec. 11, is probably a pre-Vashon valley of Voight Creek, now blocked by the till drumlin at the west edge of sec. 12.

RETREAT OF THE PUGET LOBE

Deglaciation of the Lake Tapps quadrangle is represented by a series of melt-water channels that mark successive positions of the ice margin during retreat of the glacier (pl. 2). Extensive stagnant-ice deposits are found only within the valleys of the area, where blocks of residual ice evidently lingered after the adjacent upland areas emerged from beneath the ice sheet. The absence of stagnant-ice deposits on the upland areas suggests that the glacier did not disappear by stagnant-zone retreat, but that the main body of the glacier remained active during wastage.

The initial drainage system along the glacier front occupied a high-level channel and terrace whose altitude is a little more than 1,200 feet to the east of Carbonado (fig. 22) and slightly lower to the west. The local presence of pre-Vashon drift south of this channel suggests that the channel was in existence before Vashon time. The south edge of the channel and terrace is formed by an abrupt scarp about 400 feet high. This scarp is part of a major topographic boundary that approximately follows the contact between glacial deposits of northern provenance on the north and older drift of Cascade provenance on the south.

Subsequent to withdrawal of the Puget lobe from its maximum stand and draining of the lake that occupied the Carbon River valley, coarse gravel originating in a Carbon valley glacier was again deposited in the valley. This valley glacier probably was considerably shorter than the valley glacier of Evans Creek time; the provenance of its outwash reflects a greater proportion of ice from Mount Rainier than does the Evans Creek drift. Upon further northward retreat of the Puget lobe, the Carbon River started to cut down toward its present bed, which locally is 200 to 300 feet below the outwash gravel.

During initial northward retreat of the Puget lobe, drainage flowed to the southwest through the Fox Creek channel and thence southward along the ice margin. Successive lower stands of the glacier terminus during this interval are indicated by several ice-marginal channels and ice-contact deposits along the foothills (pl. 2). At this time, with the glacier blocking drainage into Puget Sound, melt water and drainage from the Cascade Range flowed southwestward to the Pacific Ocean by way of segments of the Nisqually, Des Chutes, and Chehalis River valleys (Bretz, 1913) (fig. 14).

Upon further retreat of the ice margin, the Fox Creek channel was abandoned, and melt water flowed along the margin of the foothills around the northern end of Spar Pole Hill (pl. 2). At this time the Carbon and Puyallup River valleys east and south of Orting were still filled with masses of residual ice, and southward drainage was along a path marked by a kame terrace at an altitude of 600 to 700 feet between Coplar Creek and the south edge of the quadrangle. As this ice melted, it was replaced by a small early stage of Lake Puyallup (Bretz, 1913, p. 126–128) that lengthened as the margin of the Puget lobe withdrew northward. The lake initially discharged southward along the Ohop Valley (fig. 14) across a spillway that now lies at an altitude of about 550 feet or a little less beneath Lake Kapowsin and the Electron mudflow. Subsequent withdrawal of the ice margin uncovered a depression west of Orting whose floor was at a lower altitude than the spillway into the Ohop Valley. The higher southern part of the depression west of Orting seems to have been used by ice-marginal outwash streams while the area to the north was still occupied by ice

FIGURE 22.—View of Carbon Gorge upstream from Carbonado and Mount Rainier in distance. The Lily Creek formation crops out in upper part of scarp at the right. The scarp was cut by ponded melt water escaping from the Carbon River valley upstream from this point during and shortly after the maximum stand of the Puget lobe in the Vashon glaciation.

(p. 44). The northern part of the depression, the Kirby channel [6] (pl. 2, fig. 14), subsequently carried discharge of Lake Puyallup westward toward a broad expanse of outwash, the Steilacoom Plains of Bretz (1913, p. 136–137), that extends with minor interruptions to the Nisqually River and Puget Sound southwest of Tacoma (fig. 14). The west edge of this plain consists, in part, of deltas that were built into glacial Lake Russell.

While the lower part of the Kirby channel served as the outlet of Lake Puyallup, the ice margin of the Puget lobe temporarily lay along a line trending generally east-northeast from the vicinity of the mouth of Fennel Creek to a point about 1 mile north of Enumclaw. Melt water flowing parallel to this ice front was contained on the south by a scarp that extends northeastward from the community of Osceola. Melt water flowed along this channel across the position of the present White River and joined the Fennel Creek channel. Later, a lower southwestward-trending channel that also joined the Fennel Creek channel, may have crossed the present White River in secs. 12 and 13. Melt water flowing down the Fennel Creek channel discharged into Lake Puyallup and formed a delta (pl. 2). A wide southward swing of the channel just east of this delta probably is of ice-marginal origin and perhaps was caused by a minor readvance of the ice margin at this place. A subsequent change in course of the melt waters to a position nearly coincident with the gorge of Fennel Creek probably was caused by a slight withdrawal of the ice margin; this withdrawal probably also uncovered a lower outlet of Lake Puyallup south of Sumner (fig. 14), which caused the Kirby channel to be abandoned. While melt water still used the Fennel Creek channel, however, an even lower outlet was uncovered south of Puyallup, the Clover Creek

[6] The Kirby channel was named after Kirby School in the Tacoma South quadrangle by J. W. Robinson and A. N. Piper, U.S. Geological Survey (written communication).

channel of Bretz (1913, p. 128) at an altitude of about 360 feet. A level of Lake Puyallup at the altitude of this outlet is shown by a delta surface near the mouth of Fennel Creek.

With the subsequent uncovering of a still lower outlet, the South Tacoma channel at an altitude of about 230 feet, the history of glacial Lake Puyallup came to an end (Bretz, 1913, p. 128). This event coincided with a northward retreat of the glacier margin that resulted in the abandonment of the Fennel Creek channel in favor of a more northward course that joined the Duwamish Valley near Auburn. Although a glacial lake persisted in the Puyallup Valley (Lakes Tacoma and Russell of Bretz), no visible evidence of the lower lake levels is known in the Lake Tapps quadrangle.

Evidence of later lake levels during northward recession of the Puget lobe probably is buried beneath the Puyallup Valley floor. Fresh-water lakes persisted in the troughs of the Puget Sound lowland until the glacier melted out of the Strait of Juan de Fuca and permitted invasion of sea water.

Drillers' logs of wells drilled in the Puyallup Valley floor west of Sumner record the presence of shells below present sea level at several places. One of these places is southwest of Sumner in sec. 35, where a well (Sceva and others, 1955, p. 244) penetrated shells at a depth of 146 feet, 81 feet below sea level. The shells were not identified, but it seems probable that they are marine, inasmuch as marine shells have been found about 75 feet below sea level in the Duwamish Valley near Kent (D. R. Mullineaux, oral communication). How far up the Puyallup Valley marine water extended is not known; alluviation by the Carbon and Puyallup Rivers presumbly began as soon as the valley was free of ice, and the mouth of the rivers probably had reached a point between Orting and Sumner when marine water first entered the lowland.

RECENT TIME

PRE-OSCEOLA COURSE OF THE WHITE RIVER

The position of the present valley of the White River apparently was determined by the Osceola mudflow, and this river seems to have formerly occupied the valley of South Prairie Creek in part. Evidence that the White River is not now in its premudflow position is as follows: (1) Nowhere in exposures along the valley walls of the White River is Osceola mudflow banked against Vashon drift or older formations in a way that would suggest that the mudflow is filling a valley in older deposits. Instead, the mudflow rests on a gently undulating surface underlain by Vashon drift; (2) nowhere along the valley walls does the mudflow overlie sand and gravel that could be inferred to be White River alluvium of pre-Osceola age; (3) the presence of a soil profile almost everywhere below the mudflow along the valley walls of the White River strongly implies that the deposit is resting on a former upland drift surface rather than on a flood plain.

It might be inferred that the White River could have had a previous course on one side or the other of the present valley, which joined the present valley somewhere downstream from Buckley. Because of extensive deposits of mudflow and terrace alluvium of the White River upstream from Buckley, this possibility cannot be disproved. Outcrops of Vashon drift in the walls of the White River valley, however, rule out the possibility that such a postulated former course might have joined the present valley downstream from Buckley.

The most conclusive evidence that the White River occupied the valley of South Prairie Creek before the mudflow occurred is the presence at several localities in the valley of South Prairie Creek of remnants of the Osceola mudflow underlain by sand and gravel predominantly of Mount Rainier provenance. Deposition of this sand and gravel required the presence of a stream that headed on Mount Rainier, and, inasmuch as South Prairie Creek itself has its headwaters in the Cascade Range, this stream could only have been the White River.

Collapsed kame-terrace deposits that locally extend down both sides of the South Prairie Creek valley indicate that this valley was as wide or wider just before the Vashon as it is today. Inasmuch as the widest part of the valley lies at right angles to the direction of glacier movement, probably little or none of this widening can be attributed to scouring by the Vashon glacier. The width of the valley suggests the presence of a major stream before the Vashon glaciation, and it seems likely that the valley was occupied by the White River after the Wingate Hill glaciation.

The White River probably flowed into the valley of South Prairie Creek through the gap that trends southwestward through secs. 11 and 15 southeast of Buckley and, joining the Carbon River downstream, entered the Puyallup Valley south of Orting. If the White River did follow this route, then the present valley of the White River must have been excavated entirely in post-Osceola time.

