Postglacial Lahars From Mount Rainier Volcano, Washington

By DWIGHT R. CRANDELL

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A study of the age, extent, and origin of more than 55 postglacial mudflows and debris flows from Mount Rainier

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ABSTRACT

More than 55 lahars (mudflows and debris flows from a volcano) originated at Mount Rainier during Holocene time. These ranged in length from a few miles to 70 miles and in volume from a few million cubic yards to more than half a cubic mile. Some lahars were created by landslides of altered volcanic rock; they contain significant amounts of clay, which consists of montmorillonite and kaolinite and lesser amounts of other clay minerals, which were formed by hydrothermal alteration of rock within the volcano. Some of these lahars have been deep enough, when flowing, to fill valleys to depths of hundreds of feet; the fluidity of the lahar permitted most of it to progress downvalley and to leave in passing only a thin deposit on valley sides and terraces. Smaller lahars of the same kind seem to have progressed downvalley in a single massive wave hundreds of feet high. Clay-rich lahars originated in massive slides of clayey rock that had a high moisture content. The slides may have been triggered either by strong earthquakes or by volcanic explosions, or possibly by swelling that accompanied the ascent of molten rock into the volcano. Other lahars were created by the eruption of hot volcanic bombs, dense rock fragments, and ash onto ice and snow at the summit of the volcano. Rapid melting of snow created floods down the volcano's flanks which carried down rock debris and also picked up loose detritus on valley floors to form lahars. Still other lahars resulted from precipitation of cloudburst proportions and by glacier outburst floods. Some outburst floods may have been caused by excessive melting of ice around subglacial steam vents.

There have been repeated episodes of volcanism at Mount Rainier within about the last 10,000 years. The last major eruptive period, between about 2,000 and 2,500 years ago, witnessed the eruption of pumice and lava flows and the formation of many lahars. During this period, erosion alternated with aggradation of lahars and fluvial gravels on the valley floors of the White and Nisqually Rivers, and possibly on those of some other rivers as well. The last pumice eruption, which occurred in the mid-1800's, apparently was on a very small scale, and there is no known record of floods or lahars at that time.

If future eruptions of Mount Rainier were to be similar in scale and type to those of the last 10,000 years, the greatest hazard would be that of lahars. Because of the restriction of lahars to the lower parts of valleys away from the immediate flanks of the volcano, valley floors would be especially hazardous. In view of the increased probability of lahar formation during an eruption, valley floors should be evacuated immediately within a radius of at least 25 miles from the volcano if an eruption should begin. It is proposed that permanent residences should not be constructed on certain valley floors near Mount Rainier, that consideration be given to the relocation of campgrounds that are now in potentially hazardous areas, and that future highways and bridges be designed and located to minimize destruction by future lahars. Likewise, the planning of all other residential, economic, and recreational developments within valleys that head on the volcano should be concerned with lahars as potential geologic hazards.

Artificial traps that might prevent large lahars from entering densely populated areas now exist in the form of hydroelectric power dams and flood-control dams in some valleys. To control a lahar, reservoirs behind these dams would have to be empty. No reservoir, however, would be of any avail in controlling or diverting a lahar comparable in size with the largest that originated at Mount Rainier in postglacial time.

INTRODUCTION

Within postglacial (Holocene) time, which constitutes about the last 10,000 years, various events of a catastrophic nature have occurred at Mount Rainier. These have included repeated eruptions of pumice, lava flows, and hot volcanic bombs, and most devastating of all, recurring avalanches of rock debris from the summit and slopes of the volcano which created lahars (mudflows and debris flows from a volcano) hundreds of feet deep and many miles long. Within the last 10,000 years Mount Rainier has lost a much greater volume through these avalanches and other erosional processes than it has gained from the eruption of new lava.

Some postglacial lahars from Mount Rainier have had sufficient volume and mobility to extend into the Puget Sound lowland northwest of the volcano (fig. 1) and to spread over areas there that are now densely populated. Lahars of comparable size today would doubtlessly be disastrous. My purpose of studying the postglacial lahars was to determine their stratigraphy, physical characteristics, distribution, and especially their manner and place of origin so as to assess the potential hazards presented by future lahars from the volcano.

The study was begun in 1960 as the principal part of a broader investigation of surficial deposits in Mount Rainier National Park and in selected areas in

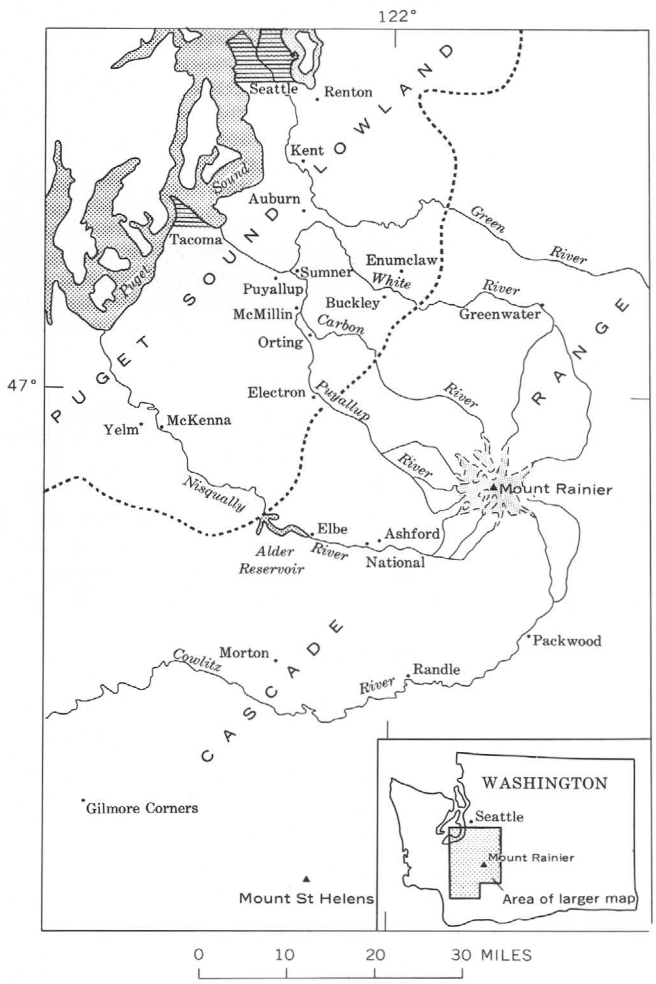

FIGURE 1.—Location of Mount Rainier with respect to the Cascade Range and the Puget Sound lowland of western Washington. The dotted line marks the approximate boundary between lowland and mountains. Patterned area around Mount Rainier indicates glaciers.

the adjacent mountains. I shared the fieldwork of the first two summers with Robert D. Miller, who assumed primary responsibility in 1961 for working out the glacial history of the upper Nisqually River valley. Donal R. Mullineaux joined the project in 1962 and undertook a study of the lithology, distribution, stratigraphy, age, and source of the postglacial pyroclastic deposits in Mount Rainier National Park. I was ably assisted in the field by my son Thomas D. Crandell (deceased) in 1960, by Jon Koloski in 1962, by Michael P. Lane in 1963, and by Jack H. Hyde in 1966.

Fieldwork in the park was greatly facilitated by the cooperation of the Superintendent and staff of the National Park Service, and grateful acknowledgement is made of the enthusiastic encouragement and help given by Vernon R. Bender, Charles J. Gebler, and Norman A. Bishop, successive Chief Park Naturalists. Appreciation is also expressed to the St. Regis Paper Co. for permission to conduct field investigations on private land west of Mount Rainier National Park.

I profited immeasurably from numerous discussions in the field with Richard S. Fiske, Clifford A. Hopson, and Aaron C. Waters, who were completing their study of the bedrock geology of the park when my investigation was just getting under way. My interest in studying the surficial geology of the park was encouraged by Professor Waters, who foresaw the desirability of having such a study to supplement their studies of the rock formations.

Unless otherwise specified, all the analyses reported here were made in the laboratories of the U.S. Geological Survey. The radiocarbon age determinations were supervised by Meyer Rubin, and grain-size analyses were supervised by Thomas C. Nichols and Edward E. McGregor. X-ray determinations of the mineralogy of silt and clay fractions of lahars and other surficial deposits were conducted by Paul D. Blackmon, Dorothy Carroll, John C. Hathaway, Edward E. McGregor, and Harry C. Starkey.

GEOGRAPHIC SETTING OF THE VOLCANO AND LAHARS

Mount Rainier volcano dominates the landscape of a large part of western Washington. It stands nearly 3 miles higher than the lowlands to the west and 1½ miles higher than the surrounding mountains. The base of the volcano spreads over an area of about 100 square miles, and lava flows that radiate from the base of the cone extend to distances of as much as 9 miles. The flanks of Mount Rainier are drained by five major rivers and their tributaries. Clockwise from the northwest the major rivers are the Carbon, White, Cowlitz, Nisqually, and Puyallup (fig. 1; pl. 1). Each river flows westerly through the Cascade Range and, with the exception of the Cowlitz, empties into Puget Sound near Tacoma, Wash. The Cowlitz joins the Columbia River in the southwestern part of the State to flow to the Pacific Ocean.

Each major river in Mount Rainier National Park occupies a deep canyon whose floor is 1,000–3,000 feet below the adjacent divides. Valley-floor gradients are 100–400 feet per mile near the park boundaries and increase markedly upstream. The valley floors of Tahoma Creek, the North and South Puyallup Rivers, and the Mowich River have gradients of 700–800 feet per mile in their upper reaches and are among the steepest in the park. The volcano's summit towers 9,000–11,000 feet above valley floors only 3–6 miles away. The flanks of the volcano itself have slopes mostly between 25° and 30°, although those of Willis Wall on the north side are between 40° and 45°.

Partly because of its position astride a high, dissected part of the Cascade Range, Mount Rainier does not have broad peripheral aprons of laharic and fluvial deposits like those fringing the base of Mount Shasta in northern California and some large stratovolcanoes elsewhere. Instead, large lahars originating on the volcano in Quaternary time repeatedly flowed far down the canyons of the Cascade Range, and some came to rest beyond the mountain front in parts of the adjoining Puget Sound lowland (Crandell, 1963b).

Within the mountains, lahars typically are found on valley floors, although the deposits of some of the largest lahars also veneer valley walls to heights of hundreds of feet. Some even mantle divides that are a thousand feet or more above valley floors near the volcano. Lahars that formed within the last thousand years commonly form low terraces or veneer other unconsolidated deposits that form the terraces. Older lahars are often found interbedded with fluvial terrace deposits, duff horizons and stumps that represent old forest floors, and thin layers of pyroclastic material.

CLIMATE

The climate of Mount Rainier National Park is cool and moist during fall, winter, and spring, but the summers are relatively warm and dry. Monthly precipitation at Paradise Park, at an altitude of about 5,400 feet, generally is greater than 10 inches from October through March and decreases to an inch or two during July (table 1). Within the period from 1956 through 1965 the highest yearly precipitation at Paradise Ranger Station was 146.31 inches in 1959, and the lowest was 94.56 inches in 1965. As much as 48 feet of snow has fallen at Paradise Park in a single winter, and snowbanks frequently linger there until late July or August. The average January and July temperatures, respectively, at Paradise Park are 26.4° and 53.0°F. Minimum daily temperatures below freezing can be expected there any month of the year, whereas at Longmire, at an altitude of 2,672 feet, daily minimum temperatures generally are above 32°F. during June, July, and August. Because of its lower altitude Longmire receives considerably less precipitation than does Paradise Park (table 1), and the January and July average temperatures there are 30.2° and 60.6°F., respectively. The long-term average annual precipitation at Longmire is about 82 inches, but within the last 40 years the annual precipitation has ranged from a low of 43.22 inches in 1952 to a high of 113.60 inches in 1933 (fig. 2).

Winds throughout the year are generally from the west. From May through August, average monthly winds are mostly from the west and southwest, and during November through January, they are from the west and northwest. The directions from which average monthly winds come during the other months range from northwesterly to southwesterly. One geologic effect of these prevailing winds was the determination of the fallout pattern of postglacial pyroclastic deposits, each of which lies mostly east of the volcano.

TABLE 1.—*Average monthly and average annual precipitation (inches) at Longmire (1) for the 51-year period preceding 1966 and at Longmire (2) and Paradise Ranger Station (3) for the period from 1956 through 1965*

[Compiled from Climatology Data published by the U.S. Weather Bureau]

	1	2	3
January	10.92	11.87	17.21
February	8.98	9.47	13.82
March	8.32	8.21	11.89
April	5.11	6.41	8.87
May	4.12	4.07	4.60
June	3.63	4.29	3.95
July	1.35	1.19	1.71
August	1.75	2.79	4.09
September	3.92	4.49	6.33
October	8.63	8.14	11.26
November	11.91	12.69	18.20
December	13.79	11.75	17.94
Annual average	82.43	85.37	119.87

TERMINOLOGY AND DISTINCTIVE FEATURES OF LAHARS

The term "lahar" is an Indonesian word that is used in this report as a general designation for deposits that have resulted from rapid mass flowage of rock debris mobilized by water and that have originated on the slopes of a volcano. The term is also used to refer to the flowing mixture of rock debris and water. This definition follows the usage of van Bemmelen (1949, p. 191) and is adopted because of the need for a general term that is independent of reference to the texture of the de-

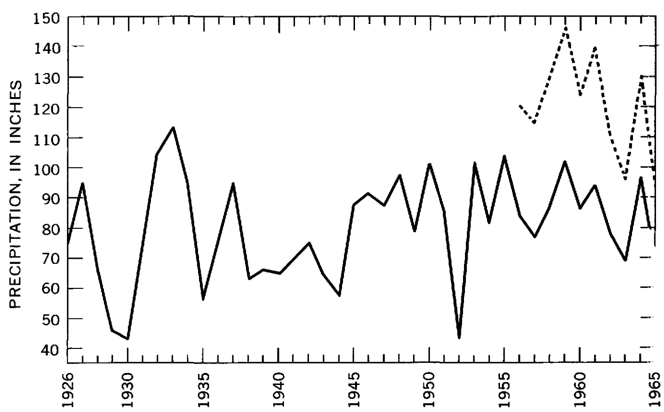

FIGURE 2.—Average annual precipitation at Longmire from 1926 through 1965 (solid line) and average annual precipitation at Paradise Ranger Station from 1956 through 1965 (dotted line).

posit and the sediment to water ratio during movement. Thus, use of the term "lahar" avoids the necessity of adoping such textural designations as debris flow and mudflow, even though these terms are conveniently applied here to certain appropriate lahars. Even though all the deposits to be described originated on a volcano, it is well to emphasize at the outset that not all of them originated as the direct and immediate result of volcanic activity.

Most of the lahars described in this report conform to the definition of either mudflow or debris flow as used by many workers. Sharp and Nobles (1953) used the term "debris flow" as a general designation for all types of rapid flowage involving rock debris of various kinds. They suggested that mudflows are a variety of debris flow in which the mud gives the mass a mode of behavior which distinguishes it from a flow of wet rock debris devoid of mud. Varnes (1958, p. 37) subsequently clarified this usage by restricting the term "mudflow" to deposits that have at least 50 percent material of sand size and smaller.

The sand fraction of a lahar may not be as important as the silt and clay fraction in imparting certain flowage characteristics to a sediment-water mixture. It has been experimentally shown that the fall velocity of sand-sized material in such a mixture decreases as the clay-fraction increases (Simons and others, 1963), and under some conditions this has the effect of allowing the coarse fraction to be suspended by less turbulence.

Bull (1964) adopted a threefold classification to describe the deposits of alluvial fans in Fresno County, Calif. His classification, shown below, was based on sorting coefficient (*So*), phi standard deviation ($\sigma\phi$), and phi quartile deviation ($QD\phi$).[1]

	So	$\sigma\phi$	$QD\phi$
Waterlaid sediments (upper limit)	3	2.3	1.6
Intermediate sediments (limits)	3–5	2.9–4.1	1.6–2.3
Mudflows (lower limit)	5	4.1	2.3

Few grain-size analyses of "waterlaid sediments" were made during the present investigation; deposits thought to be of this origin are generally referred to in this report as fluvial deposits or fluvial sediments, but some of them may also belong in Bull's category of "intermediate sediments." Although nearly all the deposits called lahars in this report are mudflows according to Bull's classification, a few samples fall within the limits of his "intermediate sediments" category. For example, a sample from the fine, graded top of the Electron Mudflow has a sorting coefficient, phi standard deviation, and phi quartile deviation that fall in the "intermediate" category; a sample from the base of the Electron at the same locality, however, has parameters characteristic of Bull's mudflows.

Some of the lahars described in this report may have been formed by "hyperconcentrated flows" (Beverage and Culbertson, 1964), which are water-sediment mixtures that have between 40 and 80 percent sediment by weight. These flows are intermediate between normal steamflow, in which there is no more than 40 percent sediment by weight, and mudflow, which has more than 80 percent sediment by weight, according to Beverage and Culbertson. Richardson (1968) suggested that some of the outburst floods that have originated in Nisqually and South Tahoma Glaciers within the last 40 years (p. 44, 58), have been "hyperconcentrated flows."

Lahars have some features in common with deposits of other origins, such as till, fluvial deposits, colluvium, and landslides. I know of no single common feature that serves to distinguish all lahars from all other kinds of deposits. Instead, many different characteristics none of which may be individually definitive, often indicate a laharic origin when considered collectively. For example, the principal features that led to the recognition of the so-called Osceola till of Willis (1898) as a mudflow were its flat topography and highly digitate pattern of distribution in the Puget Sound lowland (Crandell and Waldron, 1956). These features were considered in conjunction with the deposit's provenance, lack of sorting, coarse texture, and vertical distribution on valley walls in the Cascade Range and at Mount Rainier. We concluded that the Osceola in the Puget Sound lowland had been transported and deposited by a medium of which no part could have been appreciably higher than the present surface of the deposit, a requirement that is satisfied only by assuming that the material flowed into its present position.

The distribution of a deposit is very helpful in determining its origin, although the presence of lahars on some ridgetops close to the volcano caused much initial uncertainty concerning their mode of origin. More commonly, lahars occur on valley floors, especially at some distance away from their source. Their distribution and provenance generally are adequate to distinguish them from local colluvium.

The texture of some lahars resembles that of coarse fluvial sand and gravel deposits, with which lahars are typically interbedded. Probably the most diagnostic feature of a lahar in such a comparison is its lack of internal stratification, even though some successions of lahars form an assemblage of deposits that is bedded in gross aspect. However, each individual lahar lacks in-

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[1] A "sorting coefficient" is the square root of the ratio of the third (larger) quartile (the 75 percent value) to the first (smaller) quartile (the 25 percent value). The two percentiles refer to the percentage of material that is finer than the grain diameter for the percentile on the cumulative curve. As the degree of sorting increases, the two quartiles become more nearly equal, and the sorting coefficient approaches 1.0.

The designation "phi" is equal to the $-\log_2$ of the grain diameter in millimeters. The formula for the phi standard deviation ($\sigma\phi$) is $(\phi16-\phi84)/2$ and the formula for phi quartile deviation ($QD\phi$) is $(\phi25-\phi75)/2$.

ternal bedding because it moved and came to rest as a single mass-flowage unit. A fine line cannot be drawn between some fluvial deposits that are very crudely bedded and some lahars; in fact, the processes of transportation apparently are gradational. The transport ability of a lahar is tremendous because of its relatively high viscosity and high specific gravity; thus, large blocks of rock are common in the deposits. However, large boulders also are present in some crudely stratified fluvial deposits (fig. 18).

Many lahars closely resemble till, and the distinction between the two sometimes is not possible in the field. The striated, soled, and snubbed stones that are generally regarded as being typical of till are not very helpful in distinguishing tills from lahars. Stones with these features were not observed in any of the lahars, but neither are they abundant enough in the till to be useful criteria at Mount Rainier. Some deposits that I initially regarded as till were soon found to be of postglacial age, and their distance from the present glaciers indicates that they cannot have been formed by glacial advances of Holocene age. These deposits are interbedded with alluvium in some terraces and form veneers on others, but a laharic origin is inferred because all have a distribution that can be explained only by mass flowage.

The size distribution and sorting characteristics of some tills (fig. 3) are similar to those of many lahars. The sorting coefficients of seven samples of Evans Creek till range from 3.16 to 9.5 (avg. 6.41), and those of the lahars discussed in this report range from 3.41 to 17. It is nearly impossible to obtain a truly representative sample of these coarse deposits, and the true maximum sorting coefficient of both kinds of deposits probably is greater than 17.

Some lahars are lithologically similar to the deposits of hot dry block-and-ash flows. The high mobility of some block-and-ash flows, provided by gas contained in the flow, by entrapment, heating, and expansion of cold air (McTaggart, 1960), and by the conversion to steam of water, snow, and ice incorporated by the flow, would permit the flows to move down a valley floor in a manner similar to that of a lahar. One manner of distinguishing between the deposits of these two processes is by determining the temperature of the deposits when they were emplaced; this can be approximated from a study of the orientation of remanent magnetism and Curie temperature of the included rock fragments (Aramaki and Akimoto, 1957). The orientation is determined by the ferromagnetic mineral or minerals in the rock, which is magnetite in the andesites from Mount Rainier. As the magnetite in originally molten rock cools through its Curie point, it takes on a magnetic orientation that is parallel to the earth's magnetic field at that moment. This is known as thermoremanent magnetism (TRM). If a deposit came to rest while rock fragments in it were still above the Curie temperature of the magnetite, then the TRM orientations of the fragments should be uniform and parallel. But if the fragments cooled sufficiently before incorporation in a moving mass, or while the mass was still moving, their present TRM orientations would be random.

It seems possible that a block-and-ash flow could grade downvalley into a lahar if the following sequence of events occurred (Mullineaux and Crandell, 1962). A mass of hot rock fragments, bombs, and ash might accumulate at the summit of the volcano during an eruption and then might avalanche to form a block-and-ash flow. Snow incorporated by the flow as it crossed snowfields and glaciers could become water and steam in transit; the steam would increase turbulence, and both the steam and water would dissipate heat and increase mobility by decreasing internal friction. If the matrix cooled below the boiling point of water as the flow moved beyond the base of the volcano the mass might become a lahar as conversion of water to steam diminished. When the lahar came to rest, possibly as a result of the water and steam evaporating in such quantity that they were no longer effective lubricants, many bombs and dense rock fragments might still be hot enough to carbonize wood. In this regard, Kemmerling (1921) reported a temperature of 92°C at a depth of about 1 foot in a lahar a few days after it had been formed during the 1919 eruption of Kelut in Java. About 2 weeks after the eruption, the temperature had dropped to 50°C, and 2 weeks later the temperature had dropped to 30°C. Kemmerling also mentioned a temperature of more than 360°C in a gas vent in the same lahar, and a temperature of 100°C at the same spot a year later. He attributed the source of the heat to blocks of pumice which had been ejected by the volcano and incorporated in the lahar. Kemmerling mentioned that a person had been caught and transported some distance in another lahar from Kelut without having been burned. On the other hand, many corpses found later in the same lahar were severely burned.

The texture of some lahars resembles that of some avalanche deposits. This similarity is not surprising, for many lahars originated in avalanches, and became lahars only because substantial amounts of water were present in the rock that formed the avalanches or because water was incorporated during movement. Size data were obtained on two samples of the avalanche deposits that resulted from rockfalls at Little Tahoma Peak in 1963 (fig. 4) (Crandell and Fahnestock, 1965). The samples had sorting coefficients of 6.38 and 6.63.

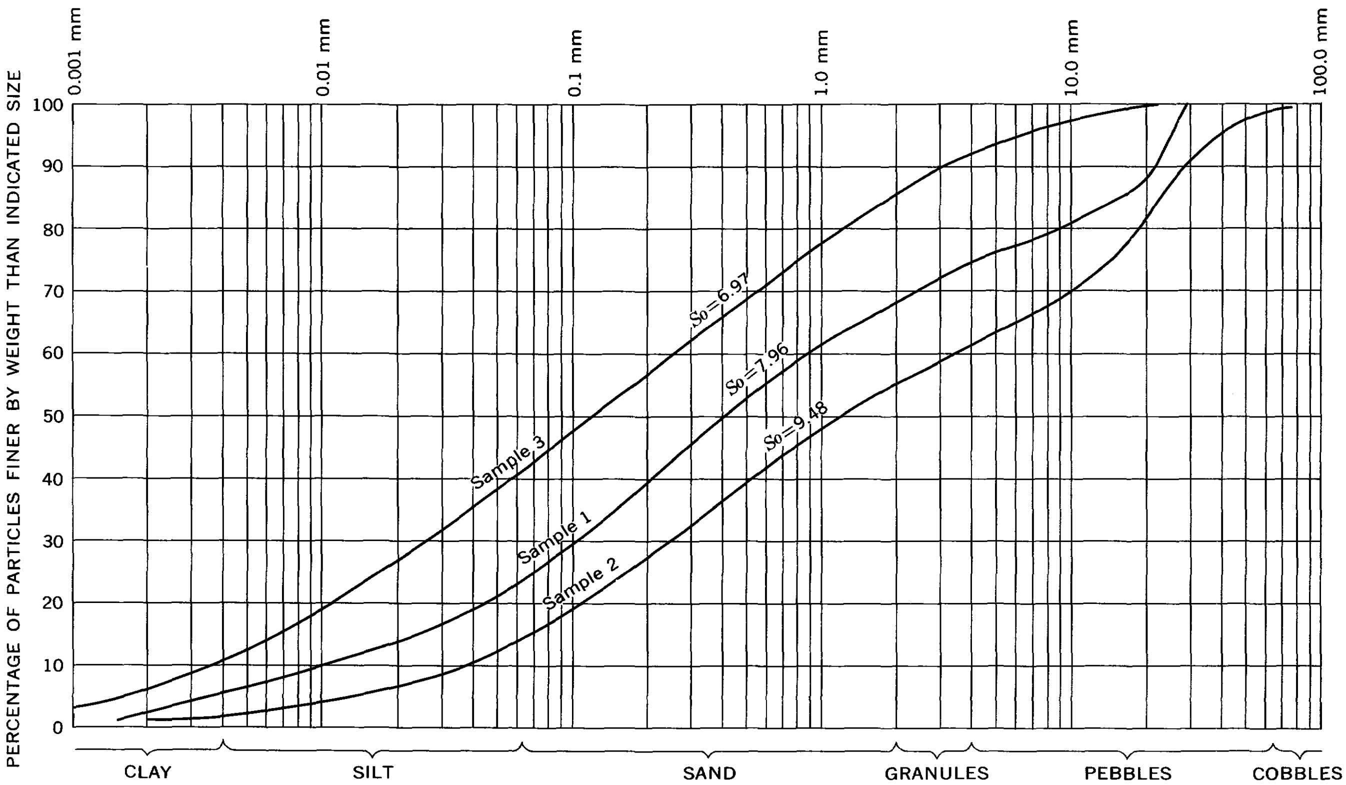

FIGURE 3.—Cumulative curves and sorting coefficients (*So*) of three samples of Evans Creek till. Sample 1 is from a cutbank of the Nisqually River in the NW¼ sec. 35, T. 16 N., R. 6 E., 1 mile southeast of Ashford, Wash. Sample 2 is from a Roadcut at Round Pass, and sample 3 is from a roadcut 1 mile southeast of Box Canyon.

Neither sorting index, however, truly represents the degree of sorting in the deposits because of my inability to include in the samples a proportionate amount of the abundant large rock fragments.

Two common features of lahars, which may help in recognition, are the presence of innumerable air spaces within the matrix and a vertical size gradation from coarse material at the base to fine material at the top. Air spaces seem to be most common in lahars that have a fine-grained matrix. Most of the air spaces are of irregular shape and range in size from a fraction of a millimeter to several millimeters, but air bubbles of spherical shape were noted in the fine-grained, graded top of a young lahar from Mount St. Helens. Bull (1964, p. A31) described bubble cavities in both water-laid deposits and mudflows in alluvial fans in California. He noted that they are more common in the mudflows and that they are larger and more spherical if the mudflow has a considerable content of clay or silty clay. Air spaces in lahars seem to have been formed by air bubbles trapped within the matrix rather than by the draining away of free water or part of the matrix after the lahar came to rest.

The vertical gradation in texture of lahars is illustrated by data in table 2. This gradation is most conspicuous where the entire thickness of the lahar is exposed and commonly it is best shown by the upper few feet of a lahar; some lahars grade imperceptibly upward from coarse, unsorted material into a silty sand that is quite well sorted. An outcrop of the middle third of a lahar, in contrast, might show no such gradation to the eye, and the gradation possibly might not even be detected from grain-size analysis. I have seen this vertical gradation in dozens of lahars at many localities in the Western United States. These lahars range in age from Tertiary to historic and in thickness from a few inches to many tens of feet. Unfortunately, however, the vertical gradation in texture is not present in all lahars, nor even in each lahar of a vertical succession of several in the same outcrop.

Size-distribution analyses of several lahars indicate that the proportion of silt and clay to the whole −2-mm (millimeter) fraction is remarkably similar for any given lahar, regardless of the horizon from which the sample came. This relation seems to be true even though the total amounts of the several size fractions change considerably from top to bottom of a given deposit. A tabulation of data from eight lahars sampled at two horizons (table 2) indicates a range in the proportion of silt and clay to the −2-mm fraction of only 0.4–3.4

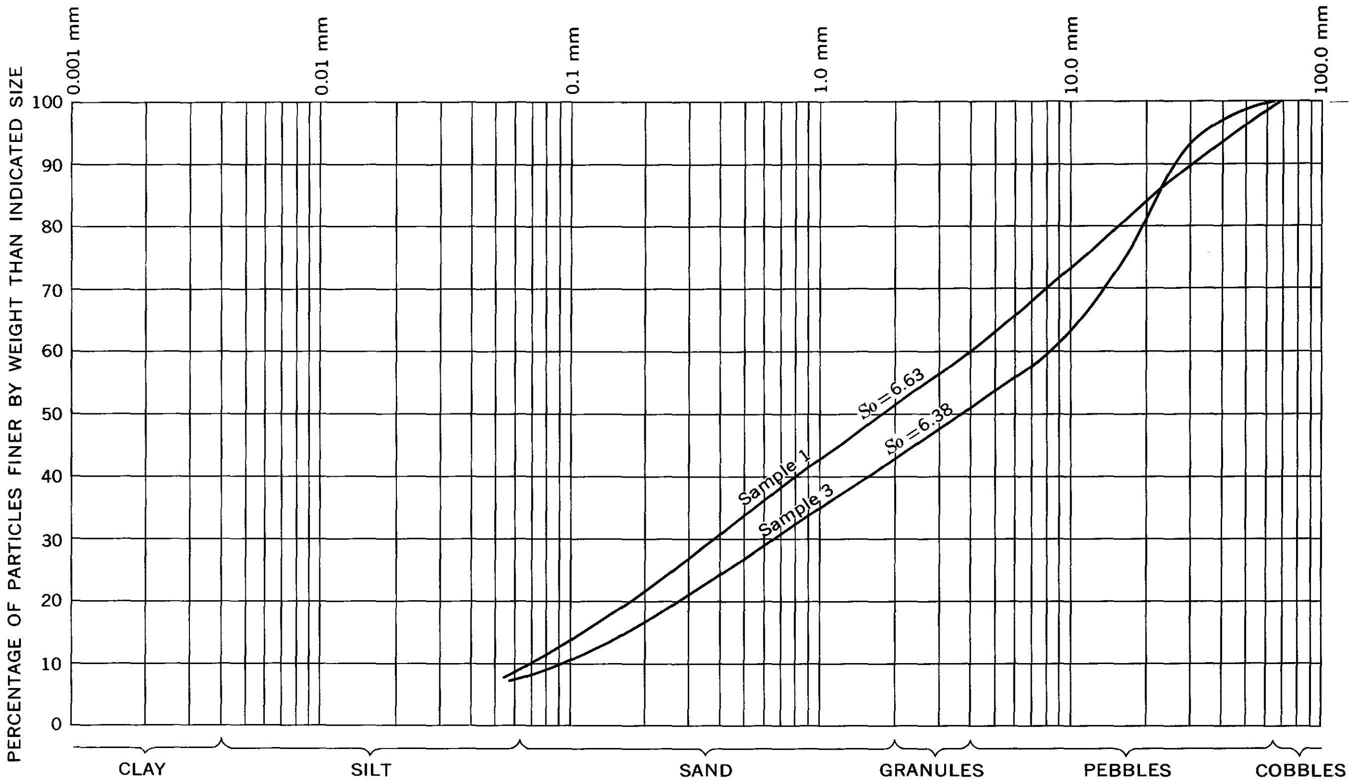

FIGURE 4.—Cumulative curves of samples from the avalanche deposits on the floor of the White River valley. (See Crandell and Fahnestock, 1965, fig. 3.) Samples 1 and 3 are from units 1 and 3 of the avalanche deposits from Little Tahoma Peak. *So*, sorting coefficient.

percent. The similarity in proportions of material within the −2-mm fraction suggests that the matrix is nearly uniform in texture and that the textural change in the lahar vertically is principally one of an upward decrease in the percentage of material larger than 2 mm.

Schmincke (1967) also called attention to the graded nature of lahars and, in addition, noted (p. 440) a basal zone less than a foot thick of vaguely stratified, fine to coarse sand in the lahars he studied. Basal zones of sand like those described by Schmincke were not noted in the lahars at Mount Rainier. I have seen beds of sand beneath many lahars of Cenozoic age in western Washington, but these beds seem to be genetically related to the underlying sequence of fluvial deposits rather than to the lahar.

One interesting and significant relation that was found in this study is the propensity of lahars to flow down a valley and to leave only a thin deposit on the valley sides and floor to mark their passage. Thick fills commonly are formed by lahars only at some distance from the volcano, mostly at places where the valleys widen and become less steep and in areas of the lowland beyond the mountain front. During the passage of some lahars of great volume, such as the Osceola Mudflow, valleys probably were filled with flowing mud to depths of hundreds of feet for many minutes. The Paradise lahar, however, probably progressed downvalley as a single rapidly moving wave of fluid material hundreds of feet high, and, except momentarily, it did not fill valleys to the maximum height recorded by its remnants.

Because of the ephemeral character of a deep flowing current of mud in a steep and narrow valley and its characteristic manner of leaving only a veneer to record its passage, some conventional inferences that can be made with regard to the aggradation and downcutting of fluvial fills are not pertinent to lahars. For example, each terrace of a flight of several in a valley may be veneered with a lahar. According to a conventional interpretation, the lahar on each terrace would represent a separate event—the lahar on the highest terrace would be the oldest, and the formation of each lahar would be followed by fluvial downcutting. However, this study has demonstrated that each terrace may be veneered with the same lahar, which was deep enough to cover them all temporarily before the fluid material drained downvalley. A corollary is that the same lahar that caps a high terrace in a flight of several terraces may lie beneath younger lahars and fluvial deposits in a lower terrace. It is important to recognize, further, that the

TABLE 2.—*Size-distribution data on eight lahars, each sampled from two different horizons*

[In each lahar the proportion of silt and clay to the whole −2-mm fraction is closely similar in both horizons]

Lahar	Lahar thickness (ft)	Horizon of sample	−0.0625 mm (percentage of silt and clay)	−2 mm (percentage of silt, sand, and clay)	−0.0625 mm / −2 mm (percentage of silt and clay to whole −2 mm fraction)
1	13	Top 1 ft	13	59	22
		Bottom 1 ft	8	37	21.6
2	>9	Top 1 ft	15	68	22.1
		5–7 ft below top	12	50	24
3	8.5	Top 1 ft	19	83	22.9
		Basal 4 ft	7	28	25
4	6.5	Top 1 ft	36	93	38.7
		Bottom 1 ft	20	57	35.1
5	18	Top 1 ft	25	70	35.7
		Bottom 1 ft	24	66	36.4
6	25	5–7 ft below top	18	54	33.3
		3–4 ft above bottom.	20	63	31.7
7	9	Top 1 ft	8	37	21.6
		Bottom 1 ft	11	52	21.2
8	8	Top 1 ft	6	34	17.6
		Bottom 1 ft	6	31	19.4

1. Uppermost lahar of three exposed in the walls of a gravel pit at Gilmore Corners, Wash. (See Mullineaux and Crandell, 1962, p. 859–860, unit 5 in measured section.) Lahar originated at Mount St. Helens volcano probably within the last 2,000 years.
2. Lowermost lahar of three at Gilmore Corners (unit 1 in measured section.)
3. Upper lahar of two in the Alderton Formation of early(?) and middle(?) Pleistocene age near Sumner, Wash. (See Crandell, 1963b, p. A78, measured section 6, unit 5.)
4. Electron Mudflow. Samples from outcrop at confluence of Carbon and Puyallup Rivers near McMillin, Wash. (See Crandell, 1963b, p. A51.) The mudflow originated at Mount Rainier about 500 years ago.
5. Lahar in the Puyallup Formation of middle(?) Pleistocene age exposed in the north wall of the Fennel Creek valley, in the NW¼ sec. 8, T. 19 N., R. 5 E., about 3.5 miles southeast of Sumner, Wash.
6. Lahar from Mount Hood volcano(?) in the Gresham Formation of middle(?) Pleistocene age. (See Trimble, 1963, p. 55.) Samples taken from roadcut outcrop in the NE¼ sec. 14, T. 1 S., R. 4 E., in the valley of the Big Sandy River east of Portland, Oreg.
7. Uppermost lahar of three in sedimentary deposits of Miocene age near Buckley, Wash. (See Mullineaux and others, 1959, p. 689, unit 6 in measured section.)
8. Middle lahar of three in sedimentary deposits of Miocene age. (See above; unit 2 in measured section.)

lahar remnants on even the highest terrace do not necessarily mark the maximum height attained by the lahar at that point while it was moving.

Despite the remarkable thickness or depth some lahars attained during movement, they evidently did not erode deeply even on fairly steep gradients. For example, lahars in some valleys are commonly found on top of relatively thin layers of sand and volcanic ash that presumably would be easy to erode. These valleys have gradients of as much as 700 feet per mile today, and they probably had comparable slopes when the lahars occurred. The inability of many mudflows to erode at their base was recognized by Blackwelder (1928). This characteristic is particularly well illustrated in western Washington by the presence of leaves between the base of a poorly consolidated lahar of Miocene age and an underlying layer of fine volcanic ash only a few inches thick (Mullineaux and others, 1959), and I have observed a similar relation in the Rocky Mountain foothills near Denver, Colo., where a semiconsolidated lahar of the Upper Cretaceous and Paleocene Denver Formation is separated by a thin layer of leaves from an underlying bed of volcanic ash. Schmincke (1967) described thin tubes that extend upward into the basal part of a Miocene or Pliocene lahar in central Washington; these tubes seem to be the molds of plants that were engulfed by the moving lahar. However, Schmincke regarded these features as low-gradient, low-velocity phenomena, because he inferred (p. 447) that on steeper gradients, closer to the source volcano, similar lahars had "picked up stream gravels and alluvium and uprooted bushes along their way" and (p. 440) that elsewhere one of the lahars was thought to have "possibly carved a creek channel in the underlying gravels."

There can be little question that lahars can and do pick up some loose materials from the surfaces over which they flow, and this erosive ability may be related not so much to degree of slope as to local turbulence caused by channel and valley configuration. Although some lahars of Pleistocene age in the southern part of the Puget Sound lowland seem to have traveled 40–50 miles from their source without appreciable contamination (Crandell, 1963b, p. A10), more than half of the pebbles in samples of the Osceola and Electron Mudflows, at comparable distances from their source, are of rocks not derived from Mount Rainier (Crandell, 1963b, p. A14).

The apparent inability of many lahars to erode, especially when spreading out on a surface of low slope, suggests that the lower part of a lahar is characterized by laminar flow rather than turbulent flow, and also that once the front of a lahar has passed a given point, the material immediately above the base at that point becomes motionless or nearly so, even though movement is continuing in the main mass at higher horizons. It is as if the lahar moved forward as a rug is unrolled; the immobilized layer (the rug) then acts as a buffer zone immediately above the underlying surface to protect it from erosion.

WAYS IN WHICH LAHARS ORIGINATE

Lahars can be grouped by origin into several categories for the purpose of discussion: (1) those that are the direct and immediate results of eruptions, (2) those that are indirectly related to an eruption or that occur shortly after an eruption, and (3) those that are not related in any way to contemporaneous volcanic activity.

Lahars that are the direct and immediate results of volcanism can be formed in many ways: some of these are discussed and a few are illustrated by examples that have occurred within historic time.

Floods and lahars are sometimes formed when a crater lake is forcefully expelled during an eruption. The Indonesian volcano Kelut on the island of Java is notorious for causing lahars in this manner. In 1919, an eruption through Kelut's crater lake spilled 39 million cubic yards of water down the south and southwest slopes of the volcano. The water picked up great quantities of loose rock debris and the resulting lahars totally or partly destroyed 104 villages and killed 5,500 people. Some lahars reached a distance of 12 miles from the volcano (Kemmerling, 1921). A crater lake can also be released by the failure of its enclosing walls. During eruptions of Seméru (Smeru) volcano, also on Java, magma rising in the cone has repeatedly pushed aside parts of the crater walls, and this material has avalanched down the sides of the volcano to produce lahars (Baak, 1949, p. 5–6).

