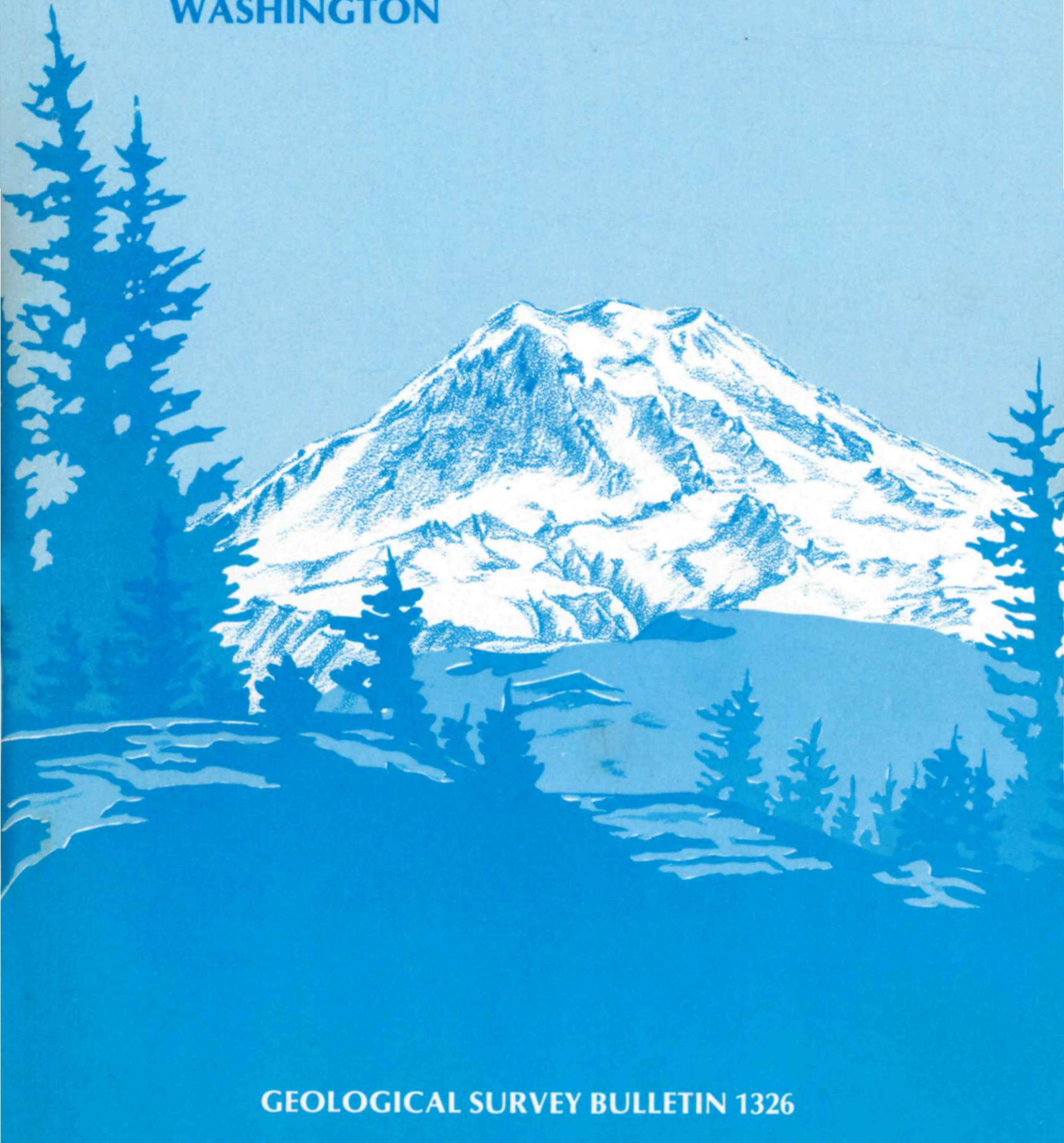
PUMICE AND OTHER PYROCLASTIC DEPOSITS IN Mount Rainier National Park, WASHINGTON