OSCEOLA MUDFLOW

About 4,800 years ago the Osceola mudflow flowed down the valley of the White River from Mount Rainier. About 4 miles east of Buckley, the mudflow entered the narrow gorge at the south end of Mud Mountain (fig. 19), where restricted flowage caused ponding of the mud upstream to the level of a wide, natural spillway, the top of Mud Mountain. Mud spilling over this threshold took two principal paths to the lowland, northwestward down the valley of Boise Creek to emerge on the lowland drift plain east of Enumclaw and westward down the valley of the White River to the plain east of Buckley. After leaving these confining valleys, the mud spread on the surface of the Vashon drift and covered some 65 square miles to depths of as much as 75 feet. A large volume of mud followed the course of the White River into what now is the valley of South Prairie Creek, temporarily filled this valley to a depth of about 200 feet east of Burnett, and spilled out to the south along a melt-water channel. A short distance to the south it intersected the valley of Wilkeson Creek, where part of the mud backed up the valley to the town of Wilkeson, and part flowed down the valley to rejoin the mudflow in the South Prairie Creek valley. Mud flowed down this valley at least as far as the confluence of South Prairie Creek and the Carbon River, and it may have extended out into the Puyallup Valley.

Because the route to the valley of South Prairie Creek was not directly in the path of the westward- and northwestward-rushing mudflow, the principal mass by-passed this valley and poured out on the Vashon drift plain, inundating all but the higher topographic features. Owing to its great mobility the mud flowed between closely adjacent drumlins of till leaving them as islands in a lake of mud. Channels in the drift surface diverted large volumes of the mudflow to form lobes that reached many miles beyond the main body of the flow. The most prominent of these followed the valley of Fennel Creek and entered the Puyallup Valley between McMillin and Alderton. Some well-drillers' logs (Sceva and others, 1955, well 20/5–30E1, p. 246, and well 19/5–6E2, p. 187) indicate that the mudflow locally is as thick as 97 feet beneath the flood plain here; this implies that when the Osceola mudflow occurred, Puget Sound still occupied the Puyallup Valley as far upstream as Alderton. This inference is further supported by evidence found by D. R. Mullineaux (oral communication) that the Duwamish Valley floor was below sea level between Renton and Kent just before formation of the Osceola mudflow.

The fact that the Osceola everywhere seems to consist of a single unit is taken as evidence that the entire mudflow was emplaced before any part of it became consolidated and that the mudflow probably spread to its fullest extent on the lowland in a short time, in hours or, at most, a few days.

By blocking existing drainage courses, the mudflow locally caused ponding and diversion of streams to new courses. The most important was the diversion of the White River from the valley of South Prairie Creek to its present course. This valley now trends westward and then northwestward, and its position may have been determined by a low area between the two mudflow lobes that entered the lowland east of Buckley and east of Enumclaw, respectively. It is possible, however, that this course was determined by depressions on the surface of the Vashon drift. With gradual dilution of the mudflow and subsequent change to a condition approaching that of a normal stream, the White River became established in the new course, and the former route to the valley of South Prairie Creek was abandoned.

Prior to the mudflow, Newaukum Creek probably flowed southwestward into the Puyallup Valley by way of the present channel of Fennel Creek, a course inherited from a melt-water channel formed during Vashon deglaciation. Newaukum Creek now turns to a northern course just northwest of Enumclaw, and follows a consequent course on the mudflow surface to the Green River valley.

The initial difficulty of the White River in downcutting in the mudflow is shown by terraces cut by the river as it swung against its embryonic valley walls. Doubtless, at first, the river was nearly fully loaded with mud and debris eroded from its banks. The downstream transport of this material, as well as subsequent removal of the underlying deposits, has contributed a very large volume of sediment to the Puyallup and Duwamish Valleys in the last 4,800 years and probably has been the chief source of alluvium that aggraded the valley above sea level (D. R. Mullineaux, oral communication).

A minor blocking of drainage occurred where a "backwater" of mudflow appears to have temporarily blocked the valley of Gale Creek, just upstream from Wilkeson. This mudflow dam has since been cut through by Gale Creek, but peat deposits remain on the valley floor.

The area occupied by the original Lake Tapps (p. 4) seems to have consisted of several southeastward-trending stream valleys which drained into Fennel Creek in sec. 23, north of Printz Basin. Although the raising of the lake level has inundated the critical area, it seems likely that this drainage was dammed by the western margin of the Osceola mudflow in secs. 16 and 21 to create Lake Tapps.

ELECTRON MUDFLOW

The Electron mudflow traveled down the Puyallup River valley about 500 years ago. This mudflow aggraded the floor of the Puyallup Valley south of

McMillin with about 15 feet of mud and rock, but its volume was not sufficient to carry the mudflow past Sumner. North of McMillin the mudflow thins and becomes discontinuous, and north of Alderton it is confined to a single narrow channel in the flood plain.

North of Alderton, the Electron and Osceola mudflows are separated by 10 or 12 feet of sand and gravel, representing valley aggradation in response to lengthening of the valley floor as the Puyallup River extended its course into Commencement Bay.

An interesting side effect of the Electron mudflow was the creation of Lake Kapowsin, 1 mile south of the quadrangle, by damming a valley tributary to the Puyallup at Electron (fig. 23). Lake Kapowsin is a body of water about 2.5 miles long and from 0.15 to 0.5 mile wide which lies within a channel cut by melt water during recession of the Puget lobe. The lake is fed chiefly by Ohop Creek and is drained by Kapowsin Creek.

The basin of Lake Kapowsin reaches a maximum known depth of 30 feet and is for the most part 20 to 30 feet deep. In the southern half of the lake, the bottom is remarkably flat; the lake has a depth of 28 feet for a distance of 1,000 feet eastward from a point 300 feet east of the shoreline at Voss Resort. To the south the lake bottom gradually rises, and to the north, the lake deepens to its maximum about 1,200 feet northeast of the shoreline at Voss Resort and then gradually becomes shallower northward.

Very little peat was found on the bottom of the lake; at the north end of the lake the maximum thickness found with a peat borer, in an examination of eight localities, was about 6 inches. Owing to the difficulty of boring at depths of 20 to 30 feet with the equipment available, bottom conditions of the middle and southern parts of the lake were not investigated with the borer. Mudflow was found everywhere on the bottom at the north end of the lake, but how far to the south it extends was not determined.

There are many large stumps in the lake, particularly in the southern part where some of them extend above the lake. The largest of these noted is 5 feet in diameter at the lake surface at a point where the lake is 22 feet deep. According to a local resident, many of the submerged trees were cut off above the lake surface during the "early days."

Bretz (1913, p. 127) suggested that Lake Kapowsin had been formed by the damming of the Ohop Valley melt-water channel by an alluvial fan built by Ohop Creek across the channel. The lowest point on this fan, determined with an altimeter, is at an altitude of about

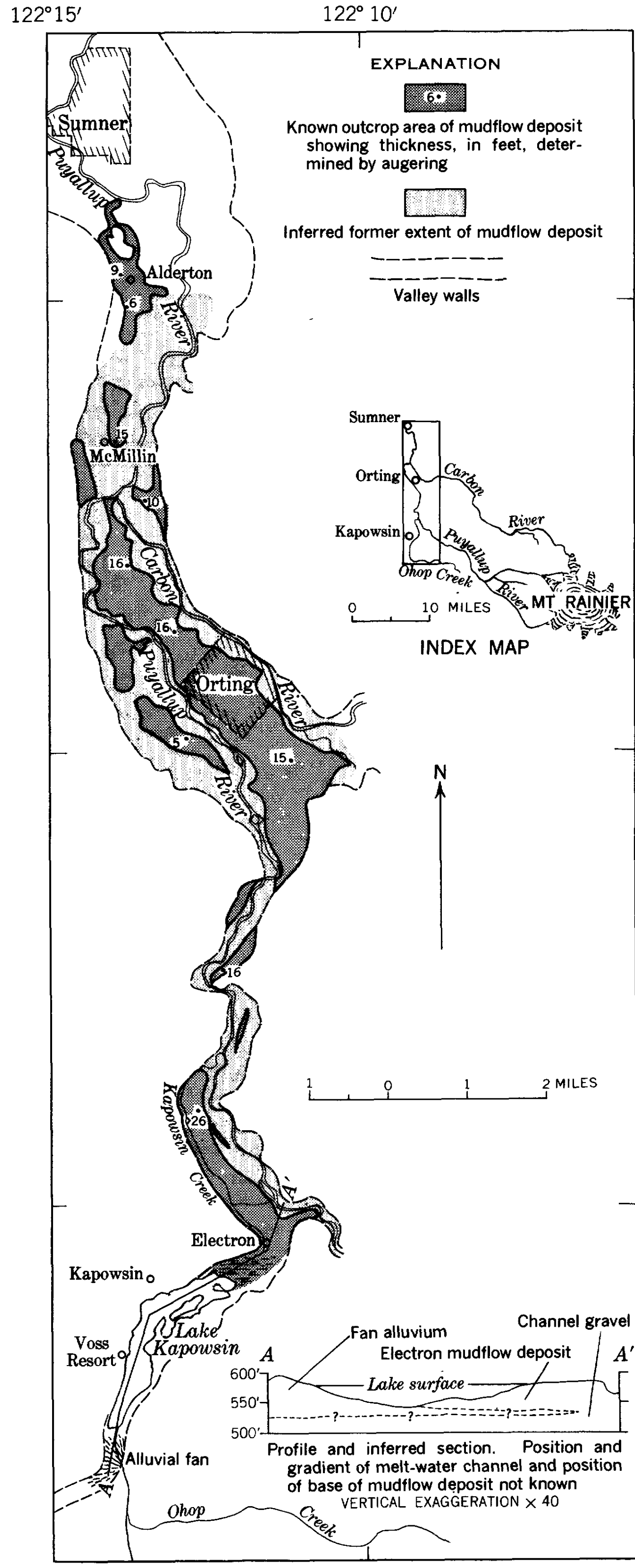

FIGURE 23.—Map showing the distribution of the Electron mudflow in Puyallup Valley and section showing the relation of the mudflow to Lake Kapowsin.