Repeated floods of hot water and hot lahars were one of the dominant features of the 1902 eruption of Mount Pelée on Martinique, and some of them were caused by emptying of the crater lake (Anderson and Flett, 1903, p. 489). Two of the largest hot lahars preceded, by 4 hours, the nuée ardente that destroyed the town of St. Pierre at the foot of the volcano (Hovey, 1902, p. 346). The contemporaneous eruptions of La Soufrière on the island of St. Vincent also caused a crater lake to empty and to form a "torrent of 'boiling hot' water and mud" (Hovey, 1902, p. 342). The front of this lahar was at least 50 feet high as it rushed down a valley that heads on the volcano.

Mud has been extruded directly by some volcanoes. According to Ōinouye (1971), mud consisting of finely divided plagioclase, hypersthene, augite, magnetite, glass, and hematite was erupted in 1910 from five craters in the summit of Usu volcano in Japan. During an eruption of Yaké Daké in Japan in 1962, hot montmorillonite-bearing mud ejected from a vent on the volcano formed a small mudflow (Morimoto and Ossaka, 1964). From a study of andesitic breccias of Tertiary age in the Cascade Range of northern California, Durrell (1944) concluded that mudflows can be extruded directly from volcanic fissures. He suggested that the solid fraction of the breccias he studied represented a highly mobile mass of andesite fragments in a matrix of comminuted andesite and alteration products and that the water was derived directly from the associated magma.

Avalanches of rock debris can cause lahars by temporarily damming rivers. The water may spill over the dam, erode it, and the entire deposit may sweep downstream as a lahar. An event of this kind occurred during an eruption of Asama volcano in Japan in 1783 when a hot avalanche dammed a nearby river. Within an hour the river overtopped the dam, eroded it, and caused it to collapse. The debris rushed downstream as a hot mudflow that traveled more than 50 miles and killed more than 1,300 people (Aramaki, 1956). During the 1929 eruption of Santa Maria volcano in Guatemala, glowing avalanches moved down into the valleys of the Río Tamblor and Río Concepcíon and produced boiling-hot lahars. The top of the lahar in the Río Tamblor was covered with incandescent rock debris, and the lahar overflowed a channel more than 300 feet deep and 250 feet wide (Sapper and Termer, 1930, reviewed by Jaggar, 1931).

Avalanches of hot rock debris have also caused lahars by melting snow and ice on a large scale. During an eruption in 1955 of Bezymianny volcano in Kamchatka, block-and-ash avalanches spread over a broad area at the east base of the cone. Snow which was melted by the hot debris caused lahars that flowed downvalley more than 45 miles (Gorshkov, 1959). During the 1938 eruption of Avacha volcano, also in Kamchatka, lahars were caused in part by the deposition of hot pyroclastic material on snow and ice (Meniailov, 1939). Solid material in the lahars consisted of breadcrusted and scoriaceous bombs in a black sand matrix.

Volcanic explosions commonly cause landslides in rocks that have been weakened by hydrothermal alteration. An explosive eruption of Tokachi-dake volcano in Japan caused a large part of the cone to collapse in 1926. An immense avalanche of hot rock fragments accompanied by steam and possibly by hot water from the crater descended the west flank of the volcano and melted an accumulation of snow. The resulting lahar poured down the mountain and reached a distance of nearly 15 miles (Tada and Tsuya, 1927). An explosion of the same volcano in 1962 caused a slide of about 4 million cubic meters of rock on one side of the cone, which became a hot lahar as it moved downslope. The slide occurred in rocks that had been extensively decomposed by fumarolic activity (Murai, 1963).

An unusually large avalanche that moved like a lahar was caused by a phreatic explosion at Bandai-san volcano in Japan in 1888. The horizontally directed force of the explosion caused the failure of a large segment of the cone. In all, 1,487 million cubic yards of rock debris flowed downslope and covered an area of 27 square miles at the base of the volcano. The mass was thought to have been in a relatively dry state during movement (Sekiyo and Kikuchi, 1889). A similar, but prehistoric, event occurred at Asama volcano when a phreatic explosion destroyed the eastern part of the cone and caused a lahar that spread over an area of about 35 square miles. The rocks involved had previously been extensively altered to clay by solfataric activity (Aramaki, 1963). An even older lahar originated from a catastrophic phreatic explosion of a pre-Asama volcano at the same site (Aramaki, 1963, p. 267).

At Lassen Peak in northern California, lahars moved down two valleys north of the volcano for a distance of more than 20 miles in May 1915. Day and Allen (1925) attributed the lahars to the rapid melting of snow on the volcano by hot rain, hot volcanic ash, and a steam blast. It seems more likely, however, that rapid melting of snow was caused by a lava flow near the summit of the volcano (Finch, 1930).

Lahars can also result indirectly from eruptions in many different ways. A crater lake may be released suddenly by failure of part of its restraining embankment for some reason not associated with simultaneous volcanism. In 1953, failure of part of the natural dam that impounded Crater Lake on Mount Ruapehu in New Zealand permitted a large volume of water to rush down the side of the volcano, where great quantities of loose ash and boulders were picked up to form a lahar. The lahar swept away a railroad bridge a few minutes before the arrival of an express passenger train, and 151 lives were lost (O'Shea, 1954).

Pyroclastic deposits that are formed during an eruption are especially susceptible to saturation during periods of heavy precipitation, and sliding and flowage of these masses commonly cause lahars. These "rain lahars" are an almost daily occurrence during the monsoon season following an eruption of the Javanese volcano Kelut (Kemmerling, 1921). A few weeks after the eruptions of La Soufrière, in 1902, heavy rains caused boiling-hot lahars to flow repeatedly down valleys that headed on the flanks of the volcano (Anderson and Flett, 1903, p. 422–424, 428–434). The sediment in the lahars was principally derived from thick deposits of hot sand-sized ash that had been formed during the eruption. Between episodes of volcanic activity at Vesuvius in 1906, rain and melting snow saturated loose rock debris on the flanks of the volcano and caused repeated lahars (Perrett, 1924, p. 102). During the 1963–1964 eruptions of Irazú in Costa Rica, flash floods resulted from runoff whose volume was greatly increased by a thin compact layer of newly erupted ash. The floods became debris flows as they scoured valley sides which were formed by poorly consolidated deposits. One debris flow caused great damage and some loss of life in the city of Cartago at the south base of the volcano (Waldron, 1967).

The last general category of lahars consists of those that are unrelated to volcanism. Mudflows and debris flows can result from saturation of loose rock debris by rain and melting snow in an alpine region wherever certain conditions are met—a source of rock debris, adequate moisture, and a steep slope. They may occur at volcanoes more often than elsewhere because of the combination there of all these conditions. Lahars are also frequently caused by the sudden release of a body of water impounded by a glacier. Although the water released may be wholly the product of glacier melting related to atmospheric conditions, a flood from a glacier on a volcano may also result from rapid, large-scale melting caused by a steam vent or by some other source of volcanic heat.

AGE AND LITHOLOGY OF MOUNT RAINIER VOLCANO

The earliest evidence of Mount Rainier volcano is present in unconsolidated deposits in the Puget Sound lowland to the northwest. These deposits include lahars derived from an active volcano at the site of Mount Rainier (Crandell, 1963b, p. A10–A11). They are interbedded with glacial drift deposited by a lobe of the Cordilleran ice sheet which moved southward down the Puget Sound lowland. The oldest known lahars were formed during the Alderton Interglaciation, of middle Pleistocene age (table 3). Stones in these lahars are chiefly hornblende- and hypersthene-bearing andesites. A hornblende-hypersthene andesite lava flow is known to occur at only one locality in Mount Rainier National Park, and its age is unknown (Fiske and others, 1963, p. 64). However, lahars that contain fragments of a hornblende-hypersthene andesite crop out in Glacier Basin on the northeast side of Mount Rainier (pl. 1), where they underlie glacial drift and lava flows of pyroxene andesite.

The oldest hypersthene-andesite lavas from Mount Rainier form thick flows that filled canyons in the Cascade Range to depths of as much as 2,000 feet (Fiske and others, 1963, p. 66–69). These old resistant flows now underlie divides that radiate outward from the

TABLE 3.—*Subdivisions of Quaternary time in western Washington*

[The Burroughs Mountain Stade occurred between about 3,000 and 2,500 years ago; the Garda Stade probably began about 800 years ago and extends to the present (Crandell and Miller, 1964; Porter and Denton, 1967, p. 198–201)]

Age	Geologic-climate unit	
Holocene	Winthrop Creek Glaciation	Garda Stade Burroughs Mountain Stade
	"Hypsithermal interval"	
Pleistocene	Fraser Glaciation	Sumas Stade Everson Interstade Vashon Stade Evans Creek Stade
	Olympia Interglaciation Salmon Springs Glaciation Puyallup Interglaciation Stuck Glaciation Alderton Interglaciation Orting Glaciation	

base of the volcano, and the sites of some of the former canyon walls or divides are now valleys. At a later stage, Mount Rainier erupted hundreds of thin lava flows and built up its present cone. Fragmental deposits interlayered with lava flows on the flanks of the volcano include well-indurated flow breccias as well as loose rubbles that may have originated as block-and-ash avalanches; pyroclastic deposits interbedded with these breccias and rubbles are few (Fiske and others, 1963, p. 75).

The early canyon-filling lavas, as well as the rocks of the modern cone, are chiefly pyroxene andesites; hypersthene is ubiquitous and is the dominant mafic mineral in most flow rocks. According to Fiske, Hopson, and Waters (1963), augite is generally abundant but slightly subordinate to hypersthene, which it encloses in some flow rocks. Brown hornblende is a sparse constituent of some flows. Flows of olivine andesite were erupted at two small satellite vents at Echo and Observation Rocks relatively late in the history of the volcano, but before the Fraser Glaciation. The most recent flows, which make up the present summit cone and which probably are no more than 2,000 years old (table 6), are of an augite-hypersthene andesite (Fiske, Hopson, and Waters, 1963). Some Holocene pyroclastic deposits erupted by Mount Rainier show somewhat greater diversity in mafic minerals than some of the flows (D. R. Mullineaux, oral commun., 1969). For example, layer D (table 5) contains variable amounts of hypersthene, augite, hornblende, and oxyhornblende.

Mount Rainier volcano seems to have been intermittently active during about the last 10,000 years, although it has apparently been much more active during some extended episodes than during others. During this time interval the volcano has erupted lava flows at least once; bombs, blocks, and ash, which caused hot avalanches, at least three times; and pyroclastic material at least 11 times. In addition, thin layers of fine-grained rock debris, which may be lithic ash, are found at many horizons in the sequence of pyroclastic deposits and may record a dozen or more eruptions that are not known to be represented by other deposits (D. R. Mullineaux, oral commun., 1969).

DATING OF LAHARS

All the lahars described in this report are of Holocene age, except for one that probably was formed during a late part of the Fraser Glaciation (table 3). The postglacial age of most lahars can be readily determined because they overlie glacial deposits formed during the Fraser Glaciation.

Many of the lahars either contain wood from which radiocarbon age determinations could be made or are closely associated with other deposits that are wood bearing. Age determinations cited here (table 4) of less than 6,000 years have been corrected by Meyer Rubin (written commun., 1969) from data provided by H. E. Suess. These corrections are based on a C^{14} half life of 5,730 years and also take into account past variations in atmospheric C^{14}. Ages of less than 6,000 years that are given in the following text will be the corrected ages in 1970 unless specified to be uncorrected ages.

Some lithologically similar lahars have been distinguished, traced, and correlated by their stratigraphic relation to pyroclastic deposits. In some places the pyroclastic deposits are interbedded with the lahars; elsewhere, the age of a given lahar can be bracketed by the presence or absence of certain pyroclastic layers on top of it. The ages of most of the pyroclastic deposits in Mount Rainier National Park are known to within a few hundred years from radiocarbon age determinations of associated organic matter or from age determinations of such matter from horizons immediately above and below each layer of pumice (table 5). All the postglacial lahars recognized in the valleys heading at Mount Rainier are shown in chronological order in table 6, together with the pyroclastic deposits which help to date them.

TABLE 4.—*Radiocarbon dates pertaining to surficial deposits less than 6,000 years old near Mount Rainier*

[The radiocarbon dates shown in the first column are based on a C^{14} half life of 5,568 years. The "true" dates shown in the next column are based on a half life of 5,730 years and are corrected for C^{14} variations in the atmosphere. (Based on a written commun. from H. E. Suess to Meyer Rubin, 1968.)]

Sample	Radiocarbon date (yr)	"True" date	Years ago in 1970[1]	Stratigraphic position of sample
W-1120	290±200	1525 A.D.	450	Wood from duff above pyroclastic layer W from Mount St. Helens.
1119	320±200	1500 A.D.	450	Wood from duff below pyroclastic layer W.
565	530±200	1380 A.D.	600	Wood from Electron Mudflow.
2113	1,050±350	950 A.D.	1,000	Wood from mudflow in Puyallup River valley.
1971	1,100±250	900 A.D.	1,050	Wood from mudflow in South Puyallup River valley.
1393	2,040±200	160 B.C.	2,150	Wood from above pyroclastic layer C from Mount Rainier.
566	2,170±200	220 B.C.	2,200	Wood from mudflow at mouth of Mowich River.
1396	2,340±200	520 B.C.	2,500	Wood from below pyroclastic layer C.
1587	2,350±250	530 B.C.	2,500	Charcoal from block-and-ash flow in South Puyallup River valley.
930	2,550±200	750 B.C.	2,700	Wood from clay above pyroclastic layer Y.
2114	2,610±350	850 B.C.	2,800	Wood from Round Pass Mudflow in Tahoma Creek valley.
1972	2,710±250	950 B.C.	2,900	Wood from Round Pass Mudflow in Puyallup River valley.
1118	2,980±250	1300 B.C.	3,250	Carbon from duff above pyroclastic layer Y from Mount St. Helens.
1115	3,500±250	2010 B.C.	4,000	Wood from peat below pyroclastic layer Y.
564	4,700±250	3600 B.C.	5,550	Wood from Osceola Mudflow.
L-223A[2]	4,800±300	3640 B.C.	5,600	Do.
L-223B[2]	4,950±300	3730 B.C.	5,700	Do.
W-2053	5,020±300	3810 B.C.	5,800	Peat from above pyroclastic layer N, below layer F, both from Mount Rainier.
UW-62[3]	5,040±150	3820 B.C.	5,800	Wood from Osceola Mudflow.

[1] Rounded off to the nearest 50 years.
[2] Lamont Geological Observatory.
[3] University of Washington.

TABLE 5.—*Source, age, and description of some postglacial pyroclastic deposits in Mount Rainier National Park*

[D. R. Mullineaux, written commun., 1970]

Pyroclastic layer	Source volcano	Approximate age (yrs)	Description
X	Rainier	>110–<150	Scattered pumice lapilli.
W	St. Helens	450	Pumice ash.
C	Rainier	>2,150–<2,500	Pumice lapilli and scattered blocks.
Y	St. Helens	>3,250–<4,000	Pumice ash.
B	Rainier	>4,000–<5,800	Pumice ash and scattered lapilli.
H	do	>4,000–<5,800	Scattered pumice lapilli.
F	do	5,700	Montmorillonite-rich lithic ash.
S	do	>5,700–<6,600	Sand- to block-sized lithic rubble.
N	do	>5,800–<6,600	Lithic ash.
D	do	>5,800–<6,600	Pumice lapilli.
L	do	>5,800–<6,600	Do.
A	do	>5,800–<6,600	Pumice ash and scattered lapilli.
O	Mazama	6,600	Pumice ash.
R	Rainier	>8,750–<11,000?	Pumice and lithic lapilli and ash.

The most distinctive and widespread pyroclastic deposits at Mount Rainier are from two other volcanoes. Layer O (table 5) has mineralogic characteristics that correspond to those of the pumice and ash that were erupted by Mount Mazama volcano at the site of Crater Lake, Oreg., about 6,600 years ago (Crandell and others, 1962; Powers and Wilcox, 1964). This pumice layer is especially useful in stratigraphic studies because it blankets the entire park and the adjoining region to a depth of 1–2 inches and is a distinctive yellowish orange.

The other two exotic pumice deposits are layers Y and W, both of which were erupted by Mount St. Helens, a volcano about 50 miles south-southwest of Mount Rainier. Layer Y is a light-yellowish-brown pumice of medium to very coarse sand size. It thickens westward from about 1 inch near the east edge of the park to about 12 inches near the southwest corner. Layer Y is between 3,250 and 4,000 years old, and for convenience it will be arbitrarily assumed to have an age of about 3,600 years.

Pyroclastic layer W is a white pumice of fine to medium sand size. It thickens from about a quarter of an inch on the west side of the park to about 3 inches near the southeast corner. A radiocarbon date of 320±200 years (W–1119) was determined for charcoal in a horizon of duff beneath layer W, and age of 290±200 years (W–1120) for charcoal in a layer above the pyroclastic deposit (Crandell and others, 1962). Radiocarbon ages of about 300 years have a "true" age of about 450 years (table 4). An age of about 450 years for pyroclastic layer W is consistent with tree-ring data, because there are trees at least 435 years old growing on the surface of deposits at Mount Rainier that are younger than the pumice.

Although most of the recognizable pyroclastic deposits in the park originated at Mount Rainier, few are widespread, distinctive, or preserved well enough to be of use in dating other deposits except in limited areas. The most useful pumice from Mount Rainier is layer C, which is mostly of lapilli size and which is widely distributed over most of the park east of the volcano. It is generally one to several inches thick and is between 2,150 and 2,500 years old. For convenience of reference, it will be assumed to have an age of about 2,300 years.

The following description of lahars and some other unconsolidated deposits at Mount Rainier contains many references to the stratigraphic relations of these deposits to certain pumice layers. The reader is urged to take special note of the following pyroclastic deposits and to remember their approximate age: layer W, about 450 years old; layer C, about 2,300 years old; layer Y, about 3,600 years old; and layer O, about 6,600 years old.

The reader may wonder why the pyroclastic deposits were not given letter designations in alphabetical order by age. Letters were arbitrarily assigned to the deposits at an early stage of the study, when only five layers were recognized (Crandell and others, 1962), to allow for the possible later addition of other layers. More than 15 pyroclastic deposits have now been distinguished and given letter designations.

ORIGIN OF THE CLAY IN SOME LAHARS

Many lahars at Mount Rainier contain substantial amounts of montmorillonite or kaolinite, or both, as well as lesser amounts of some other clay minerals. The source of these clays is a critical problem because most other unconsolidated deposits at Mount Rainier are typically poor in clay minerals. The magnitude of the problem can be illustrated by some very crude estimates of the volume of clay in the Electron and Osceola Mudflows, which, respectively, are about 600 and 5,700 years old and which originated on the west and east sides of the volcano. The Electron Mudflow has a volume of at least 200 million cubic yards in the Puget Sound lowland alone, where it has a clay-size fraction of about 9 percent; the clay-mineral content of this fraction is about 60 percent. The total clay-mineral content of the mudflow, therefore, probably is at least 10 million cubic yards. The estimated volume of the Osceola Mudflow is at least 2.6 billion cubic yards. The clay-sized fraction of nine analyzed samples averages about 9 percent, of which clay minerals make up an average of 75 percent. The mudflow, therefore, may contain as much as 150 million cubic yards of clay minerals.

The large amount of clay in some lahars seems to have a direct bearing on their manner and place of origin. The two most obvious possible origins of the clay minerals are through weathering processes and by hydrothermal alteration of rock in the volcano.[2]

Montmorillonite and kaolinite are known to be products of weathering processes and are commonly found together, although in different proportions, in many soils (Grim, 1953, p. 340–341). At Mount Rainier, I found no extensive area of rock or surficial deposits altered to clay by surface weathering processes on the lower slopes of the volcano. This lack of weathered material is readily explained by the predominance of mechanical weathering processes near and above timberline. Furthermore, in the unlikely event that clayey profiles of weathering ever existed on the flanks of the volcano, they surely would have been stripped away during the Fraser Glaciation. No such profiles have been formed in Holocene time at Mount Rainier.

Nevertheless, Fiske, Hopson, and Waters (1963, p. 85) suggested that weathered material provided the primary source of the largest Holocene lahar from Mount Rainier—the Osceola Mudflow. Crandell and Waldron (1956, p. 353) reported abundant montmorillonite in the matrix of the mudflow, which was accompanied by a kaolin mineral. They thought both of these minerals were derived from hydrothermally altered rocks of the volcano. Fiske and his colleagues, however, concluded that the primary source of the montmorillonite was in "altered water-laid pumiceous sediments and pumice-slurry flood deposits interstratified in the valley fills along the headwaters of White River." Such a deposit on the south side of Inter Fork valley, which was first identified as the Osceola Mudflow by Crandell and Waldron (1956), was described by Fiske and his coworkers as consisting of two parts—a lower part of chiefly "well-stratified sands and gravels" and an upper part of "water-laid pumiceous sediments and pumiceous mudflows now partly altered to a sticky clay." When I reexamined this outcrop during the present investigation, I found a lower unit of glaciolacustrine sand and silt interbedded with thin layers of till, all part of the Evans Creek Drift, which was deposited during the Fraser Glaciation. Size-distribution analysis of a sample of the till indicated 8 percent clay-sized material. An X-ray examination of the clay fraction revealed feldspar, cristobalite, and quartz; no clay minerals were identified. A sample of the fine-grained glaciolacustrine sediment also contained 8 percent clay-sized material, most of which consisted of feldspar and cristobalite but included a small amount of an unidentified clay mineral. The overlying unit, which was described by Fiske, Hopson, and Waters (1963, p. 86) as pumiceous sediments and pumiceous mudflows, is the Osceola Mudflow itself, which is as much as 100 feet thick here. I found no pumice within the mudflow, although several feet of young, unweathered pumice overlies it. This remnant of the Osceola is indistinguishable from the mudflow farther upvalley, where it veneers the floor and sides of Glacier Basin, as well as the ridgetops bordering the basin.

Remnants of sedimentary fills, such as those described by Fiske and his coworkers, are present in some of the valleys that head at Mount Rainier; some of the fill remnants include clayey lahars, and some include layers of fresh, unaltered pumice a few inches thick. The clay in such lahars was thought by Fiske and his associates to have been partly formed in place by weathering of pumice, and some of the clay was thought to have been transported by slopewash and derived from a blanket of weathered volcanic ash on the adjacent valley walls. As evidence of a widespread blanket of weathered ash, Fiske, Hopson, and Waters (1963, p. 80) described a layer "mostly altered to a greasy yellow clay containing abundant montmorillonite" at Mist Park and in the headwaters of Marmot Creek, both northwest of the volcano. The layer they noted at these two localities is pyroclastic layer O, the Mazama ash (table 5). Mechanical analyses of four samples of this ash, collected from outcrops at various places within Mount Rainier National Park, show that the ash contains only from 1 to 7 percent of clay-sized material (D. R. Mullineaux, oral commun., 1969). In one sample, montmorillonite and a mixed-layered montmorillonite-mica mineral each made up one part in 10 and were accompanied by a trace of kaolinite. In the other three samples, clay minerals either were absent or were present in only trace amounts. According to D. R. Mullineaux (oral commun., 1969), microscopic examination shows that delicate shard points and filaments of glass from layer O are intact, and the glass appears to be virtually unweathered. Thus, I do not believe that layer O could have provided an adequate source for the large volume of clay in the Osceola Mudflow.

Hopson, Waters, Bender, and Rubin (1962, p. 640) and Fiske, Hopson, and Waters (1963, p. 81) evidently considered the ash layer at Mist Park to be correlative with a layer of yellow clay (pyroclastic layer F) on the uplands northeast of the volcano (Crandell and Waldron, 1956, p. 355). That latter clay is, however, stratigraphically above layer O, as is demonstrated in countless natural exposures and roadcuts. In contrast to the meager clay content of layer O, the yellow clay in-

[2] I am indebted to Professor Howard A. Coombs of the University of Washington for first suggesting to me, in 1953, that the abundant clay in the Osceola Mudflow might have been derived from hydrothermally altered rock at Mount Rainier.

TABLE 6.—*Postglacial eruptions, lahars, avalan*

[Dates based on the approximate ages of bracketing pyroclastic layer

Years ago	Eruptions that produced summit cone of Mount Rainier and main pyroclastic deposits in Mount Rainier National Park	West Fork of the White River valley	Inter Fork and White River valleys	Ohanapecosh River valley	Muddy Fork of the Cowlitz River valley	Nisqually River valley
	Layer G erupted by Mount Rainier between 110 and 150 yr ago Layer W erupted by Mount St. Helens about 450 yr ago	Lahar extended at least 18 miles beyond Winthrop Glacier between 275 and 400 yr ago	Avalanches of rock debris from Little Tahoma Peak in 1963 extended as far as 4.3 miles downvalley	Lahar extended at least 6 miles beyond Ohanapecosh Glacier between 450 (W) and 3,600 (Y) yr ago		Lahar extended downvalley at least as far as Longmire in the 1860's Lahar extended at least 1 mile beyond Longmire about 400 yr ago
1,000	?------------? Lava flows erupted to form present summit cone of Mount Rainier		At least 4 lahars extended between 4 and 13 miles beyond Emmons Glacier between 1,000 and 2,300 (C) yr ago		Lahar extended at least 3.5 miles beyond Cowlitz Glacier between 450 (W) and 3,600 (Y) yr ago	At least 7 lahars extended 4.5 to 9 miles beyond Nisqually Glacier between 800 and 3,600 (Y) yr ago Lahar extended at least 25 miles beyond Nisqually Glacier sometime after 3,600 (Y) yr ago
2,000	Layer C erupted by Mount Rainier about 2,300 yr ago	Lahar extended at least 18 miles beyond Winthrop Glacier between 2,300 (C) and 3,600 (Y) yr ago	Lahar extended at least 15 miles beyond Emmons Glacier between 2,300 (C) and 3,600 (Y) yr ago			
3,000	Layer Y erupted by Mount St. Helens about 3,600 yr ago					
4,000	Layers B and H erupted by Mount Rainier between 3,600 (Y) and 5,800 (N) yr ago	Two lahars extended 11 to 18 miles beyond Winthrop Glacier between 3,600 (Y) and 5,700 (F) yr ago		Lahar extended at least 6 miles beyond Ohanapecosh Glacier between 3,600 (Y) and 6,600 (O) yr ago		At least 3 lahars extended more than 15 miles beyond Nisqually Glacier between 3,600 (Y) and 6,600 (O) yr ago
5,000	Layer F erupted by Mount Rainier about 5,700 yr ago	Osceola Mudflow extended at least 70 miles downvalley from volcano about 5,700 yr ago	Osceola Mudflow At least 5 lahars extended 2.5 to 9 miles beyond Emmons Glacier between 5,700 and 6,600 (O) yr ago			
6,000	Layer S erupted by Mount Rainier between 5,700 (F) and 6,600 (O) yr ago Layers N, D, L, and A erupted by Mount Rainier between 5,800 and 6,600 yr ago Layer O erupted by Mount Mazama at Crater Lake, Oreg., about 6,600 yr ago		Greenwater lahar extended at least 28 miles downvalley from volcano between 5,700 and 6,600 (O) yr ago			Paradise lahar extended at least 18 miles downvalley from volcano between 5,800 and 6,600 (O) yr ago
7,000				Lahar extended at least as far downvalley as Indian Bar more than 6,600 (O) yr ago		
8,000						
9,000	Layer R erupted by Mount Rainier more than 8,750 yr ago					Avalanches of clayey rock debris covered Paradise Park more than 5,800 (N) yr ago, and Van Trump Park more than 6,600 (O) yr ago

ches, and block-and-ash flows at Mount Rainier

s are followed by the letter designation of that layer in parentheses]

Kautz Creek valley	Tahoma Creek valley	South Puyallup River valley	North Puyallup River valley	South Mowich River valley	Carbon River valley	Years ago
Lahars extended downvalley to Nisqually River in 1947 At least 2 lahars extended more than 4 miles beyond Kautz Glacier within last 450 yr	Lahar extended 3.5 miles from South Tahoma Glacier in 1967 Lahar extended at least 4.5 miles beyond South Tahoma Glacier about 440 yr ago	At least 4 lahars of unknown extent have occurred within last 450 (W) yr Electron Mudflow extended about 30 miles downvalley from volcano about 600 yr ago	At least 2 lahars of unknown extent occurred more than 400 yr ago	Lahar extended at least 2.5 miles beyond South Mowich Glacier within last 450 (W) yr		1,000
At least 3 lahars extended more than 3 miles beyond Kautz Glacier between 450 (W) and 3,600 (Y) yr ago	Two lahars extended more than 2 miles beyond South Tahoma Glacier between 450 (W) and 2,800 yr ago	Lahar extended at least 14 miles beyond Tahoma Glacier about 1,000 yr ago		Lahar extended at least 3 miles beyond South Mowich Glacier between 450 (W) and 3,600 (Y) yr ago		2,000
	Round Pass Mudflow extended at least 7 miles beyond South Tahoma Glacier about 2,800 yr ago	Block-and-ash flow extended at least 3 miles beyond Tahoma Glacier about 2,500 yr ago Lahar extended at least 3 miles beyond Tahoma Glacier between 2,500 and 2,800 yr ago Round Pass Mudflow extended at least 15 miles beyond Tahoma Glacier about 2,800 yr ago	Round Pass Mudflow			3,000
						4,000
Lahar extended more than 4 miles beyond Kautz Glacier before 3,600 (Y) yr ago		Lahar of unknown extent occurred more than 3,600 (Y) yr ago		At least 1 lahar extended more than 7 miles beyond South Mowich Glacier before 3,600 (Y) yr ago	Lahar extended at least 5 miles beyond Carbon Glacier between 3,600 (Y) and 6,600 (O) yr ago	5,000
						6,000
						7,000
						8,000
						9,000

cludes from 50 to 90 percent clay-sized material, in which clay minerals make up as much as eight parts in 10. Montmorillonite is the most common mineral; it is accompanied by illite or kaolinite, or by both minerals in some samples. The stratigraphic relations and lithology of this layer of yellow clay suggest that the clay was formed at the same time as the Osceola Mudflow.

A possible source of clayey material is the masses of glacial drift that lie on the lower slopes of the volcano and in the adjacent valleys. This drift is not regarded, however, as a potential source of clayey lahars chiefly because it is typically poor both in clay-sized material and in clay minerals. The Evans Creek Drift, which is the most widespread glacial deposit in the park, is characterized by an immature soil profile with little or no clay in the thin B horizon. X-ray analyses of clay fractions of unweathered till from five localities in the park revealed clay minerals in only trace amounts in three samples and none in the other two (table 7). These data suggest that the drift is not an adequate source for clayey lahars.

From these data I conclude that neither the pyroclastic deposits nor the glacial drift at Mount Rainier could have provided an adequate source for the clayey lahars of Holocene age.

Clay minerals are well-known products of hydrothermal alteration of rock, as has been amply demonstrated by studies of hot-springs areas and of mining districts, where the clays are associated with metalliferous veins. Hydrothermal wallrock alteration at Butte, Mont., for example, has resulted in a zoned clay-mineral distribution in which montmorillonite and chlorite are farthest from the source of the hydrothermal solutions, and kaolinite lies in a zone closer to that source (Sales and Meyer, 1948). Similarly, zones of hydrothermal alteration in wallrock in the Cochiti mining district of New Mexico are represented by a kaolinite-group clay mineral (dickite), illite-kaolinite, vermiculite-halloysite, and chlorite-montmorillonite, successively, from the vein outward into the host rock of rhyolite and andesite flows (Bundy and Murray, 1959, p. 365). In some mineralized districts, similar zones of alteration seem to be superimposed (Bateman, 1950, p. 104).

Studies of hydrothermal alteration in andesite and granodiorite at Steamboat Springs, Nev., show that the principal hydrothermal clay minerals are illite, montmorillonite, and mixed-layered illite-montmorillonite (Sigvaldason and White, 1962, p. D115). Where these minerals have been leached by strongly acid solutions percolating downward from the ground surface, kaolinite is found (Sigvaldason and White, 1961, p. D117; 1962, p. D115). Similarly, alteration of basalt in Iceland by nearly neutral hot-spring waters has produced kaolinite, which is associated with montmorillonite in some areas (Barth, 1950, p. 53).

Montmorillonite and kaolinite are also closely associated in the hydrothermally altered rocks of some volcanoes (table 8). Altered andesite that is part of the solfatarized vent rocks of Brokeoff Volcano in Lassen Volcanic National Park has been described by Williams (1932) and Anderson (1935). I collected three samples of this rock from a roadcut in the NE¼NW¼ sec. 15, T. 30 N., R. 4 E., within a lateral distance of 200 feet, which were analyzed for clay mineralogy. The samples contained 10, 21, and 70 percent of clay-sized material, 80–90 percent of which consisted of clay minerals. Kaolinite, illite, and chlorite, listed in order of abundance, occurred in one sample; kaolinite and montmorillonite were identified in a second sample; and montmorillonite alone occurred in the third (table 8, samples 5–7). The clay mineralogy of these three samples clearly indicates that the presence or absence of a specific clay mineral in a single sample may have little significance with respect to the overall clay mineralogy of rocks that have been hydrothermally altered.

Active fumaroles were recognized at the summit of Mount Rainier at the time of the first authenticated climb to the top of the volcano in 1870, and the lavas

TABLE 7.—*Mineralogy of clay fractions determined from X-ray analysis of five samples of Evans Creek till in Mount Rainier National Park*

[Values are estimated parts in ten]

Till sample	Montmorillonite	Chlorite	Mica	Montmorillonite-chlorite mixed-layer mineral	Feldspar	Quartz	Amorphous silica and (or) opaline silica	Cristobalite
1			Trace		5	Trace	1	3
2	Trace	<1		Trace	4+	1+	<1	1+
3					6	1		3
4		Trace			6	1+		2
5					6+	<1		3

1. From an outcrop a few hundred feet northwest of the visitor center at Paradise Park.
2. From a roadcut opposite the Marine Memorial at Round Pass.
3. From a roadcut 1 mile southeast of Box Canyon.
4. From a roadcut in Stevens Canyon 0.3 mile west of a highway tunnel.
5. From an outcrop on the south side of the valley of Inter Fork about 1¾ miles west of White River campground.

of the summit cone have locally been hydrothermally altered to a loose, sandy, clay-bearing material. A sample obtained by Jack H. Hyde from the ground surface at the north rim of the eastern crater near Columbia Crest contained an estimated seven parts in 10 of montmorillonite in the silt and clay fraction, and the remainder of the fraction consisted of feldspar and cristobalite (table 8, sample 4).

An even larger area of altered clayey rock at Mount Rainier is now exposed in the east wall of Sunset Amphitheater (fig. 5), where a mass of yellow altered rock forms the western part of a solfatarized plug in the eroded central conduit of the volcano (Fiske, Hopson, and Waters, 1963, p. 72, 75). A sample of this rock was reported by Fiske and his coworkers (p. 75) to be opalized and to contain "some kaolinite, tridymite, cristobalite, and also a little pyrite mostly altered to limonite." They pointed out that the sample "strikingly resembles the solfatarized vent rocks of the Brokeoff volcano, near Mount Lassen" in northern California. They (p. 85) also emphasized the absence of montomorillonite from their sample and concluded from this that hydrothermally montmorillonitized rock was not available in the volcano which would provide montmorillonite for the Osceola Mudflow.

An avalanche of debris from the altered plug in Sunset Amphitheater, which occurred some time between 1910 and 1930, formed a deposit that now lies on and just beyond the end of Tahoma Glacier (fig. 5). In three samples collected from the avalanche deposit, clay-sized material made up from 17 to 31 percent of the plastic yellow matrix. Montmorillonite was identified in two of the samples and was accompanied by kaolinite in the third (table 8).

The clay mineralogy of the three samples of the avalanche deposit, as well as that of the altered rock from the summit cone, clearly indicates that hydrothermal alteration of the rocks of Mount Rainier typically produces montmorillonite or kaolinite, or both clay minerals. Altered rocks like these obviously could have been available in the past to provide the clay component of mudflows. The single sample reported by Fiske, Hopson, and Waters (1963, p. 85), in which montmorillonite was not identified, may have come from a part of the plug that had been strongly leached by acid solutions, so that montmorillonite was altered to kaolinite. Or, clay minerals in the plug may be zonally distributed like those adjacent to some hydrothermal ore veins. If the clay minerals are zonally distributed, debris derived from a specific zone could contain only one clay mineral.

In summary, montmorillonite and kaolinite, as well as some other clay minerals, are normal and expectable products of hydrothermal alteration within a volcano. Because of the inherent structural weakness of hydrothermally altered rock, the rock should be especially susceptible to large-scale failure and sliding. Moreover, if slides of altered rock were to occur in an active hydrothermal area, the slide material most likely would already be wet because of condensed steam and thus would readily become a lahar as the slide moved downslope. The evidence now available clearly indicates that all the large clayey lahars at Mount Rainier were derived from areas of hydrothermally altered rock on the volcano.

DESCRIPTION OF LAHARS

LAHARS IN THE WHITE RIVER DRAINAGE BASIN

A sequence of lahars and fluvial deposits extends down the White River and West Fork valleys for many miles beyond the base of Mount Rainier. The most voluminous units in this sequence are the Osceola Mudflow, which extended far into the Puget Sound lowland, and the older Greenwater lahar, which moved downvalley at least as far as a point 2 miles beyond the community of Greenwater.

The stratigraphic relation of these lahars to one another and to pyroclastic deposits is summarized in table 9. The term "lahar assemblage," used in this table and in the following discussion, refers to a succession of two or more lahars which may be interbedded with

TABLE 8.—*Mineralogy of clay fractions determined by X-ray analysis of hydrothermally altered andesite*

[Values are estimated parts in ten]

Sample	Montmorillonite	Kaolinite	Chlorite	Illite	Feldspar	Quartz	Cristobalite
1	6	Trace			<1	<1	2+
2	7				1	<1	1+
3	4	2			1+	<1	2
4	7				2		1
5		6	1	1			
6	7+				<1	1+	<1
7	2	3				Trace	5

1-3. From various parts of a clayey avalanche deposit at the terminus of Tahoma Glacier.

4. From the ground surface on the rim of Mount Rainier's summit cone near Columbia Crest.

5-7. From roadcuts in Lassen Volcanic National Park, Calif. (See text.)

FIGURE 5.—Avalanche deposit at and on the terminus of Tahoma Glacier. Parts of the avalanche debris are a sticky yellow clay, which is the product of hydrothermal alteration of rock within the volcano. The alteration evidently occurred in an old conduit of the volcano which is now exposed in cross section in the cliffs immediately left of the area where Tahoma Glacier spills down from the summit snowfields. The ice face in the center foreground is about 150 feet high.

alluvium. Thus, in the White River valley, the pre-Osceola lahar assemblage is a group of deposits which includes at least four lahars interbedded with fluvial gravels, all of which are younger than the Greenwater lahar and older than the Osceola Mudflow.

GREENWATER LAHAR

A lahar whose surface is dotted with scores of mounds forms terraces at several places in the White River valley as far downstream as a point about 2 miles west of the community of Greenwater (fig. 6). The largest remnants of the deposit lie on the west side of the White River valley between the mouth of Silver Creek and Buck Creek, at the mouth of the Huckleberry Creek valley, and in an area near Greenwater.

The lahar consists of gray to yellowish-brown sand to angular and subangular blocks several tens of feet in diameter. In some places abundant large rock fragments are embedded in a loose sandy matrix; elsewhere the lahar consists largely of sand- and pebble-sized material. Pebbles were picked at random from the matrix of the lahar in a shallow pit on the west side of the White River valley about 0.8 mile south-southeast of Greenwater and examined for rock types. Pebbles derived from rocks of Mount Rainier made up 73 percent of the sample, those of granodiorite made up 7 percent, and those of volcanic rocks derived from other formations of Tertiary age made up the remainder. These pebbles were mostly subrounded and subangular.