GEOLOGICAL SURVEY BULLETIN 1326

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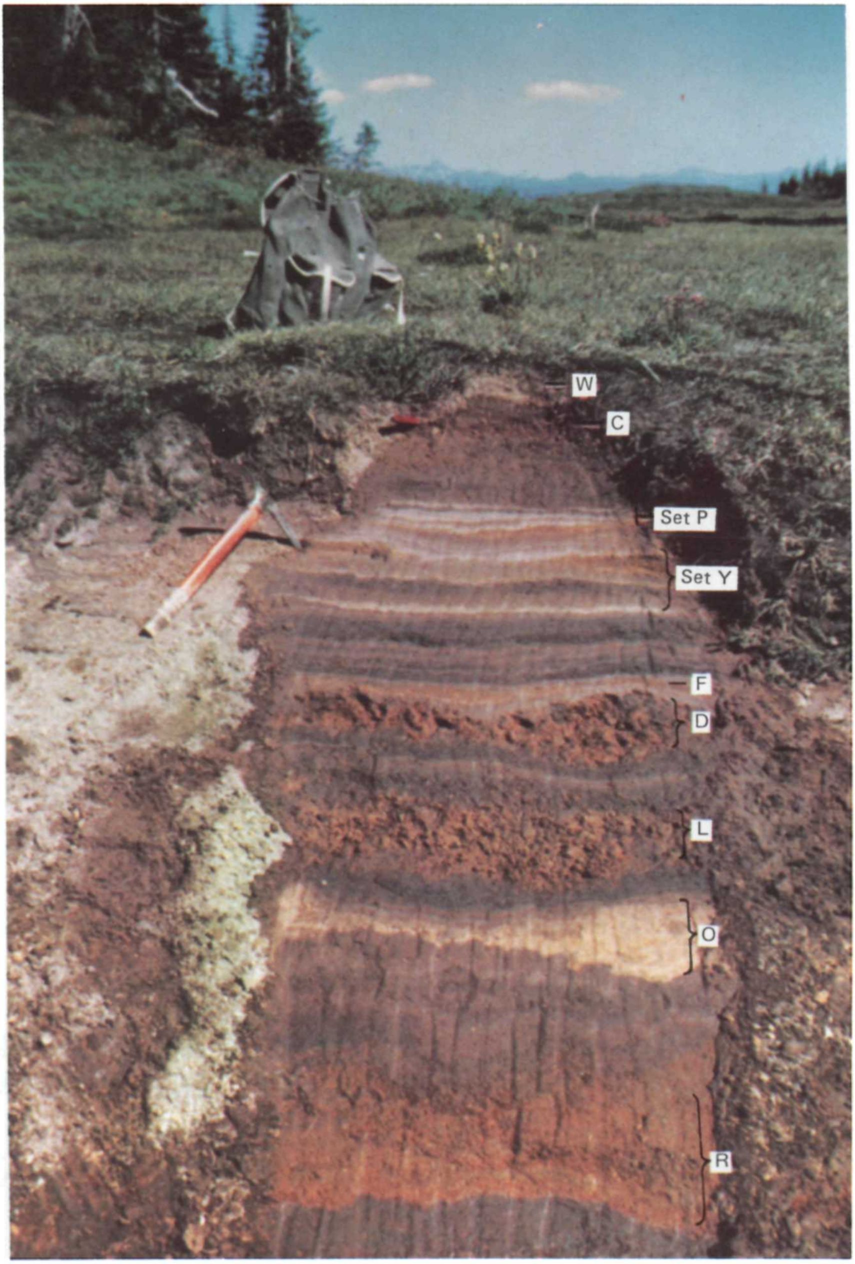

TEPHRA LAYERS in Mount Rainier National Park. Pumice and scoria layers from Mount Rainier volcano (note layers R, L, D, and C) typically are stained to fairly strong brown or reddish brown; interbedded lithic ash deposits have relatively neutral but somewhat darker brownish-gray colors. Ash beds from other volcanoes (note beds marked O, set Y, set P, and W) characteristically are lighter in color than the locally derived deposits that enclose them. Site is in an alpine meadow near Williwakas Glacier on the southeast flank of Mount Rainier.