600 feet; the level of the lake in October 1957, was about 581 feet. It does not seem probable that Lake Kapowsin has ever discharged across the present Ohop Creek fan; if a lake did exist in the melt-water channel prior to the mudflow, it must have had a short life, terminated by alluviation by Ohop Creek. The existence of a drowned forest in Lake Kapowsin suggests that, by the time the present lake was formed, the initial basin had been filled and a mature forest was growing on the site. By this time, the part of the melt-water channel north of the Ohop Creek alluvial fan drained northward into the Puyallup River.

When the Electron mudflow came down the valley of the Puyallup River from Mount Rainier, it aggraded the valley floor to a depth of probably at least 30 feet. Some of the mudflow backed southward into the northern part of the melt-water channel; the depression that remained between the toe of the mudflow and the north slope of the Ohop Creek fan formed the present basin of Lake Kapowsin. Because the top of the mudflow reached an altitude of only 583 feet at Electron, the lake spilled out to the north rather than across the higher outlet to the south across the fan. The outlet stream, Kapowsin Creek, probably followed the west margin of the mudflow because of the convexity of the mudflow surface.

CORRELATIONS

The initial detailed work on Pleistocene stratigraphy in the Puget Sound lowland by Willis (1898) revealed the presence of two major glacial stages, the Admiralty, probably of pre-Wisconsin age, and the Vashon, considered to be equivalent to the Wisconsin stage. The multiple nature of pre-Vashon glacial stages in the lowland subsequently was documented by Hansen and Mackin (1949), and both Page (1939) and Anderson (1950) recorded the multiplicity of pre-Wisconsin valley glaciation in the Cascade Range. Slow progress was made, however, on subdivision of the Pleistocene deposits in the lowland, owing to the absence of widespread weathering profiles, inability to differentiate pre-Vashon deposits by their intrinsic characteristics, and only sporadic occurrence of nonglacial deposits between the drifts. Owing to these difficulties, recent work in the lowland locally has failed to reveal any evidence of an invasion of northern ice before the Vashon glaciation (Newcomb, 1952).

The presence in the southeastern part of the lowland of thick and relatively continuous nonglacial sediments of distinctive lithologic character between drift units derived from the north made possible detailed subdivision of the Pleistocene drift sheets, and showed that the several glaciations were separated by intervals of climate similar to that of the present (Crandell, Mullineaux, and Waldron, 1958). The glacial and nonglacial intervals of the Puget Sound lowland are inferred to represent stages, probably comparable in duration to the Pleistocene stages of the midwestern United States. This inference is based on such relations as complexity of individual glaciations, thickness of weathering profiles on unconsolidated sediments, amount of erosion during nonglacial intervals, and evidence of climate and climatic trends between glaciations. No valid estimate can be made of the actual number of years involved in any one stage, but the available record clearly demonstrates four glacial stages in the lowland, separated by three interglacial stages.

The record of the Orting glaciation in the Lake Tapps quadrangle is relatively simple: only one major advance of the Puget glacial lobe can be demonstrated. North of this area, however, the Orting drift includes at least two and possibly three till sheets separated by lacustrine and fluvial sediments (D. R. Mullineaux, oral communication). The Orting glaciation thus may include two or more glacial advances, probably of early Pleistocene age.[7]

Deposits inferred to be of early Pleistocene age south of the Puget Sound lowland have been described in the Centralia-Chehalis area by Snavely and others (1958) and in the Toledo-Castle Rock area by Roberts (1958), and they have been named the Logan Hill formation (Snavely and others, 1951). This formation consists of gravel, sand, and till, locally weathered to depths of 25 to 50 feet, and probably represents a glaciation of the Cascade Range and its western foothills. Most of the formation consists of gravel which was deposited in extensive piedmont alluvial fans along the western margin of the range. In this respect, the Logan Hill formation resembles and may be in part correlative with the stream gravel of central Cascade provenance of early Orting age which is inferred to have originated as an alluvial plain built out into the Puget Sound lowland by streams draining the Cascade Range prior to the advance of the Orting glacier.

After the retreat of the Orting glacier, the climate of the lowland became warmer and eventually reached conditions comparable to those of today; by comparison with the time required for comparable climatic warming after the Vashon maximum, this warming trend in Alderton time probably took place over a period of at least 8,000 years. Because only a part, perhaps a small

[7] The term "early Pleistocene" as used here refers to early in the glacial part of the Pleistocene as recorded on the continents, although this part of the Pleistocene may constitute less than half of the elapsed time between the end of the Pliocene and the present (see Emiliani, 1955).

part, of Alderton time is represented by sediments, the Alderton probably represents a major interglacial interval.

The Stuck glaciation in the Lake Tapps quadrangle seems to have consisted of a single event: the advance and withdrawal of the Puget glacial lobe, comparable to the single advance of the lobe during the Vashon glaciation. North of the quadrangle, however, the Stuck glaciation includes two advances (Mullineaux, Crandell, and Waldron, 1957).

The Puyallup formation represents part of the post-Stuck nonglacial interval, during which the climate again became comparable to that of the present. The early part of this interval involved a far more complex forest succession and contained more major cool phases than did the warming of early post-Vashon time in the lowland (Leopold and Crandell, 1957, p. 79). This suggests that the early part of the Puyallup interglacial interval occurred over a longer period of time than did the warming interval after the Vashon glaciation.

Formation of the Wingate Hill surface and deep weathering of the Lily Creek formation (Puyallup equivalent) in the Cascade foothills similarly implies elapse of much time after deposition of the sediments, although part of the weathering profile probably dates from post-Puyallup time. Deposition of the Puyallup formation, like the Alderton formation, probably represents only a fraction of the entire interglacial interval, and it likely was followed by a long period of erosion and weathering in the lowland.

The Salmon Springs drift was deposited during two distinct advances of the Puget glacial lobe, separated by a nonglacial interval during which the climate warmed appreciably. This interval probably had a duration of at least several thousand years and suggests that the Salmon Springs drift includes the deposits of three substages. Radiocarbon age determinations indicate that the nonglacial sediments are older than 37,000 years; thus the Salmon Springs is older than the "classical" Wisconsin of the Midwest.

The Wingate Hill icecap glaciation of the Cascade Range antedates the Vashon glaciation and is inferred to precede "classical" Wisconsin. Because of the absence of deep weathering on the Wingate Hill drift, however, this drift is probably younger than the Sangamon interglacial stage.

The Vashon glaciation has generally been regarded previously as correlative with the Wisconsin stage owing to the immature weathering profile on Vashon drift and lack of substantial erosional modification of the drift surface.

John Fyles (oral communication, 1957; see Olson and Broecker, 1959, p. 10–11) of the Canadian Geological Survey, found nonglacial sediments deposited during cool, moist conditions on and adjacent to Vancouver Island, British Columbia, between 32,300±1,800 (L–424B) and 23,450±300 (L–221C) years ago. Inasmuch as these sediments accumulated in an area which would have been covered by ice early in the Vashon glaciation, the advance of the Puget lobe down the Puget Sound lowland probably began subsequent to 23,000 years ago.

Waldron, Mullineaux, and Crandell (1957) inferred from radiocarbon dates on basal peat from bogs on Vashon drift that deglaciation began not less than 14,000 years ago and that the maximum extent of the Vashon glacier was reached at a time possibly correlative with the Tazewell substage of the midwestern United States. This view is supported by the dating of limnic peat below the floor of Lake Washington (Rigg and Gould, 1957, p. 357) as 13,650±550 years (L–346A) and 14,000±900 years (L–330) (Broecker and Kulp, 1957, p. 1325). This peat postdates retreat of the Puget lobe by a time interval long enough for the glacier to melt back to the Strait of Juan de Fuca and permit marine water to invade the lowland, and for conversion of the Lake Washington basin from marine to fresh-water conditions by delta building at its south end. In view of these events, the Vashon glacier probably began to retreat at least 15,000 years ago.

ECONOMIC GEOLOGY

The chief resource in the surficial deposits used at present is sand and gravel, although future use may be made of peat and clay. Other natural resources of the quadrangle, such as coal, building stone, and bedrock suitable for riprap, concrete aggregate, and road metal will be discussed in a separate report on the bedrock of the quadrangle by L. M. Gard, Jr.

SAND AND GRAVEL

Sand and gravel deposits are abundant in the part of the quadrangle covered by the Vashon glacier, except for areas subsequently inundated by the Osceola mudflow. Because of their distance from areas of extensive construction, sand and gravel deposits have been exploited only to a small extent up to now, but continued growth of the Seattle-Tacoma metropolitan area undoubtedly will require greater use of these deposits in the future.

Proglacial stratified drift is, in general, a better source of sand and gravel than are ice-contact deposits, owing to the common occurrence of boulders, masses of till, and wide variations in grain size from place to place in the ice-contact deposits. Of the several types of proglacial sand and gravel, deltaic deposits probably are the best sorted and contain the fewest boulders and other undesirable components. Gravel in pre-Vashon formations generally is iron stained and many component pebbles are soft or readily disintegrate, making the deposit unsuited for most purposes. The thick deposits of gravel in the Orting drift are regarded as particularly unsuitable for concrete aggregate or road metal because they are so severely weathered.