The mounds on the lahar are its unique feature. They range in height from 4 to about 35 feet and are a few tens of feet to about 200 feet in diameter. Most have a roughly circular ground plan, but some are elongate in seemingly random directions. Although most mounds have a single peak, some have two or more crests. The mounds are separated by flattish areas that generally

TABLE 9.—*Sequence of lahar assemblages and their stratigraphic relation to pyroclastic deposits (layers W, C, Y, and O) in the White River and West Fork valleys*

White River valley		West Fork valley	
		Lahar and fluvial gravel	Post-Osceola lahar assemblage.
Layer W	Post-Osceola lahar assemblage.	Layer W	
Several lahars interbedded with fluvial gravels.			
Layer C		Layer C	
Lahar		Lahar	
Layer Y		Layer Y	
		Lahar	
		Lahar	
Osceola Mudflow about 5,700 years old.		Osceola Mudflow	
Several lahars interbedded with fluvial gravels.	Pre-Osceola lahar assemblage.		
Lahar			
Two bomb-bearing lahars			
Greenwater lahar			
Layer O		Layer O	

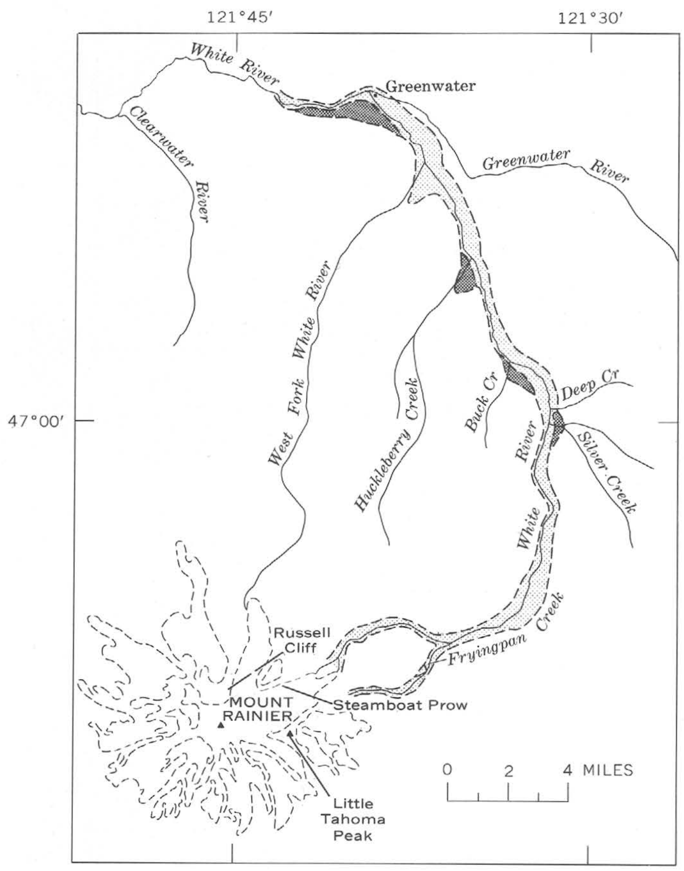

FIGURE 6.—Distribution of remnants of Greenwater lahar northeast of Mount Rainier is shown by the heavy pattern; its inferred original extent is shown in a light pattern. The lahar probably originated in massive rockslides from the northeast flank of Mount Rainier between Steamboat Prow and Little Tahoma Peak.

slope both toward the center of the valley and downvalley.

Some mounds have been partly excavated, and their internal composition can be seen. They are mostly made up of very large blocks of rock, or clusters of blocks, incorporated in an unsorted matrix of sand and smaller rock fragments. The blocks consist mostly of breccias from Mount Rainier. Two mounds were noted, however, that consist entirely of fragments of granodiorite. One of these, near the mouth of Buck Creek, consists of angular and subangular fragments, which range in maximum dimension from less than an inch to at least 6 feet (fig. 7). A search of adjacent mounds within a radius of a hundred yards located only one small boulder of granodiorite; the adjacent mounds are made up almost exclusively of rock fragments from Mount Rainier volcano, a few are made up of breccia from the Tertiary bedrock.

The core of one mound, which is about 20 feet high and 100 feet in diameter, in the area near Greenwater is made up of a large mass of flow breccia from Mount Rainier (fig. 8). The breccia is extensively altered to a plastic yellow clay, and some parts of it closely resemble the matrix of the Osceola Mudflow. This core of altered rock is veneered with a mixture of sand and rock fragments as large as a foot in diameter. The veneer is as much as 4 feet thick, and faint bedding in it that dips about 25° parallels the slope of the mound.

The core of a nearby mound, which is about 10 feet high and 50 feet in diameter, is also a block of flow breccia from the volcano, but it is not altered to clay.

The core of a mound in the same general area, but a little farther downvalley, consists of a block of reddish-brown and gray breccia which was derived from Mount Rainier. Some zones in this breccia are entirely altered to clay. A nearby mound that is about 12 feet high and 60 feet in diameter has been cut through by a road on the west side of sec. 9, T. 19 N., R. 9 E., 1 mile west of Greenwater. The interior of this mound is a jumble of angular and subangular rock fragments, and there is little or no matrix of finer material. Most of the fragments are from Mount Rainier, but a few are granodiorite and breccia derived from the Tertiary bedrock.

FIGURE 7.—Mounds on the Greenwater lahar in the Buck Creek area. The mound at the right center consists wholly of angular blocks of granodiorite; it is about 25 feet high and 100 feet in diameter. Adjacent mounds consist mostly of material derived from Mount Rainier

The distribution of mounds within remnants of the lahar seems to be random; however, two of the mound groups are elongate in a downvalley direction, and in each of them the area of mounds is separated from the adjacent valley wall by a broad shallow depression that also is underlain by the lahar.

The remnant of the lahar at the mouth of Huckleberry Creek extends back into the creek valley for more than half a mile. The surface of the lahar at the upvalley end of this backfill is about 200 feet higher than the present floor of the White River valley. Likewise, the highest remnant of the lahar in the vicinity of Buck Creek is about 200 feet higher than the White River, Although a thickness of more than 10 feet is rarely exposed, the vertical height of the lahar above the present valley floor suggests that the White River valley was filled to a depth of at least 200 feet during movement. The present surface of the lahar therefore, in most places, does not represent its original upper surface while it was moving. At the mouth of Huckleberry Creek, mounds dot the surface of the lahar in places 100 feet lower than its inferred top during movement (pl. 2).

The blocks that form the mounds probably were brought downvalley by an initial rush of the lahar, came to rest, and remained in place while much of the fine-grained fluid matrix of the lahar drained away from them and moved more slowly down the valley. The flat areas between the mounds, and between groups of mounds and the valley wall, probably were produced during this downvalley flowage of the fine-grained material.

The Greenwater lahar was not recognized within Mount Rainier National Park for certain, although three large mounds in the valley of Fryingpan Creek, about 1 mile upstream from the mouth of the valley may be part of it. Comparable mounds were not observed anywhere in the White River valley within the

FIGURE 8.—Mound on the Greenwater lahar consists of an andesite breccia which was derived from Mount Rainier and which has been extensively altered to a plastic yellow clay.

park, but their absence there may be due to burial beneath the Osceola Mudflow.

The area thought to have originally been covered by the Greenwater lahar north of the park boundary is about 8 square miles. If it is assumed that the lahar had a thickness of 100 feet throughout this area after coming to rest, its original volume would have been a little more than 800 million cubic yards.

Near the upper limit of the lahar in the Huckleberry Creek valley a roadcut exposes the deposit on top of pyroclastic layer O, which is about 6,600 years old. Although the Osceola Mudflow, which is about 5,700 years old, was not seen on top of the lahar, the topographic relations of the two deposits indicate that the Osceola is younger; thus, the Greenwater lahar is between 5,700 and 6,600 years old.

Mounds are known on the surfaces of lahars in the vicinity of other volcanoes, but they are by no means common. Aramaki (1963, p. 290–292) described a prehistoric mounded lahar on the south side of Asama volcano in Japan. This lahar resulted from a phreatic eruption that destroyed the eastern part of Kurofu-yama, the oldest of three major volcanoes that make up Asama. The material shattered by the explosion formed lahars that spread northward and southwestward beyond the volcano. The surface of the lahar southwest of the volcano is dotted with mounds arranged in groups that trend toward the southwest, the inferred direction of flowage; individual mounds are elongate in the same direction. The mounds have basal diameters of as much as 330 feet and heights up to 50 feet. The cores of most consist of very large blocks of pyroxene andesite from the volcano, some of which are 100 feet in maximum dimension.

Hills that rise above the surface of a large Pleistocene lahar at the south base of Yatsuga-dake volcano in Japan have been studied by Mason and Foster (1956). Many of these hills are substantially larger than those reported on other lahars; some have heights of as much as 700 feet and basal diameters of nearly half a mile.

These large hills do not seem to have rock cores, and Mason and Foster concluded that the material of the hills was extruded above the top of the mudflow by hydrostatic pressure while still fluid, through cracks in a dried, hardened crust.

The length of the lahar described by Mason and Foster is a little less than 15 miles, but its inferred original volume is at least 9.5 billion cubic meters, or roughly 2.3 cubic miles. The largest lahar from Mount Rainier, the Osceola Mudflow, has an inferred volume of a little more than half a cubic mile (p. 26), and the Greenwater lahar only about a third of that. Mason and Foster suggested that the lahar originated in an avalanche of loose ejecta on the side of Yatsuga-dake that possibly was triggered by an earthquake or a volcanic explosion.

A lahar whose surface is characterized by many mounds originated during an eruption of Komaga-take volcano in Japan that caused a large avalanche (Ishikawa and Yokoyama, 1962). The mounds are about 30 feet high, and their cores are formed by blocks of lava from the volcano.

Grange (1931) described the conical hills, which number in the thousands, on the slopes of Mount Egmont and Mount Ruapehu volcanoes in New Zealand. The mounds range in height from a few feet to 100 feet, but most are 25–30 feet high. The cores of most mounds that Grange examined consist of large blocks of agglomerate. He suggested that the blocks and the deposits that enclose them are of laharic origin.

A plain studded with several thousand mounds lies at the southeast foot of Galunggung (Galounggoung) volcano on Java. The mounds are as high as 230 feet, and large andesite blocks form their cores. The blocks are enclosed in a matrix of finer rock debris similar to that between the mounds. The entire deposit is as much as 70 feet thick and has an estimated volume of nearly 190 million cubic yards. The deposit heads at the mouth of a very large alcove in the southeast flank of the volcano. Escher (1925) concluded that the mounded deposit is an exceptionally large prehistoric landslide or mudflow from Galunggung. He suggested that when the side of the volcano slid outward and flowed downslope to the southeast, large blocks included in it came to rest first; continued downslope flowage of fine material lowered the overall surface of the mudflow and caused the blocks to protrude.

It is noteworthy that in several of the lahars just described, mound dimensions are similar to those of the White River valley, and cores of large blocks from the volcanoes are found in all of them. However, the Greenwater lahar may be unique in having some mound cores that consist of rock not derived from the volcano.

The Greenwater lahar is also unique among the lahars from Mount Rainier in that it contains abundant large blocks. Although the surfaces of some others have a few scattered blocks of andesite derived from the volcano, these blocks number only one or two dozen on any individual deposit. In contrast, scores of mounds thought to have block cores can be seen on nearly every remnant of the Greenwater lahar, and these seemingly deserve some special explanation. Glacial drift like that in Holocene moraines in the White River valley probably would not have been a suitable source, because blocks of rock comparable with those in mound cores are sparse. In contrast, large blocks are abundant in the 1963 rockfall and avalanche deposits from Little Tahoma Peak. (See Crandell and Fahnestock, 1965, p. A5–A8.)

The abundant blocks in the Greenwater lahar therefore probably originated in rockfalls and rockslides from the slopes of the volcano and from the walls of the White River valley. The blocks of granodiorite could have fallen from outcrops at the head of the Fryingpan Creek valley, or from the walls of the White River valley between Emmons Glacier and the mouth of Sunrise Creek.

The rockslides or rockfalls on the volcano may have been triggered by a steam explosion or by an earthquake which also shook down masses of granodiorite from the sides of the White River valley or at the head of Fryingpan Creek valley.

Evidence of a volcanic explosion some time between 5,700 and 6,600 years ago is present in the form of pyroclastic layer S in the Yakima Park area and on top of Goat Island Mountain (Crandell and Mullineaux, 1967, p. 7). The layer consists of an unsorted mixture of sand, silt, and angular rock fragments as large as 1.5 feet across and is entirely derived from Mount Rainier. The lack of new pumice or scoria suggests that the rubble was formed by a steam explosion that blew out previously solidified rock in the northeast flank of the volcano. Although there is no known way to make a firm correlation between layer S and the Greenwater lahar, the explosion that created the pyroclastic deposit could also have triggered the rockslides that caused the lahar.

The absence of clay from the matrix of the lahar points to relatively fresh rock as the chief source; however, the presence of blocks of clayey, altered rock suggests that some of the material came from areas of hydrothermal alteration. The main source area of the lahar probably lay between Little Tahoma Peak and Steamboat Prow. In fact, these two features may be the only surviving remnants of the northeast side of the volcano that was largely destroyed when the lahar was formed.

The great rockslides that created the Greenwater lahar may have stripped a mass of mostly unaltered rock from the northeast flank of the volcano, thereby not only exposing the underlying rocks that had been extensively altered by hydrothermal solutions but also removing the support from these altered rocks. Thus, the events that created the Greenwater lahar may have set the stage for the subsequent rockslides that produced the Osceola Mudflow.

PRE-OSCEOLA LAHAR ASSEMBLAGE

A sequence of lahars and fluvial deposits, hereafter referred to as the pre-Osceola lahar assemblage, is exposed at many places along the White River valley within the park. Farthest upvalley, this assemblage consists of two lahars that contain volcanic bombs and one that does not contain bombs. These three lahars are exposed in the south bank of the White River about half a mile upstream from the highway bridge over the river. Were it not for a few inches of stratified sand between them, the two bomb-bearing lahars probably could not be differentiated from one another. Both are gray, have a matrix consisting mostly of coarse friable sand, and contain abundant angular and subangular fragments of dense flow rock from Mount Rainier as large as 10 feet in diameter. Bombs, which are sparsely scattered throughout the lahars, range in maximum dimension from 6 inches to several feet; all are strongly breadcrusted, and none have been modified by erosion. Some masses of dense flow rock are also breadcrusted (fig. 9). The lower lahar is more than 20 feet thick and probably extends below the level of the White River. The upper lahar is about 12 feet thick and is successively overlain by a lahar about 20 feet thick in which bombs were not seen and by the Osceola Mudflow. The mudflow forms the top unit and caps a broad terrace about 100 feet above the river; owing to an erosional unconformity, the Osceola locally also lies below river level.

The three lahars in the assemblage contain very little silt or clay. The two bomb-bearing lahars were seen nowhere else in the valley, and their original extent is not known.

Remanent magnetism determinations made on oriented samples from three bombs in the upper lahar and from five in the lower show a random orientation of the direction of remanent magnetism; thus, the temperature of the bombs apparently was below the Curie point of the included ferromagnetic minerals when the lahar came to rest (p. 5). Although the material in the lahars could have had a temperature above the boiling point of water, it seems more likely that the masses were cooler and were moving as lahars when they came to rest, rather than as hot dry avalanches.

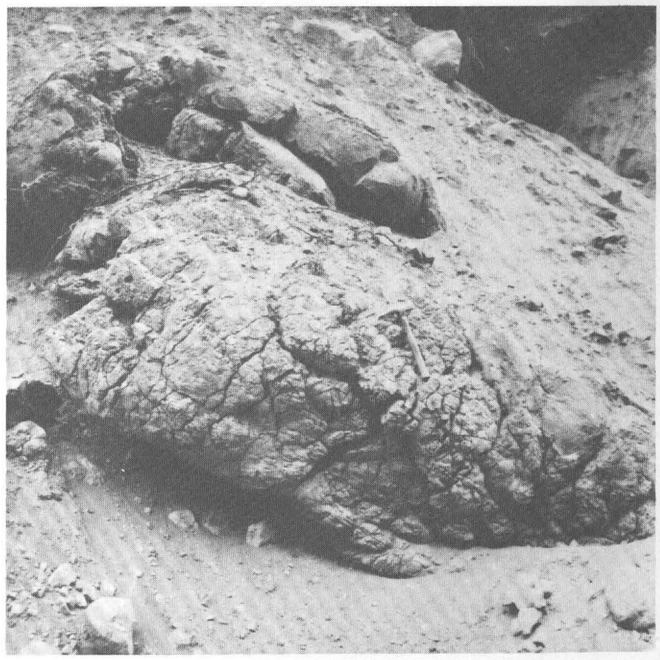

FIGURE 9.—Large breadcrusted block of dense flow rock in a lahar exposed in south bank of the White River about half a mile downstream from White River campground.

However, the lahars may have originated in such avalanches that descended Emmons Glacier and melted large amounts of snow and ice.

A roadcut on the south side of the valley near the south end of the highway bridge over the White River exposes a lahar that has a sandy matrix and is about 40 feet thick. The lahar rests on granodiorite and is overlain by the Osceola Mudflow. One or more pre-Osceola lahars also are exposed on the north side of the valley a few hundred feet northeast of the bridge.

Farther downstream, the pre-Osceola lahar assemblage is exposed on the south side of the White River about half a mile below the highway bridge across the river. In this area the assemblage is at least 80 feet thick and consists of several lahars 3–30 feet thick that are interbedded with fluvial deposits. The assemblage crops out half a mile farther downstream in a high bank near the mouth of Fryingpan Creek, where the material is mostly stratified and consists largely, if not wholly, of fluvial deposits. The assemblage also is seen in cuts along the highway between Fryingpan Creek and the White River Ranger Station and in the face of a terrace on the west side of White River 1 mile downstream from the mouth of Crystal Creek. At this northernmost exposure, more than 50 feet of coarse bouldery lahars and pebble-to-boulder gravel of fluvial origin forms a terrace that is capped with a few feet of Osceola Mudflow. The base of the lahar assemblage also apparently lies below the level of White River here.

Although it is possible that some of the deposits just described are those of the Greenwater lahar, the absence of very large blocks suggests that they are not correlative. Furthermore, the Greenwater lahar forms a fill in the White River valley north of the park that is as much as 200 feet above the valley floor. The depositional top of the pre-Osceola lahar assemblage is nowhere known to extend to a height greater than about 80 feet above the White River. Topographic relations imply that the lahar assemblage is younger than the Greenwater lahar and thus less than 6,600 years old, because the Greenwater lahar postdates pyroclastic layer O of that age.

The lahar assemblage forms a valley fill that was dissected to a depth of 200–250 feet by the White River before the Osceola Mudflow occurred. The base of the lahar assemblage is below the White River at nearly every outcrop; at many of these outcrops the Osceola unconformably overlies the lahar assemblage, and its base is also below river level. The deposition of the assemblage, which was followed by downcutting, was probably not climatically controlled, as is valley aggradation in some regions. Instead, the presence of breadcrust bombs in two of the lahars strongly suggests that the aggradation was the result of volcanism.

The pre-Osceola lahar assemblage probably originated as a direct consequence of hot rock debris avalanching down Emmons Glacier during or shortly after eruptions at the summit of the volcano. The assemblage was probably formed by floods and lahars caused by the rapid melting of snow. The building up of the lahar assemblage in the valley thus is thought to have been caused by large quantities of rock debris added to the White River as a result of volcanic activity. With the cessation of eruptions and of lahar deposition in the White River valley, the river cut down into the valley fill. No significant unconformities were noted within the lahar assemblage, and all the deposits within it probably were formed within a relatively short time, perhaps not more than a few years.

OSCEOLA MUDFLOW

The Osceola Mudflow is by far the largest mudflow of postglacial age from Mount Rainier and is one of the largest known volcanic mudflows in the world. Many of the facts concerned with the distribution, age, and origin of the mudflow have been discussed previously (Crandell and Waldron, 1956; Crandell, 1963a, b).

The Osceola was first described by Willis (1898, p. 143) as "a sheet of till that covers the plateau between the Green and White Rivers and extends southwest beyond White River about the head of Fennel Creek" (pl. 3). He correctly recognized the Mount Rainier provenance of the deposit, but thought that the Osceola had been formed by a piedmont glacier that issued into the lowland from the Cascade Range. Willis noted that knobs of Vashon till deposited during the last major glaciation are topographically higher than the surface of the adjacent Osceola deposit, and he thought that this indicated that the Osceola was somewhat older than the Vashon till.

Investigation of the Osceola (Crandell and Waldron, 1956; Crandell, 1963b; Mullineaux, 1961, 1965a, b) has shown that the mudflow overlies the Vashon Drift and that the upper part of the drift contains a soil profile. This soil was formed after the Puget glacier lobe withdrew from the southeastern part of the Puget Sound lowland, about 14,000 years ago, and before the mudflow occurred. Four radiocarbon dates obtained from wood incorporated in the mudflow range from 4,700±250 (W–564) to 5,040±150 (University of Washington radiocarbon date No. 62; this report, table 4). When corrected for variations in atmospheric C^{14} and for a C^{14} half life of 5,730 years, these ages range from 5,550 to 5,800 years; a "true" age of about 5,700 years is here arbitrarily assumed for the Osceola Mudflow.

DISTRIBUTION AND VOLUME

Within Mount Rainier National Park the Osceola Mudflow underlies terraces in the White River and West Fork valleys and veneers valley sides above the terraces. The mudflow is, however, not well preserved in these valleys near the volcano because of erosion by younger valley glaciers. The largest outcrops of the Osceola close to the volcano are in the valley of Inter Fork. Near the mouth of the valley the mudflow is banked against a lateral moraine of Evans Creek Drift, which constricted the valley and caused the mudflow to accumulate behind it to a thickness of as much as 100 feet. Farther upvalley, the mudflow veneers bedrock and glacial drift on the floor of Glacier Basin and on the floor of a high cirque directly north of the basin. During the Winthrop Creek Glaciation, Inter Glacier reworked part of the mudflow deposit and formed a series of lateral moraines in the upper part of Glacier Basin.

The mudflow is preserved at many places on the ridgetops at the head of Inter Fork valley; the highest outcrop is at the top of Steamboat Prow at an altitude of 9,700 feet. On the ridgetop between Glacier Basin and the unnamed cirque directly to the north, several feet of the mudflow veneers a lava flow. Iron oxide, apparently derived from the mudflow, has impregnated the flow rock, forming a resistant iron-rich crust at its surface. This crust was recognized by Fiske, Hopson, and Waters (1963, p. 85), but they thought that it had formed beneath deeply weathered volcanic ash, whereas the crust in fact lies beneath a remnant of the mudflow.

Downstream from Inter Fork, above White River campground, the Osceola blankets a lateral moraine on the north valley wall to a height about 500 feet above the present valley floor. Pits dug on the crest of the next higher lateral moraine, which is about 1,000 feet above the valley floor, revealed a clayey deposit in the stratigraphic position of the Osceola Mudflow. The deposit is pale yellow and contains small rock fragments; it may be part of pyroclastic layer F (table 5; p. 12). The mudflow evidently did not reach this height on the valley wall.

According to information provided by H. W. Anderson of the U.S. Geological Survey (written commun., December 1964), the Osceola Mudflow was penetrated at a depth of about 50 feet during drilling for a water well at the Silver Creek Ranger Station, on the White River valley floor near the north boundary of the park. The well was still in the mudflow when drilling was stopped at a depth of about 200 feet. The mudflow veneers the sides of the valley to a height of about 125 feet a few miles downstream from the Silver Creek Ranger Station. At Federation Forest State Park, about 14 miles downstream from Silver Creek, a well was reported by Mr. Anderson to have entered the Osceola Mudflow at a depth of about 200 feet beneath the valley floor. In this area the top of the mudflow forms a terrace that is about 35 feet higher than the White River (fig. 10).

This information from drilling on the valley floor indicates that the valley was at least 200 feet deeper when the mudflow occurred than it is today. The mudflow must have temporarily filled the valley near Silver Creek Ranger Station to a depth of more than 300 feet during movement.

The Osceola Mudflow also coats valley sides and forms terraces in the West Fork valley. The highest outcrop of the mudflow in the West Fork drainage basin, other than the one on Steamboat Prow, is at an altitude of about 6,800 feet just west of Winthrop Glacier. The mudflow crops out in streambanks along the West Fork and Winthrop Creek at many places. On the east bank of the river at the mouth of Winthrop Creek, the base of the mudflow is below river level, and its eroded top is 25 feet above the river. Successively above the mudflow are a layer of organic matter that contains logs, a coarse gravel deposit, and another lahar.

At a point about 2.5 miles upstream from the mouth of West Fork valley the Osceola veneers the northwest valley wall to a height of about 320 feet above the valley floor, and at the mouth of the valley the mudflow extends below river level. If the pre-Osceola valley of West Fork was as deep as that of the White River (see above), the Osceola may have temporarily reached a depth of at least 500 feet in the lower part of the West Fork valley.

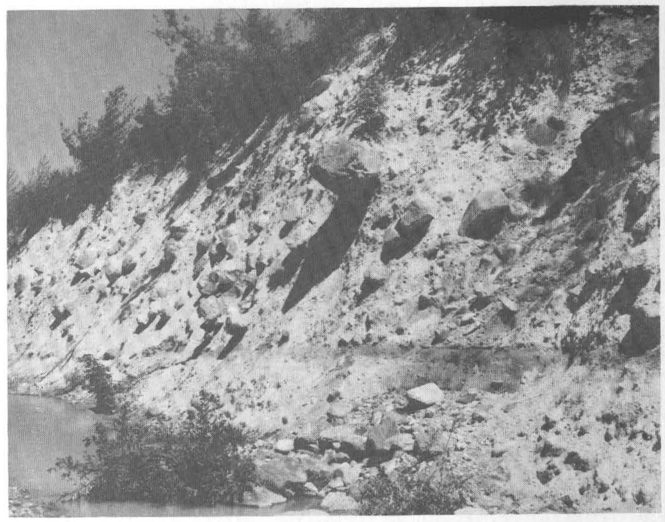

FIGURE 10.—Osceola Mudflow exposed in the face of a terrace 2 miles southeast of Greenwater. Drilling for a well a few miles downstream from this point revealed that the mudflow extends to a depth of about 200 feet beneath the valley floor. The largest boulder in the center of the photograph is about 6 feet in diameter. The fluvial sand and gravel that underlies the mudflow in the foreground probably is an old terrace deposit that was mantled by the Osceola.

Forty miles downvalley from Mount Rainier, just inside the Cascade mountain front, the White River passes through a bedrock gorge that is now blocked by Mud Mountain Dam. The gorge lies at the south edge of the White River valley, which is about 3 miles wide in this vicinity. A long, narrow, flat-topped ridge (Mud Mountain) several hundred feet high, which extends southward across the broad White River valley, is made up largely of unconsolidated deposits that range in age from early or middle Pleistocene to late Pleistocene. The Osceola Mudflow was temporarily at least 450 feet deep in this part of the valley and cascaded in a sheet nearly a hundred feet deep down the west slope of Mud Mountain to the floor of a glacial melt-water channel. The mudflow poured from the Mud Mountain area into the Puget Sound lowland along several different routes (pl. 3).

West of the mountain front the Osceola spread widely on a plain of Vashon till and melt-water deposits. The mudflow is only a few feet thick on some topographic scarps and till drumlins; elsewhere it is as much as 75 feet thick. A high degree of fluidity permitted the mudflow to flow long distances down narrow topographic depressions on the drift plain. As a result the

Osceola finally came to rest in the lowland as a lobe as much as 8 miles wide and 20 miles long with very uneven, or digitate, margins (pl. 3).

The mudflow profoundly changed the lower course of the White River. Before the mudflow, the river turned southward where it debouched from the mountain front and followed the valley of South Prairie Creek to join the Puyallup River near Orting. When the mudflow rushed out onto the drift plain, one lobe of it extended down the old White River valley, but the greatest share flowed northwesterly across the plain, inundating all but the highest relief features. As the mudflow became more dilute and approached the consistency of a muddy stream, it became the White River; this river began to cut a new valley along the axis of the broad lobe, trending northwestward toward Auburn (Crandell, 1963b).

The mudflow crops out in banks of the Puyallup River and has been penetrated in wells drilled into the flood plain south of Sumner (Crandell, 1963b). The Osceola also has been identified at a depth of about 265 feet below sea level, beneath the floor of the Puyallup-Duwamish valley, 4 miles northwest of Auburn (Luzier, 1969, p. 14). At the time of the mudflow the Puyallup-Duwamish valley was an arm of Puget Sound between Orting and Renton. This arm was filled first by the mudflow and later by deposits of the White River (Mullineaux, 1961, p. 185; Crandell, 1963b, p. A68).

At least 30 blocks of reddish-brown breccia derived from Mount Rainier are scattered on the surface of the mudflow. The largest measures 30 by 40 feet and stands 20 feet above the mudflow surface; it is located about 4 miles west of Enumclaw. Nearly all these blocks are situated along topographic breaks in the mudflow surface that coincide with scarps in the buried drift plain. More than half the blocks in the Buckley-Enumclaw area lie along a northwest-facing scarp 1 mile west of Enumclaw that represents a side of a buried melt-water channel; the opposite side was formed by the glacier itself (Crandell, 1963b, p. A66, pl. 2). Blocks are probably concentrated along this scarp because the mudflow thinned considerably while flowing over it, and the large blocks became grounded on the underlying surface much as icebergs become grounded in shallow water. The presence of lower ground immediately northwest of the scarp permitted the fine matrix of the mudflow to drain away and leave blocks standing above the surrounding surface. The concentration along this scarp, as well as a lack of blocks to the southeast, suggests that this was the first place in the lowland where the mudflow thinned sufficiently for the blocks to become grounded.

The volume of the Osceola Mudflow can be estimated on the basis of the known area of distribution of the flow, if several assumptions are made concerning its total inferred area and thickness: The mudflow originally covered a total land area of at least 100 square miles, in addition to a submerged area in the Puyallup River valley where the mudflow extended into a former arm of Puget Sound (pl. 3). The mudflow probably extended as far south in the Puyallup River valley as the confluence of the Puyallup and Carbon Rivers, as far west as the town of Puyallup, and northward in the Green River valley to the outskirts of Kent and covered a submerged area of at least 27 square miles. The mudflow has subsequently been removed from a considerable part of its former total area by stream erosion or has been buried by younger alluvium. The mudflow ranges in thickness from a few feet to at least 200 feet. It is a reasonable assumption that the Osceola had an original average thickness of 20 feet over the land areas it covered; if it did, the mudflow would have had a volume of about 2 billion cubic yards. If the Osceola had had a comparable average thickness in the submerged areas, there would have been an additional volume of about 660 million cubic yards, making a probable total volume of a little more than half a cubic mile.

TEXTURE AND MINERALOGY

Grain-size distribution studies were made of samples of the Osceola Mudflow taken from outcrops at nine localities in the Cascade Range (samples 29–37, table 10), from a point near Auburn to Glacier Basin (pl. 3). Most of the samples were collected from a 3-foot-wide vertical trench at a depth of 4–7 feet below the mudflow surface. Because boulders are sparse at this depth, the samples represent the average texture of the mudflow in this zone. At greater depths, the cobble and boulder content increases and coarse material makes up a large proportion of the lower third of the deposit.

The texture of the samples at each locality is shown in table 10; the clay-sized fraction of the samples ranges from 6 to 12 percent, the silt-sized fraction from 11 to 16 percent, and the sand-sized fraction from 28 to 41 percent. The sorting coefficients of these samples range from 9 to 16.34 and average 11.53. The cumulative curves prepared from the size-distribution data are presented in figure 11.

The overall texture of the mudflow does not seem to change with increasing distance from its source. The sample having the highest proportion of material smaller than 2 mm, as well as the lowest sorting index (sample 35), came from the crest of Mud Mountain. The material sampled there is a veneer left after the main body of the mudflow spilled across the top of a ridge (p. 25).

TABLE 10.—*Size-distribution data from samples of postglacial lahars and a block-and-ash flow from Mount Rainier*

[Arranged by age from youngest at top to oldest at bottom]

Sample	Size distribution (percentage)			Median diameter (mm)	Sorting		
	Clay (<0.004 mm)	Silt (0.004–0.0625 mm)	Sand (0.0625–2 mm)		Sorting coefficient (So)	Phi standard deviation ($\sigma\phi$)	Phi quartile deviation ($OD\phi$)
1	4	10	49	0.8	8.10	4.35	3.03
2	4	11	60	.6	3.41	2.78	1.78
3	2	10	35	2.8	13.40	4	4.10
4	7	7	32	2.9	5.48	3.95	2.48
5	3	11	31	4	7.75	3.85	2.98
6	11	25	58	.1	3.94	3.15	1.70
7	7	13	37	1	8.83	4.36	3.15
8	9	18	45	.3	7.42	4.74	2.90
9	3	11	29	4.2	8.72	4.2	3.13
10	6	----------	40	3.6	8.88	3.94	3.20
11	12	17	40	.4	9.75	4.95	3.29
12	5	13	33	1.9	10.60	4.58	3.42
13	8	16	21	1.1	14.18	5.13	3.83
14	5	17	36	.8	11.20	4.76	3.50
15	7	13	33	1.6	9.56	4.54	3.28
16	9	13	45	.5	6.70	4.16	2.75
17	7	----------	43	2	5.48	3.43	2.72
18	5	----------	38	3.2	10.82	3.56	3.44
19	1	5	46	1.5	6.63	3.99	2.74
20	1	5	51	1.1	4.64	3.11	2.21
21	1	15	37	1.5	9.84	4.80	3.30
22	2	10	27	12.5	13.20	----------	3.73
23	1	13	31	4.2	13.60	4.66	3.77
24	5	28	44	.2	7.75	4.35	2.90
25	1	7	16	13	9.04	2.90	1.53
26	2	16	32	2	14.56	4.97	3.88
27	4	15	33	1.4	15.75	4.91	3.99
28	3	14	27	4.3	16.25	4.94	4.03
29	9	13	28	2	11.53	5.23	3.54
30	12	16	31	.7	16.34	5.79	4.10
31	8	15	35	.8	11.27	4.82	3.50
32	9	12	31	1.6	12.85	5.25	3.70
33	7	11	33	1.8	14.63	5.12	3.88
34	8	15	35	.9	11.62	4.90	3.58
35	8	15	41	.6	9	4.58	3.18
36	7	13	35	1.3	10.02	4.61	3.18
37	6	14	36	1	11.79	4.95	3.20
38	2	12	36	2	10.86	4.38	2.34
39	9	----------	51	1	6.25	3.53	2.70
40	7	35	33	.1	10.20	5.22	3.76
41	3	18	32	1.3	17	5.03	4.10

1. Kautz Creek lahars of 1947. North bank of Nisqually River ½ mile upstream from mouth of Kautz Creek. Sample of a fairly coarse lahar.
2. Kautz Creek lahars of 1947. Same location as sample 1. Sample of a relatively fine-grained lahar.
3. Post-Osceola lahar in West Fork valley. Roadcut at the west side of sec. 26, T. 19 N., R. 9 E. Sample of unoxidized lahar that overlies pyroclastic layer Y.
4. Lahar in South Puyallup River valley. Exposure adjacent to Wonderland Trail near south abutment of footbridge over South Pupallup River (fig. 25). Sample of unit 3 in measured section 10.
5. Lahar in South Puyallup River valley. Same location as sample 4. Sample of unit 1 in measured section 10.
6. Electron Mudflow. Streambank at confluence of Carbon and Puyallup Rivers near McMillin in the Puget Sound lowland. Sample taken from top foot of mudflow.
7. Electron Mudflow. Same location as sample 6. Sample taken from basal foot of mudflow.
8. Electron Mudflow. North bank of Puyallup River about 1 mile downstream from the mouth of the Mowich River, in the SW¼ sec. 34, T. 17 N., R. 6 E. (fig. 25). Sample of unit 4 in measured section 7.
9. Lahar in Tahoma Creek valley. North bank of Tahoma Creek 1.25 miles upstream from Tahoma Creek campground (fig. 25). Sample of lahar that is unit 9 in measured section 9.
10. Lahar in Tahoma Creek valley. Same location as sample 9. Sample of lahar that is unit 6 in measured section 9.
11. Lahar in South Puyallup River valley. North bank of South Puyallup River at Wonderland Trail footbridge (fig. 25). Sample of 1,000-year-old lahar.
12. Round Pass Mudflow. Same location as sample 9. Sample of unit 3 in measured section 9.
13. Round Pass Mudflow. Roadcut at Round Pass (fig. 25). Sample of brown facies of mudflow.
14. Round Pass Mudflow. Roadcut at Round Pass. Sample of purplish-gray facies of mudflow.
15. Round Pass Mudflow (fig. 25). North bank of Mowich River at its mouth. Sample of mudflow at a horizon about 20 feet above river level.
16. Lahar in Puyallup River valley. Same location as sample 8. Sample of 1,000-year-old lahar that is unit 2 in measured section 7.
17. Lahar in Muddy Fork valley. Terrace on east side of Muddy Fork, and 65 feet higher than river level, about ½ mile upstream from highway bridge at Box Canyon. Sample of a pre-W, post-Y lahar that underlies the terrace.
18. Lahar in Nisqually River valley. Roadcut in terrace on east side of the Nisqually River near the mouth of the Paradise River. Sample of a post-Y, pre-W lahar that directly underlies the terrace.
19. Block-and-ash flow deposit in South Puyallup River valley. Roadcut 0.2 mile northwest of bridge over river (fig. 25). Sample of coarse facies of deposit that contains breadcrust bombs and is about 2,500 years old.
20. Block-and-ash flow deposit in South Puyallup River valley. Roadcut 0.4 mile northwest of bridge over river. Sample of fine facies of deposit represented by sample 19.
21. Lahar in Nisqually River valley. Roadcut 0.2 mile southwest of Longmire. Sample of unit 6 in measured section 4.
22. Post-Osceola lahar in West Fork valley. Same location as sample 3. Sample of oxidized lahar that underlies pyroclastic layer Y.
23. Paradise lahar. Bank adjacent to parking lot 200 feet northwest of visitor center at Paradise Park.
24. Paradise lahar. Cut adjacent to trail to Paradise ice caves, near west base of Mazama Ridge.
25. Paradise lahar. Bank along Paradise River about ½ mile northeast of Narada Falls.
26. Paradise lahar. Roadcut about ½ mile east of Ricksecker Point.
27. Paradise lahar. Same location as sample 21. Sample of unit 4 in measured section 4.
28. Paradise lahar. Roadcut near the center of sec. 5, T. 14 N., R. 8 E., in the Nisqually River valley near the south edge of Mount Rainier National Park.

Footnotes continued on following page.

Footnotes continued from previous page.

29. Osceola Mudflow. Bank of Inter Fork near old Storbo Camp in Glacier Basin.
30. Osceola Mudflow. Roadcut about ½ mile north of highway bridge over Fryingpan Creek.
31. Osceola Mudflow. Roadcut in the West Fork valley about ½ mile north of the mouth of Jim Creek.
32. Osceola Mudflow. Roadcut in the White River valley along U.S. Highway 410 about 0.1 mile north of the mouth of Ranger Creek.
33. Osceola Mudflow. Bank on east side of the White River in the NW¼ sec. 14, T. 19 N., R. 9 E., 2 miles southeast of Greenwater.
34. Osceola Mudflow. Roadcut along U.S. Highway 410 near the mouths of East and West Twin Creeks.
35. Osceola Mudflow. Roadcut near the center of the south edge of sec. 8, T. 19 N., R. 7 E. (approach road to spillway at Mud Mountain Dam).
36. Osceola Mudflow. Exposure along the north wall of the White River valley near the center of the SE¼ sec. 29, T. 20 N., R. 6 E., about 2.5 miles northwest of Buckley in the Puget Sound lowland.
37. Osceola Mudflow. Exposure at top of bluff overlooking the Green River valley, at the east edge of sec. 28, T. 21 N., R. 5 E., about 2 miles southeast of the town of Auburn in the Puget Sound lowland.
38. Lahar in Nisqually River valley. Same location as sample 21. Sample of unit 1 in measured section 4.
39. Lahar in White River valley. South bank of river about midway between White River campground and highway bridge across river. Sample of lowest bomb-bearing lahar.
40. Lahar at Van Trump Park. Bank of shallow ravine about 800 feet northeast of trail shelter. Sample from lahar that pre-dates pyroclastic layer O and that may have originated more than 11,000 years ago.
41. Lahar at Paradise Park. Same location as sample 23. Sample of lahar that underlies the Paradise lahar.