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OTHER PYROCLASTIC DEPOSITS IN
Mount Rainier National Park,
WASHINGTON

By
Donal R. Mullineaux

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UNITED STATES
DEPARTMENT OF THE INTERIOR

ROGERS C. B. MORTON, Secretary

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PUMICE AND OTHER PYROCLASTIC DEPOSITS IN MOUNT RAINIER NATIONAL PARK, WASHINGTON

By DONAL R. MULLINEAUX

ABSTRACT

At least 22 layers of tephra—volcanic ash and coarser airfall pyroclastic debris—can be recognized among the postglacial deposits in Mount Rainier National Park. Each of these tephra layers records a separate eruptive event. Eleven of the layers were erupted from Mount Rainier; 10 originated at Mount St. Helens volcano 80 km (50 miles) south-southwest of Mount Rainier; and the other came from prehistoric Mount Mazama at the present site of Crater Lake, Oreg., 440 km (275 miles) south of Mount Rainier. Two tephra beds, layer O from Mount Mazama (6,600 years old), and layer Yn from Mount St. Helens (3,400 years old) covered the entire park. These two form highly conspicuous light-colored layers among the darker tephra erupted from Mount Rainier. They are especially valuable marker beds that delineate the boundaries of three nearly equal segments of the approximately 10,000 years of postglacial time. Layer Yn, locally more than 30 cm (12 in.) thick, is the most voluminous tephra deposit in the park. Only one other tephra bed from Mount St. Helens is conspicuous, layer W, about 450 years old; the others are thin and obscure.

All but one of the tephra layers erupted from Mount Rainier contain abundant vesicular fragments that were formed by explosive eruptions of molten lava. The thickest and coarsest three layers from Mount Rainier (layers L, D, and C) form well-defined lobes that extend east of the summit vent; layers L, D, and C are nearly absent in the western part of the park. All three, where thick, are conspicuous deposits that can be recognized in a variety of environments. Seven smaller, generally thinner deposits form less well defined lobes east of the summit and are recognized only where exposures are relatively good. One of these smaller deposits is the only layer composed wholly of solid rock fragments and, so, does not record eruption of molten lava. Another one, which was erupted early in the 19th century, represents the most recent eruption of Mount Rainier that resulted in a recognizable deposit.

One other layer from Mount Rainier (layer F) is a widespread, generally thin ash that consists of three overlapping ash beds. In contrast to most of the tephra layers, which contain little or no clay minerals, the lower and upper beds of layer F are rich in montmorillonitic clay. The middle bed, however, consists of mineral crystals and pumice and contains little or no clay. Layer F was laid down at the time the Osceola Mudflow originated at Mount Rainier. The eruptions that formed layer F may have triggered the mudflow.

Color, size, thickness, gross composition, and stratigraphic position permit field identification of most of these layers where the sequence is fairly complete. The content and refractive index of iron-magnesium minerals, however, are particularly useful for initially establishing the sequence of beds present and for identifying beds that occur alone. Three mineral pairs are especially common: (1) hypersthene and augite, generally occurring with olivine and less commonly with hornblende; (2) hypersthene and hornblende; and (3) cummingtonite and hornblende. The hypersthene-augite suite is found in all tephra from Mount Rainier; olivine is absent in only two of those layers, and hornblende occurs in three. The other two pairs of minerals commonly occur without other iron-magnesium minerals and are characteristic of Mount St. Helens ash layers.

The tephra record shows that Mount Rainier has erupted at very irregular intervals throughout the last 10,000 years. The earliest postglacial eruption was more than 8,750 years ago, then the volcano was relatively quiet until about 6,500 years ago. It was especially active between about 6,500 and 4,000 years ago, when 8 of the 11 known tephra layers from Mount Rainier were ejected, including 4 of the 6 most voluminous deposits. No eruption of Mount Rainier is recorded in the tephra sequence between 4,000 and 2,500 years ago. The most voluminous postglacial tephra deposit was erupted between 2,500 and 2,000 years ago. Since that time, the 19th-century eruption is the only one known to have produced a tephra layer.