The only sand and gravel deposit being exploited in the Sumner 7½-minute quadrangle, while fieldwork was in progress, is a deltaic deposit in the east wall of the Puyallup Valley east of Sumner. The lateral limits of this delta are not exposed, and it seems likely that the gravel is banked against a pre-Vashon valley wall, cut into oxidized and weathered gravels in the Stuck and Salmon Springs drifts. In the opinion of the writer, the largest and best undeveloped source of gravel in this quadrangle is the delta deposit along the east Puyallup Valley wall south of Fennel Creek.

No gravel is currently being excavated on a large scale in the Orting 7½-minute quadrangle, although abundant supplies exist in the kame terraces. Material from pits in the west face of the kame terrace south of Fiske Creek, in sec. 20, T. 18 N., R. 5 E., has been used as aggregate for bituminous highway surfacing. Gravel from higher kame terraces in secs. 27 and 28 has been used rather extensively for road metal in the foothills. In the foothills above the limit of the Puget lobe, where gravel is virtually nonexistent, road metal is needed owing to the fine grained plastic nature of soils present in Wingate Hill drift, the Lily Creek formation, and volcanic breccia. Most road metal in this area must either be hauled from deposits of Vashon drift or prepared by crushing fresh bedrock.

Gravel is scarce in the southern part of the Wilkeson 7½-minute quadrangle, but large supplies are available in the extensive kame-terrace deposits in the northern part. The only known source of sand and gravel south of Carbonado is the alluvium of the Carbon River underlying the present flood plain. Gravel in the Evans Creek drift is mostly unsuited as a source of road metal, unless crushed, owing to its large content of cobbles and boulders.

In the Buckley quadrangle, gravel must be hauled several miles for road surfacing in some areas on the Osceola mudflow plain, although melt-water deposits are conveniently located at the margins of the plain in many places. In this quadrangle, most of the gravel currently used north of the White River comes from the kame field north of Enumclaw. Deposits of kame-terrace gravel in sec. 12 northwest of South Prairie and sec. 8 northeast of South Prairie have been used for road surfacing in recent years. Terrace alluvium in the White River valley is not regarded as a suitable source of road metal owing to the fact that the upper 10 to 15 feet of the deposit is a clayey sand in most places, and the underlying gravel commonly is very bouldery.

CLAY

Two sources of clay formed by weathering exist in the quadrangle. These are parts of the Lily Creek formation and volcanic breccia that have been exposed to weathering for a long time in places that have been protected from erosion. Weathering of the volcanic breccia seems to be largely a product of pre-Lily Creek time, and deeply weathered bedrock in the Lake Tapps quadrangle generally is found only where it has been protected from erosion by the Lily Creek formation. A deep profile of weathered material probably once was present on the Lily Creek formation throughout its outcrop area as a residual weathering product, but subsequent erosion by the Wingate Hill glacier and by streams has left only scattered remnants of this profile.

Some of the residual clay deposits of the quadrangle have been investigated for their suitability as sources of refractory clay by the Bureau of Mines (J. G. Schlagel, mining engineer, Division of Mineral Technology, written communications to H. J. Kelly, chief, Division of Solid Fuels Technology, Region I, January 1, 1959). The information on refractory grades of clay given in the following sections has been taken from this communication.

Glover (1941) discusses the origin, classification, and physical properties of clays and describes their occurrence in King and Pierce Counties.

VOLCANIC BRECCIA

Residual clay in volcanic breccia is limited to the area between Voight Creek and the Puyallup River. East of Voight Creek the bedrock is principally sandstone, shale, and coal; west of the Puyallup River, bedrock is buried by glacial drift.

A readily accessible outcrop of deeply weathered breccia is adjacent to Beane Creek in the SW¼NW¼ sec. 23 on the south side of Spar Pole Hill. This deposit probably is fairly extensive below the 1,400-foot contour on the east side of Beane Creek in the NW¼ sec. 23 beneath thin deposits of Vashon drift, although drilling will be required to outline the deposit. A preliminary analysis of this clay made by the Bureau of Mines indicated that it has a pyrometric cone equivalent (P.C.E.) rating of less than 19 and is nonrefractory.

Clay beds exposed in the valley floor of Kings Creek in the NW¼SE¼ and SW¼NE¼ sec. 34 also are weathered breccias. These deposits are partly of nonrefractory grade and partly of low (P.C.E., 19 to 26) to medium (P.C.E., 27 to 30) refractory grade.

LILY CREEK FORMATION

Clay deposits formed by weathering of the Lily Creek formation are exposed on the eastern slope of Cowling Ridge and in the area between Cowling Ridge and the Carbon River valley. Because of widespread cover of Wingate Hill drift in this area, the Lily Creek formation seldom is exposed except in artificial excavations. On the west side of a logging road in the SW¼NW¼ sec. 30, T. 18 N., R. 6 E., the Lily Creek has been weathered to a residual low-refractory clay, at least 6 feet thick. Deposits examined by Schlagel along this same road in the NE¼NE¼ sec. 25, a short distance northwest of the outcrop just described, contain nonrefractory clay and high- and low-refractory clay.

X-ray analyses indicate that halloysite, a member of the kaolinite clay-mineral group, is the most common clay mineral in the deeply weathered Lily Creek formation.

VASHON DRIFT

A small deposit of laminated silt and clay of Vashon age in the NW¼SE¼ sec. 7, southeast of Dieringer, was used for making half a million or so common bricks about 1890, according to a local resident. These bricks were made by hand and, after drying in the sun, were fired for about 2 weeks in open-hearth kilns. The silt and clay are exposed over till near the road junction at this locality, and it is inferred that the deposit was formed in an arm of Lake Puyallup during recession of the Vashon glacier. Its maximum thickness is about 20 feet.

FILL MATERIAL

The physical properties of most fill material generally are of secondary importance to nearness of the material to the fill site. Because of the costs involved in long-distance haulage of common fill, barely suitable materials frequently are used simply because they are available nearby. Till and sand and gravel in the Vashon drift probably are the most desirable fill materials in the quadrangle, but the compactness of the till is a deterrent to easy excavation. Formations of pre-Vashon age probably will seldom be used as fill in the lowland, because nearly everywhere they are overlain by a thick overburden of Vashon drift. Sand and gravel in these formations is easily excavated, but interbedded very compact till and mudflows are excavated only with difficulty even with mechanized equipment.

The Osceola mudflow is used extensively for fill in highway construction, but its low plasticity index of 2 makes it necessary to control moisture content carefully during fill emplacement. Once the fill is emplaced and dried out, the material seems to become stable if it is kept well drained. When certain fine materials are disturbed, they lose internal strength and turn into viscous liquids even though the moisture content remains unchanged. This property is known as sensitivity, and an increase of internal strength after such material comes to rest is known as thixotropy. The behavior of the Osceola when it is worked with power equipment may be explained in part by sensitivity and thixotropy of the fine fraction in the deposit, although these properties are modified by the presence of coarser material in the mudflow. The Osceola is easily excavated, and very large boulders are generally found only in the lower half of the deposit; these may be as large as 5 to 10 feet in diameter.

The Electron mudflow probably has characteristics similar to those of the Osceola, but because it forms wide expanses of the Puyallup Valley floor, it has not been extensively used for fill material.

The Wingate Hill drift is regarded as a poor source of fill except in places where its usual overburden of volcanic ash and mixed ash and till is not present or where they can be readily removed. The parent material of the drift is compact bouldery till which is found at depths of a few feet to 15 feet below the surface.

The Lily Creek formation also is a poor source of fill, because it is difficult to excavate where it is unweathered, owing to the presence of many very compact mudflows. Where it is weathered, the abundance of clay makes the formation undesirable.

TRAVERTINE

A small deposit of "lime" was reported by Willis and Smith (1899) in the SE¼SW¼ sec. 7, about 0.6 mile east of McMillin; at the time of their investigation the deposit already was nearly exhausted. Willis and Smith suggested that the "lime" is a hot-spring deposit which formed on top of Vashon gravel of Vashon age. The travertine forms cellular and botryoidal masses on top of and within delta gravel, which it cements. Flowing springs are not now present at this locality, although the travertine is demonstrably of post-Vashon age. This occurrence of travertine is unique in the area, and inasmuch as no rocks or sediments rich in calcium carbonate are known in this part of the lowland, the source of the deposit is an unsolved problem.

PEAT

Deposits of peat formed in Recent time are common along the margins of natural lakes in the quadrangle, but only one had been exploited at the time of this investigation. This is a small bog deposit in sec. 5, northwest of Lake Tapps, where the peat is about 10 feet thick and rests directly on till on the margins of the bog and on clay in the central parts of the bog. Some of the the other Recent peat deposits of the area are described elsewhere in this report (p. 52) and by Rigg (1958).

The thickest bed of peat seen within Pleistocene sediments is in the SE¼NW¼ sec. 21, T. 18 N., R. 5 E., where Fiske Road crosses Fiske Creek. Here a compact peat bed, 11.5 feet thick, in the Puyallup formation. is overlain by sand of Mount Rainier provenance and underlain by a bed of clay, 1 foot thick. Its areal extent is not known.