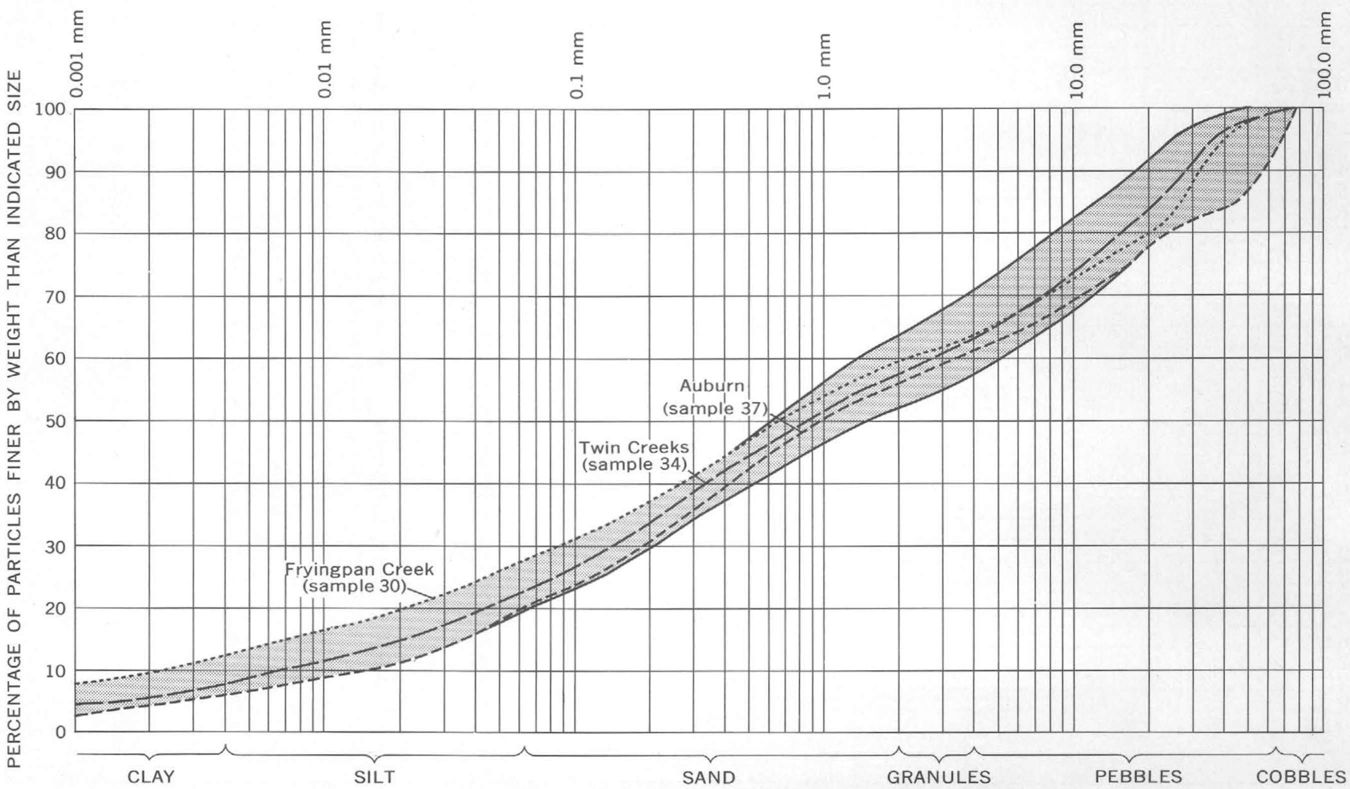

FIGURE 11.—Cumulative curves of the size distribution of samples of the Osceola Mudflow. The shaded zone represents the area covered by the curves of samples from eight localities; three of these samples are represented by individual curves as labeled; sample number refers to table 10.

The samples obtained from two different localities in the Puget Sound lowland (localities near Auburn and Buckley, samples 37 and 36) show about the same degree of sorting. Furthermore, the sorting coefficient of the sample obtained at the outcrop near Auburn (sample 37) is nearly the same as that of the sample from Glacier Basin (sample 29), even though the two localities are nearly 70 miles apart. The only downvalley change in texture noted in the lowland is an apparent decrease in the maximum size of stones in the basal zone of the mudflow, but this observation was not quantitatively verified.

The highest sorting coefficient, 16.34, was determined on a sample from the locality near Fryingpan Creek (sample 30). Although the sample came from near the top of the outcrop there, the actual top of the mudflow during flowage probably was 100–200 feet higher than the sample horizon. The deposit from which the sample was obtained is a veneer left after most of the mudflow passed downvalley.

The Osceola Mudflow is unique among the lahars in the White River drainage basin because of its relatively high clay content. Clay minerals make up from 60 to 80 percent of the clay-sized fraction of each sample. Montmorillonite and kaolinite predominate in various proportions in every sample of the deposit (table 11, samples 29 through 37), and other clay minerals are present in some samples. The remainder of the clay-sized

TABLE 11.—*Mineralogy determined by X-ray analysis of clay-sized fraction of lahars*

[Values are estimated parts in 10. Localities and ages of the samples are given in table 10. Leaders (---), not present; Tr., trace; n.d., not determined]

Sample	Montmorillonite	Kaolinite	Kaolinite-montmorillonite mixed-layer mineral	Chlorite	Mica	Montmorillonite-chlorite mixed-layer mineral	Mica-montmorillonite mixed-layer mineral	Mica-chlorite-montmorillonite mixed-layer mineral	Kaolinite-halloysite	Feldspar	Quartz	Amorphous silica	Cristobalite	Iron oxide
2	---	---	---	---	---	---	---	---	---	9	---	n.d.	1	n.d.
3	1	2	2+	---	---	---	---	---	---	1+	---	Tr.	1+	−1
4	5	---	---	---	---	---	---	---	---	2	---	n.d.	3	n.d.
5	5	---	---	---	---	---	---	---	---	2+	---	n.d.	2+	n.d.
6	6	Tr.	---	---	---	---	---	---	---	2	---	n.d.	1	n.d.
8	3	---	---	1	---	---	---	---	---	3	−1	n.d.	2+	n.d.
9	3+	Tr.	---	---	---	Tr.	---	---	---	2	---	Tr.	2+	1+
11	4	---	---	---	---	---	---	---	---	4	---	n.d.	2	n.d.
12	Tr.	---	---	1+	−1	−1	---	---	−1	2+	---	−1	1+	Tr.
14	3	---	---	---	---	1	---	---	---	3	Tr.	−1	2	−1
15	4	---	---	---	---	---	---	---	---	3	---	n.d.	3	n.d.
16	3	---	---	---	---	---	---	---	---	4	---	n.d.	3	n.d.
18	---	---	---	---	---	---	---	---	---	3	---	1	6	n.d.
21	Tr.	---	---	---	---	---	---	---	---	5	---	−1	3	1
23	3+	2	---	---	---	---	---	---	---	1+	Tr.	−1	1+	1
27	Tr.	---	---	---	---	---	---	---	4	2	---	−1	2	−1
29	5	3	---	---	Tr.	---	---	---	---	1	1	n.d.	1	n.d.
30	6	1	---	---	---	---	---	---	---	Tr.	3	n.d.	1+	n.d.
31	3	2	---	---	---	---	---	3	---	1	1	n.d.	−1	n.d.
32	6	2	---	---	---	---	Tr.	---	---	1	1	n.d.	1	n.d.
33	5	2	---	---	---	---	Tr.	---	---	3	Tr.	n.d.	1+	n.d.
34	2	2	---	---	2	2	---	---	---	1	1	n.d.	−1	n.d.
35	1	2	---	---	2	1	---	---	---	1	2	n.d.	−1	n.d.
36	3	2	---	---	2	1	Tr.	---	---	1	1	n.d.	1	n.d.
37	3	2	---	---	2	---	---	1	---	1	1	n.d.	1+	n.d.
38	2	---	---	---	---	Tr.	---	---	---	4+	Tr.	−1	−2	Tr.
40	---	---	---	---	---	---	---	---	---	1+	---	8	1	n.d.
41	3+	−1	---	---	---	Tr.	---	---	---	1+	---	Tr.	2	1+

fraction in all samples consisted chiefly of plagioclase, quartz, and cristobalite. In the sand-sized fractions, the heavy mineral suite is dominated by hypersthene, which makes up as much as 95 percent of the sample. The light fraction consists mostly of rock fragments, glass, and feldspar.

Atterberg limits were determined on the −0.420-mm fraction of eight samples (samples 29–37) of the Osceola Mudflow from outcrops in the Cascade Range and Puget Sound lowland and are as follows:

	Plastic limit	*Liquid limit*	*Plasticity index*
Range	19–28	28–42	2–15
Average	24.6	33	8.4

A plasticity index of 2 was determined on mudflow samples 34 and 36. These, and other low plasticity indices, indicate a need to control moisture content carefully when the mudflow is used to construct a fill. The Osceola was used extensively in the impermeable core of Mud Mountain Dam, and some unusual construction problems were encountered because of its properties. Before emplacement in the fill, it was necessary to pass the material through heated rotating drums to remove excess moisture and to erect a huge canvas tent over the core to shield it from precipitation.

ORIGIN

The Osceola Mudflow apparently originated in avalanches of hydrothermally altered rock from the summit of Mount Rainier. The presence of the mudflow high on the flank of the volcano at Steamboat Prow indicates that the flow came from above that point, and its distribution in Glacier Basin and the cirque north of the basin suggests that debris that descended the volcano surmounted Steamboat Prow and cascaded into Glacier Basin in a sheet or sheets many hundreds of feet thick. The clay mineralogy of the mudflow is most readily explained if the avalanches originated in an extensive mass of rock that had previously been hydrothermally altered in large part to clay.

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The water component of the mudflow may have been as much as 800 million cubic yards during movement if it is assumed that the material required a water content of 33 percent in order to flow. The rock debris probably was derived from an active hydrothermal area on the volcano; if so, the clayey material could have had a high moisture content from condensation of steam. Moreover, if the avalanches contained steam as well as hot rock debris, snow could have been melted to provide added moisture as the masses moved down the flank of the volcano.

An adequate source of material was not known when the Osceola was first recognized as a mudflow. Crandell and Waldron (1956, p. 360) suggested that the mudflow was initiated by a volcanic explosion that expelled masses of hydrothermally altered rock from the northeast flank of the volcano, but I (Crandell, 1963a) later suggested that the mudflow originated at the summit of the cone. The source area I postulated also accounted for a "missing summit" of the volcano that was first noted by Russell (1898). The present summit of Mount Rainier is at the top of a young lava cone constructed within a large depression about 1¼ miles across; high points on the rim of this depression are at Point Success, Gibraltar Rock, and along the ridge between Liberty Cap and Russell Cliff. These high points indicate that the summit of the volcano was removed above an altitude of about 14,000 feet. Both Russell (1898) and Matthes (1914) suggested that the top of the volcano had been blown off by a mighty volcanic explosion, but Coombs (1936) proposed that the former summit was removed piecemeal during a series of eruptions. Fiske, Hopson, and Waters (1963) concluded that the summit was lowered by subsidence into magma, by outward slumping and flowage of solfatarized rock in the central part of the volcano, or by headward glacial erosion into the weak core rock. I (Crandell, 1963a) proposed that the summit of the volcano slid off and formed very large rockslides and avalanches that descended the northeast side of the cone to form the Osceola Mudflow.

The discovery by D. R. Mullineaux (oral commun., 1969) of newly erupted material in an airlaid deposit formed at the same time as the Osceola Mudflow suggests that the rockslides and avalanches were caused by volcanism. The airlaid deposit is layer F (table 5), and its correlation with the mudflow is based on stratigraphic relations, on its resemblance to the matrix of the mudflow, and on the similar radiocarbon ages of the two deposits. Layer F does not occur on top of the Osceola Mudflow and thus cannot be younger, and organic material beneath layer F at Cowlitz Park has an age of 5,800 years (table 4, sample W-2053).

According to Mullineaux, layer F is made up of three units in the Yakima Park–Berkeley Park area. The basal unit, 1–3 inches thick, consists mostly of clay and fragments of dense rock, about half of which have been strongly altered. The clay is mostly montmorillonite. The middle unit, ¼–1 inch thick, consists mostly of glass-encrusted mineral euhedra and pumice, and the top unit is 1–3 inches of clay that contains abundant altered and unaltered dense rock fragments as well as mineral euhedra and pumice. Mullineaux believes layer F to be primarily of pyroclastic origin. He concludes that the pumiceous ash and lapilli in layer F demonstrate an eruption of magma and visualizes that the following sequence of events occurred. A phreatic explosion threw dense rock fragments and clay onto areas northeast of the volcano; this explosion was closely followed by an explosive eruption of magma that formed the thin layer of pumiceous ash and lapilli. Still later, pumiceous material was erupted along with dense rock fragments and clay. The initial explosion probably caused the slides of altered rock that formed the Osceola Mudflow, but perhaps less likely, the rockslides could have been triggered by earthquakes accompanying the eruption.

There is little evidence concerning the behavior in detail of the Osceola Mudflow, and one can only speculate about its characteristics during flowage. The mudflow probably moved downvalley in a series of large surges, each initiated by an avalanche of moist, clayey rock debris. The mudflow's tremendous volume resulted in hydraulic damming and ponding at valley constrictions in the Cascade Range and caused inundation of a broad area of the lowland. In the absence of any topographic or stratigraphic evidence to the contrary, it is assumed that the Osceola's entire fluid mass came to rest before any part of it dried enough to solidify. The time involved in the formation, movement, and emplacement of the mudflow may have been several days, or as little as a few hours.

POST-OSCEOLA LAHAR ASSEMBLAGE

Deposits in the White River valley that are younger than the Osceola Mudflow include at least four lahars and as many or more fluvial deposits; these are referred to collectively as the post-Osceola lahar assemblage. The assemblage is typically exposed in the face of a terrace near the mouth of Fryingpan Creek (measured section 1). The basal five units in this section evidently were deposited in a swamp adjacent to the White River; they seem to record a stable flood plain following the Osceola Mudflow, when the valley floor was at a level similar to that of the present. Some time after 2,700 years ago (see unit 5, measured section 1), alluvium and a thin lahar

Measured section 1

[South bank of White River near mouth of Fryingpan Creek, Mount Rainier National Park]

	Thickness (ft.)	(in.)
19. Sand, very fine		½
18. Pyroclastic layer W (about 450 years old)		2
17. Sand, very fine, pinkish-gray		½
16. Sand, very fine, yellowish-brown		1
15. Sand and coarse bouldery gravel of fluvial origin, light-yellowish-brown	19	0
14. Lahar: rock fragments as large as 8 in. in yellowish-brown sand matrix; rock fragments are mostly angular and subangular Mount Rainier rock types, a few of granodiorite and breccia from Ohanapecosh Formation. Material in uppermost 2½ ft. grades up from granule gravel, which contains scattered pebbles and cobbles, to medium sand	3	0
Minor erosional unconformity.		
13. Lahar: rock fragments as large as 12 in. in matrix of purplish-gray coarse sand; grades into uniform medium sand at top	6	0
12. Sand, fine, horizontally stratified, purplish-gray	2	0
11. Lahar: grades from pebble-sized material in a purplish-gray sand matrix at base to coarse sand at top	2	0
10. Sand and pebble to boulder gravel of fluvial origin, iron-strained; contains lenses of openwork gravel	3	0
9. Sand, very fine, purplish-gray to light-yellowish-brown	1	6
8. Peat	1	6
7. Lahar: grades from angular rock fragments of pebble size in a purplish-gray sand matrix at base to very coarse purplish-gray sand at top	2	0
6. Pebble-and-cobble gravel of fluvial origin, purplish-gray, lenticular; as thick as	1	3
5. Sand and silt, purplish-gray; contain scattered rock fragments and logs; lenticular; sample of wood from this unit is 2,700 years old (table 4, sample W–930); as thick as	2	0
4. Pyroclastic layer Y (about 3,600 years old): includes contorted layer of peat above fairly pure basal layer of pumice 8 in. thick	1	6
3. Clay, peaty, gray to light-yellowish-brown		2
2. Volcanic ash(?), sand-sized, micaceous, light-brownish-gray		3
1. Clay, woody and peaty; contains logs	>5	0

were deposited, but a continued-stable flood plain is indicated by the overlying peat (unit 8). Flood plain stability ended when lahars and fluvial deposits aggraded the valley by at least 35 feet.

The lahars exposed in the section near the mouth of Fryingpan Creek consist mainly of sand and fine gravel (fig. 12), but lahars of considerably coarser texture occur in the same assemblage both upstream and downstream.

A series of terraces is cut into, or formed by, the lahar assemblage along the valley wall at several places between the mouth of Inter Fork and Fryingpan Creek.

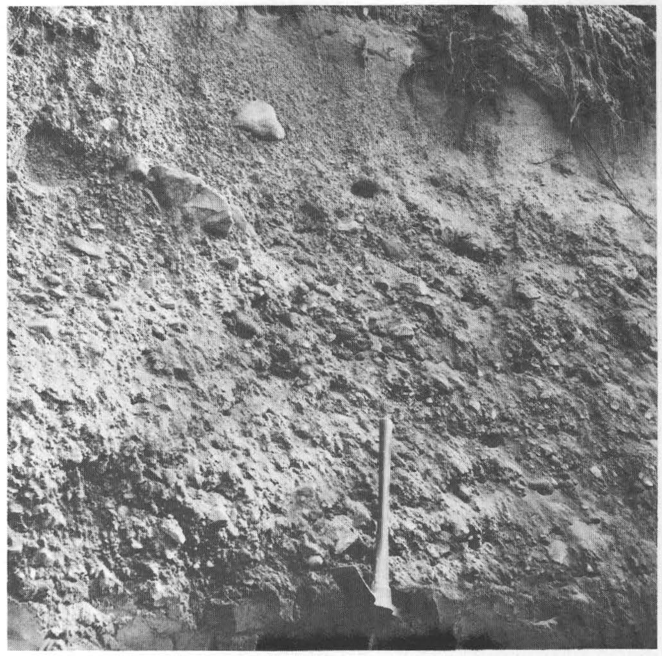

FIGURE 12.—Lahar exposed near the mouth of Fryingpan Creek grading from sand- and pebble-sized material in the lower two thirds to a well-sorted medium sand at the top. The lahar is unit 13 of measured section 1. The pick head is at the contact of the lahar with an underlying fluvial sand deposit.

White River campground is situated on one of these terraces. The terrace is about 3,600 feet long and is about 30 feet above White River at its upper end and about 45 feet at the downstream end. Its gradient is about 280 feet per mile, whereas that of the river is about 300 feet per mile in this segment of the valley. A cut in the face of the terrace at the campground exposes crudely stratified fluvial gravel overlain by a lahar that contains boulders as large as 4 feet in diameter. Pyroclastic layer W veneers the terrace, but layer C is absent, even though present on the adjacent valley wall.

On the south side of the valley, opposite from and just downstream from White River campground, a 40-foot terrace is formed by a lahar 15–30 feet thick that overlies the Osceola Mudflow. A higher terrace here lies about 80 feet above the river, but the material that forms it is not exposed.

On the north side of the valley, just downstream from the highway bridge over the White River, post-Osceola terraces are found at heights of about 10, 15, and 30 feet. A quarter of a mile farther downstream, on the south side of the river, a lahar older than pyroclastic layer W forms a terrace about 30 feet above the flood plain. The lahar consists of angular rock fragments in a matrix of purplish-gray sand. A still-higher terrace in the same vicinity, which is formed by one or more lahars younger than pyroclastic layer C but older than layer W, is about 45 feet above the river.

Near the north boundary of the park, at Silver Creek Ranger Station, U.S. Highway 410 is situated on a post-C, pre-W terrace that is only a few feet above the surface of the flood plain and is probably underlain by a lahar. This terrace is littered with boulders as large as 10 feet in diameter. A little farther downstream, in the vicinity of Silver Creek Lodge, a terrace that is about 60 feet above the river is underlain by pre-W alluvium and a lahar. On the west side of the valley and still farther downstream, a terrace at a comparable height above the flood plain is underlain by a pre-C sandy lahar about 4 feet thick, beneath which are pyroclastic layer Y and the Osceola Mudflow. A diagrammatic cross section of the valley floor in this area is shown on plate 2.

POST-OSCEOLA LAHAR ASSEMBLAGE IN THE WEST FORK VALLEY

At least four post-Osceola lahars have been recognized in the West Fork valley north of Mount Rainier National Park; two are older than pyroclastic layer Y, one is younger than Y and older than layer C, and one is younger than layer W. Only one post-Osceola lahar was recognized within the park.

One pre-Y lahar crops out in a roadcut near the mouth of the valley on the west side of sec. 26, T. 19 N., R. 9 E. (Greenwater quadrangle). It is at least 4 feet thick and consists of subangular to subrounded stones in a matrix of oxidized dark-yellowish-brown sand. The lahar overlies the Osceola Mudflow and underlies, in the same outcrop, pyroclastic layer Y, another lahar, and pyroclastic layers C and W. Its top is about 50 feet higher than the West Fork of the White River. Grain-size analysis of a sample of the lahar indicated a median diameter of 12.5 mm and a sorting coefficient of 13.2 (table 10, sample 22). An oxidized lahar 3–4 feet thick, which probably is correlative with the one just described, crops out in a roadcut 1.5 miles farther upvalley in the NE¼ sec. 33.

A second pre-Y lahar is exposed 3.5 miles farther upvalley in a small borrow pit near the mouth of Jim Creek. It is more than 10 feet thick and contains boulders as much as 8 feet in diameter. The matrix of the upper part of the lahar grades upward from sand-and-cobble gravel to medium and coarse gray sand. Some of the large boulders are of granodiorite, but all the smaller fragments and the matrix seem to have been derived from Mount Rainier.

A post-Y, pre-C lahar that is about 6 feet thick is exposed near the mouth of West Fork valley at the roadcut in sec. 26 just mentioned. Size analysis of a sample from a zone 4–5 feet below the top of the lahar indicated a median diameter of 2.8 mm and a sorting coefficient of 13.40 (table 10, sample 3).

A deposit that probably is part of the same lahar occurs in a streambank exposure on the north side of the valley about 1 mile away, near the center of sec. 23. There, the lahar is 20 feet thick and consists almost wholly of rock fragments derived from Mount Rainier. It overlies a succession of deposits that includes, from top to bottom, 3 feet of fluvial sand derived from Mount Rainier, a layer of humic material a few inches thick, pyroclastic layer Y, and the Osceola Mudflow, the base of which is below river level.

A broad area of the floor of the West Fork valley near its mouth is underlain by the youngest post-Osceola lahar. The lahar and fluvial deposits associated with it form a terrace 25–30 feet higher than West Fork. The lahar is a lenticular, bouldery deposit as much as 8 feet thick where it is exposed in a gravel pit south of West Fork, near the center of sec. 33. Granodiorite boulders as large as 12 feet in diameter are scattered over the surface, and boulders as large as 7 feet in diameter can be seen in the walls of the gravel pit. The lahar's matrix is purplish-gray sand and granule gravel. The lahar overlies as much as 15 feet of stratified purplish-gray sand and fine gravel that rests on top of the Osceola Mudflow. The absence of pyroclastic layer W from the top of the lahar indicates that it is less than 450 years old, and ring counts of tree stumps on the lahar's surface indicate an age of more than 275 years.

Within Mount Rainier National Park, a post-Y lahar is exposed at the mouth of Winthrop Creek in the West Fork valley. It consists of 16 feet of angular and subangular rock fragments, which range in size from granules to boulders, in a purplish-gray sand matrix. The lahar overlies a bed of silt, clay, and sand 1 foot thick that contains pumice derived from layer Y. This fine deposit overlies about 20 feet of poorly sorted pebble to boulder gravel, which rests on top of the Osceola Mudflow.

LAHARS IN THE NISQUALLY RIVER VALLEY

Postglacial deposits in the Nisqually River valley within Mount Rainier National Park include at least 12 lahars, more than eight fluvial deposits, and three layers of volcanic ash. Their sequence is as follows:

Several lahars and associated fluvial deposits.	Lahar assemblage D.
Pyroclastic layer W (about 450 years old)	
At least seven lahars and at least eight fluvial deposits.	Lahar assemblage C.
Peat	
Pyroclastic layer Y (about 3,600 years old)	
Peat and peaty silt	

Paradise lahar	Lahar assemblage B.
Fluvial sand and gravel	Do.
Pyroclastic layer O (about 6,600 years old)	
Two lahars interbedded with fluvial deposits.	Lahar assemblage A.

Although many of the lahars are intermittently exposed in the valley from the vicinity of Christine Falls downstream beyond the park boundaries, their general similarity makes correlation difficult or impossible. This large group of lahars and alluvium is divided for convenience of discussion into four lahar assemblages, each consisting of two or more lahars or alluvial deposits, which are separated by pyroclastic deposits. The most widespread deposit that is recognized within these assemblages is the Paradise lahar, which also mantles the Paradise Park area. This lahar, and a similar one at Van Trump Park, will be discussed first; this discussion will be followed by a description of the assemblages along the floor of the Nisqually River valley.

PARADISE LAHAR

Ridges and valleys between Panorama Point and Ricksecker Point are veneered with a yellowish-orange deposit of angular to subrounded rock fragments in a plastic matrix consisting of a mixture of sand, silt, and clay. Although originally the deposit was informally designated as the Paradise debris flow (Crandell, 1963a), its name is changed here to Paradise lahar because of the textural variability within it. The lahar is younger than pyroclastic layer O and predates layer D; it was formed some time between about 5,800 and 6,600 years ago (table 5).

Blocks as large as 8 feet in diameter are embedded in the lahar, and even larger masses are scattered on its surface. Iron oxide occurs within the deposit as thin layers and lenses, and as thin coatings on most rock fragments. The lahar is 1–5 feet thick in most outcrops, although thicknesses of as much as 15 feet are not uncommon. Owing to its general thinness, the lahar does not have a constructional topography of its own in most places, but mantles ridges, knobs, and depressions formed of bedrock and glacial drift. At Reflection Lakes, however, the surface of the lahar is hummocky, and the lakes occupy shallow basins in the deposit. In outcrops along the floor of the Nisqually River valley the lahar is 2–8½ feet thick, but it veneers the valley sides to a height of more than 100 feet near the mouth of the Kautz Creek valley.

Nearly everywhere that the base of the Paradise lahar is exposed along the Nisqually River valley it rests directly on pyroclastic layer O, and there is little or no evidence of erosion along the contact. A layer of forest duff several inches thick lies on top of the lahar at several places and underlies pyroclastic layer Y and a younger lahar.

In the Paradise Park area the lahar underlies the surface south of Panorama Point and from Mazama Ridge westward to the young lateral moraines of Nisqually Glacier (pl. 3). According to D. R. Mullineaux (oral commun., 1969), the lahar is represented on Mazama Ridge by a deposit a few inches thick that underlies pyroclastic layer D and other layers just south of Sluiskin Falls. The maximum height of the lahar deposit in that area is about 600 feet above the floor of Paradise Valley. Farther south, a large lobe of the lahar underlies the Reflection Lakes area.

Evidently the Paradise lahar entered the Reflection Lakes area through a saddle on Mazama Ridge that is about 200 feet higher than the floor of Paradise Valley. A thin remnant of the lahar that crops out along the highway at Reflection Lakes (measured section 2) indicates that the lahar initially filled that area to a level at least 20 feet higher than the present lake level. However, the surface of the lahar was subsequently lowered as the still-fluid material drained away to the west and rejoined the main mass of the lahar in the Paradise River valley (pls. 1, 3). The west end of the largest lake may be dammed by laharic material that flowed off Mazama Ridge.

High remnants of the Paradise lahar both upstream and downstream from Narada Falls indicate that a very large mass of material moved down the Paradise River valley. The most conspicuous remnant is exposed in a roadcut near Ricksecker Point (fig. 13). The lahar there is a few feet thick and directly overlies pyroclastic layer O at a height of about 800 feet above the floor of the Paradise River valley. Because of the position of the lahar on a south-facing slope overlooking the valley, there seems to be no other way to explain its presence except by the temporary filling of the valley with the lahar to a height of at least 800 feet.

Measured section 2

[Roadcut south of the center of the largest lake at Reflection Lakes]

	Thickness (ft)	Thickness (in.)
9. Colluvium: reworked volcanic ash and forest duff	1–2	0
8. Pyroclastic layer Y		4–6
7. Colluvium: reworked pumice and forest duff	2.5	0
6. Paradise lahar: unsorted mixture of angular to subrounded pebbles and cobbles in matrix of sand, silt, and clay	2–4	0
5. Sand, gray		6
4. Pyroclastic layer O		1–2
3. Sand, gray		0–5
2. Evans Creek till: gray, lenticular		0–6
1. Granodiorite (bedrock)		------

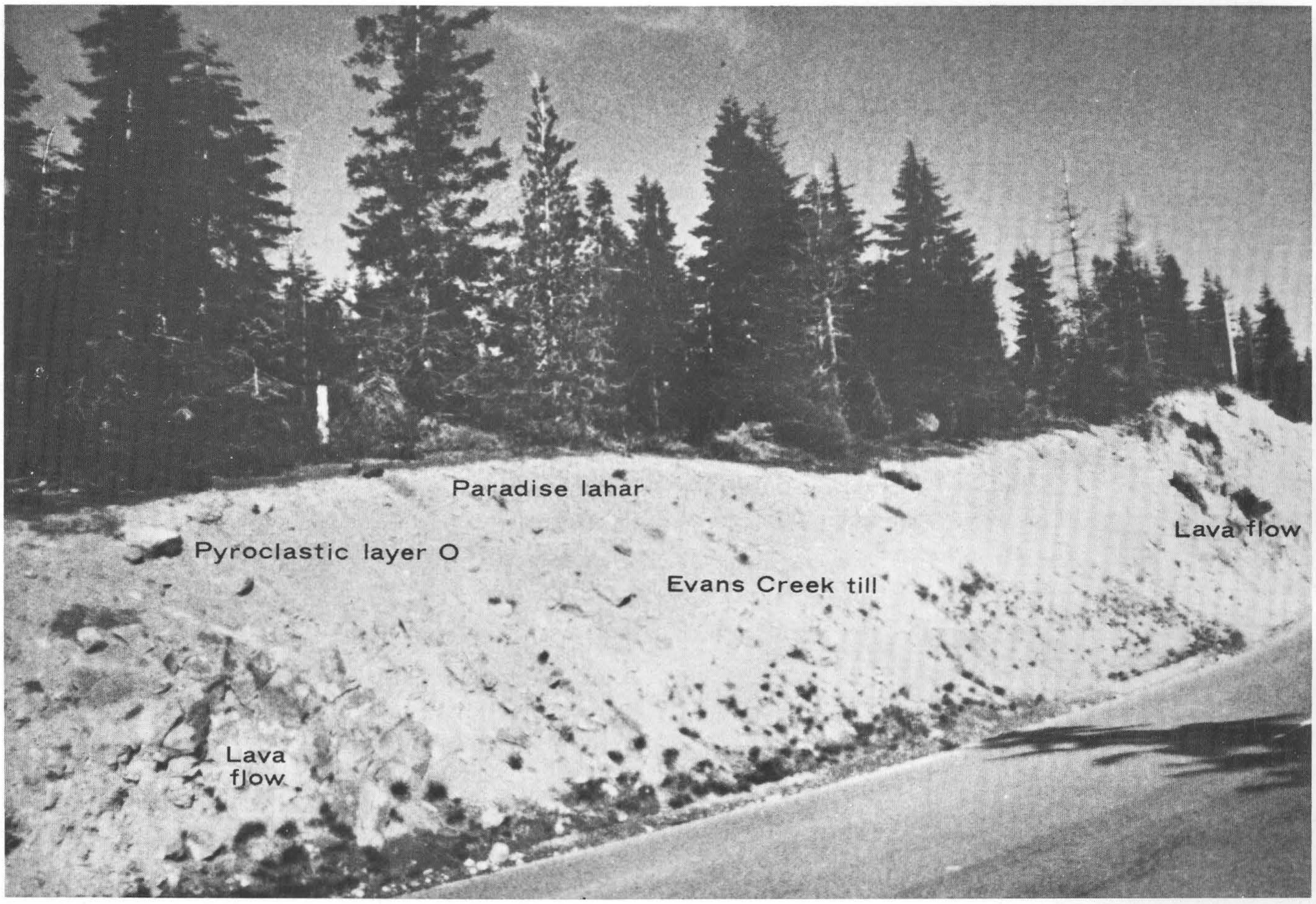

FIGURE 13.—Paradise lahar above pyroclastic layer O in roadcut half a mile east of Ricksecker Point. Beneath layer O are Evans Creek till and a lava flow from Mount Rainier. This outcrop is about 800 feet higher than the floor of the adjacent Paradise River valley and indicates that the lahar was at least 800 feet deep here.

Farther down the valley the Paradise lahar forms part of assemblage B. Its vertical extent indicates that the valley was at least as deep when the lahar was moving as it is today and that the lahar was temporarily several hundred feed deep at Longmire. The lahar was identified as far downvalley as a point near the mouth of Tahoma Creek, and it may be one of several lahars that crop out in the valley near National, 12 miles west of Longmire.

Stones in the lahar are principally of Mount Rainier provenance. Identification of 100 pebbles in the deposit at Reflection Lakes and at Longmire showed 75 and 80 percent, respectively, to be of Mount Rainier origin. At Reflection Lakes the deposit contains only 5 percent granodiorite in the pebble-sized fraction, but this rock type makes up 20 percent of the pebbles at Longmire. The greater proportion of granodiorite at Longmire may be due to incorporation of loose gravel from the Nisqually flood plain.

Three samples of the lahars from the Paradise Park area contained 1–5 percent clay, 7–28 percent silt, and 16–44 percent sand (table 10, samples 23, 24, 25). X-ray examination of a sample from an outcrop near the visitor center at Paradise Park indicated that montmorillonite and kaolinite are the predominant clay-sized minerals (table 11, sample 23). They are accompanied by small amounts of cristobalite, feldspar, iron oxide, and quartz. Amorphous silica constituted 6.4 percent of the clay-sized fraction. It is of interest to note that a sample of Evans Creek till (table 7, sample 1) from the same outcrop had mostly feldspar and cristobalite in the clay-sized fraction, and only a trace amount of clay mineral was found. Some samples of the lahar are among the most poorly sorted of those examined in this study (fig. 14). It is especially interesting to note the poor sorting of the lahar at Ricksecker Point (sample 26). The deposit there must represent a zone in the upper

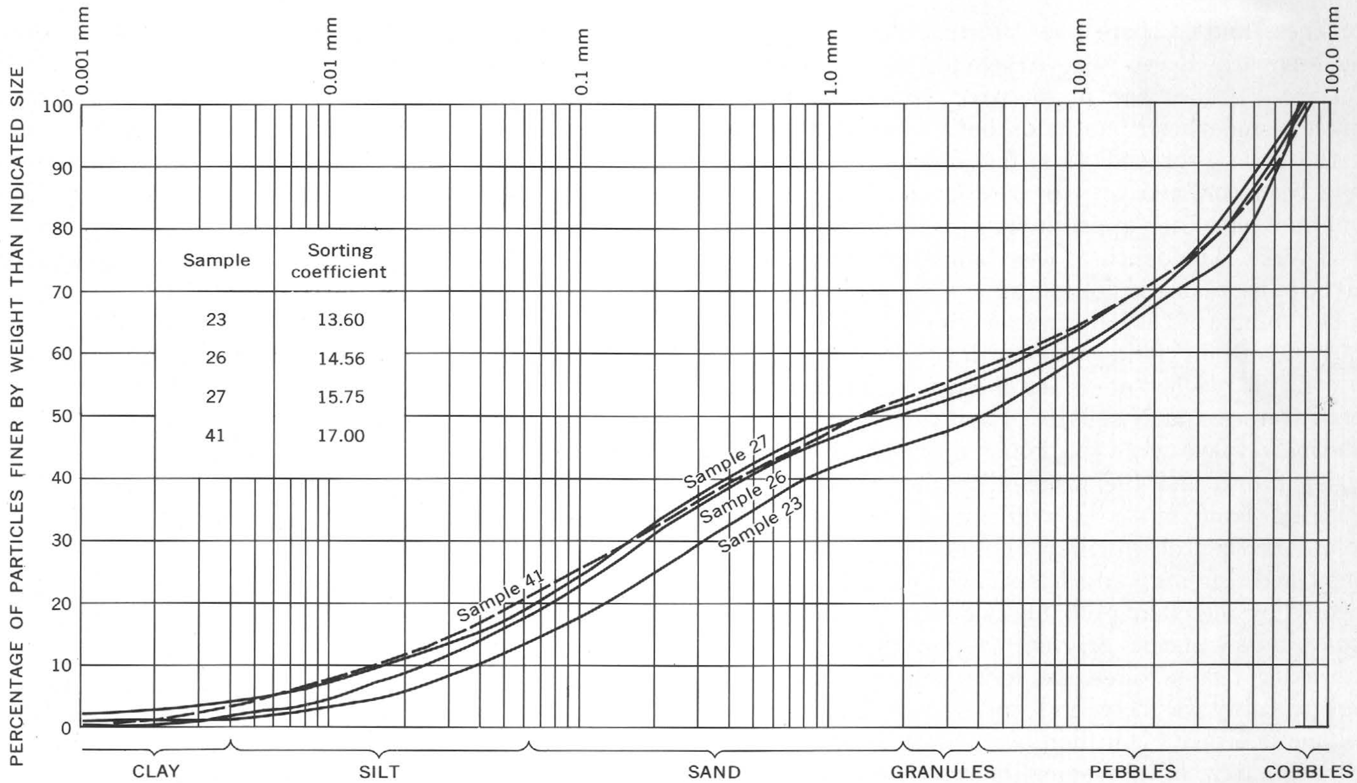

FIGURE 14.—Cumulative curves of size distribution of the Paradise lahar (solid lines) at three localities and of an older lahar (dashed line) at Paradise Park. Sample 23 is from an outcrop near the visitor center at Paradise Park, 26 is from an outcrop near Ricksecker Point, and 27 is from measured section 4 at Longmire. Sample 41 is from the older lahar, at the same locality as sample 23. The samples are those described in table 10.

10–20 feet of a lahar that was momentarily at least 800 feet deep in the Paradise River valley during flowage.

Silt and clay made up about 19 percent of a sample (27) of the Paradise lahar that was taken from an outcrop near Longmire. (See measured section 4.) X-ray diffraction analysis of the clay-sized fraction of this sample showed a kaolinite-halloysite mixed-layer mineral, and cristobalite, feldspar and a small amount of iron oxide (table 11, sample 23). Amorphous silica made up 8.3 percent of the clay fraction.

The distribution of the Paradise lahar in the area between Panorama Point and Ricksecker Point suggests that the lahar originated in one or more huge avalanches of moist rock debris that swept down the south flank of the volcano. The clay mineralogy of the deposit indicates that it was derived in part from hydrothermally altered rocks, perhaps at the summit of Mount Rainier. Although I once thought that the deposit at Paradise Park was of the same age as the Osceola Mudflow (Crandell, 1963a, p. B139), I now know that the Paradise lahar is somewhat older because it is stratigraphically below pyroclastic layer D, which is older than the Osceola (D. R. Mullineaux, oral commun., 1969). It seems likely that counterparts of the slides that resulted in the Greenwater lahar in the White River valley caused the Paradise lahar and were triggered in the same way (p. 22).

Although the distribution of the lahar in the Paradise Park area indicates that the lahar originated in an avalanche down the south side of Mount Rainier, the area of transition from an avalanche to a lahar is not known. At Paradise Park, where the transition may have occurred, grain-size distribution in samples of the deposit indicate a rather wide variability in texture and a range in sorting coefficients of 7.75–13.6 (samples 23–28, table 10). Median diameters range from 0.2 to 13 mm in these samples. Samples obtained from two locations farther downvalley (samples 27, 28), where there is little doubt that movement was that of a lahar, have sorting coefficients of 15.75 and 16.25 and median diameters of 1.4 and 4.3 mm, respectively. One might expect that the deposit would be most poorly sorted where it was moving as a rapid avalanche and that it would show somewhat better sorting where it was moving as a lahar. However, the opposite seems to be true, if the samples described here are representative.

The original volume of the Paradise lahar is difficult to determine because the deposit is highly variable in thickness, and nowhere does it form a broad thick fill in the Nisqually River valley. Beyond the community of National, 6 miles west of the park, Evans Creek Drift directly underlies surfaces on both sides of the river; if the lahar reached this far downvalley, it must have been confined to a narrow channel, and its top could not have been appreciably higher than the present flood plain. The depth of the channel of the Nisqually River at that time is not known.

The volume of the lahar was originally estimated to be 400–500 million cubic yards on the basis of the heights to which it reached on valley sides, the assumption that the Paradise and Nisqually River valleys were simultaneously filled with the lahar upstream from Ricksecker Point, and the probability that the lahar was draining from one area while its crest was passing points farther downvalley (Crandell, 1963a). Subsequent geologic mapping has shown that the total area covered by the lahar probably is no more than about 13 square miles, and its original average thickness in this area after it came to rest and lost much of its water content probably was between 5 and 10 feet. The estimated volume is either 67 million or 134 million cubic yards, according to whether the smaller or larger average thickness value is used in the computation.

The great depth of the Paradise lahar at some places, notably in the lower Paradise River valley, seems entirely out of proportion to such a relatively small volume, even if it is assumed that the lahar probably contained an additional volume of water of as much as one-third of the estimated volume of the deposit. The anamolous relations involved can be illustrated by considering the capacity of the lower Paradise River valley. Near Ricksecker Point, the valley has a cross-sectional area of about 130,000 square yards up to a height of about 800 feet above the valley floor. The 1-mile segment of the valley immediately east of Ricksecker Point has an estimated volume of at least 230 million cubic yards up to a similar height. Thus, it is apparent that even the total estimated volume of the lahar could not entirely fill this short valley segment at one time. The problem becomes even more acute when it is remembered that a considerable part of the estimated volume of the lahar remained in the area above the lower Paradise River valley and in the Nisqually River valley above Ricksecker Point. Moreover, to explain the great depth of the lahar in the Paradise River valley by any conventional means, it is necessary not only to have this valley segment full of mud, but simultaneously to have mud of comparable thickness in the Nisqually River valley at the mouth of the Paradise River.