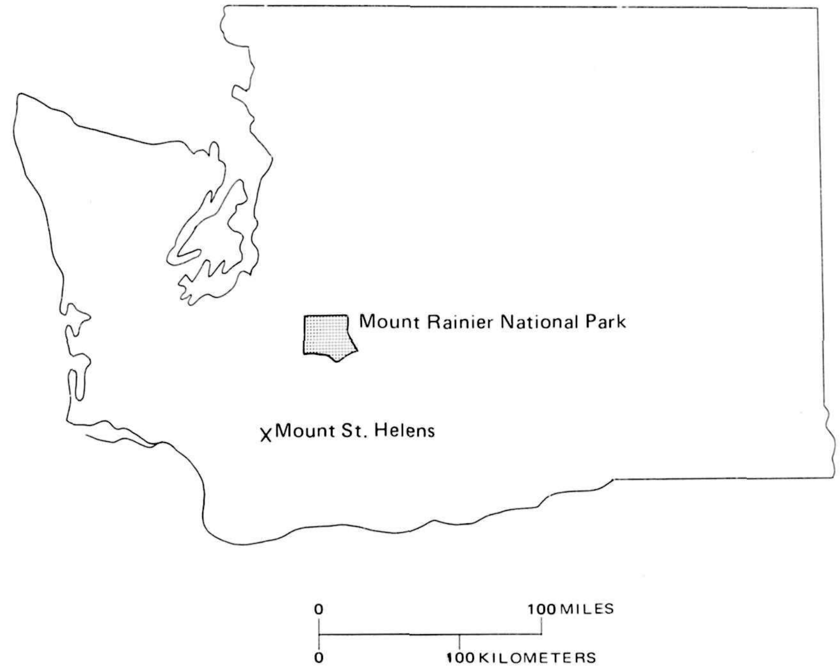
Large tephra deposits from Mount Rainier that consist chiefly of pumice and scoria probably resulted from eruptions that were preceded by the rise of molten rock into the volcano from a considerable depth. Such an upward movement of magma expectably would be accompanied by earthquakes and by increased flow of heat and gases from the volcano. Thus, an initial explosive eruption probably would be preceded by recognizable signs. A pyroclastic eruption that ejected only fragments of previously solidified rock, however, might occur with no preliminary movement of magma, and perhaps without even significantly increased heat or gas emission. Such an eruption might occur without any kind of recognizable preliminary events.

Hazards from pyroclastic eruptions include the effects of impact and accumulation of tephra fragments, of volcanic gases, and of secondary landslides, mudflows, and floods set off by the eruptions. Eruptions of molten material, because they probably would be preceded by warning signs, are potentially less dangerous to persons than nonmagmatic eruptions that might occur with no warning.

Introduction

Many volcanic eruptions within the last 10,000 years—roughly the time since the last major glaciation—are recorded by thin widespread layers of volcanic airfall debris, called tephra, that blanket much of Mount Rainier National Park in western Washington (fig. 1). Twenty-two of these layers were studied in detail to document the recent eruptive history of Mount Rainier volcano and to identify "marker beds" that could be used to date other kinds of geologic deposits. The appearance of some of the tephra deposits is shown in the frontispiece, and their sources and ages are listed in table 1.

Eleven of these layers were erupted by Mount Rainier. Their source is shown by coarse fragment size on the flanks of that volcano, by rapid decreases in thickness and grain size away from it, or by distribution limited to the area near Mount Rainier. Because prevailing winds in



LOCATION OF MOUNT RAINIER NATIONAL PARK and Mount St. Helens, western Washington. (Fig. 1)

TABLE 1.—*Tephra units, their source volcanoes, and approximate ages*

[Boldface letter indicates conspicuous unit. Ages of layers X and W were determined by tree-ring counts; all other ages are in radiocarbon years. (See text p. 24-26.)]

Tephra unit	Source volcano	Approximate age
X	Mount Rainier	150
W	Mount St. Helens	450
C	Mount Rainier	2,200
Set P (4 layers)	Mount St. Helens	2,500-3,000
Set Y 2 layers	...do	3,000-3,300
Yn	...do	3,400
2 layers	...do	3,500-4,000
B	Mount Rainier	4,500
H	...do	4,700
F	...do	5,000
S	...do	5,200
N	...do	5,500
D	...do	6,000
L	...do	6,400
A	...do	6,500
O	Mount Mazama	6,600
R	Mount Rainier	> 8,750

this region are from the west, most of the Mount Rainier tephra was carried east of the summit, into the eastern part of the park.