ENGINEERING GEOLOGY

The relation of geology to several engineering problems is discussed in the following sections in the hope that an understanding of the cause of certain problems will help in determining solutions. The engineering properties of map units in the quadrangle have not been investigated in detail; some of these properties, however, are discussed in an "Engineering Soils Manual" (McLerran and Krashevski, 1954) which is used in conjunction with the Soils Survey maps of King and Pierce Counties (Paulson and others, 1952; Anderson and others, 1955).

FOUNDATION CONDITIONS

The wide range of foundation conditions that exists in the surficial deposits of the Lake Tapps quadrangle depends in large part on the subsequent history of the deposits as well as their original physical properties. Most units of pre-Vashon age have undergone consolidation, owing to compaction by one or more overriding glaciers. These units therefore have high-bearing strength, as do also till and gravel deposited during the advance of the Vashon glacier. Sand and gravel deposited during recession of the glacier, however, have not been compacted in this manner, although the loads of highways and small buildings in the quadrangle do not seem to have exceeded the bearing capacity of these materials. Materials with the lowest bearing strength include Recent lacustrine sediments, fine alluvium underlying the floors of the Puyallup and Duwamish Valleys, and the Osceola mudflow.

The Osceola mudflow becomes highly unstable when disturbed and when near its liquid limit, which ranges from 22 to 30 percent; seemingly the bearing strength of the deposit would be low in areas of a high water table. Buildings in such areas on the mudflow, however, seem to have stable footing and show no signs of settling. This apparent anomaly seems to be best explained by the presence of a zone 10 to 12 feet thick, in the upper oxidized part of the deposit, which is cemented with iron oxides and perhaps also with secondary silica leached from the upper 2 or 3 feet of the mudflow (fig. 24). Most construction to date in areas underlain by the mudflow has been within this oxidized and cemented zone, and evidently this zone has sufficient bearing capacity for most light construction. The largest building in Buckley, for example, is the brick high school. Inspection of the lower walls of this building in 1959 by the writer, accompanied by H. Wade Leroy, Buckley City Engineer, revealed no excessive cracking that might be related to subsidence, although the foundation of the building is within the upper part of the Osceola mudflow.

FIGURE 24.—Exposure of Osceola mudflow overlying Vashon drift in the north wall of the White River valley in the SW¼ sec. 34, north of Buckley. The cemented zone of the mudflow above the dashed line forms a somewhat more resistant layer in the upper 10 feet of exposure. Vashon drift includes till and overlying sand and pebble gravel.

During construction of new buildings at the Rainier State School east of Buckley several years ago, unoxidized mudflow in excavations for footings below the oxidized zone of the mudflow was found to have practically no bearing strength under unconfined compression (D. T. Carroll, of the Naramore, Bain, Brady, and Johanson Architectural Firm, Seattle, oral communication). According to Mr. Carroll, the width of footings was increased as much as 100 percent in places, and excavations for the footings were completely plugged with concrete on the assumption that, if the mudflow were not compressible and if it could not squeeze upward around the footings, the deposit would support the loads placed upon it.

The writer observed the low-bearing strength of the mudflow in an excavation near a sawmill southwest of Buckley. In this excavation a sharp horizontal boundary about 10 feet below the original ground surface could be seen between oxidized material above and unoxidized mudflow below. The unoxidized mudflow was so "soupy" that it would sink beneath the feet of a person walking on it.

It seems probable that the oxidized and cemented zone in the upper part of the mudflow represents the maximum range in height of the water table and that the cementation is largely the result of seasonal alternations of moisture conditions that promote excessive oxidation, hydration, and dehydration (Anderson and others, 1955, p. 82–83).

In order to avoid foundation problems, excavations made in areas underlain by the Osceola mudflow should not be made deeper than about 8 feet in order to keep footings above the unoxidized part of the deposit. Footings probably also should be widened as the lower limit of the oxidized zone is approached.

Excavation and construction below the oxidized zone should be avoided unless preliminary test drilling indicates the presence of firm material at shallow depths below the mudflow.

The Electron mudflow is impregnated and partly cemented with secondary iron oxides throughout its entire thickness in most places where not overlain by later deposits, although nowhere is the deposit as firmly cemented as is the upper part of the Osceola mudflow. The writer is not aware of any foundation problems in the Electron mudflow and suggests that its bearing characteristics are as good as those of the fine alluvium of the valley floor.

EARTHQUAKE DAMAGE

The quadrangle has been affected by three major earthquakes in the past 20 years. The first occurred on November 13, 1939, and its epicenter was about 42 miles west of Seattle; it was felt over an area of 212,000 square miles (Barksdale and Coombs, 1946, p. 351). The intensity of the quake was reported by Barksdale and Coombs as VII− on the modified Mercalli scale. An earthquake on February 14, 1946, affected an area in excess of 225,000 square miles in the northwest and had a maximum intensity of VII on the modified Mercalli scale. The provisional instrumental epicenter of this quake was reported by the U.S. Coast and Geodetic Survey to lie about 15 miles west of Tacoma (Barksdale and Coombs, 1946, p. 353). A small-scale isoseismal map of this earthquake compiled by Barksdale and Coombs shows the western part of the Lake Tapps quadrangle to have had an intensity of VI and the east half an intensity of V. Possibly the VI- isoseismal line lay along the east edge of the Puyallup Valley. The last major quake occurred on April 14, 1949; it had a magnitude of VIII on the modified Mercalli scale, and its epicenter was in the vicinity of Ketron Island in Puget Sound, just 18 miles west of Alderton (Nuttli, 1952, p. 21). During this quake, goods on store shelves were thrown to the floor, brick chimneys and a few old brick walls fell, facades fell from the fronts of a few buildings, and telephone poles and trees swayed back and forth (Enumclaw Courier-Herald, April 14 and 21, 1949; Buckley News-Banner, April 15 and 22, 1949).

During the 1949 earthquake, buildings in and about Sumner were damaged more severely than those in the Enumclaw-Buckley area. One home, whose type of construction is not known, was demolished. Also, merchandise fell from store shelves, 200 brick chimneys collapsed, brick walls fell down at the Standard Brands plant on the northern outskirts of town, books fell from shelves in the high school library, and wide cracks opened in the ground in many places. In some places, water was forceably ejected from fissures in the ground (Sumner News-Index, April 14 and 21, 1949). In Puyallup, brick walls and roofs collapsed, windows were broken, gas and water mains were broken in many places, and it was estimated that at least 75 percent of the brick chimneys in the city were damaged (Puyallup Valley Tribune, April 14 and 21, 1949). Cracks were reported in the ground surface near the Puyallup River west of town and also between Puyallup and Sumner. Mud and water were ejected from cracks in the ground in the northwestern part of Puyallup and clam shells are reported to have been ejected from a crack 2 feet wide along Stewart Avenue in the business section of Puyallup.

Newspaper accounts and conversations with residents in the quadrangle indicate that more damage to buildings resulted from the 1949 earthquake on the floor of the Puyallup Valley than in the area of the Osceola mudflow. This was true also of the November 13, 1939, earthquake (Coombs and Barksdale, 1942, p. 2). Substantial damage is to be expected during major earthquakes on the valley floor, as it is underlain by unconsolidated water-soaked sand. Relatively little damage to structures on the mudflow in the past may be attributed to the fact that almost all foundations are within the oxidized and cemented zone in the upper part of the deposit. During an earthquake, this zone or layer probably permits each building to move as a unit.

Inasmuch as there are so few buildings located on Vashon drift in the quadrangle, it is not possible to evaluate its seismic stability. In general, however, buildings on till should show less damage than those on any other surficial material in the quadrangle.

SUBSIDENCE

Collapse of old coal mines has caused subsidence of the ground surface at several places in the vicinity of Carbonado. Each subsidence, although originating in bedrock, also has caused the collapse of surficial deposits. This has resulted in the formation of almost circular pits in some places, as, for example, on the northwest slope of Gleason Hill near the center of the east edge of sec. 4 and on the floor of a small valley tributary to the Carbon in the NW¼SE¼ sec. 4. These pits superficially resemble kettles in stratified drift except for their freshness and the steepness of the slopes. In other places, collapse of mines in steeply dipping coal seams has formed closely adjacent parallel trenches, as much as 50 feet deep and hundreds of feet long. The two largest subsidence areas seen by the writer are 0.2 mile northeast of the reservoir in sec. 34 northeast of Carbonado and along a scarp that runs diagonally northeastward through the NW¼ sec. 34, near the center of the quarter section. The trend of these trenches is northwestward, parallel to the strike of the beds in the Puget group. An isolated trench of this type, closely adjacent to State Highway 5 near BM 1209 southeast of Carbonado, is 50 to 200 feet wide, as much as 40 feet deep, and is about 900 feet long. Its trend is approximately N. 30° W. Future construction in secs. 32, 33, and 34 north of Carbonado and in sec. 4 in the vicinity of Carbonado should be planned with the possibility of coal-mine subsidence in mind.

DRAINAGE

Surface drainage in most of the quadrangle is good; the widespread deposits of stratified drift of Vashon age are the best drained of the surficial units. Drainage on the till of Vashon age is good in sloping areas but is poor in depressions, owing to the compactness and fine-grained character of the till matrix. Some till-floored depressions between adjacent drumlins contain intermittent swamps. Recent lacustrine sediments are poorly drained, inasmuch as most of them lie in undrained depressions. Owners of farms on the floor of the Puyallup Valley between Orting and McMillin informed the writer that the soil on the Electron mudflow usually is "waterlogged" in the spring months and dries out during the summer to form a hardpan. Drainage ditches have been excavated in some places to alleviate the poor surface drainage.