On the basis of the assumption that the estimated volume of the lahar is not grossly in error, the most probable explanation of the contradictory relations just described is that the lahar moved across Paradise Park and down the Paradise River valley in a single massive transient wave with a height of as much as 800 feet. Such a wave must have been generated by a large avalanche of wet, clayey, rock debris from an area high on the south flank of the volcano, or perhaps at its summit. Because of momentum the avalanche-generated wave swept across Paradise Park, rather than moving directly down the Nisqually River valley. The valley swings from a southward course to a southwestward course just west of Panorama Point. Here the great momentum of the wave, created by a vertical drop of perhaps as much as 8,000 feet, carried it up over the east valley wall. The wave surmounted the ridge between Panorama Point and Alta Vista, surged across Paradise Park, and slopped up onto Mazama Ridge just south of Sluiskin Falls. The bulk of the material, however, was deflected by Mazama Ridge to the southwest and down the Paradise River valley.

The transient wave probably lost much of its height when it debouched from the Paradise River valley at Ricksecker Point. Its momentum must have carried it high on the flank of Rampart Ridge along the west side of the Nisqually River valley. At Longmire, a little more than 1 mile downvalley, the lahar was at least 80 feet and probably several hundred feet deep. As the lahar wave progressed farther down the Nisqually River valley, it gradually lost height as the valley widened and as more and more volume was lost by material being left behind as a coating on the lower valley walls and valley floor.

OLDER LAHAR AT PARADISE PARK

An older lahar that underlies the Paradise lahar is exposed at several places in the Paradise Park area. The contact between the two deposits is marked by a humic zone several inches thick that formed in and on the lower lahar (fig. 15; measured section 3).

A grain-size distribution analysis of a sample of the lower lahar from the measured section indicates 21 per-

Measured section 3

[Trench exposure temporarily open during construction of sidewalk and retaining wall at the northwest edge of the Paradise Visitor Center in September 1966 (fig. 15)]

	Thickness (ft)	Thickness (in)
5. Pyroclastic layer W		1
4. Pyroclastic layer Y	1	3
3. Paradise lahar: light-yellowish-brown (2.5*Y* 6/4) to brownish-yellow (10*YR* 6/6) mixture of rock fragments, sand, silt, and clay; humified in upper 4–6 in	1	8
2. Older lahar: light-yellowish-brown (2.5*Y* 6/4) mixture of rock fragments, sand, silt, and clay; humified in upper 1–3 in	2–3	0
1. Evans Creek till: gray (2.5*Y* 4/0)	>5	0

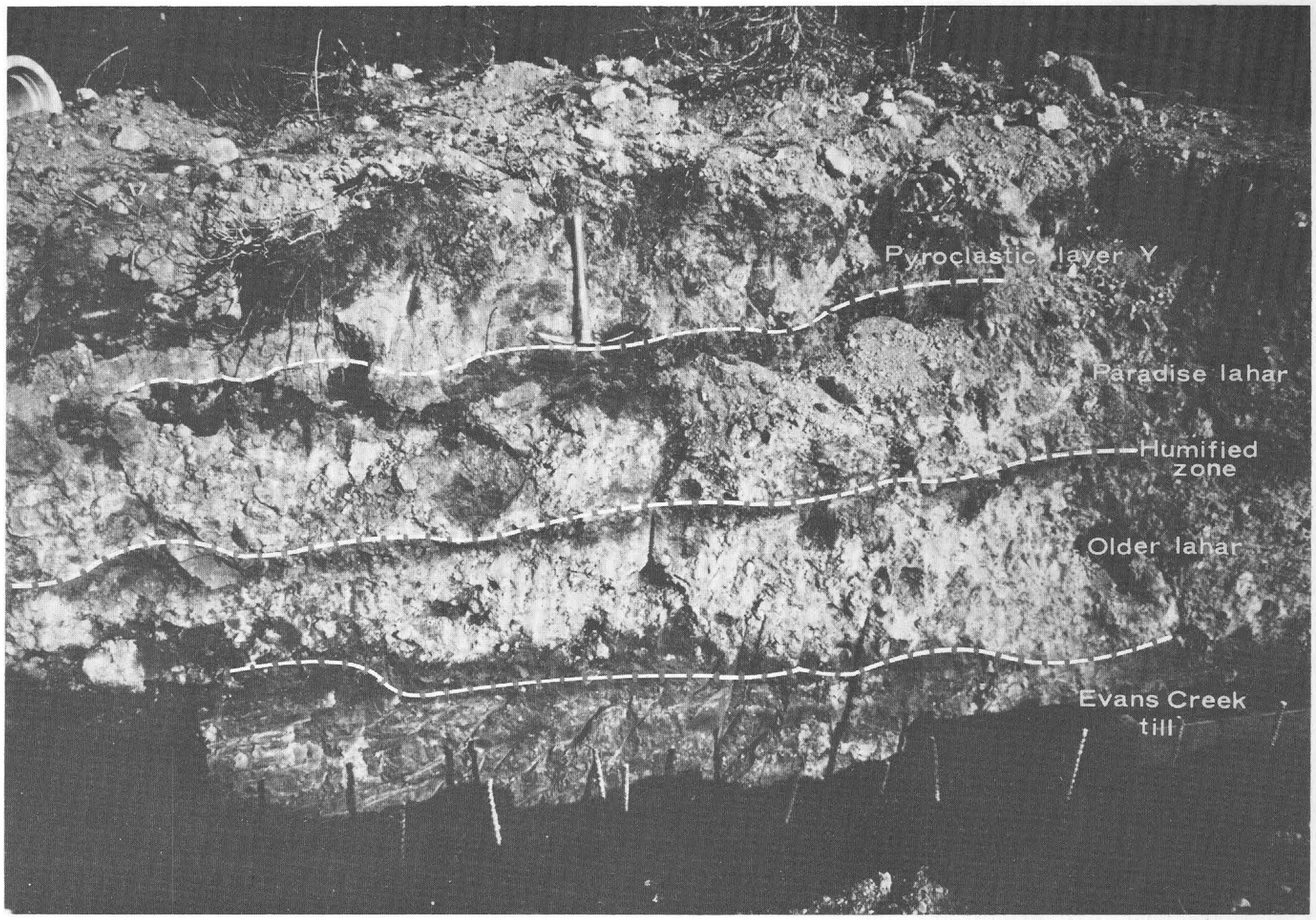

FIGURE 15.—Outcrop of the Paradise lahar and an older lahar in a trench excavated for a retaining wall at the north edge of the visitor center at Paradise Park (measured section 3).

cent clay and silt and 32 percent sand (table 10, sample 41; fig. 14). The sample had a median diameter of 1.25 mm and a sorting coefficient of 17.

The clay minerals in a sample of the older lahar were chiefly montmorillonite and a small amount of kaolinite. The remainder of the clay-sized fraction was cristobalite, feldspar, and iron oxide (table 11, sample 41).

The older lahar at Paradise Park probably originated in a slide of hydrothermally altered rock from the summit or south flank of the volcano. It may be correlative with the lahar that is older than layer O at Van Trump Park. (See below.)

LAHARS AT VAN TRUMP PARK

At Van Trump Park, the ridge between Van Trump and Comet Creeks is veneered with a yellowish-orange lahar, which is older than pyroclastic layer O and which consists of stones up to 1½ feet in diameter in an unsorted matrix of sand, silt, and clay. On the ridgetop the deposit ranges in thickness from a few inches to as much as 4 feet, but the lahar is as much as 6 feet thick on the east slope of the ridge, where it overlies Evans Creek till and a lava flow from Mount Rainier. It extends down the east side of the ridge to the floor of Van Trump Creek, but it was not seen on Cushman Crest or the ridge at the west edge of Van Trump Park.

The lahar's distribution suggests that it was formed by an avalanche of rock debris on the south flank of the volcano. Although the lahar was not identified in the Van Trump Creek valley below Van Trump Park, it may be represented in the Nisqually River valley by one of the lahars of assemblage A.

The lahar is not present on top of a lateral moraine of Van Trump Glacier. The lateral moraine probably is of Sumas age (table 3). However, the lahar does overlie Evans Creek Drift in areas just beyond the moraine. This relation suggests that the mudflow occurred during the Everson Interstade.

A sample of the lahar from an outcrop about 800 feet northeast of the Van Trump trail shelter contained 42 percent clay and silt and 33 percent sand (table 10, sample 40). The sample had a median diameter of 0.1 mm and a sorting coefficient of 10.2. X-ray analysis of the clay-sized fraction of the lahar resulted in the identification of glass (probably amorphous silica), feldspar, and cristobalite.

A series of younger lahars is exposed in the valleys of Van Trump and Comet Creeks. The basal lahar of this series in the Van Trump Creek valley is a purplish-gray bouldery deposit 1–2 feet thick that underlies pyroclastic layer O and unconformably overlies a gray fluvial gravel as much as 10 feet thick. Above layer O is a bouldery reddish-brown lahar at least 3 feet thick. It is overlain by pyroclastic layer Y, above which is another reddish-brown lahar, only about 1 foot thick, in which the coarsest material is of pebble size. This deposit is overlain by pyroclastic layer W and a post-W gray lahar 1.5–6 feet thick that is oxidized to a depth of about 1 foot. The gray lahar is overlain by scattered boulders and coarse, unsorted, lenticular deposits that were formed by a still younger lahar or flood. These deposits form low bouldery ridges that trend downvalley.

At least two bouldery lahars form low terraces in the Comet Creek valley upstream from Comet Falls. The lower terrace is about 5 feet above Comet Creek and is underlain by a lahar and fluvial gravel; the upper terrace is about 12 feet higher and is underlain by a lahar.

The lahars in the Van Trump drainage basin occur in the same stratigraphic position with respect to pyroclastic deposits as some of those in the Nisqually River valley. Lahars having a reddish-brown matrix, similar to that of some deposits in the Van Trump Creek valley, were not recognized along the Nisqually River.

LAHAR ASSEMBLAGE A

Lahar assemblage A contains the oldest postglacial deposits recognized in the Nisqually River valley. These deposits consist of two lahars and interbedded fluvial sand that overlie Evans Creek Drift and predate pyroclastic layer O. The assemblage is intermittently exposed in streambank outcrops between Longmire and a point about 1½ miles downstream, where the Nisqually River turns westward. Sporadic exposures as far west as the mouth of the Tahoma Creek valley suggest that the deposits originally extended downstream beyond the park boundary.

In exposures ½–1½ miles downstream from Longmire, the lahars in assemblage A are composed of angular to subrounded pebbles, cobbles, and boulders as large as 12 feet in diameter in a friable, purplish-gray, silty sand matrix (fig. 16). The matrix contains voids, and some small lenses of pebbles within the lahars have openwork texture. The top 2–3 feet of the upper lahar is oxidized to a light yellowish brown, and films of iron oxides coat the surfaces of most stones. At one locality, a layer of humus occurs at the top of the upper lahar immediately beneath pyroclastic layer O, but no wood was seen in either lahar. In most outcrops, the two lahars rest directly on one another, but at one locality they are separated by 1–2 feet of stratified sand and pebble gravel.

The maximum thicknesses of these lahars are difficult to determine because their base and top are rarely seen in the same outcrop. At an exposure adjacent to the Nisqually flood plain in the NW¼ sec. 5, the lower lahar is 8 feet thick, but its base is not exposed. The greatest exposed thickness of the upper lahar is only 4–5 feet, but the vertical distance between its base and top is 37 feet at a locality 1½ miles downstream from Longmire. Although the lahar must thus have been at least 37 feet deep during movement, nowhere are the veneers that were left on valley sides after its passage known to reach a comparable thickness.

A sample of the oldest lahar of assemblage A at Longmire (unit 1, measured section 4) was analyzed for size distribution and clay mineralogy (tables 10, 11, sample 38; fig. 17). The sample was taken from a zone about 4½ feet below the top of the deposit in the outcrop. X-ray analysis of the fine fraction of the sample resulted in the identification of montmorillonite

Measured section 4

[Riverbank outcrop on the west side of the Nisqually River in center of the NE¼ sec. 32, T. 15 N., R. 8 E., at Longmire]

	Thickness (ft)	Thickness (in)
8. Duff; thickness variable, as thick as		6
7. Pyroclastic layer W		1–2
6. Lahar: subangular to subrounded pebbles, cobbles, and boulders in matrix of sand and silt, unsorted and unstratified, mottled light yellowish brown and purplish gray	2	0
5. Pyroclastic layer Y: contains scattered fragments of charcoal in upper 2 in	1	1
4. Paradise lahar: subangular to subrounded pebbles, cobbles, and boulders in matrix of silt and sand, slightly plastic, unsorted and unstratified; matrix purplish gray, but stones coated with yellowish-brown iron oxides	8	6
3. Sand, coarse to fine, lenticular; contains scattered pebbles; as thick as	4	0
2. Pyroclastic layer O		1–3
1. Lahar: angular to subrounded pebbles, cobbles, and boulders in matrix of silt and sand; has some zones that show faint planar structures that suggest bedding; has some layers of openwork gravel a few inches thick; purplish gray, oxidized to light yellowish brown in upper 2–3 feet	>10	0

The base of unit 1 is below the level of the adjacent flood plain.

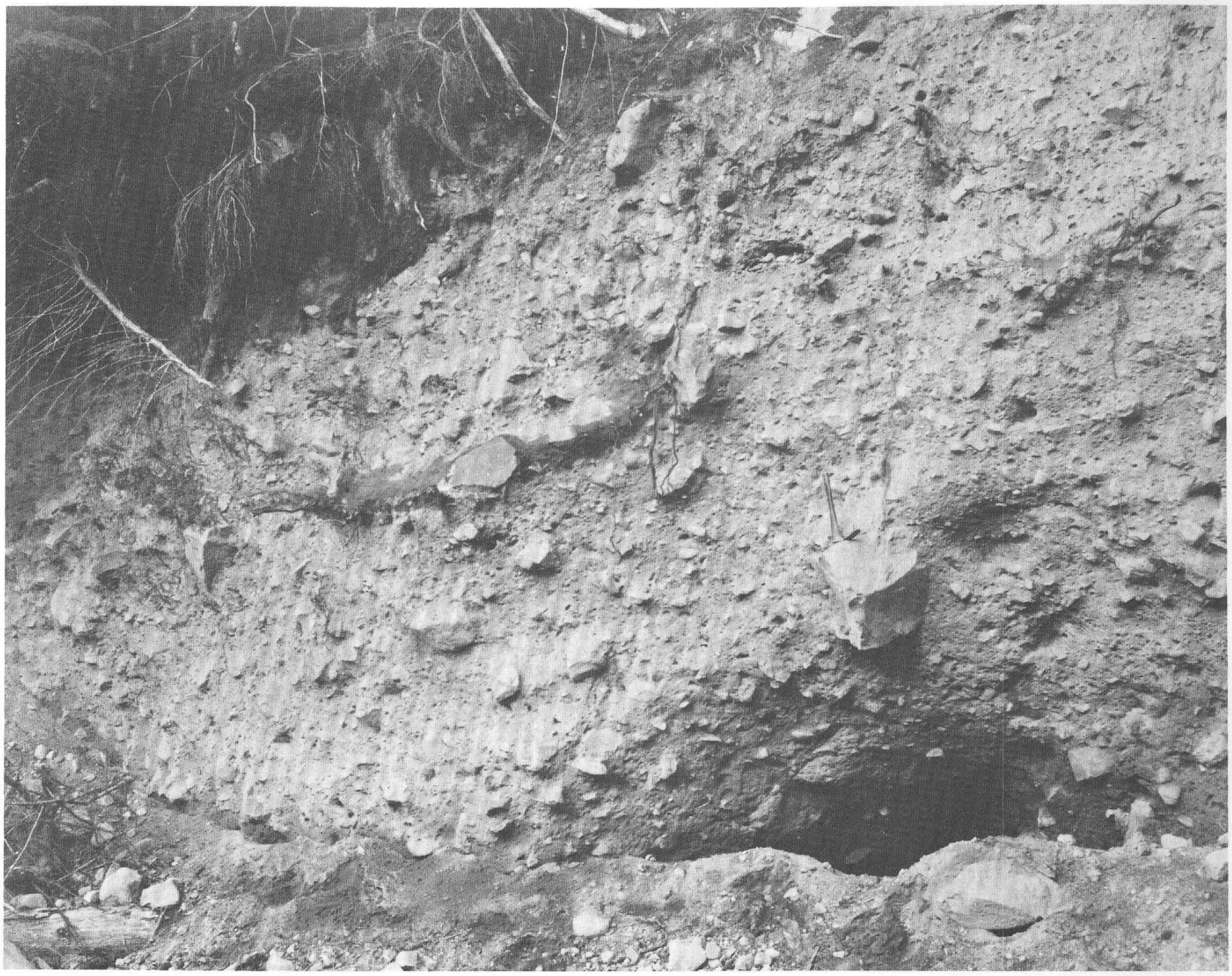

FIGURE 16.—Lahar in streambank on west side of Nisqually River flood plain at measured section 4, about a quarter of a mile southwest of Longmire. The lahar shown here, which is older than pyroclastic layer O, is unit 1 in the measured section.

(2 parts in 10). The rest of the clay-sized fraction consisted chiefly of feldspar and cristobalite.

The lahars in assemblage A could be the downvalley correlatives of the older lahar at Paradise Park or of the lahar at Van Trump Park that is older than pyroclastic layer O.

LAHAR ASSEMBLAGE B

Lahar assemblage B is overlain by more recent deposits at most places along the valley floor and is best exposed in the faces of terraces along the Nisqually River. The most extensive lahar in assemblage B is the Paradise lahar, which has already been described. The basal part of the assemblage is a deposit of sand and gravel that was noted at three localities. One is in a roadcut at a switchback near the mouth of Van Trump Creek, where pebble to boulder gravel underlies pyroclastic layer Y. The Paradise lahar was not seen here, and units beneath the gravel are not exposed. The top of the gravel deposit is about 70 feet higher than the Nisqually River.

Fluvial gravel and the Paradise lahar are also exposed in a series of outcrops about 1,000 feet upstream from the bridge to Longmire campground (measured section 5). The gravel is a crudely stratified deposit of cobbles and boulders more than 15 feet thick. Its base locally lies below river level. In one streambank outcrop the gravel overlies 4 feet of fine sand, which is underlain by talus. In another outcrop the Paradise lahar is 3 feet thick and overlies the fluvial gravel at a height of about 15 feet above the flood plain. A short distance upstream, however, the base of the lahar is below the level of the flood plain; there, the lahar is overlain by fluvial gravel younger than pyroclastic layer Y.

Measured section 5

[East bank of Nisqually River about 1,000 ft upstream from bridge at Longmire]

	Thickness (ft)	Thickness (in)
12. Pyroclastic layer W: white pumiceous ash		2
11. Lahar: angular to subrounded pebbles, cobbles, and boulders in matrix of purplish-gray sand	10	0
10. Sand and pebble to boulder gravel; boulders as large as 5 ft across; dark yellowish brown	12	0
Erosional unconformity.		
9. Lahar: angular to subrounded pebbles, cobbles, and boulders, as much as 4 ft across, in matrix of purplish-gray sand	6	0
8. Pebble to boulder gravel; both crossbedding and horizontal bedding locally present; purplish gray, but iron stained along some bedding surfaces	3	0
7. Lahar: angular to subrounded boulders, as much as 4 ft across, in matrix of purplish-gray sand; as thick as	13	0
6. Sand and pebble to boulder gravel, dark-yellowish-brown; boulders are as large as 3 ft in diameter	6	0
5. Peat interbedded with medium to coarse sand; individual beds of each are lenticular; as thick as	2	0
4. Pyroclastic layer Y: yellow pumiceous ash, lenticular; as much as	1	3
3. Peat and peaty silt; contains fragments of wood; as thick as		6
2. Paradise lahar: angular to subrounded boulders in plastic clay and sand matrix; purplish gray where unoxidized, light yellowish brown where locally oxidized; as thick as	15	0
Erosional unconformity.		
1. Pebble to boulder gravel, crudely stratified, purplish-gray; extends beneath level of adjacent flood plain; more than	15	0

A third exposure in which fluvial deposits underlie the Paradise lahar is at measured section 4, a short distance downstream from Longmire. Here the top of the fluvial deposit is about 15 feet above flood-plain level.

After the formation of lahar assemblage A, and for some time after deposition of pyroclastic layer O about 6,600 years ago, the Nisqually River evidently was flowing on a surface lower than the present flood plain. Later, but before the Paradise lahar was formed, the river aggraded to a profile that was at least 15 feet higher than it is now in the vicinity of Longmire, only to cut down again to a lower profile before the Paradise lahar occurred. The causes of this aggradation and downcutting are not known. The Nisqually River flood plain seems to have been nearly stable between the time the Paradise lahar occurred and deposition of pyroclastic layer Y about 3,600 years ago.

LAHAR ASSEMBLAGE C

Lahar assemblage C consists of fluvial gravels and lahars which are stratigraphically between pyroclastic layers Y and W (p. 32). The fluvial deposits are best exposed in banks along the west side of the Nisqually River between Van Trump Creek and Longmire. Just south of Van Trump Creek the lahar assemblage is represented by poorly sorted fluvial gravel (fig. 18) about 25 feet thick, locally capped by two lahars that are 3 and 5 feet thick. In this area and farther downvalley the lahar assemblage forms terraces that are from 20 to 80 feet above the adjacent Nisqually River flood plain. The terrace on which the entrance road is situated has a gradient of about 250 feet per mile.

At the mouth of the Paradise River valley a terrace underlain by the assemblage extends a few hundred yards back into the valley, and the river flows along the south edge of the terrace's southward-sloping surface. An outcrop in the face of the terrace a quarter of a mile north of the Paradise River reveals a series of four lahars separated by beds of fluvial sand and granule gravel 1–2 feet thick. The lowest lahar exposed is more than 15 feet thick and consists of an unsorted rubble that contains angular and subangular blocks as large as 7 feet in maximum dimension in a matrix of purplish-gray sand. Blocks in the rubble consist of andesite that was derived from the volcano and granodiorite. The three overlying lahars are texturally similar and are from 1 to 4 feet thick. The clay-sized fraction of the uppermost lahar consists of cristobalite, feldspar, and glass (probably amorphous or opaline silica, or both); no clay minerals were identified by X-ray examination (table 11, sample 18). This lahar probably is correlative with the one that caps the terrace at Cougar Rock campground on the opposite side of the valley. The lahar at the campground is at least 5 feet thick, and blocks on its surface are as large as 14 feet in maximum dimension.

The stratigraphic complexity of lahar assemblage C is well illustrated by outcrops on both sides of the Nisqually River about a quarter of a mile north of Longmire (measured section 5). There are six terraces within the valley in this area, at heights ranging from 20 to about 80 feet above the river. The stratigraphic succession of the deposits and the relation of the deposits to the terraces are shown diagrammatically on plate 2. The sequence of events that can be inferred from this cross section follows. The sequence depends on an uncertain correlation of individual gravel deposits and lahars. If the correlations are incorrect, the sequence would be different in detail but not in overall complex character.

18. Downcutting to level of present flood plain.
17. Aggradation of fluvial deposit J.
16. Downcutting probably of at least 20 feet.

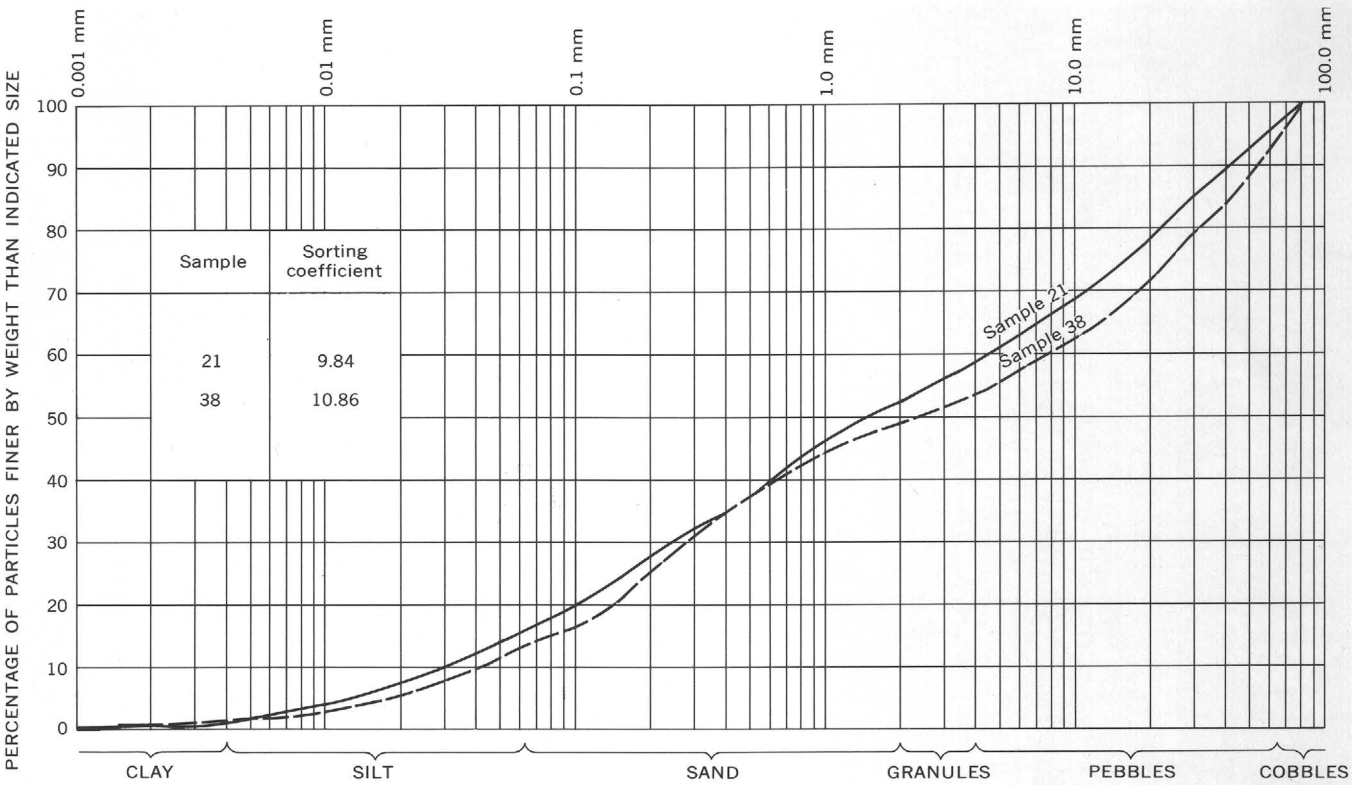

FIGURE 17.—Cumulative curves of grain-size distribution of lahars near Longmire. Sample 38 is unit 1 of measured section 4, and sample 21 is unit 6.

15. Deposition of pyroclastic layer W about 450 years ago.
14. Deposition of lahar I.
13. Downcutting of about 20 feet.
12. Aggradation of about 30 feet by fluvial deposit H.
11. Downcutting of about 35 feet.
10. Deposition of lahar G.
9. Aggradation of at least 20 feet by fluvial deposit F.
8. Downcutting of at least 20 feet.
7. Aggradation of about 40 feet by fluvial deposit E.
6. Downcutting of unknown amount.
5. Deposition of lahar D.
4. Deposition of fluvial gravel C.
3. Deposition of lahar B.
2. Channel of Nisqually River represented by fluvial deposit A.
1. Deposition of peat and pyroclastic layer Y on top of Paradise lahar.

In reconstructing these events, I assumed that the presence of a lahar at a certain height does not necessarily imply that the valley was filled by solidified lahar to that height. This is because lahars typically attain a "high-water mark" formed by a transient crest and may only leave veneers on preexisting terraces of various heights as the bulk of the flow drains on down the valley.

ORIGIN OF LAHAR ASSEMBLAGES IN THE NISQUALLY AND WHITE RIVER VALLEYS

The histories of the White and Nisqually River valleys are strikingly similar during the period between deposition of pyroclastic layers Y and W. When layer Y was formed about 3,600 years ago, both valley floors were at or near their present altitudes, and peat was being deposited in both valleys, probably in back swamps adjacent to the flood plains or on low swampy terraces. At this time flood plains in both valleys probably were relatively stable and Mount Rainier volcano had long been dormant, or nearly so. A radiocarbon date on wood from a bed of clay in the White River valley indicates that the White River flood plain was still relatively stable until some time after 2,700 years ago (p. 30). Some time later, however, both valley floors changed drastically as the rivers began alternately to aggrade and erode.

Possible explanations for the drastic change in the habit of the White and Nisqually Rivers, as well as that of some other rivers that head on the volcano, include the following three factors: tectonic movement of the land, climatic change, or most likely, an episode of volcanism. The relatively short time during which the valley floors were repeatedly aggraded and eroded suggests that recurring vertical movements of the land were

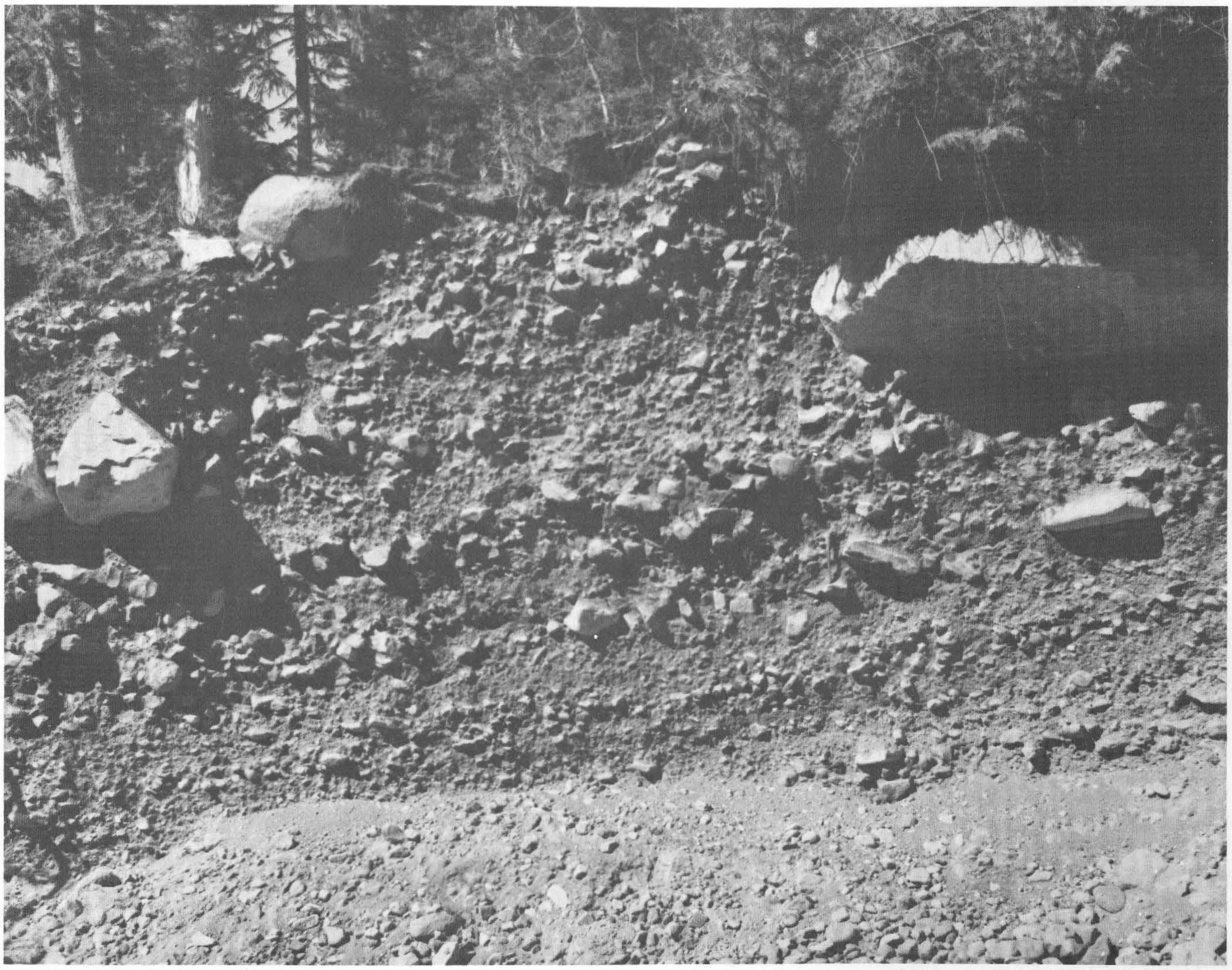

FIGURE 18.—Crudely stratified poorly sorted fluvial gravel in lahar assemblage C, exposed in west bank of Nisqually River near the mouth of Van Trump Creek. The large granodiorite boulder at the upper right is about 11 feet long; handle of pick beneath boulder is about 17 inches long.

not the cause. Nor is it likely that the climate could have changed sufficiently and often enough in this interval to account for the recurring cutting and filling. Climate changes generally alter the discharge-load ratio of streams and cause them to erode or aggrade. Aggradation of a valley floor in a basin occupied by valley glaciers typically occurs during a glacial episode, and downcutting follows during late glacial and early interglacial time; in such an environment most of the remainder of the interglacial interval is normally characterized by relative stability of the flood plain (Schumm, 1965, and references therein). At Mount Rainier the valleys in question contain glaciers today at their heads, and there is little question that these glaciers have been present, though variable in size, throughout Holocene time.

The lahar assemblages must predate trees growing on them. In the White River valley a tree more than 700 years old was found on a terrace underlain by the lahar assemblage just downvalley from the terminal moraine of Emmons Glacier. Sigafoos and Hendricks (1961, p. A16) thought that the forested surface of this terrace is at least 1,000 years old. In the Nisqually River valley I found a living tree at least 790 years old on the surface of lahar assemblage C near Cougar Rock campground. The lahar assemblages in both valleys probably were formed prior to 1,000 years ago.

The interval during which the White and Nisqually Rivers repeatedly aggraded and eroded coincides generally with the Winthrop Creek Glaciation (table 3). During the Burroughs Mountain Stade of that glaciation, which probably occurred between 3,000 and 2,500 years ago, most glaciers in the park were no larger than they were at the beginning of the present century, and Emmons and Nisqually Glaciers were somewhat smaller (Crandell and Miller, 1964). Most of the lahar assemblage in the White River postdates pyroclastic layer C, which was erupted about 2,300 years ago, and thus its origin seemingly cannot be related to climatic or glacial events of Burroughs Mountain time. The stratigraphic relation of lahar assemblage C in the Nisqually River valley to pyroclastic layer C cannot be directly determined.

The oldest known moraines of the Garda Stade of the Winthrop Creek Glaciation were formed about 750 years ago (Crandell and Miller, 1964). Inasmuch as the lahar assemblages in the Nisqually and White River valleys evidently are more than 1,000 years old, both predate the oldest known glacial advance of the Garda Stade. The assemblages in both valleys probably were formed during the interval between the two glacial stades of the Winthrop Creek Glaciation and thus have no genetic relation to glaciation. It is pertinent to note that in no valley heading on Mount Rainier is there a depositional record of large-scale aggradation and downcutting during the Garda Stade comparable to that represented by lahar assemblage C in the White and Nisqually River valleys.

Aggradation of the complex lahar assemblages in the two valleys and the periods of downcutting recorded within the assemblages probably were caused by intermittent eruptive activity of the volcano at the time the present summit cone was formed. Eruptions of the lava flows that form the cone could have caused a succession of floods down the flanks of the volcano by melting extensive fields of snow and ice at the summit. Some floods may have been transformed into lahars as they picked up loose material from taluses, glacial drift, and alluvium on the valley floors. Temporary aggradation farther downvalley, resulting from a series of lahars and debris-laden floods, probably was quickly followed by downcutting between eruptions, when the discharge of rivers approached or returned to normal. Subsequent floods and lahars, separated by periods of downcutting, formed the deposits that underlie the terraces.

The lahars of these assemblages in valleys on the east and south sides of the volcano seem to be nearly or wholly lacking in clay minerals. This lack is attributed to the derivation of the rock debris in the lahars chiefly from talus, glacial drift, alluvium, and newly erupted detritus, rather than from hydrothermally altered rocks of the volcano.

The proposed cause-and-effect relation between building of the summit cone and the formation of the lahar assemblages cannot be proved, but it is consistent with all the known facts. The cone-building eruptions are not dated, but they are thought to have occurred during a late part of an extended episode of volcanism, early parts of which are represented by the formation of a bomb-bearing block-and-ash flow deposit in the South Puyallup River valley that is about 2,500 years old and by the eruption of pyroclastic layer C.

If this cause-and-effect relation is valid, the relative abundance of lahars and fluvial deposits in the White River valley may be due to the fact that the summit cone was built on the east side of the depression formed at the top of the volcano by the landslides that led to the Osceola Mudflow. Floods caused by melting snow and ice at the summit descended Emmons, Winthrop, Nisqually, and Kautz Glaciers. Lahars of post-Y, pre-W age in each of the valleys below these glaciers probably originated during the building of the summit cone. Comparable lahar assemblages of the same age are lacking in the Ohanapecosh, Mowich, and Carbon River valleys, probably because none of these valleys drain the summit cone of the volcano.

LAHAR ASSEMBLAGE D

Assemblage D in the Nisqually River valley consists of alluvium and lahars, younger than the 450-year-old pyroclastic layer W, that form low, tree-covered terraces adjacent to the modern flood plain. The park headquarters building, museum building, many of the residences, and maintenance buildings at Longmire are constructed on a coarse bouldery lahar that is part of this unit. The oldest tree I found on this deposit started to grow in the 1860's. The lahar evidently topped the west riverbank immediately downstream from the site of the bridge over the river at Longmire and formed a lobe that spread westward into the Longmire meadow. The presence of old trees around the lobe's south margin indicates that it did not rejoin the lahar along the center of the valley. A similar but older lahar forms the terrace on the opposite side of the valley at Longmire campground. The terrace is 5–10 feet higher than the surface of the adjacent channeled and unvegetated flood plain of the Nisqually River. The oldest tree I found on the lahar at the campground started to grow about 400 years ago, and the absence of pyroclastic layer W indicates that the lahar cannot be older than about 450 years. The surface of the lahar is crossed by south-trending gullies 1–5 feet deep and is strewn with boulders as large as 4 feet in diameter.

Small lahars have occurred in the upper reaches of the Nisqually River valley several times within the last few decades. Descriptions of some of these lahars are in the files of the National Park Service, and they have recently been discussed by Richardson (1968).

On October 14, 1932, a lahar destroyed a highway bridge across the Nisqually River just below Nisqually Glacier. Eyewitnesses told of a mixture of rock debris, mud, and water which had a front 25 feet high and 150 feet wide and which advanced rapidly downvalley toward the bridge. The impact of the flowing mass carried away the center span of the reinforced concrete bridge, which was 27 feet wide, 55 feet long, and weighed an estimated 40 tons. The bridge was carried more than half a mile downstream. The observers reported that the moving mass resembled wet concrete except for being darker in color, and they stated that large boulders in it were thrown 10–30 feet into the air as the mass moved forward. The lahar evidently terminated on the flood plain between the highway bridge and Longmire.

Two years later, on October 24 and 25, 1934, a series of four floods or lahars again carried masses of debris down the Nisqually River valley. This time rock debris was dumped to a depth of 15 feet on top of a new highway bridge. Richardson (1968) described other "glacier outburst floods" that occurred in October 1947 and October 1955. At the same time as the 1947 flood, lahars moved down the Kautz Creek valley (p. 46).

LAHARS IN THE NISQUALLY RIVER VALLEY DOWNSTREAM FROM THE PARK

Lahars of Holocene age are present in the Nisqually River valley at least as far downstream as Elbe. Although they have not been seen in the valley below Alder Dam, it seems likely that remnants also underlie the part of the valley inundated by Alder Reservoir. Upstream from the reservoir, the deposits are divided into two groups by their stratigraphic relation to pyroclastic layer Y; thus, the pre-Y lahar assemblages A and B of the upper part of the valley are grouped here, as are the post-Y assemblages C and D.

The deposits older than layer Y include at least two lahars as well as fluvial gravel. These deposits crop out in streambank exposures on both sides of the Nisqually River downstream from the Kernahan Road, which is a north-south road that crosses the river 3 miles west of the park. On the south side they form a terrace about 40 feet above the flood plain, which abuts a hill of drift-veneered bedrock. An exposure in the face of this terrace 0.6 mile downstream from the Kernahan Road reveals 15–20 feet of fluvial gravel, overlain by a pre-Y lahar about 20 feet thick. The sand and gravel may be outwash of Evans Creek age. A similar sequence occurs on the north side of the valley only a few hundred yards downstream, where two lenticular lahars, with a total thickness of about 12 feet, overlie 30 feet of fluvial gravel.