Each of these tephra layers represents one or more explosive eruptions, and the extent, thickness and content of each tell something about the size and kind of the eruption that produced it. Although the tephra gives evidence of many eruptions, those eruptions did not significantly change the form of the volcano, which was mostly built long before 10,000 years ago. Moreover, the explosive eruptions are not the only eruptions, or even the only kinds of eruptions, that have occurred within the last 10,000 years. Other outbursts caused huge avalanches to cascade down the volcano's slopes, and quieter eruptions of flowing lava built a young cone at the top of the volcano less than 5,000 years ago (fig. 2).

The deposits of tephra, however, are the only record of many eruptions of Mount Rainier, and they add to our knowledge of the eruptive history of the volcano. This historical record has been used, in turn, to evaluate the likelihood of future eruptions of Mount Rainier and how they might affect man and his use of the surrounding area (Crandell and Mullineaux, 1967).

The other 11 tephra layers came from volcanoes other than Mount Rainier, as is shown by their broad distribution and fairly uniform thickness and grain size. In contrast to the rather limited extent of Mount Rainier tephra, some layers from distant volcanoes cover the entire park. The ages of most of these foreign tephra deposits have been determined by measuring the content of radioactive carbon in wood or peat associated with them. Because they are relatively conspicuous and distinctive as well as widespread, they are especially useful for establishing the ages of a wide variety of geologic deposits with which they are interbedded.

The possibility of future eruptions and of their consequences is of interest and significance to residents of the region near Mount Rainier. Furthermore, visitors to Mount Rainier National Park may share this interest and may wish to examine the tephra deposits there. Consequently, this report is intended to serve park visitors who are not earth scientists, as well as professional geologists. Toward that end, the sequence and general character of all the tephra deposits are briefly described in mostly nontechnical terms in the first part of the report. That description is followed by sections that discuss some conclusions of the study. Detailed descriptions of the tephra units and petrographic and chemical data that are of interest mostly to professional geologists are presented in later sections of the report (p. 27-80).

PREVIOUS WORK AND ACKNOWLEDGEMENTS

Tephra on the slopes of Mount Rainier was mentioned but not described in detail in early reports like those of Smith (1900) and

MOUNT RAINIER VOLCANO viewed from the east, showing the young summit cone (arrow) and the barren upper slopes of rock, snow, and ice. (Fig. 2)

Coombs (1936). Carithers (1946) studied pumice deposits erupted at Mount St. Helens and noted that some of them extended into Mount Rainier National Park. Crandell and Waldron (1956) described the sequence of tephra deposits in the park relative to the Osceola Mudflow. Crandell's later use of several tephra layers as marker beds led to the study to determine the diagnostic features, sources, and ages of the most conspicuous layers by Crandell, Mullineaux, Miller, and Rubin (1962). Concurrently, Waters investigated the young tephra deposits in the park, and Hopson and Bender evaluated published accounts of volcanic activity in historic time to determine the age of the most recent eruptions of Mount Rainier (Hopson and others, 1962; Fiske and others, 1963). Those studies led to some conclusions substantially different from those of our 1962 report—and of this one—regarding the age and source of the most recent tephra layers. (See p. 36.)

Preliminary results of the present study have been used for an evaluation of volcanic hazards at Mount Rainier (Crandell and Mullineaux, 1967) and in reports on other aspects of geology in the park (Crandell, 1969a, 1969b, 1971).

Study of the tephra deposits was made concurrently with, and has benefited substantially from, other U.S. Geological Survey investigations in the park that included research on lahars and glacial deposits by D. R. Crandell, R. D. Miller, and H. H. Waldron and on vegetation recovery by R. S. Sigafoos and E. L. Hendricks. R. E. Wilcox provided advice concerning petrographic criteria likely to distinguish one tephra deposit from another and methods especially suitable for their examination (Wilcox, 1962), and the minerals and their optical properties were identified on a spindle stage developed by Wilcox (1959b). Radiocarbon dates cited in the report were determined in the laboratory of the U.S. Geological Survey under the supervision of Meyer Rubin. Chief Park Naturalist N. A. Bishop and many other National Park Service people provided countless courtesies and abundant information about the park that also significantly helped the investigation.