Owing to the very low surface slope on the Osceola mudflow, and to the local presence of undrained depressions, surface drainage in many areas on this mudflow is poor. To improve drainage, many farmers in the areas around Enumclaw and Buckley have ditched and tiled their fields extensively. Many of these ditches and tiles, however, are not entirely effective owing to the low lateral permeability of the mudflow. Many shallow depressions on the surface contain ponds during wet weather, and unless artificially drained, swampy ground lasts in some of them throughout the summer.

MEASURED SECTIONS

Measured section 1

[Location: along logging road in NE¼ sec. 8, T. 18 N., R. 6 E., 1 mile southwest of Carbonado]

	Ft	*In.*
Wingate Hill drift:		
9. Till, moderate-yellowish-brown, very compact; central Cascade and Mount Rainier provenance	11	0
Lily Creek formation:		
8. Sand and pebble to boulder gravel; deeply weathered; oxidized to moderate yellowish brown; central Cascade and Mount Rainier provenance	71	0
7. Mudflows; deeply weathered; poorly exposed succession of 2 or possibly 3 mudflow deposits; consist mostly of fragments of Mount Rainier lava in silt and sand matrix; each mudflow grades upward from pebble-size fragments at base to sand at top	36	0
6. Sand and pebble to boulder gravel, moderate-yellowish-brown; cut-and-fill stratification; predominantly of Mount Rainier provenance; gravel becomes progressively more deeply weathered upward in section	60	0

(Units 4 and 5 are resting in a channel cut into sand and gravel represented by units 3 and 6. Measured thicknesses are not duplicated)

Lily Creek formation—Continued

	Ft	In.
5. Mudflows; basal mudflow contains rounded to subrounded cobbles and boulders of Mount Rainier and central Cascade provenance, as as large as 3 ft., in matrix of silt and sand; middle mudflow is monolithologic, about 4 ft. thick, and contains angular rock fragments, 1 in. or less in diameter, of Mount Rainier provenance in silt and sand matrix; uppermost mudflow is similar to basal mudflow	75	0
4. Mudflow; contains angular to subangular pebble- to cobble-size fragments of Mount Rainier lava in purplish-gray silt and sand matrix; locally cut out by unit 5	3	6
3. Sand and pebble to cobble gravel, gray; contain lenses of granule and pebble gravel; Mount Rainier provenance; locally cut out by unit 5	13	0
2. Sand, medium to coarse, moderate-yellow (5 Y 7/6); contains scattered pebbles and cobbles; Mount Rainier provenance	±15	0
Exposed thickness of formation	273	6
1. Puget group. (Altitude of top about 1,410 ft.)		

Measured section 2

[Location: gully cut into scarp adjacent to Kings Creek in SE¼ sec. 34, T. 18 N., R. 5 E.]

Vashon drift; forms surface above an altitude of 1,460 ft.

Lily Creek formation:

	Ft	In.
6. Mudflow; very compact mixture of angular to subangular pebble- to boulder-size rock fragments in silt and sand matrix; monolithologic, Mount Rainier provenance; deposit may include more than one mudflow	69	0
5. Clay and silty clay, brownish-gray, massive; contains carbonized wood fragments; grades into peaty clay at top	4	3
4. Mudflow, yellowish-brown, very compact, heterolithologic; contains subrounded pebbles, cobbles, and boulders in sand matrix	30	0
3. Sand, fine to coarse, very compact; contains thin beds of silt, as much as 2 in. thick, and lenses of pebbles	11	0
2. Mudflow, purplish-gray, monolithologic angular and subangular pebble-size rock fragments in silt and sand matrix; Mount Rainier provenance	1	0
1. Sand, medium to coarse, purplish-gray, very compact, horizontally bedded; Mount Rainier provenance	>6	0

Slopewash.

Exposures of the Lily Creek formation and bedrock in the valley floor of Kings Creek indicate that the base of this section measured in the scarp is about 200 feet higher than the base of the Lily Creek.

Measured section 3

[Location: SE¼SE¼ sec. 29, T. 19 N., R. 5 E.; section measured along county road on east valley wall of Carbon River at Orting]

Vashon drift:

	Feet
3. Sand, medium to coarse, and local lenses and beds of fine pebble gravel	>15
2. Till, unoxidized	>10

Orting drift:

	Feet
1. Sand and pebble to cobble gravel; contain scattered small boulders and local lenses of medium and coarse sand and openwork gravel; overall color of formation light yellowish brown; individual stones are coated with yellowish-brown iron oxides, granitic stones crumble when struck by pick. Prevailing rock type is andesite probably derived from lower Keechelus andesitic series, Fifes Peak andesite, and Snoqualmie(?) granodiorite	>165

(Surface of Carbon River.)

Measured section 4

[Location: ravine in SE¼NW¼ sec. 29, T. 19 N., R. 5 E.]

Vashon drift:

	Feet
4. Sand and pebble to boulder gravel, unoxidized; enclose lenticular sheet of unoxidized till, 1 to 15 ft thick, near base	>60

Orting drift:

	Feet
3. Sand and pebble to cobble gravel and scattered small boulders in yellowish-brown sand matrix; many stones readily disintegrate under blow of a pick	30–60
2. Till, dark-yellowish-orange; iron and manganese(?) oxides coat stone surfaces and joints; stones weathered as in gravel	2– 8
1. Sand and gravel as in unit 3, above	>70
Total thickness of Orting drift	>138

(Surface of Carbon River.)

Measured section 5

[Location: gullies under transmission line of Bonneville Power administration in center sec. 1, T. 19 N., R. 4 E., about 0.5 mile southwest of Alderton, Wash.]

Vashon drift:

	Feet
19. Pebble and cobble gravel and sand; unoxidized	>50

Salmon Springs drift:

	Feet
18. Sand and pebble to cobble gravel; contain scattered boulders, as much as several feet in diameter, and lenticular beds of sand; oxidized throughout; central Cascade and northern provenance	23

Puyallup formation:

	Feet
17. Mudflow; contains coarse brownish-gray sand and granules and, at base, scattered pebbles; grades upward into medium to very coarse brown sand and scattered granules; uppermost 10 inches is kaolinized; no visible stratification; Mount Rainier provenance	8
16. Sand and pebble to boulder gravel, oxidized; Mount Rainier and central Cascade provenance	4
15. Mudflow, unsorted, unstratified; angular to subrounded pebble-, cobble-, and boulder-size fragments in very compact olive-brown silty sand matrix; Mount Rainier provenance	21
14. Volcanic ash, pale-yellow; heavy minerals consist predominantly of hypersthene and hornblende in equal proportion	.5
13. Sand and silt, fine to medium, brownish-gray	1

	Feet
Puyallup formation—Continued	
12. Sand and pebble to cobble gravel, oxidized; cut-and-fill stratification; Mount Rainier provenance	14
11. Sand, medium to very coarse, gray and purplish-gray, compact; contains scattered granules and pebbles of light-gray andesite and thin lenses of sand-size yellow pumice; crossbedded in part (includes Puyallup sands of Willis); Mount Rainier provenance	70
10. Sand, silt, and volcanic ash, pinkish-gray and gray, very compact; grade upward into medium to coarse gray sand; horizontally laminated	16
Thickness of Puyallup formation	134.5
Stuck drift:	
9. Sand and pebble to cobble gravel, oxidized	13
8. Till, very compact; contains subangular to rounded pebbles and cobbles in grayish-brown sandy silt matrix	5
7. Sand and pebble to cobble gravel, oxidized; contains scattered boulders as large as 4 ft in diameter	6
Thickness of Stuck drift	24
Alderton formation:	
6. Sand, silty, fine, gray and purplish-gray, horizontally laminated, very compact; contains carbonized fragments of vegetation and a 15-in. layer of pale-yellow volcanic ash near top	4
5. Pebbles and granules of white pumice in pinkish-gray ash matrix; unstratified	2
4. Sand, medium to coarse, and very compact beds of angular gray granule gravel	8
3. Mudflow, unsorted, unstratified, very compact, angular to subangular pebble- to cobble-size rock fragments in gray sand matrix; grades upward into angular pebble- and granule-size fragments in sand matrix; Mount Rainier provenance	11
2. Sand, medium to very coarse, brownish-gray, horizontally bedded; Mount Rainier provenance	3
1. Mudflow, unsorted, unstratified, very compact; contains angular to subangular pebble- to boulder-size rock fragments in reddish-gray to grayish-brown silty sand matrix; grades upward into angular pebble- and granule-size fragments. Mount Rainier provenance. Base not exposed	>24
Thickness of Alderton formation	>52

Slopewash, about 75 ft vertically down to level of Puyallup River flood plain at an altitude of about 100 ft.