Another lahar older than layer Y was noted near stream level in the face of a 20-foot terrace in the same area. An outcrop at the upstream end of the terrace exposes a compact lahar, whose base is below river level; this lahar is overlain by lenticular fluvial gravel and sand. The fluvial deposit is unconformably overlain by layer Y, above which is another fluvial gravel.

Near the mouth of Big Creek, 2½ miles downstream from Kernahan Road, outcrops in the face of a terrace that is older than pyroclastic layer Y show in descending order a lahar 18 inches thick, lenticular sand 20 inches thick, and a lenticular lahar as much as 10 feet thick. The lower lahar lies in a channel cut into fluvial boulder gravel 12–20 feet thick. The terrace is about 25 feet above the Nisqually flood plain.

Fluvial gravels and lahars along the Nisqually River valley that are younger than layer Y form low terraces adjacent to the flood plain. The most extensive deposit floors a channel south of the flood plain for a distance of 5 miles between the park and Ashford. The channel, which marks a former course of the Nisqually River, is separated from the modern flood plain by ridges and knobs of drift-veneered bedrock. The gradient of the channel is less steep than that of the flood plain, so the relative height of the channel increases downstream. At its upstream end, the channel's floor is only about 5 feet above the present Nisqually flood plain, but at its west end it is 35 feet above the flood plain. Exposures of the deposits beneath the channel are poor and for the most part reveal only a few feet of poorly sorted sand and gravel. In some shallow exposures the texture of this material resembles that of coarse lahars with a sand matrix.

Near the east end of the channel there is a gap in the bedrock ridge that separates the channel from the Nisqually River flood plain. In a shallow cut in the floor of the gap can be seen a compact sandy lahar 3 feet thick which overlies a 20-inch layer of Y pumice. A shallow excavation in the floor of the channel near a mill pond (SW¼ sec. 36, T. 15 N., R. 6 E.) 0.4 mile west of Kernahan Road shows 6 feet of boulder gravel. Most of the boulders are less than 1½ feet in diameter, but a few are as large as 8 feet. Farther west, downcutting by Catt Creek into the channel deposit has exposed lahars interbedded with fluvial sand.

From the mouth of Mineral Creek to Elbe, deposits younger than layer Y consist principally of fluvial sand and fine gravel. However, a lenticular lahar crops out in the north bank of the Nisqually River (SW¼ sec. 26, T. 15 N., R. 5 E.) 0.2 mile downstream from the railroad bridge south of Park Junction. The deposit is as much as 12 feet thick and lies in a channel about 125 feet wide which is floored by pebble to boulder gravel and sand. Farther downstream, most exposures on the valley floor are of deposits of medium to very coarse gray sand and granule gravel. Such a deposit was exposed in 1962 in the sides of a trench used as a trash dump by the residents of Elbe, in the NE¼ sec. 29, T. 15 N., R. 5 E. There the sand and gravel deposit is about 5 feet thick and contains granule-sized pumice derived from layer Y; it overlies a sandy lahar more than 2 feet thick in which there are a few scattered cobbles.

The generalized sequence of postglacial events in the valley downstream from the park, reconstructed from the deposits preserved in terraces, is as follows (event 1 is the oldest):

1. Aggradation by fluvial gravel from a surface below the present flood plain to one at least 20 feet higher.
2. Deposition of lahar, locally as much as 20 feet thick, to form a surface 40 feet higher than the present flood plain.
3. Downcutting of valley floor to a level below present flood plain.
4. Deposition of lahar on valley floor.
5. Deposition of thin fluvial gravel on valley floor.
6. Deposition of pyroclastic layer Y.
7. Aggradation of valley floor by fluvial gravel to surface 10–15 feet higher than present.
8. Deposition of lahar as much as 12 feet thick on valley floor.
9. Downcutting of at least 20 feet to level of present valley floor.

The complex sequence of aggradation and downcutting that is recorded by the deposits, terraces, and unconformities within lahar assemblage C upvalley from Longmire is only poorly represented in the valley west of the park. However, both the channel south of the flood plain and that followed by the Nisqually River today were aggraded during the deposition of that assemblage. It seems likely that the effects of the recurring episodes of aggradation and downcutting diminished progressively downvalley and that they may not have extended as far as the Puget Sound lowland.

KAUTZ CREEK VALLEY LAHAR ASSEMBLAGE

The floor of Kautz Creek valley is underlain by an assemblage of lahars and fluvial deposits into which the creek has cut a trench about 3½ miles long, 100–200 feet wide, and as much as 75 feet deep; the south end of the trench is about 1½ miles upstream from the mouth of the creek. Exposures in the sides of the trench reveal a succession of unweathered gray fluvial deposits and lahars interbedded with horizons of forest duff and tree stumps (fig. 19) and pyroclastic layers Y and W. Beyond the edges of the trench the surface of the assemblage is interrupted by old channels of Kautz Creek that are separated by ridges and terraces. Parts of the surface are forested (fig. 20) and some of these forested areas are older than pyroclastic layer W. Because of the convex surface of the assemblage (pl. 2), Pyramid Creek flows along its west margin for about 3½ miles before joining Kautz Creek.

Pyroclastic layer Y and deposits beneath it were seen at only three places along the valley floor, although the pumice mantles the valley walls above the surface of the lahar assemblage. A buried pumice deposit was first noted by Hopson, Waters, Bender, and Rubin (1962) in the east wall of the trench about three-fourths mile upstream from the Wonderland Trail bridge across Kautz Creek, and my associates and I (Crandell and others, 1962) subsequently also examined the sequence of deposits exposed there. In that outcrop, pyroclastic layer Y overlies cobble-and-boulder gravel and is overlain by interbedded fluvial gravels and lahars (measured section 6). Layer Y also crops out in the east bank of the creek about 1½ miles upstream from its mouth. At a third outcrop the pumice overlies a lahar more than 12 feet thick. This locality is about 100 yards downstream from the south end of the "box canyon" of the Kautz, which is a bedrock-walled constriction in the valley southeast of Pearl Falls and 5 miles northeast of the Entrance Road. The "box canyon" is about a quarter of a mile long and 250–300 feet wide.

The lower pyroclastic deposit at measured section 6 was referred to by Hopson, Waters, Bender, and Rubin (1962, p. 641) as "the main ash fall of sand- to granule-sized pumice, which constitutes the major part of the youngest ash blanket from Mount Rainier." They found stumps of two trees in the bed of Kautz Creek 25 feet from the wall of the trench, which they thought were rooted in the deposit beneath the pumice. Radiocarbon age determination of their sample of wood from one of these stumps indicated an uncorrected age of 350±250 years (W–925). However, microscopic examination of pumice taken from the outcrop led D. R. Mullineaux (in Crandell and others, 1962) to conclude that it is pyroclastic layer Y. Layer Y has been bracketed by uncorrected radiocarbon dates of 3,500±250 (W–1115) and 2,980±250 years (W–1118) (table 4; Crandell and others, 1962). The marked increase in grain size and thickness of the pumice layer toward Mount St. Helens indicates that this volcano was its source.

The relations at the Kautz Creek locality and the addition of a "correction factor" to the radiocarbon date led Hopson and his associates to conclude that the

Measured section 6

[East bank of Kautz Creek about 3,000 ft upstream from Wonderland Trail footbridge across creek]

	Thickness (ft)	Thickness (in)
21. Lahar: boulders and cobbles in medium- to fine-sand matrix. Deposited in October 1947	2–8	0
20. Duff, silty, dark-grayish-brown; contains roots and wood fragments		6
19. Boulders; 1–4 ft in diameter, in matrix of stratified coarse sand	3	0
18. Sand, fine to medium, gray; horizontally stratified and interbedded with layers of yellowish-gray silt	2	0
17. Duff; contains fragments of carbonized wood		2
16. Silt and fine sand, yellowish-gray, horizontally bedded; contains pebbles and granules near top	1	0
15. Duff and roots (radiocarbon sample W–1120, uncorrected age: 290±200 years, see table 4)		¼–½
14. Sand, fine, gray		¼–½
13. Pyroclastic layer W: white pumiceous ash		½–2
12. Sand, fine, gray		½
11. Duff, wood, and carbonized wood fragments (radiocarbon sample W–1119, uncorrected age: 320±200 years)		½–1 ½
10. Sand, fine to medium, gray; contains scattered cobbles		6
9. Lahar: pebbles and cobbles in compact sand and granule matrix; gray	2	0
8. Sand, medium; mostly horizontally stratified but has some faint crossbedding; contains reworked pumice of layer Y and wood fragments	5	0
7. Lahar: boulders and cobbles in fine- to medium-sand and granule matrix	2	6
6. Duff mixed with gray fine sand; contains fragments of charcoal		½–2
5. Sand, fine, gray; contains reworked pumice of layer Y and wood fragments	½–2	0
4. Lahar: boulders as large as 4 ft in diameter in gray sand and granule matrix	15	0
3. Sand, fine to medium, stratified, lenticular	1–3	0
2. Pyroclastic layer Y: yellow pumiceous ash		8
1. Pebble-to-boulder gravel and sand	1+	0

latest eruptions of Mount Rainier occurred about 500 years ago. However, the pumice deposit on which they based this conclusion is not an eruptive product of Mount Rainier. A probable explanation for the relatively young radiocarbon date they cited is that the stump from which they took their sample was at a horizon stratigraphically above the pumice deposit, instead of below it, as they thought.

Most of the lahars and fluvial deposits exposed in the walls of the Kautz Creek trench are younger than layer Y, but some are older and some younger than layer W. The lahars range from layers less than 1 foot thick to unstratified, unsorted beds 20 feet thick that contain boulders as much as 10 feet across. Despite their unconsolidated nature, the alluvium and lahars stand in very steep and locally vertical banks along the trench. Although the lahars are not cemented, the fine material in them makes them somewhat more coherent than fluvial gravels in which the fine component is less abundant. The layers of fluvial gravel are distinguished chiefly by the presence of bedding and by somewhat better sorting. However, the overall range in texture in a thick lahar and some comparably thick fluvial deposits does not appear to be appreciably different.

Layers of forest litter in the lahar assemblage range from beds of duff less than an inch thick to accumulations of logs and organic trash that may represent log jams in stream channels that were subsequently buried by lahars or alluvium. The only horizon of duff that is easily traceable along the trench walls is that associated with layer W. Stumps are commonly rooted in material just beneath layer W (fig. 19).

The youngest deposits of the lahar assemblage in the Kautz Creek valley were formed during the night of October 2–3, 1947, and during the early morning hours of October 3. Details of the events that preceded and accompanied the lahars are largely taken from reports by R. K. Grater (1948; unpub. data, Oct. 28, 1947, in files of the National Park Service) and from an unpublished, undated report by C. E. Erdmann and Arthur Johnson of the U.S. Geological Survey, also in the files of the National Park Service.

According to Erdmann and Johnson, rain started to fall a few hours after midnight on October 1 and reached its greatest intensity between 5 and 9 a.m. on October 2. A total of 5.85 inches fell at the Ranger Station at Paradise Park between 4:30 p.m. October 1 and the same time the next day, but very little fell during the early hours of October 3. During the downpour, a cloudburst evidently occurred in the upper part of the Kautz Creek drainage basin, and an additional amount of water may have been contributed by a "glacier outburst flood" from Kautz Glacier (Richardson, 1968, p. D83). The discharge of Kautz Creek increased greatly during the daylight hours of October 2, and between 7 and 8 p.m., high water washed out the entrance road bridge over the creek. The first lahar occurred between 10 and 11 p.m. and was heralded by a dull roar and vibration of the ground as it advanced down the valley. A succession of lahars flowed downvalley during the night, and the last occurred at 8 a.m. the next morning. The lahars were described by eyewitnesses as having the consistency of wet concrete, carrying along vegetation and boulders as large as 13 feet in diameter.

After the lahars ceased, Kautz Creek was flowing in a trench 30–75 feet deep and 100–200 feet wide south

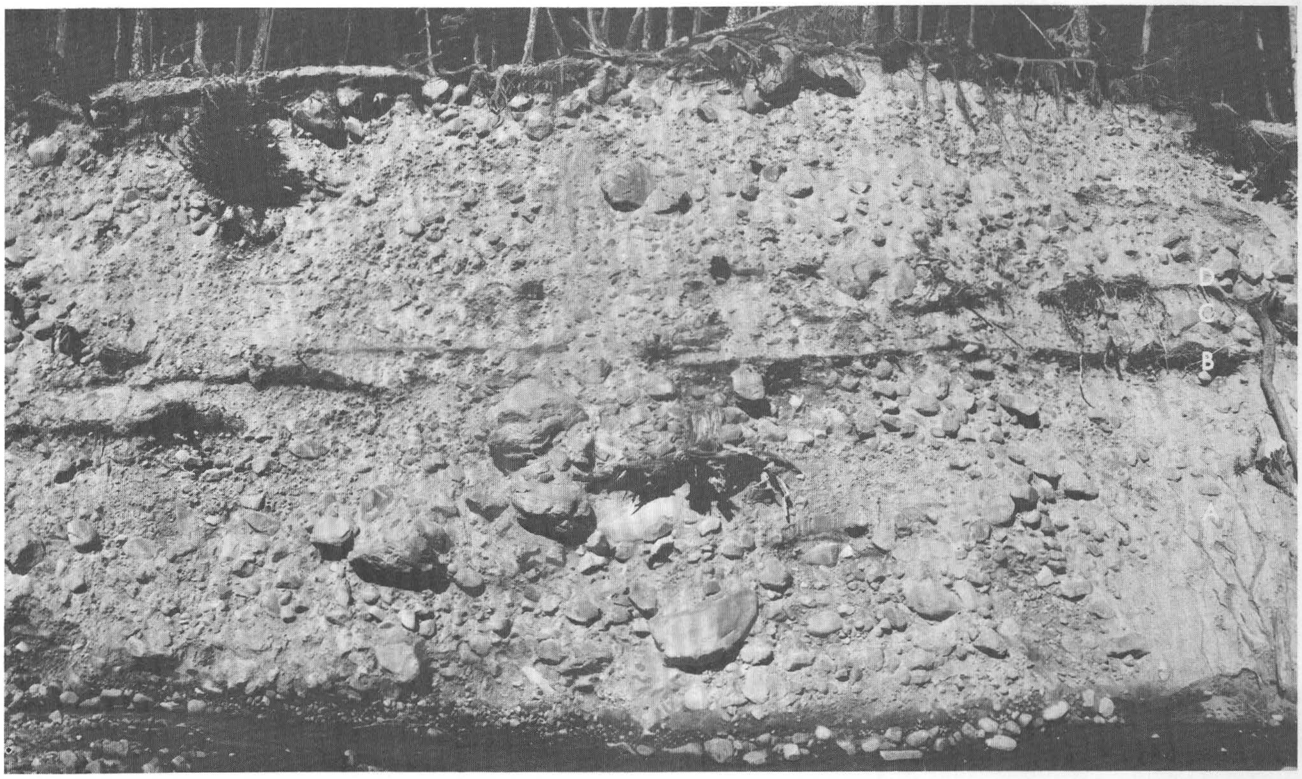

FIGURE 19.—Deposits in west bank of Kautz Creek, about 0.35 mile downstream from the Wonderland Trail. The cobble-and-boulder gravel (A) at the base is probably a fluvial deposit. It is overlain by a layer of duff and roots (B), above which is a lenticular lahar (C) a few feet thick. Above the lahar, at the right side of the photograph, is a layer of roots and duff (D) which includes pyroclastic layer W. Above this are other lahars and fluvial deposits.

of the "box canyon." How much of this trench existed before the lahars occurred is not clear; Grater (1948, p. 279) stated that "an entirely new stream channel was cut, with the old bed of Kautz Creek left high on the side of the canyon." The topography of the valley floor suggests, however, that the present trench could have been localized along a preexisting channel (pl. 2.) Remnants of the 1947 lahars form discontinuous narrow strips along the edges of the trench, and although they locally extend beyond the trench in lobes, they do not veneer wide areas in the upper part of the valley. Their distribution suggests that the lahars were largely confined to the trench and that the trench either predates them or was formed contemporaneously. The narrow strips of laharic deposits are generally less than 10 feet thick, but near the south end of the trench they are as much as 18 feet thick.

Even though the present trench may have been localized along a former course of Kautz Creek, that stream course undoubtedly was cut down and widened at some time on October 2 or 3. Evidence from the lahar assemblages exposed in the Kautz Creek valley and in other valleys at Mount Rainier indicates that lahars themselves are not effective erosional processes at the gradients found on most valley floors below the glaciers. If this is true, downcutting of the trench probably was accomplished not by the lahars themselves, but by floodwaters.

During the morning of October 3, according to the report of Erdmann and Johnson, the valley floor downstream from the trench aggraded about 28 feet where it is crossed by the entrance road. The area of aggradation forms a fan whose base, along the Nisqually River, has a breadth of about 2,500 feet. The area narrows northward to 500 feet or less and apexes at the mouth of the trench. Although the fan in the lower part of the valley probably contains most of the coarse debris transported on October 2 and 3, much of the fine material was carried downstream by the Nisqually River and was deposited on the floor of Alder Reservoir. Grater (1948) estimated the total volume of the lahars and flood deposits to be at least 50 million cubic yards.

During a subsequent investigation of the upper Kautz Creek valley, R. K. Grater (unpub. data, 1947; 1948) found that the lower 1-mile segment of Kautz Glacier had largely disappeared, and a gorge 300 feet deep and as much as 900 feet wide had been cut into the ice. Grater inferred that the gorge had been cut by excessively high

FIGURE 20.—Bouldery surface of a pre-W lahar assemblage that underlies the floor of the Kautz Creek valley about 1 mile north of the Wonderland Trail crossing of Kautz Creek.

runoff, aided by toppling of ice masses as the glacier was undercut. Blocks of ice, accompanied by masses of glacial drift that slid from the precipitous canyon walls, created temporary dams in the "box canyon," the failure of which caused floods of water and masses of saturated debris to flow down the valley. Repetition of sliding and damming caused successive lahars and floods to surge down the valley. The trench of Kautz Creek probably was cut by the floods, and this erosion itself may have created lahars as the undercut sides of the trench toppled into the floodwaters.

Samples of some of the fluvial gravels and lahars deposited on October 3, 1947, were obtained from an outcrop in the bank of the Nisqually River along the south edge of the fan (fig. 21). The size distribution of four samples, and other data, are shown in table 12 and figure 22. X-ray analysis of a sample of one of the lahars (sample 2, table 11) indicated that the silt and clay fractions consist almost wholly of plagioclase feldspar.

TABLE 12.—*Grain-size distribution data on deposits formed by floods and lahars in October 1947 in the Kautz Creek valley*

Unit (fig. 21)	Description	Thickness (ft)	Clay (percent)	Silt (percent)	Sand (percent)	Median diameter (mm)	Sorting coefficient
4	Sand and pebble gravel	3–4	1	5	53	1.6	2.32
3	Lahar	3.5	4	11	48	.8	8.10
2	do	1.5	3	11	51	.63	3.41
1	Sand and granule gravel	>2	1	3	40	2.75	3.38

FIGURE 21.—Lahars and fluvial sand and gravel deposited near the mouth of Kautz Creek in October 1947. Units 2 and 3 are fine and coarse lahars, respectively; units 1 and 4 are probably both fluvial deposits.

On August 23, 1961, a short-lived flood was observed in Kautz Creek at the entrance road bridge by Park Service personnel (fig. 23). This flood occurred during a dry spell and thus apparently originated from the release of unusual amounts of melt water by Kautz Glacier. Photographs of the flood and eyewitness accounts suggest that the flood was heavily laden with both fine and coarse rock debris, but not so extensively as to form a viscous mudflow. In its proportion of water to rock debris, the flood may have been a "hyperconcentrated flow" (Beverage and Culbertson, 1964; p. 4, this report).

Photographs taken of various parts of the Kautz Creek trench in the vicinity of Wonderland Trail before and after the flood indicate that the increased discharge caused aggradation in some parts of the trench, removed loose debris along the sides, and in some places resulted in sideways erosion into the lower parts of the trench walls (fig. 24). If the increased discharge had been appreciably greater and of longer duration, wholesale sloughing of the trench walls probably would have

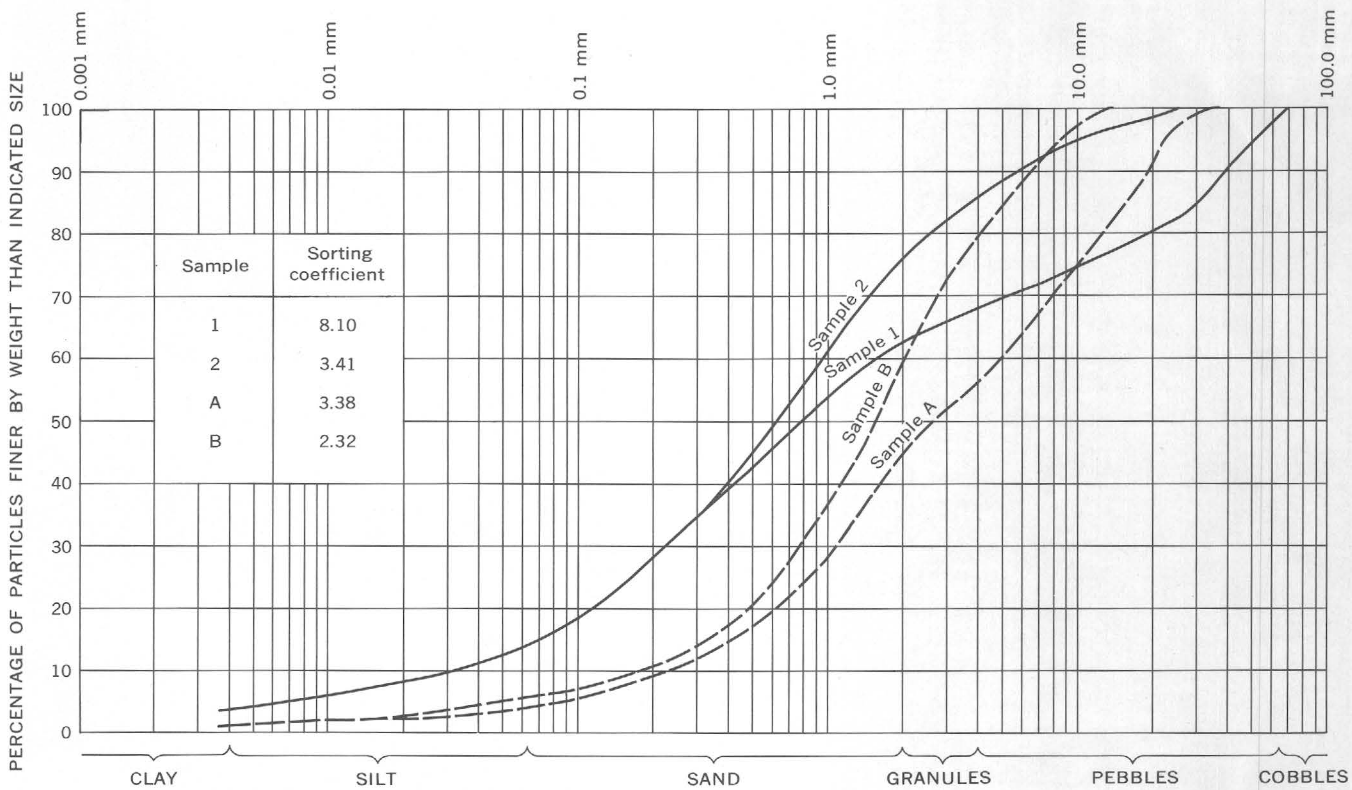

FIGURE 22.—Cumulative curves of size distribution of deposits formed by floods and lahars in the Kautz Creek valley in October 1947. Samples 1 and 2 are both from lahars; samples A and B are probably both fluvial deposits and are from units 1 and 4, respectively, in figure 21.

resulted from undercutting, and lahars might have been formed.

I traversed the Kautz Creek valley from Wonderland Trial to the entrance road on September 13, 1961, and found that the flood had been at least 6 feet deep and perhaps as much as 12 feet deep in places because it had overflowed the stream channel where the banks are that high. Part of this channel depth, however, may have been caused by stream downcutting following the flood's passage. At the entrance road, the flood was confined to the channel of Kautz Creek (fig. 23).

This flood formed bouldery ridges in some places on the flood plain. Boulders and trees in its path were coated up to a height of 4 feet with a cementlike slurry of coarse sand in places where the flow was not confined to a well-defined channel. The slurry had been subsequently washed off the lower 1½ feet of these boulders and trees; thus, the passage of the flood evidently was followed by high discharge of relatively clear water before Kautz Creek returned to normal.

LAHARS IN THE VALLEYS OF TAHOMA CREEK AND THE NORTH AND SOUTH PUYALLUP RIVERS

Nine lahars were recognized in the valleys of Tahoma Creek and the two branches of the Puyallup River; their age and stratigraphic relation to some other Holocene deposits present on the west side of the volcano are as follows:

Two or more lahars of unknown age.
Lahar about 440 years old.
Pyroclastic layer W (about 450 years old).
Electron Mudflow about 600 years old.
Lahar about 1,000 years old.
One or more lahars of unknown age.
Bomb-bearing block-and-ash flow about 2,500 years old.
One or more lahars of unknown age.
Round Pass Mudflow about 2,800 years old.
Pyroclastic layer Y (about 3,600 years old).
Lahar of unknown age.

The Round Pass Mudflow, the 1,000-year-old lahar, and the Electron Mudflow occur in more than one vallay and are described first; others, which are not known in more than one valley, are discussed subsequently, according to the valley in which they are found.

ROUND PASS MUDFLOW

Roadcuts at Round Pass (fig. 25) expose a mudflow as much as 25 feet thick, which overlies pyroclastic layer Y and underlies layer W. The color of the mudflow is purplish to pinkish gray where seen in the roadcuts. The deposit is here named the Round Pass Mud-

FIGURE 23.—Flood in Kautz Creek channel at entrance road on August 23, 1961. The character of the water surface and the muddiness of the water suggest that the flood was a "hyperconcentrated flow." The dead trees in the background were killed by the 1947 lahars and floods in the Kautz Creek valley. National Park Service photograph.

flow; its type locality is at Round Pass. Roadcuts on the north side of the Tahoma Creek valley between the valley floor and Round Pass show a veneer of mudflow a few inches to as much as 6 feet thick on top of layer Y and Evans Creek Drift. In one exposure, reworked pumice from layer Y forms irregular masses within the mudflow. The Round Pass Mudflow crops out along the trail to Lake George (fig. 25) up to an altitude of about 4,350 feet, which is about 350 feet higher than the pass and a little more than 1,000 feet above the floor of the Tahoma Creek valley.

The Round Pass Mudflow also underlies parts of Indian Henrys Hunting Ground, which is on the divide between Tahoma Creek and Kautz Creek. The southwest margin of the mudflow ends there in an abrupt front about 17 feet high (fig. 26) where it is crossed by the Wonderland Trail about 300 yards south of a patrol cabin (pl. 1). The boundary between the mudflow and the adjacent Evans Creek Drift is conspicously marked by the absence or presence of pyroclastic layer Y. At Indian Henrys Hunting Ground the mudflow extends to a maximum altitude of about 5,350 feet, which is nearly 1,000 feet higher than the floor of the Tahoma Creek valley directly to the north.

The Round Pass Mudflow crops out at several places along the Tahoma Creek valley. One of these outcrops is a streambank exposure about 1 mile upvalley from Tahoma Creek campground (measured section 9). There the mudflow unconformably overlies coarse fluvial gravel, from which it is separated by pyroclastic layer Y, and is as much as 20 feet thick. The mudflow contains boulders as large as 6 feet in maximum dimen-

FIGURE 24.—Banks of Kautz Creek about half a mile upstream from the Wonderland Trail shortly after the flood of August 23, 1961. The high discharge steepened and locally undercut streambanks. The sparsely vegetated areas on the terraces on both sides of the creek were covered by the lahars and floods of October 1947. National Park Service photograph.

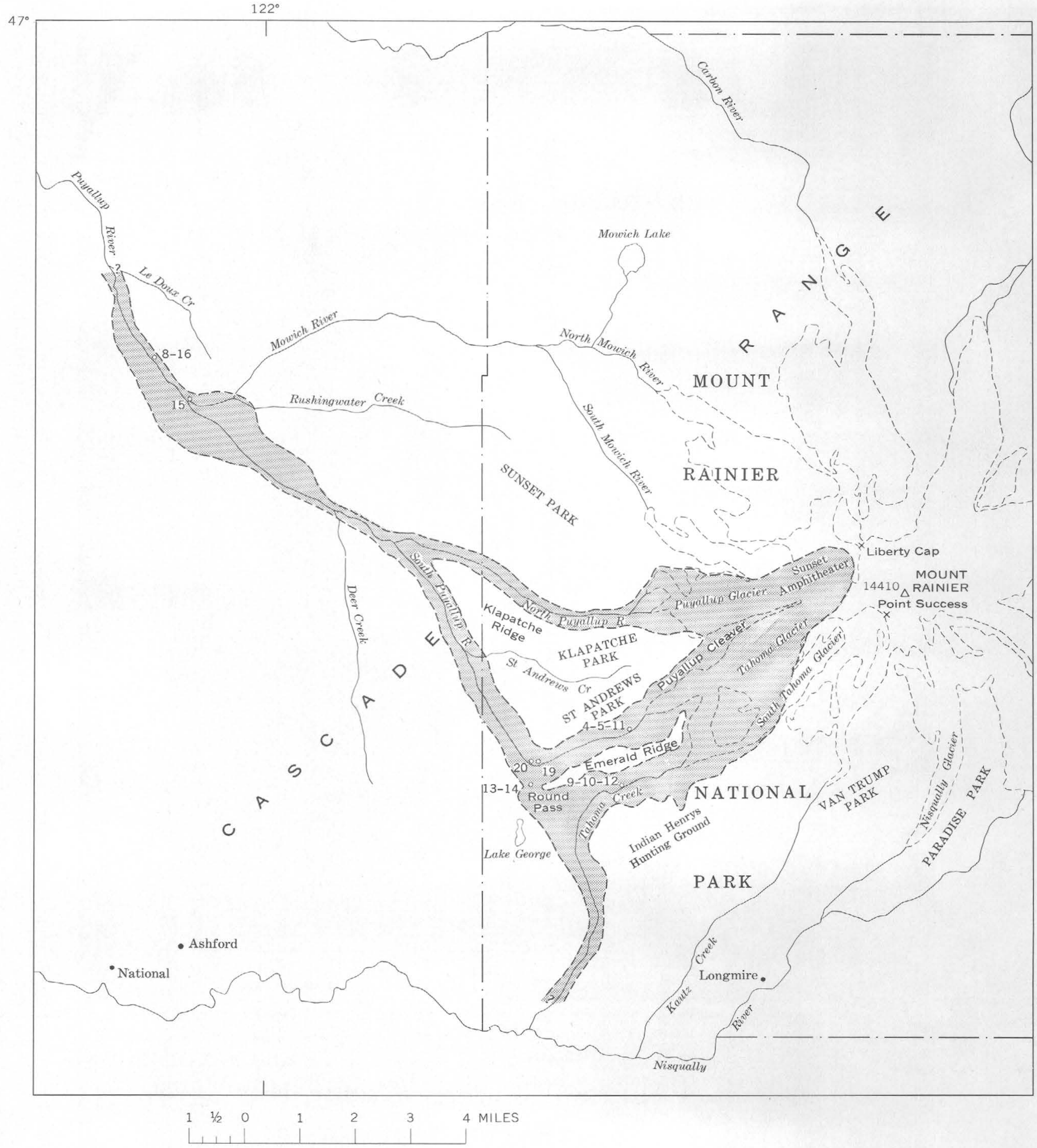

FIGURE 25.—Inferred original extent of Round Pass Mudflow. The west edge of the Cascade Range lies about 4 miles beyond the northwest corner of the map. Numbers show localities of samples (table 10) of the Round Pass Mudflow and other lahars west of the volcano.

sion and logs as large as 4 feet in diameter. The mudflow was identified downvalley to a point about 1 mile north of the Nisqually River. At that point it caps a terrace which is about 60 feet higher than the Tahoma Creek flood plain.

In the North and South Puyallup River valleys I recognized the mudflow as far downstream as a point 10 miles beyond the park boundary, and it may have extended even farther. Remnants of the mudflow veneer the valley walls of the North Puyallup River up to a

FIGURE 26.—South edge of Round Pass Mudflow along the Wonderland Trail at Indian Henrys Hunting Ground. The front of the mudflow is about 17 feet high; surface to the right is underlain by thin Evans Creek Drift and bedrock and veneered with pyroclastic layer Y. The pumice is absent from the mudflow.

maximum height of about 350 feet above the valley floor directly north of Klapatche Park. Farther downstream, a quarter of a mile west of Mount Rainier National Park, the mudflow coats the valley walls to a maximum height of about 240 feet. The mudflow, exposed there in cuts along logging roads, lies on top of layer Y (fig. 27) and talus. In these exposures, the base of the pumice layer contains many small pieces of charcoal, but none were noted either at the top of the layer or in the overlying mudflow. About three-quarters of a mile farther downvalley, near the mouth of the North Puyallup River, cuts along another logging road expose the Round Pass Mudflow up to a height of a little more than 200 feet above the river.

In the South Puyallup River valley, remnants of the mudflow coat the valley walls to a height of about 1,000 feet above the river at a point 1.7 miles north of Round Pass, about 350 feet at the mouth of St. Andrews Creek just west of the park, and about 250 feet at the northwest end of Klapatche Ridge (fig. 25). Near the mouth of the Mowich River, 5½ miles farther downstream, the highest remnants are 160 feet higher than the Puyallup River, and the base of the mudflow is below river level. An imaginary line connecting these high remnants of the mudflow has a downvalley slope of about 550 feet per mile between Round Pass and the mouth of St. Andrews Creek, whereas the valley floor now has a gradient of about 300 feet per mile between these points. However, this line might not represent the sloping upper surface of a continuous, deep, flowing stream of mud, but instead could record the maximum height reached by one or more transient waves of the mudflow. Below St. Andrews Creek, where the valley widens appreciably, the slope, as reconstructed from high mudflow remnants, decreases and becomes more nearly parallel to the present slope of the valley floor.

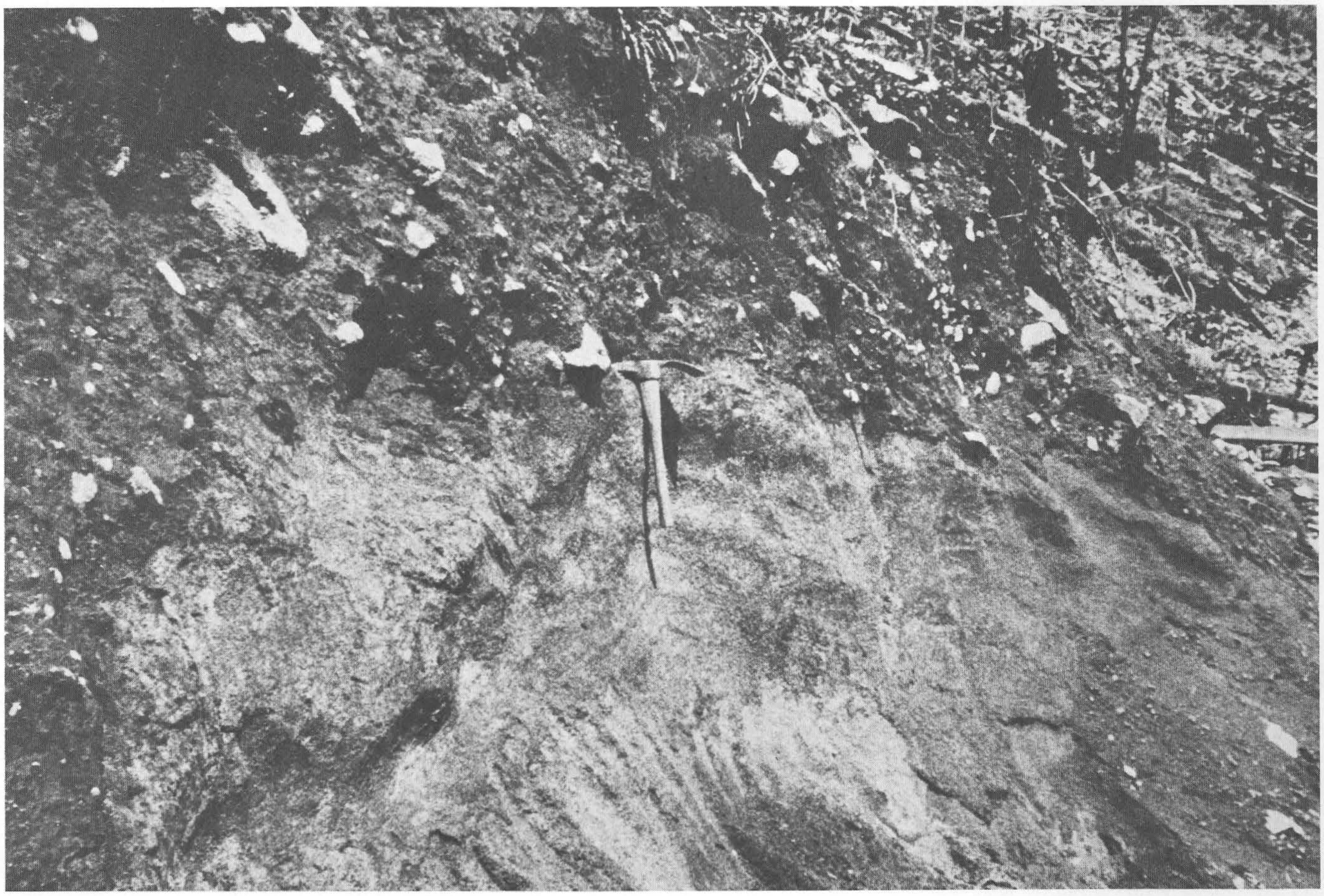

FIGURE 27.—Round Pass Mudflow on top of pyroclastic layer Y at a point 240 feet above the floor of North Puyallup River valley a quarter of a mile west of the park.

The Round Pass Mudflow underlies a broad area in the Puyallup River valley from the mouth of Deer Creek downstream to the mouth of LeDoux Creek. The Puyallup River has cut a trench as much as 100 feet deep into this mudflow fill. Although the Round Pass Mudflow may underlie the floor of the Puyallup River valley beyond the mountain front, I did not recognize it in outcrops while mapping the valley nor did I identify it in logs of wells beneath the valley floor.

Two samples of the mudflow at Round Pass were examined for grain-size distribution, and one was examined for clay mineralogy. The samples contained 24 and 22 percent silt- and clay-sized material, respectively, and had sorting coefficients of 14.18 and 11.2 (table 10, samples 13 and 14). Montmorillonite is the predominant clay mineral; it is accompanied by feldspar and cristobalite in the clay-sized fraction (table 11, sample 14).

A sample of the Round Pass Mudflow from an outcrop near the mouth of the Mowich River contained 20 percent silt and clay; montmorillonite made up about four parts in 10 of the clay (tables 10 and 11, sample 16). Cumulative curves of grain-size distribution of samples of the mudflow from two localities are shown in figure 28.

A sample taken from 1–2 feet below the top of the mudflow at measured section 9 in the Tahoma Creek valley contained 18 percent clay and silt and had a sorting coefficient of 10.6 (table 10, sample 12). The clay-sized fraction of the sample consisted mostly of feldspar and cristobalite and contained small amounts of several clay minerals (table 11, sample 12).

Atterberg limits were determined for one sample of the Round Pass Mudflow from the outcrops at Round Pass. The plastic limit of the sample was 20, and the liquid limit 25; thus, it had a plasticity index of 5.