Measured section 6

[Location: composite section measured along old road grade on west wall of Puyallup River valley in NW¼ sec. 12, T. 19 N., R. 4 E., about ¾ mile northwest of McMillin]

	Ft	In.
Salmon Springs drift:		
16. Till, oxidized	>7	0
15. Cobble to boulder gravel	0–13	0
Erosional unconformity.		
Puyallup formation:		
14. Sand, medium to coarse, purplish-gray	15	0
13. Silt, peaty silt, and medium sand	1	8
12. Silt, massive, grayish-brown	2	0
11. Sand, fine, horizontally bedded, dark-grayish-brown	5	0
10. Silt, massive, light-olive-brown		8
Stuck drift:		
9. Gravel and till	10–40	0
Erosional unconformity.		
Alderton formation:		
8. Sand, fine to coarse; Mount Rainier provenance	12–20	0
7. Silt and fine sand	2	0
6. Peat, interbedded with silt and diatomaceous silt	1	0
5. Mudflow, purplish-gray; Mount Rainier provenance	6–>20	0
4. Sand, fine to medium, gray; Mount Rainier provenance	10–15	0
3. Sand and pebble gravel; central Cascade and Mount Rainier provenance	14	0
2. Mudflow, purplish-gray; Mount Rainier provenance	10–15	0
Orting drift:		
1. Sand and pebble gravel, medium to coarse, dark-yellowish-orange; northern and central Cascade provenance	>25	0

Measured section 7

[Location: west wall of Puyallup River valley in northeast corner of SW¼SE¼ sec. 18, T. 18 N., R. 5 E.]

	Ft	In.
Vashon drift:		
14. Sand and pebble to boulder gravel	85	0
Puyallup formation:		
13. Sand, coarse, and pebble to cobble gravel	10	0
12. Silt and fine sand, brown to gray	2	2
11. Silty peat		4
10. Volcanic ash, light-brown		9
9. Peat and silty peat		9
8. Sand, fine to medium, gray to brown	3	0
7. Silty peat	1	0
Orting drift (may include Stuck drift):		
6. Sand and pebble to cobble gravel	15	0
5. Till, oxidized	4	0
4. Sand and pebble to boulder gravel	33	0
3. Sand and granule to pebble gravel	9	0
2. Silt, pebbly, brown		6
1. Sand and pebble to boulder gravel; oxidized	>100	0

Measured section 8

[Location: bluff at northwestern outskirts of Sumner]

	Feet
Vashon drift:	
9. Sand and pebble gravel, unoxidized	12
Salmon Springs drift:	
8. Sand and pebble to cobble gravel, dark-yellowish-orange; cut-and-fill stratification in places; predominantly of Cascade provenance, but contains sand beds of Mount Rainier provenance near top	75
7. Sand, fine to medium, dusky-yellow, locally crossbedded; northern provenance	28
Erosional unconformity.	
Puyallup formation:	
6. Sand and pebble gravel, purplish-gray; Mount Rainier provenance	5
5. Sand and pebble to cobble gravel, purplish-gray; Mount Rainier provenance	10
4. Sand, medium to coarse, purplish-gray; Mount Rainier provenance	4
Erosional unconformity.	
Stuck drift:	
3. Sand and pebble to cobble gravel, dark-yellowish-orange; northern provenance	7–20
2. Till, moderate-olive-brown; contains lenses of sand and gravel; northern provenance	17
1. Sand and pebble to cobble gravel; northern and central Cascade provenance; contains lenses of purplish-gray sand of Mount Rainier provenance	>16

Measured section 9

[Location: NW¼SE¼ sec. 12, T. 20 N., R. 5 E., in east wall of White River valley]

	Feet
Osceola mudflow (thickness not determined).	
Vashon drift:	
9. Till, unoxidized except for brown podzolic soil profile at top	15
8. Sand and pebble to boulder gravel, unoxidized	25
Salmon Springs drift:	
7. Sand and pebble gravel, oxidized; lie in channels cut into units 6 and 5	0–8
6. Till, moderate-olive-brown; very stony	0–7
5. Sand, medium to coarse, gray; cut-and-fill stratification	0–8
Erosional unconformity.	
Stuck drift:	
4. Till, unoxidized, contains scattered pebbles and cobbles in silt matrix; 4-inch humified zone at top	13
3. Sand, fine to medium, brown; contains scattered pebbles	18
2. Silt, horizontally laminated, contains scattered small pebbles; some beds greatly contorted	20
1. Sand and pebble to cobble gravel, oxidized	>22
(Surface of White River flood plain).	

Measured section 10

[Location: southeast corner SW¼NW¼ sec. 8, T. 19 N., R. 5 E., on south wall of Fennel Creek valley]

	Ft	In.
Vashon drift:		
18. Sand and pebble to cobble gravel, unoxidized	50	0
Puyallup formation (altitude of top about 340 ft):		
17. Sand, fine to medium, grayish-brown, horizontally bedded	>4	0
(Covered interval)	10	0
16. Sand, medium to coarse, grayish-brown; Mount Rainier provenance	3	0
15. Silt, pinkish-gray		6
14. Sand and granule gravel and scattered pebbles, medium to coarse, gray	1	0
13. Sand and pebble to cobble gravel; Mount Rainier provenance	2	6
12. Diatomaceous earth, white- to yellowish-gray; peaty in basal 5 inches		10
11. Peat	1	0
10. Mudflow, gray; contains pebble- to boulder-side rock fragments in silty sand matrix; concentration of boulders at base; Mount Rainier provenance	16	0
9. Mudflow; contains medium to coarse sand and granule gravel and scattered pebbles; poorly sorted; Mount Rainier provenance	7	0
8. Sand, fine to medium, gray, horizontally bedded	4	6
7. Mudflow (as unit 9), gray; Mount Rainier provenance	6	0
6. Mudflow; contains pebble- to boulder-size rock fragments in silty sand matrix; Mount Rainier provenance	5	6
5. Sand, fine to medium, gray	3	0
4. Mudflow, monolithologic; contains angular pebbles and small cobbles in silty sand matrix; Mount Rainier provenance	6	0
3. Sand, fine, and silt, horizontally liminated	3	0
Thickness of Puyallup formation	73	10
Stuck drift:		
2. Sand and pebble to cobble gravel; northern provenance	7	0
(Covered interval)	7	0
Alderton formation:		
1. Sand and pebble to boulder gravel; central Cascade and Mount Rainier provenance	>30	0

Measured section 11

[Location: banks of Fennel Creek at Victor Falls in NE¼ sec. 9, T. 19 N., R. 5 E.]

	Feet
Puyallup formation (top at about 400 ft):	
4. Mudflow, monolithologic; Mount Rainier provenance	> 5
3. Sand, medium; contains lenses of granule and pebble gravel	10
2. Mudflow, monolithologic, very compact; forms cap rock of Victor Falls; Mount Rainier provenance	15
1. Sand and pebble to cobble gravel, gray; contains scattered boulders; Mount Rainier provenance	>60

Measured section 12

[Location: center sec. 12, T. 20 N., R. 5 E., in east wall of White River valley]

	Ft	In.
Osceola mudflow	10	0
Vashon drift:		
10. Sand and pebble to cobble gravel; till; unoxidized	48	0

Erosional unconformity.

	Ft	In.
Salmon Springs drift:		
9. Sand and pebble to cobble gravel, yellowish-brown	12	0
8. Till, dark-grayish-brown	13	0
7. Sand and pebble and cobble gravel, yellowish-brown	5	0
Erosional unconformity.		
Nonglacial sediments of Puyallup age:		
6. Silt, sand, and peat beds	3	7
5. Silt and sand	2	.4
4. Sand, medium to coarse, and granule gravel; contains scattered pumice pebbles; cut-and-fill stratification	5	6
3. Silt, sand, and peat beds	4	8
2. Sand, very fine, and silt	4	6
Stuck drift:		
1. Till, dark-gray	>28	0

Measured section 13

[Location: east wall of White (Stuck) River valley, in gully 150 feet east and another gully 400 feet north of southeast corner of the SW¼ sec. 18, T. 20 N., R. 5 E., in vicinity of Salmon Springs, about 1 mile northeast of Sumner, Wash. (composite section)]

	Feet
Vashon drift:	
11. Sand and pebble to cobble gravel; unoxidized	>30
Salmon Springs drift (upper part):	
10. Sand, very fine, and silt, light-olive-gray	2.0
9. Sand and pebble to cobble gravel; oxidized; northern provenance in part	37.0
Nonglacial sediments:	
8. Silt and clay, pale-yellowish-brown	.5
7. Peat, very compact, black, and silty peat	.3– 1.5
6. Silt, brownish-gray; rich in vegetative debris	1.5
5. Volcanic ash	.5– 1.0
Salmon Springs drift (lower part):	
4. Sand and pebble to cobble gravel; oxidized; northern provenance	20 –27
Puyallup formation:	
3. Sand, medium to coarse, and lenses of granule to pebble gravel; poorly defined cut-and-fill stratification; Mount Rainier provenance	30.0
Stuck drift:	
2. Till, very compact; unoxidized	2 – 5
1. Sand and pebble to cobble gravel; oxidized; northern provenance	>20

REFERENCES

Allen, V. T., and Nichols, R. L., 1946, Weathered gravels and sands of Oregon and Washington: Jour. Sed. Petrology, v. 16, no. 2, p. 52–62.

Anderson, N. R., 1950, Multiple glaciation in the White River valley near Enumclaw, Washington [abs.]: Geol. Soc. America Bull., v. 61, no. 12, pt. 2, p. 1519–1520.

Anderson, W. W., Ness, A. O., and Anderson, A. C., 1955, Soil survey of Pierce County, Washington: U.S. Dept. Agriculture Soil Survey Rept., ser. 1939, no. 27, 88 p.

Barksdale, J. D., and Coombs, H. A., 1946, The Puget Sound earthquake of February 14, 1946: Seismol. Soc. America Bull., v. 36, no. 4, p. 349–354.

Bretz, J H., 1913, Glaciation of the Puget Sound region: Washington Geol. Survey Bull. 8, 244 p.

——— 1920, The Juan de Fuca lobe of the Cordilleran ice sheet: Jour. Geology, v. 28, p. 333–339.

Broecker, W. S., and Kulp, J. L., 1957, Lamont natural radiocarbon measurements IV: Science, v. 126, no. 3287, p. 1324–1334.

Cary, A. S., and Carlston, C. W., 1937, Notes on Vashon stage glaciation of the South Fork of the Skykomish River valley, Washington: Northwest Sci., v. 11, p. 61–62.

Coombs, H. A., 1936, The geology of Mount Rainier National Park: Washington Univ. Pubs. in Geology, v. 3, no. 2, p. 131–212.

——— 1938, Mount Baker and Mount Rainier in Washington [abs.]: Geol. Soc. America Bull., v. 49, no. 12, pt. 2, p. 1874.

Coombs, H. A., and Barksdale, J. D., 1942, The Olympic earthquake of November 13, 1939: Seismol. Soc. America Bull., v. 32, p. 1–6.

Crandell, D. R., and Gard, L. M., Jr., 1959, Geology of the Buckley quadrangle, Washington: U.S. Geol. Survey Geol. Quad. Map GQ–125.

Crandell, D. R., Mullineaux, D. R., and Waldron, H. H., 1958, Pleistocene sequence in southeastern part of the Puget Sound lowland, Washington: Am. Jour. Sci., v. 256, p. 384–397.

Crandell, D. R. and Waldron, H. H., 1956, A Recent volcanic mudflow of exceptional dimensions from Mount Rainier, Washington: Am. Jour. Sci., v. 254, p. 349–362.

Dawson, G. M., 1890, On the later physiographical geology of the Rocky Mountain region in Canada, * * *; Royal Soc. Canada Trans., v. 8, sec. 4, 74 p.

Deevey, E. S., Gralenski, L. J., and Hoffren, Väinö, 1959, Yale natural radiocarbon measurements IV: Am. Jour. Sci. Radiocarbon Supp., v. 1, p. 144–172.

Emiliani, Cesare, 1955, Pleistocene temperatures: Jour. Geology, v. 63, p. 538–578.

Engineering News, 1912, The White River power development in Washington: Eng. News, v. 67, no. 15, p. 704–707.

Flint, R. F., 1957, Glacial and Pleistocene geology: New York, John Wiley and Sons, 553 p.

Flint, R. F., and Rubin, Meyer, 1955, Radiocarbon dates of pre-Mankato events in eastern and central North America: Science, v. 121, no. 3149, p. 649–658

Glover, S. L., 1941, Clays and shales of Washington: Washington Dept. Conserv. Devel., Div. Mines and Geology Bull. 24, 368 p.

Goddard, E. N., chm., and others, 1948, Rock-color chart: Washington, D.C., Natl. Research Council; republished by Geol. Soc. America, 1951.

Hansen, H. P., 1938, Pollen analysis of some interglacial peat from Washington: Wyoming Univ. Pub. 5, p. 11–18.

——— 1947, Postglacial forest succession, climate, and chronology in the Pacific Northwest: Am. Philos. Soc. Trans., new ser., v. 37, pt. 1, 130 p.

Hansen, H. P., and Mackin, J. H., 1940, A further study of interglacial peat from Washington: Torrey Botanical Club Bull., v. 67, p. 131–142.

——— 1949, A pre-Wisconsin forest succession in the Puget lowland, Washington: Am. Jour. Sci., v. 247, p. 833–855.

Henshaw, F. F., and Parker, G. L., 1913, Water powers of the Cascade Range, Part 2, Cowlitz, Nisqually, Puyallup, White, Green, and Cedar drainage basins: U.S. Geol. Survey Water-Supply Paper 313, 170 p.

Leopold, E. B., and Crandell, D. R., 1957, Pre-Wisconsin interglacial pollen spectra from Washington State, U.S.A.: Ver. der vierten Internat. Tagung der Quartarbotaniker 1957, p. 76–79.

Mackin, J. H., 1938, Eastern margin of the Puget glacial lobe [abs.]: Geol. Soc. America Proc. 1937, p. 248.

——— 1941, Glacial geology of the Snoqualmie-Cedar area, Washington: Jour. Geology, v. 49, p. 449–481.

Matthes, F. E., 1914, Mount Rainier and its glaciers: Washington, U.S. Dept. Interior, 48 p.

——— 1942, Report of committee on glaciers 1941–1942: Am. Geophys. Union Trans., pt. 2, p. 374–392.

McLerran, J. H., and Krashevski, S. H., 1954, Soils of King County, Washington: Washington Eng. Soils Manual, Washington State Council for Highway Research, pt. 3, 107 p.

Mullineaux, D. R., Crandell, D. R., and Waldron, H. H., 1957, Multiple glaciation in the Puget Sound basin, Washington [abs.]: Geol. Soc. America Bull., v. 68, no. 12, pt. 2, p. 1772.

Mullineaux, D. R., Gard, L. M., Jr., and Crandell, D. R., 1959, Continental sediments of Miocene age in Puget Sound lowland, Washington: Am. Assoc. Petroleum Geologists Bull., v. 43, p. 688–696.

Mundorff, M. J., Weigle, J. M., and Holmberg, G. D., 1953, Ground water in the Yelm area, Thurston and Pierce Counties, Washington: U.S. Geol. Survey open-file rept., 122 p.

Newcomb, R. C., 1952, Ground-water resources of Snohomish County, Washington: U.S. Geol. Survey Water-Supply Paper 1135, 133 p.

Nuttli, O. W., 1952, The western Washington earthquake of April 13, 1949: Seismol. Soc. America Bull., v. 42, p. 21–28.

Olson, E. A., and Broecker, W. S., 1959, Lamont natural radiocarbon measurements V: Am. Jour. Sci., v. 257, p. 1–28.

Page, B. M., 1939, Multiple alpine glaciation in the Leavenworth area, Washington: Jour. Geology, v. 47, p. 785–815.

Paulson, E. N., Miller, J. T., Fowler, R. H., and Flannery, R. D., 1952, Soil survey of King County, Washington: U.S. Dept. Agriculture, Soil Survey Rept., ser. 1938, no. 31, 106 p.

Rigg, G. B., 1926, Washington, *in* Naturalists's guide to the Americas: Baltimore, The Williams and Wilkins Co., p. 168–180.

——— 1958, Peat resources of Washington: Washington Div. Mines and Geology Bull. 44, 272 p.

Rigg, G. B., and Gould, H. R., 1957, Age of Glacier Peak eruption and chronology of postglacial peat deposits in Washington and surrounding areas: Am. Jour. Sci., v. 255, p. 341–363.

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

Roberts, W. J., 1916, Some of the problems in the flood control of the White-Stuck and Puyallup Rivers: Pacific Northwest Soc. of Engineers Proc., v. 15, no. 3, 40 p.

Sceva, J. E., 1957, Geology and ground-water resources of Kitsap County, Washington: U.S. Geol. Survey Water-Supply Paper 1413, 178 p.

Sceva, J. E., Wegner, D. E., and others, 1955, Records of wells and springs, water levels, and quality of ground water in central Pierce County, Washington: U.S. Geol. Survey open-file rept., 261 p.

Shapiro, Leonard, and Brannock, W. W., 1956, Rapid analysis of silicate rocks: U.S. Geol. Survey Bull. 1036 C, p. 19–56.

Snavely, P. D., 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. Geol. Survey Bull. 1053, 159 p.

Snavely, P. D., Jr., Roberts, A. E., Hoover, Linn, and Pease, M. H., Jr., 1951, Geology of the eastern part of the Centralia-Chehalis coal district, Lewis and Thurston Counties, Washington: U.S. Geol. Survey Coal Inv. Map C8, 2 sheets.

Stearns, H. T., and Coombs, H. A., 1959, Quaternary history of Upper Baker Valley, Washington [abs.]: Geol. Soc. America Bull., v. 70, no. 12, pt. 2, p. 1778.

U.S. Weather Bureau, 1953, Climatological data, Washington, annual summary 1952: Climatological data for the United States by secs., v. 56.

——— 1954, Climatological data, Washington, annual summary 1953: Climatological data for the United States by secs., v. 57.

——— 1957, Climatological data, Washington, annual summary 1956: Climatological data for the United States by secs., v. 60.

——— 1959, Climatological data, Washington, annual summary 1958: Climatological data for the United States by secs., v. 62.

Varnes, D. J., 1958, Landslide types and processes, *in* Eckel, E. B., Landslides and engineering practice: Highway Research Board Spec. Rept. 29, 232 p.

Waldron, H. H., Mullineaux, D. R., and Crandell, D. R., 1957, Age of the Vashon glaciation in the southern and central parts of the Puget Sound basin, Washington [abs.]: Geol. Soc. America Bull., v. 68, no. 12, pt. 2, p. 1849–1850.

Warren, W. C., 1941, Relation of the Yakima basalt to the Keechelus andesitic series: Jour. Geology, v. 49, p. 795–814.

Willis, Bailey, 1898, Drift phenomena of Puget Sound: Geol. Soc. America Bull., v. 9, p. 111–162.

Willis, Bailey, and Smith, G. O., 1899, Description of the Tacoma quadrangle: U.S. Geol. Survey Geol. Atlas, Tacoma Folio 54.

Wolman, M. G., and Leopold, L. B., 1957, River flood plains: some observations on their formation: U.S. Geol. Survey Prof. Paper 282–C, p. 87–109.

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[Major references are in italic]

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