Because remnants of the Round Pass Mudflow can be found on the slopes of the volcano at least as far as the east end of Emerald Ridge and to an altitude of nearly 7,000 feet on the ridge that extends from St. Andrews Park to Puyallup Cleaver, I presume that the mudflow originated somewhere on the flank of the volcano upslope from these points. The mudflow's clay

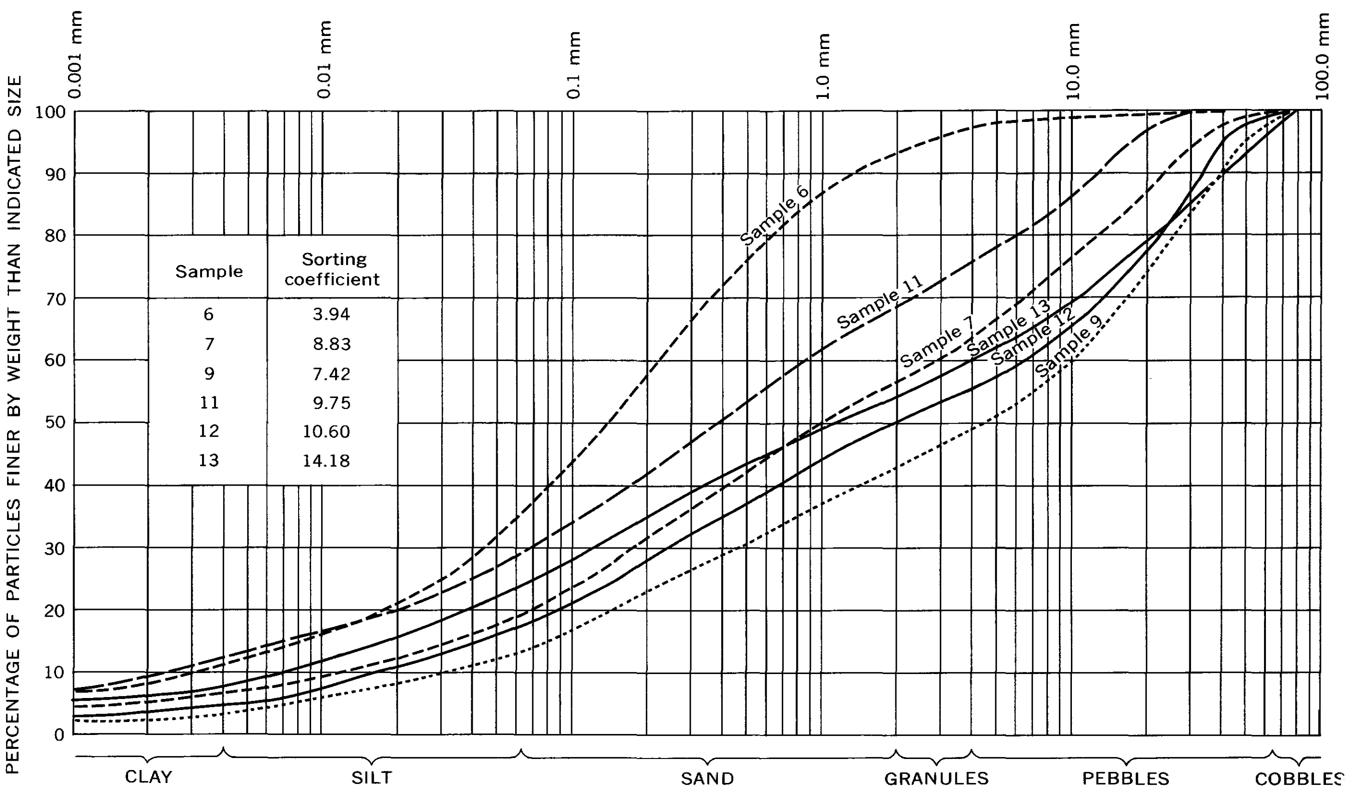

FIGURE 28.—Cumulative curves of size distribution of samples of the Electron Mudflow (samples 6 and 7), lahar that is unit 9 in measured section 9 in the Tahoma Creek valley (sample 9), 1,000-year-old lahar in the South Puyallup River valley (sample 11), and the Round Pass Mudflow (samples 12 and 13).

mineralogy suggests derivation from masses of altered and partly altered rock similar to those now present in the east wall of Sunset Amphitheater (p. 17). The mudflow probably originated as a massive avalanche or series of avalanches of this kind of rock. The distribution of the mudflow as a veneer on older deposits in the valleys close to Mount Rainier indicates that the mud was very fluid and that almost all of it drained away after the crest of the mudflow passed downvalley.

The heights reached by the mudflow suggest that the flow had enough volume to fill temporarily the upper South Puyallup and Tahoma Creek valleys to a depth of at least 1,000 feet, either as a flowing stream of mud or as one or more large waves. The mass of the mudflow needed to form a deep flowing stream of mud probably is adequately represented in the Puyallup River drainage by extensive deposits which probably have a volume of at least 200 million cubic yards in the area west of the park. Because of its water content, the lahar must have had a substantially greater volume while moving. Deposits of comparable volume have not been found in the Tahoma Creek valley, and the mudflow apparently had a depth of only a few tens of feet at a point just 4 miles downvalley from Round Pass. These relations may have resulted from movement of the mudflow down Tahoma Creek valley as a single huge transient wave, which progressively decreased in height, similar to that inferred for the Paradise lahar (p. 36). Substantial amounts of the mudflow were left only in areas where a low slope did not permit it to drain away; elsewhere veneers only a few thick were left on the sides and floor of the valley. Different volumes of the mudflow in the three valleys may have resulted from slightly different directions of initial downslope movement of successive avalanches from Sunset Amphitheater, which caused unequal amounts of debris to move into the respective valleys. Or, the different volumes could have been caused by unequal lateral distribution of rock debris within a single enormous avalanche.

Three radiocarbon dates have been determined on wood from logs contained in the Round Pass Mudflow. One of these was from a streambank exposure in the Tahoma Creek Valley (measured section 9); it had a radiocarbon age of 2,610±350 years (W–2114). Two other samples were from streambank outcrops near the mouth of the Mowich River. One sample, from the north bank 500 feet upstream from the river's mouth, had a radiocarbon age of 2,170±200 years (W–566). The other, from the south bank 500 feet further upstream, had an age of 2,710±250 years (W–1972). When corrected, these three dates are about 2,800, 2,200, and 2,900 years, respectively (table 4). The reason for the substantial age difference is not known because there is no stratigraphic evidence in the outcrops near the mouth of the Mowich River of two mudflows. I assume that the Round Pass Mudflow is about 2,800 years old.

1,000-YEAR-OLD LAHAR

A clayey lahar initially recognized at a streambank outcrop in the South Puyallup River valley near the Wonderland Trail bridge was first thought to be the Round Pass Mudflow, but a radiocarbon date of 1,100±250 years (W–1971) on a log from the outcrop showed it to be younger. The lahar also was subsequently identified 10 miles farther downstream by a radiocarbon date of 1,050±350 years (W–2113) on a log from a pre-Electron lahar at measured section 7. When corrected, these two dates are about 1,050 and 1,000 years, respectively (table 4).

At the Wonderland Trail outcrop in the South Puyallup River valley, the lahar is more than 10 feet thick; its base is below the river, but bedrock probably is not far below river level there. On top of the lahar is a bouldery lahar about 6 feet thick that may be only a few decades old. The 1,000-year-old lahar is compact, clayey, and yellowish brown. It contains about 29 percent silt and clay (table 10, sample 11) in which the clay-sized fraction consists of montmorillonite, cristobalite, and feldspar (table 11, sample 11).

Atterberg limits determined on a single sample of the mudflow obtained from the Wonderland Trail outcrop are as follows: plastic limit 21, liquid limit 25, and plasticity index 4.

The 1,000-year-old lahar may have a correlative in the Tahoma Creek valley, where, at measured section 9, there are two lahars younger than the Round Pass Mudflow but older than pyroclastic layer W.

ELECTRON MUDFLOW

The Electron Mudflow was named from Electron, a small community beside the Puyallup River at the west margin of the Cascade Range (Crandell, 1963b, p. A50). Remnants of the mudflow underlie much of the valley floor from Electron northward to the outskirts of Sumner (pl. 3). The mudflow is an unsorted mixture of subangular to subrounded rock fragments in a purplish-gray matrix of sand, silt, and clay. It generally exhibits a size gradation upward from coarse material at the base to fine material at the top. Samples of the bottom foot and top foot of the mudflow from a section 6½ feet thick near McMillin were examined for grain-size distribution. The bottom and top samples had median diameters of about 1 and 0.1 mm and a silt and clay content of 20 and 36 percent, respectively (table 10, samples 7 and 6). The cumulative curves of these samples are shown in figure 28. In the clay-sized fraction of sample 6, montmorillonite made up an estimated six part in 10, plagioclase feldspar two parts, and cristobalite one part.

A sample of the Electron Mudflow from the outcrop at measured section 6 contained about 27 percent silt and clay, in which montmorillonite and chlorite together made up about four parts in 10, with the former clay mineral predominating (tables 10 and 11, sample 8). The remainder of the silt and clay fraction consisted of feldspars and quartz.

Rocks from Mount Rainier volcano made up an average of 41 percent and older rocks of the Cascade Range 59 percent of samples of pebbles collected from the mudflow at five different localities in the lowland (Crandell, 1963b). The most distinctive rock in the mudflow in the lowland is a scoriaceous, black, hypersthene andesite, which occurs as boulders as large as 5 feet in diameter. These are mostly found lying on the surface of the mudflow. The largest boulders, however, are of a reddish-brown breccia derived from the volcano, some of which are at least 35 feet in maximum observable dimension. These large boulders were seen mostly in an area extending from Orting southward for a distance of about 2 miles. This distribution probably is a result of a more gentle gradient in this area than along the valley farther upstream. The gradient of the mudflow is about 68 feet per mile just downstream from the mountain front at Electron; however, at a point 2 miles south of Orting the valley widens, and the gradient decreases to about 34 feet per mile. The very large masses of breccia probably lodged on the old valley floor in this area as the mudflow spread laterally, thinned, and decreased in velocity.

Hand augering and power augering, in addition to natural exposures, show the mudflow to overlie fluvial sand and gravel deposited by the Puyallup and Carbon Rivers; the mudflow itself is overlain by fluvial sand and silt deposited by overbank floods. A wood fragment obtained from the mudflow near Electron had a radiocarbon age of 530±200 years (W–565; Crandell, 1963b, p. A51). When corrected, this age is about 600 years (table 4).

The Electron Mudflow has been tentatively identified at many places along the Puyallup River valley between Electron and the lower slopes of Mount Rainier. The following units crop out in a streambank on the north side of the river about 1 mile downstream from the mouth of the Mowich River (measured section 7).

Measured section 7

[Streambank on north side Puyallup River in the SW¼ sec. 34, T. 17 N., R. 6 E.]

	Thickness (ft)
4. Electron Mudflow: subrounded to subangular pebbles, cobbles, and boulders as large as 7 ft across in plastic matrix of purplish-gray clayey sand	9
Erosional unconformity.	
3. Sand and pebble to boulder gravel, lenticular; contains some layers of openwork pebble gravel, oxidized to yellowish brown; as thick as	3
2. Lahar: subrounded to subangular pebbles, cobbles, and boulders as large as 3 ft across in plastic matrix of purplish-gray clayey sand, mottled with yellowish-brown iron oxide; lenticular; contains logs and wood fragments, one of which was dated as about 1,000 years old (table 4, sample W–2113); as thick as	5
1. Sand and pebble to boulder gravel	>1
Covered, to river level	4

Unit 2 in measured section 7 is the 1,000-year-old lahar described previously; this lahar and the Electron Mudflow lie within a valley eroded into the Round Pass Mudflow by the Puyallup River. The top of the lahars and alluvium within this valley is only a little more than 20 feet above river level, whereas the top of the Round Pass Mudflow in this area is about 100 feet above the river.

Near the mouth of St. Andrews Creek, just west of the park boundary, the Electron Mudflow is about 6 feet thick and overlies a sandy lahar more than 15 feet thick. The two deposits form a terrace in the South Puyallup River valley whose top is about 50 feet above river level. Ring counts of recently cut stumps indicate that some trees on the terrace were at least 435 years old. Inside the park two clayey lahars, one of which may be the Electron, overlie the bomb-bearing block-and-ash flow; the three deposits are superposed in a cut (measured section 7) along the West Side Road near the South Puyallup River bridge.

Measured section 8

[Cut along the West Side Road about ½ mile northwest of the South Puyallup River bridge]

	Thickness (ft.)	(in.)
4. Lahar: subangular to subrounded pebbles, cobbles, and boulders as large as 2 ft across in a plastic clayey yellowish-brown sand matrix	4	6
3. Lahar: angular to subangular rock fragments as large as 4 in. across in a purplish-gray sand matrix; lenticular. Locally, only fine sand occurs at this horizon, which contains scattered grains of pumice W and bits of carbonized wood		6
2. Electron(?) Mudflow: subangular to subrounded pebbles, cobbles, and boulders as large as 2 ft in diameter in a plastic clayey yellowish-brown sand matrix	7	0
1. Bomb-bearing block-and-ash flow	>10	0

The Electron Mudflow underlies about 14 square miles of the Puyallup River valley in the Puget Sound lowland. In this area its thickness ranges from a few inches to more than 26 feet; it is generally about 15 feet thick from McMillin southward to a point 2 miles south of Orting. If an average thickness of 15 feet is assumed for the area beyond the mountain front, the deposit has a volume of a little more than 200 million cubic yards. An additional amount of unknown area and volume lies between the lowland and its source, 22 miles away, on the west flank of Mount Rainier.

The clay-mineral content of the Electron Mudflow suggests an origin like that proposed for the other clayey mudflows from Mount Rainier; thus, the Electron probably was caused by massive slides of moist, hydrothermally altered rock. These slides may have been triggered by an earthquake or by a volcanic explosion.

The Electron Mudflow may have occurred at a time when the volcano was dormant, for we have found no deposits that indicate an eruption about 600 years ago.

LAHAR ASSEMBLAGE IN THE TAHOMA CREEK VALLEY

Four lahars have been recognized in the valley of Tahoma Creek; three are older than pyroclastic layer W, and one is younger. All are younger than layer Y. The sequence is as follows:

Several small lahars and floods in 1967, 1968, and 1970.
Lahar about 440 years old.
Pyroclastic layer W (about 450 years old).
Two or more lahars of unknown age.
Round Pass Mudflow about 2,800 years old.
Pyroclastic layer Y (about 3,600 years old).
Coarse fluvial gravel.

Seldom can more than one post-Round Pass lahar be recognized in a single outcrop, but streambank exposures about 1 mile upvalley from the Tahoma Creek picnic area reveal an unusually complete section (measured section 9). In these outcrops, lithologically similar lahars in the assemblage can readily be differentiated because of the presence of interbeds of alluvium, volcanic ash, and forest duff. Especially striking in the measured section is the reddish-brown zone at the top of one lahar (unit 5). The association of this zone with abundant carbonized wood indicates that its color is the result of a forest fire. One can speculate that the forest fire was caused by the hot, bomb-carrying block-and-ash flow in the South Tahoma Creek valley about 2,500 years ago (p. 64). When some of the lahars are traced along the outcrop beyond the limit of a lenticular interbed, the contact between them disappears, and they are so similar that they cannot be differentiated.

The youngest lahar in measured section 9 also underlies low terraces at Tahoma Creek picnic area and veneers terraces between the picnic area and recent mo-

Measured section 9

[North bank of Tahoma Creek 1¼ miles upstream from Tahoma Creek picnic area]

	Thickness (ft)	(in)
9. Lahar: subangular to subrounded cobbles and boulders as large as 2 ft in diameter in matrix of silt and sand; no apparent sorting or stratification; oxidized throughout to brownish yellow (10YR 6/8); contains wood fragments and logs as large as 3 ft in diameter	6	0
8. Pyroclastic layer W: lenticular; as thick as		½
7. Duff; contains bits of carbonized wood; stumps rooted in unit 6 extend up through 7 and 8 and are truncated by unit 9. Horizontally bedded, medium to coarse fluvial sand 2–3 in. thick locally underlies the duff		1–6
6. Lahar: lithologically similar to unit 9; lenticular; as thick as	3	0
5. Lahar: lithologically similar to unit 9; uppermost 1–4 in. is reddish brown (5YR 5/4); at top is a lenticular layer of carbonized wood 1–4 in. thick. Lahar is lenticular; as thick as	3	0
4. Sand, fine to medium, and granule gravel, horizontally bedded, lenticular; as thick as	1	0
3. Round Pass Mudflow: subangular to subrounded cobbles and boulders in a purplish-gray matrix of sand, silt, and clay; contains scattered wood fragments throughout and in a concentration near the base; sample of wood from log had an age of 2,800 years (sample W–2114, table 4); lenticular; as thick as	20	0
2. Pyroclastic layer Y: lenticular; as thick as		8
1. Fluvial gravel: cobbles and boulders as large as 5 ft across in purplish-gray coarse sand matrix; crudely stratified; thickness more than	20	0

raines of South Tahoma Glacier. The lahar is exposed south of the creek in the banks of a small tributary that is crossed by the Wonderland Trail; the highest remnants of the deposit in this vicinity are a little more than 200 feet higher than the valley floor of Tahoma Creek. The oldest trees growing on the lahar are at least 435 years old. Inasmuch as the lahar is younger than pyroclastic layer W (fig. 29), it probably is about 440 years old.

Grain-size analysis of a sample taken from the lower 2 feet of the lahar at measured section 9 showed a median diameter of 4.2 mm and a sorting coefficient of 8.72 (table 10, sample 9); the cumulative curve of its size distribution is shown in figure 28. The sample contained 14 percent clay- and silt-sized material. The clay fraction consisted of about three parts in 10 of clay minerals, almost wholly montmorillonite, although traces of kaolinite and a montmorillonite-chlorite mixed-layered clay were also identified. The remainder of the clay fraction consisted mostly of cristobalite, feldspar, and iron oxide (table 11, sample 9).

Each of the lahars in the Tahoma Creek valley originated in avalanches of clay and partly altered rock on the west flank of Mount Rainier. These avalanches probably were caused by rockfalls in Sunset Amphitheater, which moved southward across Tahoma Glacier and into the head of the Tahoma Creek valley.

Lahars and floods occurred in the Tahoma Creek valley in late August and September of 1967. Their formation was heralded on August 29 by a short-lived flood on Tahoma Creek. On the afternoon of the 29th, probably between 1 and 1:30 p.m., the Wonderland Trail footbridge across the creek was washed out, and shortly thereafter the stream rose between 1 and 2 feet at Tahoma Creek picnic area (then a campground). At the footbridge, the creek flows through a channel constricted by a low bedrock cliff on the south and a ridge of very large boulders on the north, and the channel is only about 30 feet wide. The flood had a crest in this channel about 15 feet above the normal stream level. On the morning of August 30, the creek was still unusually high and muddy.

The flood occurred on a clear day after a long spell of warm dry weather and probably was caused by the sudden release of a considerable volume of water that had been impounded within South Tahoma Glacier. According to David L. Fluharty (oral commun., September 1967), Fire Control Aid at the Gobblers Knob Fire Lookout, the water that caused the flood seemed to emerge at an icefall on South Tahoma Glacier at an altitude of about 7,500 feet. Gobblers Knob is about 1½ miles west of Tahoma Creek picnic area and is 2,500 feet higher in elevation (pl. 1.)

Two days after the flood, at about 8:40 p.m. on August 31, Mr. Fluharty reported hearing a loud roar coming from the Tahoma Creek valley. Park Ranger James D. Erskine (oral commun., September 1967), who arrived at the Tahoma Creek campground between 9 and 9:30 p.m., found that the part of the campground that is only 5 feet above the river was being buried by a slurry of mud and boulders that resembled wet concrete.[3] By means of a powerful flashlight he was able to see large boulders being moved by the slurry along the main channel of Tahoma Creek, and he also noted that many small stones were being thrown, with a forward projection, above the surface of the moving mass. Erskine reported that there was a deafening roar, and the ground was vibrating very strongly under his feet at the west edge of the campground. He left the area because of concern for his safety; when he returned about an hour later, relatively clear water was flowing in the main channel, and shallow water was also flowing across the low part of the campground. Richardson (1968) inferred that the

[3] The campground had been closed by the National Park Service on August 30 because of an extremely high danger from forest fires.

FIGURE 29.—Lahar resting on top of fluvial cobble-and-boulder gravel at measured section 9 in the Tahoma Creek valley. Separating the two deposits is ¼–½ inch of duff and pyroclastic layer W. Three more lahars occur in the stratigraphic interval between layer W and the fluvial gravel in outcrops out of view to the right.

rapidly moving mass seen by Erskine was a "hyperconcentrated flow" (p. 4), but because of a lack of data on the sediment-to-water ratio, it will be referred to here as a lahar.

The deposit in the campground area now is no more than about 3 feet thick and consists of boulders as large as 2 by 3 by 4 feet in a matrix of medium to coarse sand (fig. 30). The lahar evidently terminated a short distance from the campground, for I could not identify deposits formed by it on the valley floor at a point about 1 mile downstream.

At the Wonderland Trail footbridge over Tahoma Creek, the lahar banked up on the south channel wall to a maximum height of about 25 feet. Two hundred yards downstream, on the outside of a bend, the lahar banked up to a maximum height of 35 feet, whereas on the inside of the bend on the opposite bank, 150 feet away, it only reached a height of 15 feet. The lahar left a coating of sand and granule-sized material on the tops and sides of boulders and tree trunks, but this material had been washed off by the creek up to a height of 6 feet after the lahar passed downvalley.

The lahar of August 31 was caused by a flood similar to, but evidently of greater volume than, the one of August 29. The second flood issued from the glacier at the icefall and carved a deep channel down the glacier's surface (fig. 31). Upon reaching the valley floor, the floodwaters picked up large amounts of loose glacial drift and alluvium and were transformed into a lahar.

The peak discharge of Tahoma Creek at the campground was estimated by Richardson (1968) to be about 24,000 cfs, of which perhaps half consisted of sediment.

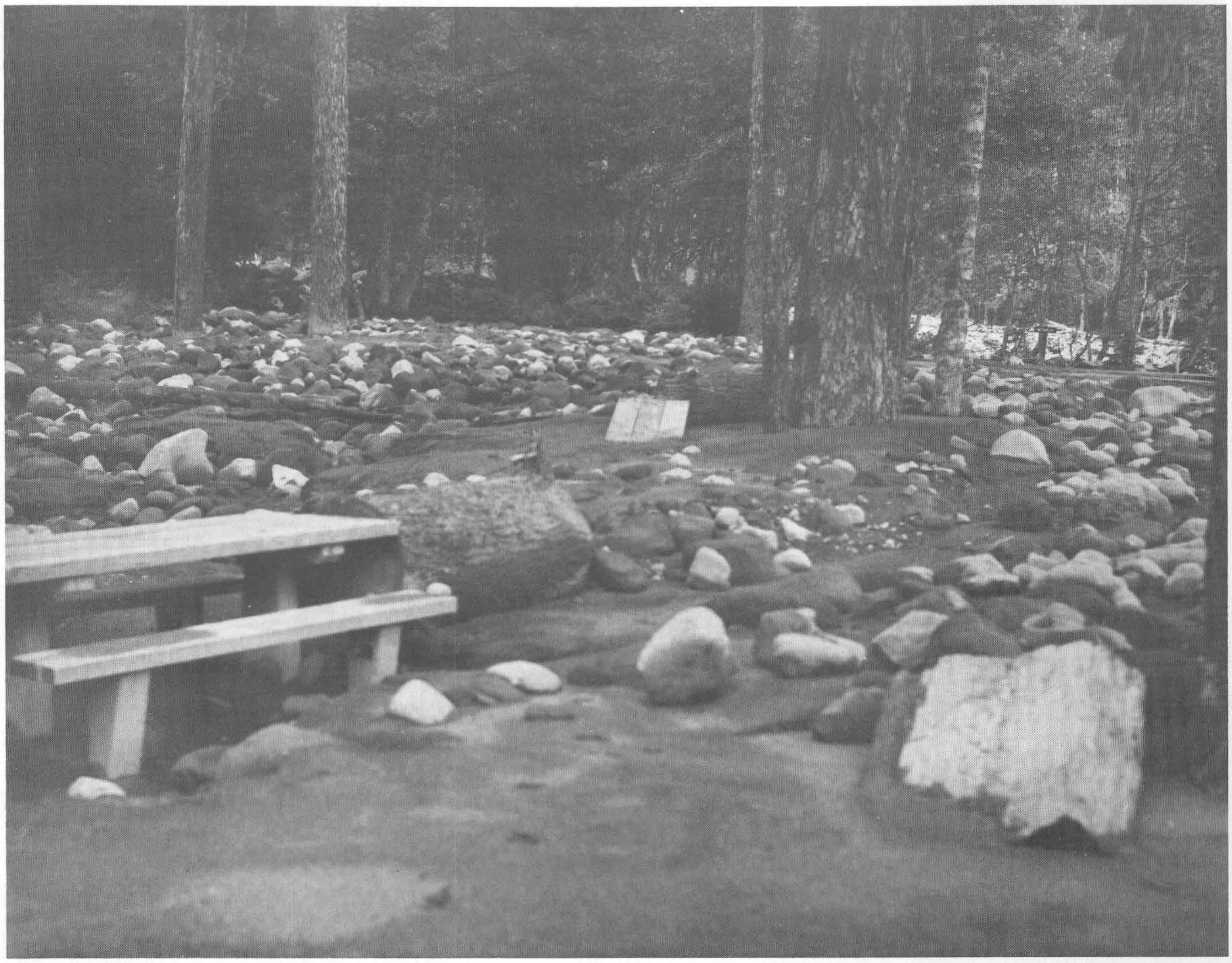

FIGURE 30.—Bouldery deposit left in Tahoma Creek picnic area (then a campground) on evening of August 31, 1967. The photograph was taken on the following day. The unvegetated part of the Tahoma Creek flood plain is faintly visible in the background.

A flood crest was reached about 10:30 p.m. at the highway bridge across Tahoma Creek, 4.3 miles below the campground. From high-water marks left by the flood crest, Richardson estimated a peak discharge there of only about 100 cfs and inferred that the higher discharge farther upstream had been dissipated by channel storage and infiltration downstream from the campground.

Evidently the conditions that led to the lahar and floods continued for some time, because a small lahar moved downvalley as far as the campground on September 15, 1967 (N. A. Bishop, Chief Park Naturalist, oral commun., 1968). Floods not associated with rainfall also moved down the valley from time to time during the summer of 1968, and one again inundated Tahoma Creek picnic area on August 21, 1970.

The cause for large volumes of water to be released suddenly and repeatedly by South Tahoma Glacier is not known, but there is a possibility that the floods were related to thermal activity of volcanic origin. On the afternoon of September 23, 1967, Miss Marilyn Siehl (oral commun., September 1967) of Tacoma, Wash., was in the vicinity of the Wonderland Trail footbridge across Tahoma Creek with a companion when she heard what she described as a loud explosion from the direction of Mount Rainier. The explosion was followed by a rumbling noise and a vibration of the ground underfoot. She quickly moved to a vantage point from which she could see the volcano and observed clouds of what she believed to be brown dust and white water vapor ("steam") billowing from a west-facing cliff at the head of South Tahoma Glacier. Miss Siehl observed

FIGURE 31.—Aerial view of the debris-covered surface of South Tahoma Glacier (at right). The channel down the middle of the glacier was carved by floods in late August and early September 1967 that issued from the icefall at the right center. Circle indicates the area in which a rock fall occurred in February 1969. The glacier is about 500 feet wide near its terminus. Photograph taken September 18, 1967, by Austin S. Post, U.S. Geological Survey.

the clouds the rest of the afternoon and evening from the point where the Wonderland Trail crosses Emerald Ridge and noted that clouds were still being formed the next morning when she left the area. She described the weather both days as hot, dry, and clear.

Hikers and climbers reported seeing an unusual number of dust clouds rising from the area near the head of South Tahoma Glacier earlier in the summer, and some days these could also be seeen from Longmire. It seems likely that the clouds were caused by recurring rockfalls. Small rockfalls continued at the same general locality at least until mid-October (N. A. Bishop, oral commun., 1968) (fig. 32).

While at Longmire one evening in August 1968, D. C. Thompson and Duane Nelson of the National Park Service observed four or five clouds of what seemed to be water vapor which rose at intervals above the cliffs at the head of South Tahoma Glacier. They noted that each of these white clouds was followed by a cloud which was brown and apparently consisted of rock dust. Another observer witnessed a similar succession of clouds at the same place a few days later (D. C. Thompson, oral commun., 1969). The recurrence of clouds of what seemed to be water vapor and of dust could have resulted from a succession of small steam explosions which caused repeated rockfalls.

On February 16, 1969, still another event occurred on the west side of Mount Rainier which may bear on the origin of the recent floods and lahars in the South Tahoma Creek valley. Local newspapers in western Washington reported that on the afternoon of that day Mr. and Mrs. Oliver Edmonds of Seattle had seen "steam and smoke" rising from the west side of the volcano for about 45 minutes. Their viewpoint was in the vicinity of Buckley, which is about 25 miles northwest of Mount Rainier. On February 20, Jack H. Hyde of Tacoma Community College, and Stewart Lowther of the University of Puget Sound, flew over the west flank of the volcano in an attempt to find the cause of the reported "steam and smoke." They found an area of newly deposited rock debris lying on the snow-covered surface of South Tahoma Glacier at an altitude of between 6,500 and 7,000 feet near the point in the icefall at which floods emerged in late August 1967 (fig. 31).

The clouds observed on the west side of Mount Rainier on February 16 may have been caused by water vapor rising from a short-lived steam vent and by dust originating in a small rockfall that resulted from a steam explosion. Thus, there has been a repetition of events in the area of South Tahoma Glacier which may have been caused by some kind of thermal phenomena. It seems likely that the repeated floods in Tahoma Creek were caused by abnormal melting of South Tahoma Glacier around steam vents.

LAHAR ASSEMBLAGE IN THE SOUTH PUYALLUP RIVER VALLEY

At least eight lahars are present in the valley of the South Puyallup River, only one of which is older than pyroclastic layer Y. The sequence is as follows:

Four lahars younger than layer W.
Pyroclastic layer W (about 450 years old).
Lahar about 1,010 years old.
Bomb-bearing block-and-ash flow about 2,500 years old.
Lahar and fluvial deposits.
Round Pass Mudflow about 2,800 years old.
Pyroclastic layer Y (about 3,600 years old).

The pre-Y lahar is dark brown and has a clayey plastic matrix. It is a foot or less thick and was observed in a roadcut at Round Pass. It occurs between layer Y and the underlying Evans Creek till in an outcrop 100 feet southwest of the Marine Memorial there, and the lahar is texturally similar to the Round Pass Mudflow which is above layer Y in the same exposure. Layer Y and the lahar are separated by a mixed layer about 10 inches thick, which probably is colluvium derived from both units. Perhaps downslope movement of the pumice and the lahar occurred after part of the pumice had been deposited, but before the upper, clean pumice was laid down. The pre-Y lahar was not recognized elsewhere, and the significance of this single outcrop is not known. However, it may record a lahar that was temporarily at least 600 feet deep in the South Puyallup River valley.

An inexplicable section that may be due partly to local downslope creep or flowage is exposed in a cut along the West Side Road on the valley wall about 500 feet directly north of Round Pass. Here a very compact, greenish-gray deposit 14 feet thick which texturally resembles a mudflow is overlain by a purplish-gray mudflow 2 feet thick. The contact between the two units is indistinct, and the units may be facies of the same deposit. Above them is a layer a few inches thick of duff and carbonized wood mixed with gray sand. The duff and sand layer is conformably overlain by a third mudflow which is lenticular and as much as 32 inches thick and which has a layer of duff and wood fragments. The upper duff layer contains a few pumice grains of layer W. Conformably above the duff is a fourth mudflow, as much as 5 feet thick, which is unconformably overlain by still another layer of duff and carbonized wood mixed with gray sand, and by a fifth mudflow, also 5 feet thick. Some of these deposits probably are of colluvial origin and were derived from other mudflows on the side of the South Puyallup River valley, but it is not

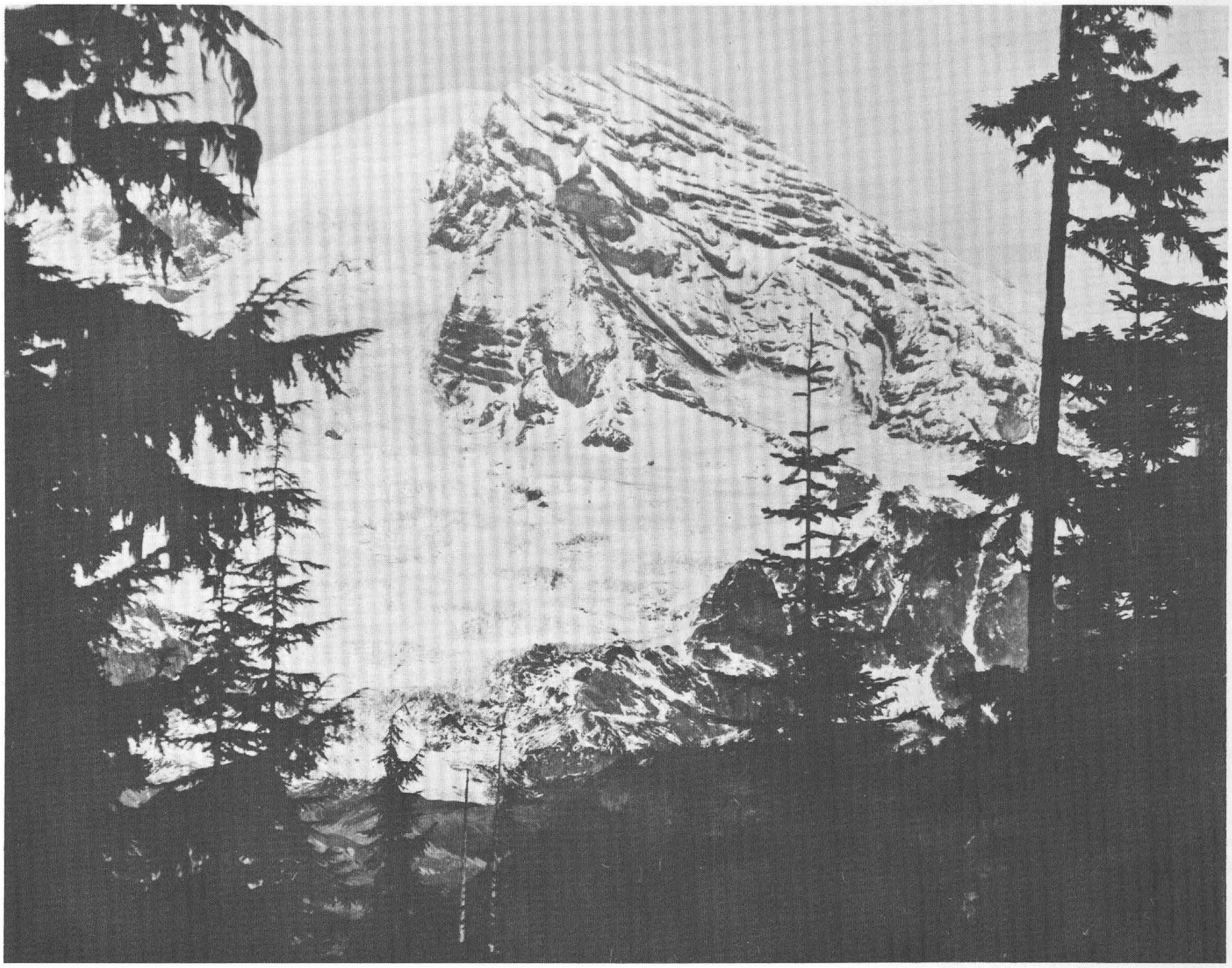

FIGURE 32.—Straight slanting area of dirty snow, formed by rockfall debris below Point Success, heads at a cliff where a steam vent was witnessed on September 23–24, 1967. The rockfall debris reaches down to the head of South Tahoma Glacier. Photograph taken with a telephoto lens at Round Pass October 8, 1967, by N. A. Bishop, National Park Service.

known which deposits represent the original mudflows in the valley and which ones might be colluvium.

Several lahars are exposed in a trail cut in the front of a terrace at the Wonderland Trail footbridge across the South Puyallup River (measured section 10). The terrace is about 42 feet above river level. The basal lahar of this section contains about 14 percent silt and clay. Montmorillonite makes up about half of this size fraction, and feldspar and cristobalite the other half (table 11, sample 5). The lahar that is designated as unit 3 in the measured section contains about 14 percent silt and clay (table 10, sample 4) about half of which consists of montmorillonite; the remainder is mostly feldspar and cristobalite (table 11, sample 4).

A lahar is exposed in a cutbank on the north side of the river to a height of about 10 feet directly opposite the measured section. It is very compact, yellowish brown, and does not resemble any of the lahars in the measured section nearby, all of which probably are

Measured section 10

[In south bank of the South Puyallup River at Wonderland Trail bridge]

	Thickness (*ft*)	(*in.*)
5. Lahar: boulders as large as 6 ft in diameter in a purplish-gray matrix of silt and sand	4–8	0
4. Fluvial deposit: sand and pebble-to-cobble gravel, poorly sorted	5	0
3. Lahar: cobbles and boulders in a yellowish-brown sand, silt, and clay matrix	7	6
2. Lahar: cobbles and boulders in a purplish-gray matrix of medium to coarse sand	6	0
1. Lahar: boulders and cobbles in a yellowish-brown matrix of sand, silt, and clay	>6	0

Covered interval of 10 feet to river level.

younger. A log taken from the lahar in the north bank was reported to have a radiocarbon age of 1,110±250 years (W–1971). The lahar is overlain by a bouldery lahar about 6 feet thick that is younger than any of the deposits in the measured section. Bedrock crops out in the riverbed a few hundred feet upstream from the measured section.

Size analysis of a sample of the 1,100-year-old lahar indicated that it contains about 37 percent silt and clay (table 10, sample 11). X-ray examination of this size fraction indicated the presence of montmorillonite, cristobalite, and feldspar (table 11, sample 11).

BLOCK-AND-ASH FLOW IN THE SOUTH PUYALLUP RIVER VALLEY

One of the most interesting deposits on the west side of Mount Rainier contains innumerable light-olive-gray breadcrust bombs. The deposit resembles some lahars in its coarse, unsorted texture and distribution, but the presence of charcoal suggests that the deposit was formed by a hot dry flow of rock debris. The results of a remanent magnetism study of rock fragments in the deposit indicated emplacement of the debris at a high temperature.

The block-and-ash flow deposit is well exposed in cuts along the West Side Road in the South Puyallup River valley (figs. 33, 34). From a distance it resembles glacial drift, and a succession of sharp-crested ridges cut through by the road could easily be mistaken for lateral moraines. However, when each ridge is followed a short distance upvalley, it is found to merge with a terrace that represents the flattish top of the deposit. The ridges are simply narrow interfluves between adjacent small valleys cut into the deposit. The top of the block-and-ash flow is about 135 feet above the river near the highway bridge and about 200 feet a mile further upvalley.

Bombs in the deposit have black glassy interiors, range in diameter from 6 inches to 4 feet, and have breadcrusted exteriors (fig. 35). Most are highly vesicular, and many have large voids in their interiors, adjacent to which the rock is locally iridescent. Some bombs are nearly spherical, but most are flat on one or more sides. The bombs are very abundant and are randomly distributed throughout a loose matrix of purplish-gray sand and small angular to subangular fragments of dark-gray to black glassy rock. Only a few bombs are present in the northwesternmost outcrop of the block-and-ash flow along West Side Road, and the deposit there consists mostly of material smaller than 4 inches in diameter.

Where the base of the block-and-ash flow is exposed, it is flat and lies on a lenticular fluvial gravel a few feet

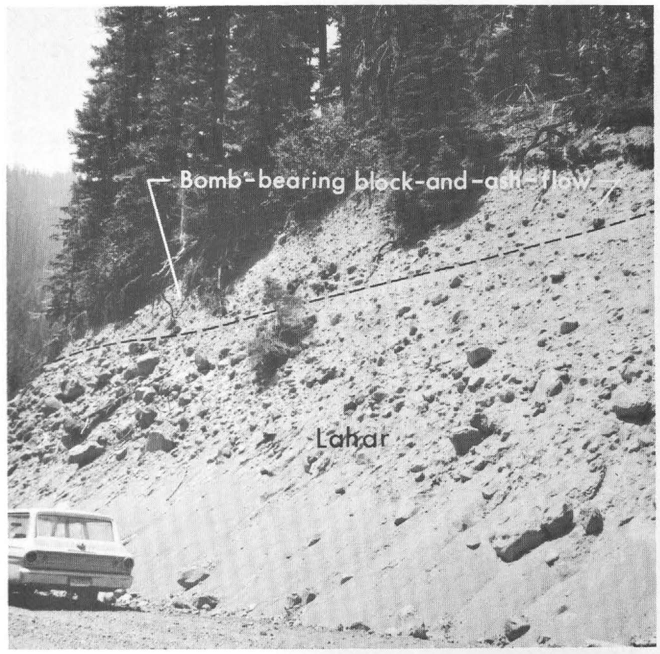

FIGURE 33.—Bomb-bearing block-and-ash flow deposit in outcrop along the West Side Road near the South Puyallup River overlies a coarse lahar that does not contain any bombs. The contact is marked by a thin horizontal layer of light-gray sand.

thick or on a very coarse lahar that lacks bombs and is more than 15 feet thick.

The bomb-bearing deposit was not identified in the South Puyallup River valley outside of the park, although a lahar that forms a terrace 50 feet higher than the river west of the park contains much scoriaceous black andesite. This lahar, which was seen in cuts along a logging road near the mouth of St. Andrews Creek, may have been derived from the block-and-ash flow.

Grain-size distribution was determined on samples of the coarse-grained and the fine-grained facies of the block-and-ash flow; no bombs were included in either sample. The sample of the coarse-grained facies contained 6 percent silt and clay and had a median diameter of 1.5 mm (table 10, sample 19); its sorting coefficient was 6.63, and the cumulative curve of the size distribution is polymodal (fig. 36). The sample of the relatively fine-grained facies is texturally similar. It contained 6 percent silt and clay and had a median diameter of 1.1 mm (table 10, sample 20); its sorting index was 4.64, and its cumulative curve also was polymodal.

A log completely converted to charcoal, about 6 inches in diameter and 4 feet long, was found 1 foot above the base of the bomb-bearing deposit, resting on and against bombs. The log had no bark and was surrounded by a layer of white sand, silt, and clay a fraction of an inch thick. The charcoal was relatively fragile,

FIGURE 34.—Outcrop of a relatively fine grained facies of the bomb-bearing block-and-ash flow along the West Side Road near the South Puyallup River. A large breadcrust bomb is just left of the pick, but most other rock fragments are of dense rock.

and probably could not have been transported without being broken into small fragments. The wood probably was fresh when incorporated by the block-and-ash flow and was converted to charcoal by heat retained in the adjacent bombs and rock fragments after the flow came to rest. The radiocarbon age of a sample of the log was 2,350±250 years (W–1587), and the corrected age is about 2,500 years (table 4).

Samples oriented with respect to magnetic north and the horizontal were taken from eight bombs and five dense rock fragments in the deposit exposed along the West Side Road. Examination of cores taken from these samples indicated that the north-seeking poles in all but four have northward dips of 50°–72° and that their azimuths lie within 20° of magnetic north (fig. 37). This strong preferred orientation of thermoremanent magnetism suggests that most of the bombs and many of the dense rock fragments were above the Curie

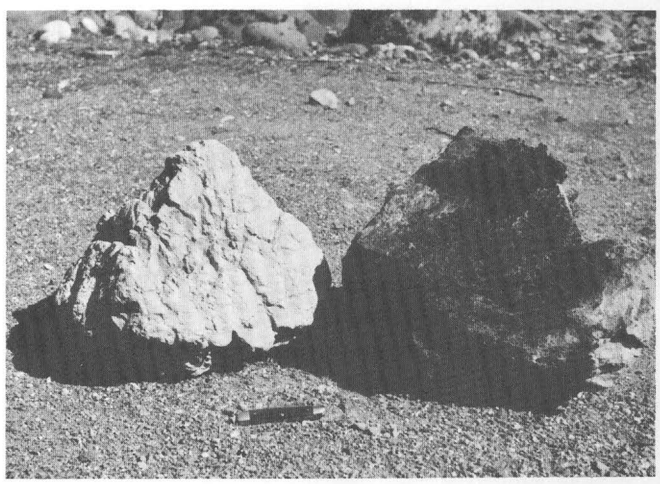

FIGURE 35.—Breadcrust bombs from the block-and-ash flow in the South Puyallup River valley. The bomb on the right has been broken open to show the highly vesicular interior.

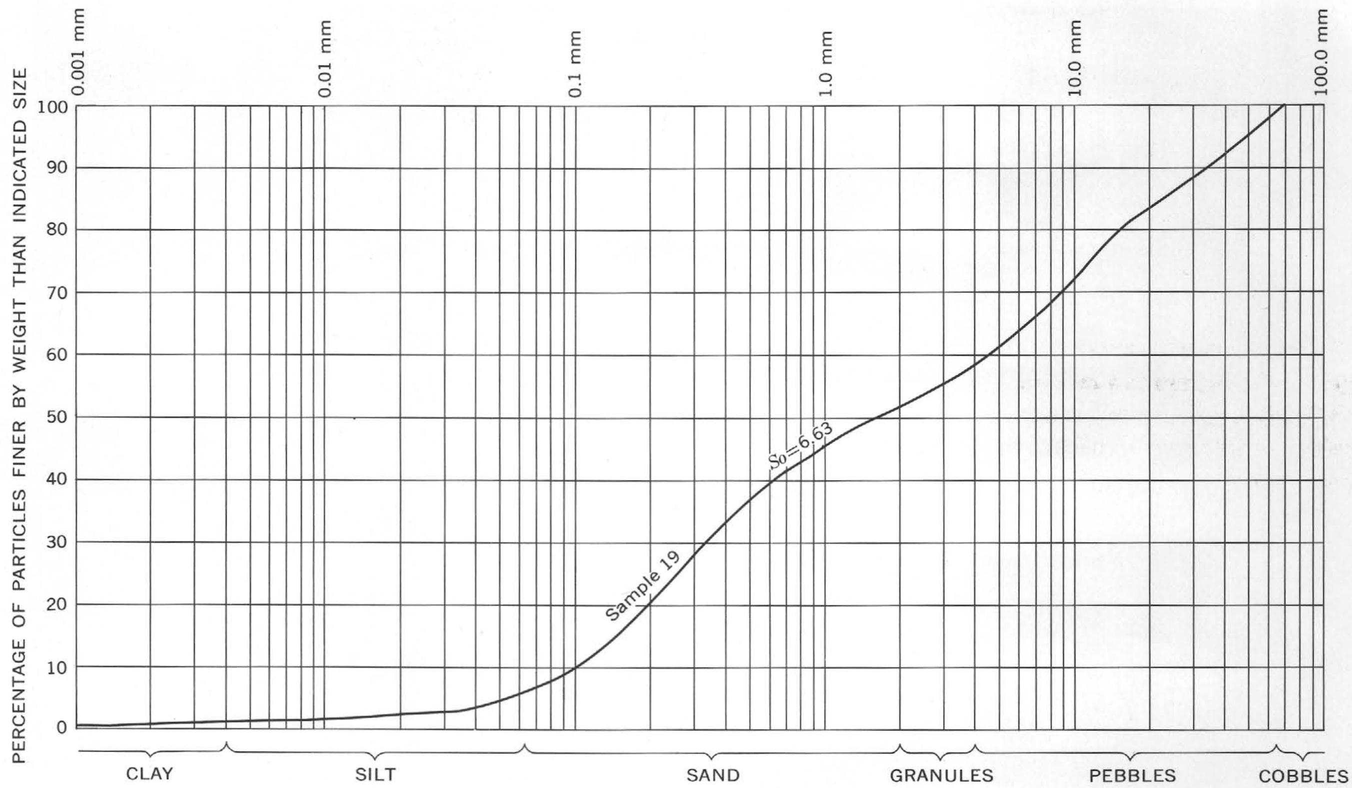

FIGURE 36.—Cumulative curve of the size distribution of the relatively coarse facies of the bomb-bearing block-and-ash flow in the South Puyallup River valley. *So*, sorting coefficient.

point of the magnetite in the rock when the block-and-ash flow came to rest. The few samples that do not have this orientation presumably had cooled below the Curie point during movement of the flow.

The Curie temperature of a sample of dense rock from the block-and-ash flow was experimentally determined to be 517°C during both heating and cooling of the sample (Richard R. Doell, unpub. commun., 1968). The Curie temperature of a sample of a breadcrust bomb was found to be 485°C during heating and 332°C during cooling. Both samples were taken from rocks in the deposit whose remanent magnetism was oriented toward magnetic north (fig. 37).

These Curie-point determinations indicate that rock fragments were still several hundred degrees centigrade above the boiling point of water after movement of the rock debris had stopped. In view of these high temperatures, it seems unlikely that any incorporated water could have remained in the liquid state long enough to have provided mobility to the debris. Thus, I conclude that the debris was moving not as a lahar but as a block-and-ash flow which owed its mobility to entrained hot air, steam, and perhaps other gases.

The close similarity in age of the bomb-bearing block-and-ash flow (about 2,500 years) and pyroclastic layer C (between 2,150 and 2,500 years) suggests that both originated during the same episode of volcanism.

LAHARS IN THE NORTH PUYALLUP RIVER VALLEY

Three lahars were recognized in the North Puyallup River valley, the oldest of which is probably correlative with the Round Pass Mudflow. In exposures near the north end of the West Side Road this lahar consists of a mixture of angular and subangular rock fragments as large as 8 feet in maximum dimension in a plastic matrix of yellowish-brown silty and clayey sand. Along the Wonderland Trail on the south side of the North Puyallup River valley, the Round Pass Mudflow is present up to an altitude of about 3,920 feet—a height of about 400 feet above river level.

Younger lahars form two terraces on the north side of the valley downstream from the end of the West Side Road, 55 and 90 feet higher than the North Puyallup River. A boulder about 20 feet in diameter was seen near river level in the lahar that makes up the lower terrace, and living trees 3–4 feet in diameter and as much as 400 years old are growing on the terrace. Boulders as large as 8 feet across lie on the upper terrace, and although no trees were cored, the largest are of comparable diameter with, or a little larger than, the largest

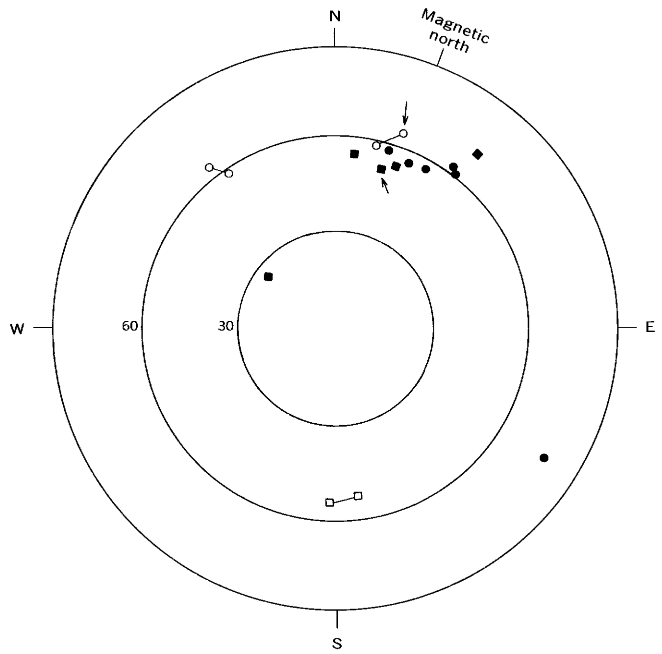

FIGURE 37.—Point diagram of azimuth and dip of north-seeking poles in dense rock fragments (squares) and bombs (circles) from block-and-ash flow in the South Puyallup River valley. A 1-inch core from each sample was split into two pieces for determination of the direction of remanent magnetism; open circles or squares tied together represent the results of determination on the two pieces, and the solid circles and squares represent determinations on two pieces that coincided or nearly coincided in azimuth and dip. The two samples on which Curie temperatures were determined are indicated by arrows.

trees on the lower terrace. An exposure of the material making up the upper terrace was not seen, but the size of boulders on the terrace suggests that it is underlain by a lahar. Pyroclastic deposits were seen on neither terrace.

LAHARS IN THE MOWICH RIVER VALLEY

Inside Mount Rainier National Park the South Mowich River valley contains at least one lahar that is older than pyroclastic layer Y, one younger than layer Y but older than layer W, and one that is younger than layer W. The pre-Y lahar crops out in the streambank on the north side of the river about a mile upstream from its mouth. There it forms a terrace whose top is about 30 feet above the adjacent flood plain. Farther upstream, two post-Y lahars can be seen in scattered outcrops in the face of a terrace whose height above the flood plain ranges from a few feet to as much as 25 feet. This difference in height seems to be due to variations in slope of the flood-plain surface. The post-W lahar at the surface of the terrace is yellow to yellowish brown and contains abundant angular to subangular fragments of altered rock. It ranges in thickness from 3 to at least 15 feet and closely resembles some post-Y lahars in the Puyallup River and South Tahoma Creek valleys.

The post-W lahar was seen as far downstream as a point about 1.5 miles above the mouth of the South Mowich River. In some outcrops the lahar is on top of fluvial sand and gravel, and in others it overlies a coarse gray lahar which contains pumice reworked from layer Y and which includes angular and subangular boulders as large as 4 feet in diameter. The maximum thickness of the gray lahar is at least 20 feet.

One or more lahars that are older than pyroclastic layer Y are present in the Mowich River valley downstream from the park. In the SW¼ sec. 30, T. 17 N., R. 7 E., a lahar that contains boulders as large as 5 feet forms a terrace that is about 25 feet above the Mowich River flood plain. Farther upstream, in the S½ sec. 29, outcrops reveal a lahar that consists of angular and subangular rock fragments as large as 3 feet in a matrix of purplish-gray silt and sand. This deposit extends to a height of at least 40 feet above the flood plain. At one place, in the SW½ sec. 29, a compact lahar that contains boulders as large as 7 feet may be a facies of the lahars previously described or it may be an entirely different deposit. The stratigraphic relation of these lahars to those of the Puyallup River valley is not known.

LAHAR IN THE CARBON RIVER VALLEY

The only lahar observed in the Carbon River valley is on the south side of the valley opposite Chenuis Falls. It is as much as 10 feet thick and consists of angular and subangular rock fragments as large as 6 feet across in a matrix of purplish-gray medium to coarse sand. The lahar lies on top of bedrock and is overlain by pyroclastic layer Y.

The scarcity of lahars in this valley may be due in part to the configuration of the volcano above the head of Carbon Glacier. At the top of Willis Wall a ridge extends eastward from Liberty Cap to Russell Cliff. I believe this ridge to be the north rim of a depression in the volcano that was left when massive slides to the northeast created the Osceola Mudflow. Because of the ridge, a flood originating at or near the summit of the volcano would be diverted away from the head of Carbon Glacier. This ridge is the largest remnant of the old crater rim, and its preservation may be due to a lack of hydrothermal alteration or to less intense alteration in these rocks than in those elsewhere on the volcano.

LAHARS IN THE MUDDY FORK OF THE COWLITZ RIVER AND OHANAPECOSH RIVER VALLEYS

A single lahar was found in the Muddy Fork valley above Canyon Bridge (pl. 1), but none downstream from it. About half a mile north of the highway bridge over the Muddy Fork, terraces on both sides of the valley are 50 or 60 feet higher than the flood plain. The terrace on the west side is formed by a coarse fluvial deposit of sand and pebble-to-boulder gravel in which there are boulders as large as 5 feet in diameter. The terrace deposit on the east side of the valley is capped by a lahar 13 feet thick. It is made up of angular to subrounded rock fragments as much as 5 feet in diameter in a dark-yellowish-brown matrix of silt and sand. X-ray analysis of the clay-sized fraction of the lahar indicated the presence of feldspar, cristobalite, and glass, and a lack of clay minerals. The only pyroclastic deposit on top of it is layer W, and it seems likely that the lahar as well as the underlying fluvial deposits are the same age as lahar assemblage C in the Nisqually River valley and that they originated in the same manner (p. 43).

Lahars were noted in the Ohanapecosh River valley at Indian Bar and near the mouth of Chinook Creek. The part of the valley that lies between these two places was not examined because accessibility is relatively difficult. Streambank outcrops in the meadow at Indian Bar reveal a lahar that consists of subangular to subrounded rock fragments in a purplish-gray matrix of silty sand. The lahar is more than 5 feet thick and extends beneath the base of the outcrops. It is overlain by a fluvial sand and pebble-to-boulder gravel deposit 2–3 feet thick and by layer O and younger pyroclastic deposits. A short distance upstream from the mouth of Chinook Creek a compact lahar is exposed where the East Side Trail crosses the Ohanapecosh River. The lahar is between 5 and 10 feet thick, and it overlies sand and pebble-to-boulder gravel about 5 feet thick that is mantled with pyroclastic layers Y and W.

THE ASSOCIATION OF LAHARS WITH VOLCANISM

The possible relation of lahars at Mount Rainier to volcanism was of paramount concern in this study. The possibility of lahar formation would undoubtedly be increased by the phenomena that are typically associated with eruptions. There are a number of indications, or lines of indirect evidence, that link the formation of some lahars to contemporary volcanism. The presence of fresh volcanic bombs in a lahar suggests that the lahar was caused in some way by an eruption. The eruption of pyroclastic material at the same time a lahar is formed carries a strong implication that the lahar was caused by volcanism. The occurrence of lahars within a general period during which pyroclastic deposits were erupted is another, but less satisfactory, basis for inferring a causal relation. Still another line of reasoning to support the association of lahar formation with volcanism is the presence of complex assemblages of fluvial deposits and lahars whose aggradation is best explained by repeated floods from the volcano. These floods, in turn, are most readily explained by repeated eruptions of hot pyroclastic debris or lava onto snow and ice. Finally, because of their size and composition, some lahars could only have been caused by tremendous slides from the volcano. The most probable causes of these slides are volcanic explosions, earthquakes associated with volcanism, and possibly lateral spreading or tilting of parts of the volcano caused by the rise of magma; however, nonvolcanic earthquakes cannot be ruled out as possible triggering mechanisms.

The lahars discussed below seem to have been triggered by eruptions or to have occurred during known periods of eruptive activity; lahars for which there is no independent evidence of contemporaneous volcanism are not mentioned here.

Evidence of the age of lahars and eruptions before 6,600 years ago is too fragmentary to relate them with confidence. The oldest eruptions recorded by pyroclastic deposits are those that produced layer R more than 8,750 years ago (tables 5, 6). Lahars older than layer O have been found in the valleys of Van Trump Creek and the Nisqually River, but their age with respect to layer R is not known.

The Paradise lahar is between 5,800 and 6,600 years old and thus was formed sometime during an interval of repeated pumice eruptions (table 6). Pyroclastic layer N, formed during this interval, is younger than the Paradise lahar, but any one of the eruptions that produced layers A, L, D, or S could have triggered the avalanche that caused the lahar. The Greenwater lahar, also formed by avalanches of rock debris, may have been caused by the same volanic explosion that produced pyroclastic layer S. (p. 22). Most of the pre-Osceola lahar assemblage in the White River valley probably was formed after the Greenwater lahar occurred. The two bomb-bearing lahars in the assemblage evidently were caused by eruptions of hot rock debris and bombs.

A detailed study of airlaid deposits contemporaneous with the Osceola Mudflow indicates that an eruption led to the formation of the Osceola (p. 30).

The last major episode of volcanic activity began with the formation of the block-and-ash flow in the South Puyallup River valley about 2,500 years ago. The evidence that it was hot clearly shows that the flow was associated with an eruption. A lahar older than pyroclastic layer C in the White River valley may have been formed at about the same time. Pyroclastic layer C was erupted next in sequence, after which the summit lava cone of the volcano was built and accompanied by aggradation of lahar assemblages in the valleys of the White River, Nisqually River, and Kautz Creek. Lahars probably also moved down the Muddy Fork, West Fork, and Van Trump Creek valleys at the same time.

This attempt to assign individual lahars or lahar assemblages to certain eruptive episodes leads to the speculation that there is a genetic relation between kinds of volcanic activity and certain types of lahars. Lahars at Mount Rainier that lack a considerable content of clay and clay minerals probably resulted from eruptions that produced large quantities of blocks and lithic ash or from eruptions during which much ice and snow was melted by hot pyroclastic debris or lava flows. Lahars that contain a significant amount of clay (perhaps 5 percent or more) seem to be derived from old, hydrothermally altered parts of the volcano, and some may have been started by phreatic explosions. Such explosions may not necessarily have been accompanied by the eruption of new magma.

HAZARDS FROM FUTURE LAHARS

A recent evaluation of volcanic hazards at Mount Rainier (Crandell and Mullineaux, 1967) was based on an examination of the events that have occurred there during the last 10,000 years, as inferred from a study of the surficial deposits of the park. We concluded that if future phenomena of the same type and magnitude occur with the same frequency as in the past, the direct danger from lahars greatly exceeds that from lava flows and pumice eruptions. Lahars are especially dangerous because of their possible very large size and ability to move long distances, and also the speed with which they can move. In areas downstream from the lower slopes of the volcano, their effects would be mostly confined to valley floors and the lower parts of valley walls.

The scale of the hazard presented by lahars might be illustrated by a brief review of their number and frequency in Holocene time. The deposits of at least 55 different lahars, representing a vast range in size, have been recognized in the various valleys that head on Mount Rainier (table 6), and many more probably occurred whose deposits were not seen or recognized during this study, or had been removed by erosion. Some areas have been affected by lahars more often than others; the valleys of the White and Nisqually Rivers and Tahoma Creek have been devastated frequently during certain intervals of postglacial time. Large lahars have moved down the White River valley at least 10 times within the last 6,600 years; thus, the average frequency of large lahars in that valley has been at least one per 660 years. In the Nisqually River valley the average frequency indicated by 12 lahars in the last 10,000 years is at least one per 830 years, and in the Tahoma Creek valley, four lahars in about the last 3,300 years indicate an average frequency of at least one per 825 years. Even though they are roughly similar, these indicated minimium average frequencies do not signify repetition of lahars at regularly spaced intervals. During a long interval when the volcano is dormant, few, if any, large lahars might occur. However, conditions that lead to lahar formation are substantially increased during relatively brief intervals of volcanic activity. It has been noted elsewhere in this report that at least seven lahars occurred in the Nisqually River valley during a relatively brief interval. In fact, lahars caused in various ways could occur again and again in more than one valley within a space of only a few weeks, as they did during the eruption of Mount Pelée in May and June of 1902 (Hovey, 1902, p. 346–347) and during the eruption of Irazú Volcano (Waldron, 1967, p. I 1–I 17).

In regard to the speed of lahars, Kemmerling (1921) noted that during the 1919 eruption of Kelut in Java, the passage of lahars down valleys lasted only 45 minutes, and some lahars had an average speed of 45 miles per hour. A velocity of about 56 miles per hour was reported by Iida (1938, p. 681) for a mudflow at Mount Bandai in Japan in 1938. Waldron (1967, p. I 24) found velocities of as much as about 22 miles per hour in debris flows that resulted indirectly from eruptions of Irazú Volcano in Costa Rica. He reported that the flows having the highest velocities had sediment concentrations between 60 and 74 percent. These were "hyperconcentrated flows," according to the terminology of Beverage and Culbertson (1964; this report, p. 4).

One conclusion reached from the present study is that the largest lahars of postglacial time originated in massive slides and avalanches of hydrothermally altered rock. Presumably, therefore, future slides and lahars may originate in those parts of the volcano that have been affected by hydrothermal alteration. The only large outcrops of altered rock known today are at the head of Sunset Amphitheater, but smaller areas are also present high on the west side of the volcano at the heads of North and South Mowich Glaciers.

Although the visible outcrop area of altered rock is small today, there may be large masses of such rock tens or hundreds of feet below the surface at many places within the volcano. Because of the possibility that such zones exist at depth, we cannot be certain that a massive rock slide comparable to those that produced the Greenwater and Paradise lahars, or the Osceola, Round Pass, and Electron Mudflows, will not occur again, triggered perhaps by a severe earthquake or by a volcanic explosion.

The chance that a destructive lahar will affect a given segment of a valley decreases with distance from the volcano. Thus, on the basis of the events of the last 10,000 years, a devastating lahar might cover the floor of the Nisqually River valley within or close to the park on an average of at least once in 800 years, and in the White River valley at least once in 600 years. In contrast, beyond the Cascade mountain front, the White River valley has been affected by only one lahar within the last 10,000 years, and the Nisqually River valley apparently by none.

Ways of reducing the hazard of future lahars include the evacuation of valley floors and zoning the valley floors to prevent construction of permanent residences and other installations within areas that are relatively hazardous. In addition, existing dams could be utilized to trap all or part of a lahar and prevent it from reaching populous areas.

One of the greatest difficulties to overcome in the evacuation of critical areas probably will be the inability of people to comprehend the nature of the threat facing them in the event of a future eruption. For this reason, extensive publicity should be given, at the first sign of renewed volcanism, of the possible consequences of an eruption. In this way the residents of areas that might be affected by lahars and floods could be forewarned that rapid evacuation might become necessary.

To be most effective, evacuation of people from valley floors would require foreknowledge of which valley or valleys might be affected. This information might be available if an eruptive vent appeared low on a flank of the volcano, because lahars would then most likely be restricted to the drainage basin heading on that slope of the cone. However, an eruption at the present summit crater could affect valleys on almost any side of the volcano. Furthermore, inasmuch as the subsurface distribution of possible large masses of hydrothermally altered rock is not known, it should be assumed that a large clayey lahar also could originate on any side of the volcano.

The valley floors adjacent to the park that have been inundated most frequently by lahars are not yet densely populated. From the standpoint of the lahar hazard alone it seems appropriate to recommend that permanent residences should not be constructed on the floor of the Nisqually River valley, downstream from the park, on surfaces that are less than 20 feet above river level. Construction is also inadvisable on the floors of the White River and West Fork valleys between the park and Greenwater (pl. 3). In addition, new campgrounds and other recreational facilities within and adjacent to the park could be constructed, and existing facilities relocated, in areas of low or nonexistent hazards. A related consideration should be the design and location of new bridges and highways to accommodate or avoid floods and lahars of small to moderate dimensions, so that routes will remain usable for safe evacuation if an eruption should result in these phenomena.

Within the mountains, the topographic setting is especially significant in areas that are on or closely adjacent to valley floors, for the degree of hazard decreases with greater height. Sites less than 10 feet above present rivers are susceptible to inundation by floods and lahars of modest size, whatever their origin. Sites 30 feet or higher above the rivers probably would be affected only by major floods or lahars resulting from volcanism of some kind. In the Nisqually River valley west of the park, for example, the terrace along the north side of the river for about 4 miles west of Ashford is less hazardous with respect to lahars and floods because of its height than is the valley floor farther west. The cross-section area and configuration of the valley below and adjacent to a terrace also is important because it will affect the capacity of that part of the valley to accommodate a flood or lahar without inundating the terrace.

Large dams in valleys downstream from Mount Rainier could trap all or part of a lahar if reservoirs behind the dams were empty. Such a trap now exists in the White River valley in the form of Mud Mountain Dam, which would substantially reduce the hazard of a lahar no larger than the Electron Mudflow. The flood-control reservoir created by the dam is designed to store 106,000 acre-feet of water, which is the equivalent of about 170 million cubic yards and roughly comparable to the inferred volume of the Electron Mudflow in the Puget Sound lowland. The dam is an earthfill structure that has an impervious core made up chiefly of material derived from the Osceola Mudflow. If the reservoir could not accommodate the entire volume of a lahar, mud would initially discharge through the concrete spillway and then might overtop the dam itself. Spillover would proceed down the White River valley, but probably would not be a threat unless it were deep enough to overtop the valley wall near Buckley or of sufficient volume to reach the Auburn urban area.

Similarly, Alder Dam could trap a lahar in the Nisqually River valley, but only if the reservoir had previously been drained. Otherwise a lahar would displace the lake very rapidly and would cause it to spill over the concrete-arch dam and flood the valley below. The capacity of the reservoir is 232,000 acre feet, or about 375 million cubic yards. The only areas of relatively dense population along the Nisqually River between Alder Dam and Puget Sound are at the small communities of

Yelm and McKenna. Yelm is situated 50–75 feet higher than the river, but parts of McKenna are close to the flood plain.

Lahars were not recognized in the Cowlitz River valley outside the park during this study, although the valley has been inundated by floods within historic time. A future lahar that would have the volume of the Electron Mudflow would bury the valley floor at Packwood and perhaps also at Randle. A lahar no larger than the Electron might not extend much beyond Randle because of the loss of volume and velocity as it spread across the broad, gently sloping floor of the valley west of Packwood.

I recommend that responsible authorities establish procedures to be followed if Mount Rainier should again become active. These procedures should include the following:

1. The development and installation of a detection system in certain critical valleys, whereby a large flood or lahar could be detected at an early stage.
2. The development of a warning system, whereby residents of valley floors could be warned, either night or day, of a need for immediate evacuation.
3. The establishment of an evacuation plan for areas likely to be threatened by floods or lahars.
4. A plan for lowering the level of Alder Reservoir in the event of a major eruption.
5. Plans for restricting travel in hazardous areas.

There is a strong likelihood that a lahar could travel with such speed that a warning system for individual lahars would provide little benefit except for areas many miles from the volcano. For the purpose of planning, it should be assumed that a lahar might travel at a speed of as much as 50 miles per hour. For this reason, especially, valley floors within a radius of at least 25 miles from the center of the volcano should be evacuated as soon as possible after an eruption actually began.

REFERENCES CITED

Anderson, C. A., 1935, Alteration of the lavas surrounding the hot springs in Lassen Volcanic National Park: Am. Mineralogist, v. 61, no. 4, p. 240–252.

Anderson, Tempest, and Flett, J. S., 1903, Report on the eruptions of the Soufrière in St. Vincent in 1902 and on a visit to Montagne Pelée in Martinique, Pt. 1: Royal Soc. London Philos. Trans., ser. A, v. 200, p. 353–553.

Aramaki, Shigeo, 1956, The 1783 activity of Asama Volcano, Pt. 1: Japanese Jour. Geology and Geography, v. 27, no. 2–4, pt. 1, p. 189–229.

——— 1963, Geology of Asama Volcano: Tokyo Univ. Fac. Sci. Jour., v. 14, pt. 2, p. 229–443.

Aramaki, Shigeo, and Akimoto, Syun-iti, 1957, Temperature estimation of pyroclastic deposits by natural remanent magnetism: Am. Jour. Sci., v. 255, no. 9, p. 619–627.

Baak, J. A., 1949, A comparative study on recent ashes of the Java volcanoes Smeru, Kelut, and Merapi: Buitenzorg, Java, Mededeel. Algem. Proefstation voor Landbouw, no. 83, 60 p.

Barth, T. F. W., 1950, Volcanic geology, hot springs, and geysers of Iceland: Carnegie Inst. Washington Pub. 587, 174 p.

Bateman, A. M., 1950, Economic mineral deposits [2d ed.]: New York, John Wiley & Sons, Inc., 916 p.

Bemmelen, R. W. van, 1949, The geology of Indonesia; v. 1A, General geology of Indonesia and adjacent archipelagoes: The Hague, Govt. Printing Office, 732 p.

Beverage, J. P., and Culbertson, J. K., 1964, Hyperconcentrations of suspended sediment: Jour. Hydraulics Div., Am. Soc. Civil Engineers Proc., v. 90, no. HY6, p. 117–128.

Blackwelder, Eliot, 1928, Mudflow as a geologic agent in semiarid mountains (with discussion by Joseph T. Singewald, Jr.): Geol. Soc. America Bull., v. 39, no. 2, p. 465–483.

Bull, W. B., 1964, Alluvial fans and near-surface subsidence in western Fresno County, California: U.S. Geol. Survey Prof. Paper 437–A, p. 71P.

Bundy, W. M., and Murray, H. H., 1959, Argillization in the Cochiti mining district, New Mexico *in* Swineford, Ada, ed., Clays and clay minerals: Internat. Ser. Mons. Earth Sci., v. 2, p. 342–368.

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

Crandell, D. R., 1963a, Paradise debris flow at Mount Rainier, Washington *in* Short papers in geology and hydrology: U.S. Geol. Survey Prof. Paper 475–B, p. B135–B139.

——— 1963b, Surficial geology and geomorphology of the Lake Tapps quadrangle, Washington: U.S. Geol. Survey Prof. Paper 388–A, p. A1–A84.

Crandell, D. R., and Fahnestock, R. K., 1965, Rockfalls and avalanches from Little Tahoma Peak on Mount Rainier, Washington: U.S. Geol. Survey Bull. 1221–A, 30 p.

Crandell, D. R., and Miller, R. D., 1964, Post-Hypsithermal glacier advances at Mount Rainier, Washington *in* Geological Survey research 1964: U.S. Geol. Survey Prof. Paper 501–D, p. D110–D114.

Crandell, D. R., and Mullineaux, D. R., 1967, Volcanic hazards at Mount Rainier, Washington: U.S. Geol. Survey Bull. 1238, 26 p.

Crandell, D. R., Mullineaux, D. R., Miller, R. D., and Rubin, Meyer, 1962, Pyroclastic deposits of Recent age at Mount Rainier, Washington *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 450–D, p. D64–D68.

Crandell, D. R., and Waldron, H. H., 1956, A Recent volcanic mudflow of exceptional dimensions from Mount Rainier, Washington: Am. Jour. Sci., v. 254, no. 6, p. 349–362.

Day, A. L., and Allen, E. T., 1925, The volcanic activity and hot springs of Lassen Peak [California]: Carnegie Inst. Washington Pub. 360, 190 p.

Durrell, Cordell, 1944, Andesite breccia dikes near Blairsden, California: Geol. Soc. America Bull., v. 55, no. 3, p. 255–272.

Escher, B. G., 1925, L'Eboulement préhistorique de Tasikmalaja et le volcan Galounggoung; Leidsche Geologische Mededeelingen, Deel 1, Aflevering 1, X1 1925, blz. 8–21; reviewed by Palmer, H. S., 1929, Volcanic mud-flow in Java: Volcano Letter 253.

Finch, R. H., 1930, Mud flow of Lassen volcano: Volcano Letter 266, p. 1–3.

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

Gorshkov, G. S., 1959, Gigantic eruption of the volcano Bezymianny: Bull. Volcanol., ser. 2, v. 20, p. 77–109.

Grange, L. I., 1931, Conical mounds on Egmont and Ruapehu volcanoes: New Zealand Bull. Sci. and Technology, v. 12, p. 376–384.

Grater, R. K., 1948, The flood that swallowed a glacier: Nat. History, v. 57, p. 276–278.

Grim, R. E., 1953, Clay mineralogy: New York, McGraw-Hill Book Co., Inc., 384 p.

Hopson, C. A., Waters, A. C., Bender, V. R., and Rubin, Meyer, 1962, The latest eruptions from Mount Rainier volcano: Jour. Geology, v. 70, no. 6, p. 635–647.

Hovey, E. O., 1902, Observations on the eruptions of 1902 of La Sourfrière, St. Vincent, and Mt. Pelé, Martinique: Am. Jour. Sci., 4th ser., v. 14, p. 319–358.

Iida, Kumizi, 1938, The mud flow that occurred near the explosion crater of Mt. Bandai on May 9 and 15, 1938, and some physical properties of volcanic mud: Tokyo Imp. Univ., Earthquake Research Inst. Bull., v. 16, pt. 3, p. 658–681 [in Japanese, with English summ.].

Ishikawa, I., and Yokoyama, I., 1962, Komaga-take volcano *in* Guidebook for excursions, International Symposium on Volcanology: p. 35–42.

Jaggar, T. A., Jr., 1931, Eruption of Santa Maria [Guatemala] November 1929: Volcano Letter 356, p. 1–4.

Kemmerling, G. L. L., 1921, De uitbarsting van den G. Keloet in den nacht van den 19den op den 20sten Mei 1919: Dienst Mijnwezen, Vulkanol, Mededeel., no. 2, 120 p. [in Dutch].

Luzier, J. E., 1969, Geology and ground-water resources of southwestern King County, Washington: Washington Div. Water Resources Water-Supply Bull. 28.

McTaggart, K. C., 1960. The mobility of *nuées ardentes:* Am. Jour. Sci., v. 258, no. 5, p. 369–382.

Mason, A. C., and Foster, H. L., 1956. Extruded mudflow hills of Nirasaki, Japan: Jour. Geology, v. 64, p. 74–83.

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

Meniailov, A. A., 1939, The eruption of Avacha in 1938: Kamchatka Volcanol. Sta. Bull. 6, p. 21–27.

Morimoto, Ryohei, and Ossaka, Joyo, 1964, Low temperature mud-explosion of Mt. Yaké, Prefs. Nagano-Gifu, central Japan, on 17th June 1962 as an example of endogenous katamorphism of volcanic rock at the destructive stage of the volcano [abs.]: Bull. Volcanol., v. 27, p. 49–50.

Mullineaux, D. R., 1961, Geology of the Renton, Auburn, and Black Diamond quadrangles, Washington: U.S. Geol. Survey open-file report, 202 p.

——— 1965a, Geologic map of the Auburn quadrangle, King and Pierce Counties, Washington: U.S. Geol. Survey Geol. Quad. Map GQ–406.

——— 1965b, Geologic map of the Black Diamond quadrangle, King County, Washington: U.S. Geol. Survey Geol. Quad. Map GQ–407.

Mullineaux, D. R., and Crandell, D. R., 1962, Recent lahars from Mount St. Helens, Washington: Geol. Soc. America Bull., v. 73, no. 7, p. 855–869.

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, no. 3, p. 688–696.

Murai, Isamu, 1963, A brief note on the eruption of the Tokachi-dake volcano of June 29 and 30, 1962: Tokyo Univ. Earthquake Research Inst. Bull., v. 41, pt. 1, p. 185–208.

Ōinouye, Y., 1917, A few interesting phenomena on the eruption of Usu: Jour. Geology, v. 25, no. 3, p. 258–288.

O'Shea, B. E., 1954, Ruaphu and the Tangiwai disaster: New Zealand Jour. Sci. and Technology, sec. B, v. 36, no. 2, p. 174–189.

Perrett, F. A., 1924, The Vesuvius eruption of 1906: Carnegie Inst. Washington Pub. 399, 151 p.

Porter, S. C., and Denton, G. H., 1967, Chronology of Neoglaciation in the North American Cordillera: Am. Jour. Sci., v. 265, no. 3, p. 177–210.

Powers, H. A., and Wilcox, R. E., 1964, Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak: Science, v. 144, no. 3624, p. 1334–1336.

Richardson, Donald, 1968, Glacier outburst floods in the Pacific Northwest *in* Geological Survey research 1968: U.S. Geol. Survey Prof. Paper 600–D, p. D79–D86.

Russell, I. C., 1898, Glaciers of Mount Rainier, with a paper on the rocks of Mount Rainier, by G. O. Smith: U.S. Geol. Survey 18th Ann. Rept., pt. 2, p. 349–423.

Sales, R. H., and Meyer, Charles, 1948, Wall rock alteration at Butte, Montana: Am. Inst. Mining Metall. Engineers Trans., v. 178, p. 9–35.

Sapper, Karl, and Termer, Franz, 1930, Der Ausbruch des Vulkans Santa Maria in Guatemala vom 2–4 November 1929: Zeitschr. Vulkanologie, v. 13, no. 2, p. 73–101.

Schmincke, H. U., 1967, Graded lahars in the type sections of the Ellensburg Formation, south-central Washington: Jour. Sed. Petrology, v. 37, no. 2, p. 438–448.

Schumm, S. A., 1965, Quaternary paleohydrology, *in* Wright, H. E., Jr., and Frey, D. G., eds., The Quaternary of the United States: Princeton, Princeton Univ. Press, p. 783–794.

Sekiya, S., and Kikuchi, Y., 1889, The eruption of Bandai-san: Imp. Univ. Japan Coll. Sci. Jour., v. 3, pt. 2, p. 91–172.

Sharp, R. P., and Nobles, L. H., 1953, Mudflow of 1941 at Wrightwood, Southern California: Geol. Soc. America Bull., v. 64, no. 5, p. 547–560.

Sigafoos, R. S., and Hendricks, E. L., 1961, Botanical evidence of the modern history of Nisqually Glacier, Washington: U.S. Geol. Survey Prof. Paper 387–A, 20 p.

Sigvaldason, G. E., and White, D. E., 1961, Hydrothermal alteration of rocks in two drill holes at Steamboat Springs, Washoe County, Nevada *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 424–D, p. D116–D122.

——— 1962, Hydrothermal alteration in drill holes GS–5 and GS–7, Steamboat Springs, Nevada, *in* Short papers in the geologic and hydrologic sciences: U.S. Geol. Survey Prof. Paper 450–D, p. D113–D117.

Simons, D. B., Richardson, E. V., and Haushild, W. L., 1963, Some effects of fine sediment on flow phenomena: U.S. Geol. Survey Water-Supply Paper 1498–G, p. G1–G47.

Tada, Fumio, and Tsuya, Hiromichi, 1927, The eruption of the Tokachidake Volcano, Hokkaido, on May 24, 1926: Tokyo Univ. Earthquake Research Inst. Bull., v. 2, p. 49–84 (English summ., p. 49–50).

Trimble, D. E., 1963, Geology of Portland, Oregon, and adjacent areas: U.S. Geol. Survey Bull. 1119, 119 p.

Varnes, D. J., 1958, Landslide types and processes, Chapt. 3 *of* Eckel, E. B., ed., Landslides and engineering practice: Natl. Research Council, Highway Research Board Spec. Rept. 29, p. 20–47.

Waldron, H. H., 1967, Debris flow and erosion control problems caused by the ash eruptions of Irazú Volcanic, Costa Rica: U.S. Geol. Survey Bull. 1241–I, p. I 1–I 37.

Williams, Howel, 1932, Geology of the Lassen Volcanic National Park, California: California Univ. Dept. Geol. Sci. Bull., v. 21, no. 8, p. 195–385.

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

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