TERMINOLOGY

Familiarity with a few technical terms is necessary for the nongeologist to understand the descriptions or to use the report to identify tephra deposits in the field. The term **pyroclastic** will be used to refer to an explosive eruption that ejects fragments of rock from a volcano. **Tephra** refers to fragments that have been thrown through the air by a pyroclastic eruption or to deposits of such particles. These fragments may be erupted either as pieces of rock that had previously cooled and solidified or as clots of fluid or plastic molten material. **Magma** refers to molten rock within the earth's crust; it may move upward into a volcano and subsequently be erupted, either quietly or explosively, as **lava** at the surface.

The term **vesicular** refers to rocks that have a large amount of visible pore space. Vesicular tephra is formed by explosive eruption of gas-rich magma that is stiff enough to hold the gas. The gas expands and creates bubbles in the molten rock, which then cools rapidly and hardens to a rock "froth." **Pumice** is highly vesicular tephra and is light in color. **Scoria** is somewhat less vesicular tephra and is darker in color; the darker color usually indicates that the rock is richer in iron and magnesium but poorer in silica than the pumice. Pumice and scoria fragments at Mount Rainier consist largely of volcanic glass because the lava cooled too rapidly to permit mineral crystals to form after its eruption. However, they do contain crystals that formed in the magma before it was erupted.

Tephra fragments that are nonvesicular are called **lithic** in this report. They can form if lava is low in gas content when it is erupted, or if the lava is already solid when erupted. At Mount Rainier, they have been formed mostly by explosions that break and eject pieces of older, previously solidified lava. Most lithic fragments in the park contain both volcanic glass and mineral crystals. Individual crystals and fragments of crystals are also common in tephra layers but are abundant only in fine-grained deposits (table 2).

The primary name applied to most tephra deposits indicates the particle size and commonly is used with an adjective that indicates the kinds of particles (table 2). **Blocks** and **bombs** (table 2) fall close to the volcanic vent from which they were erupted because they are large. Smaller **lapilli** and **ash** particles (table 2) tend to be carried higher into the air and are blown farther horizontally by the wind. The wind-carried lapilli and ash commonly fall in long "tongues" or "lobes" that extend downwind from the source vent. The grain size and thickness of the tephra particles decrease progressively away from the vent and also from the central "axis" of the lobe toward its sides. (See fig. 23.)

Fine volcanic ash can be carried for hundreds or even thousands of miles by wind; if a volcanic explosion carries ash high enough into the atmosphere, it can circle the earth. Thus, very coarse fragments in a tephra layer indicate that the source vent was nearby, and a rapid increase in fragment size within a short distance can reveal the direction to that vent. In contrast, fine-grained ash that is relatively uniform in thickness and grain size over a broad area suggests that the source was distant.

Some thin tephra beds that came from Mount St. Helens are grouped for discussion into two **sets.** Each set includes several tephra beds, each of which contains the same principal iron-magnesium minerals and which differs in mineral content from tephra beds that lie below and above them at Mount St. Helens (Mullineaux, Hyde, and Rubin, 1972).

TABLE 2.—*Terminology applied to tephra particles*

[Diameter of particles (see scale below) is shown in parentheses]

Character of particles	Particle terms		
	Ash (<0.4 cm)	Lapilli (0.4-3.2 cm)	Bombs and blocks (>3.2 cm)
Vesicular	Pumice or scoria ash	Pumice or scoria lapilli.	Pumice or scoria blocks and bombs.
Nonvesicular	Lithic ash	Lithic lapilli	Lithic bombs or lithic blocks.
Crystalline	Crystal ash	([1])	([1])

[1] Crystals are generally less than 0.4 cm in diameter.

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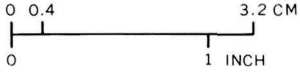


GENERAL SETTING

The tephra deposits can be studied best in the park along streambanks in moist, gently sloping alpine meadows, which are common on ridges and in shallow basins between altitudes of about 5,000 and 7,000 feet (1,500 and 2,000 m). In these meadows, other postglacial deposits rarely are thick enough to hide the tephra. Moreover, even thin beds often are well preserved because they have not been disturbed by burrowing animals or tree roots. In addition, the colors of the tephra are more intense there, because the deposits usually are wet. Several layers make very conspicuous bands along both natural and artificial cuts. Other less conspicuous layers can be made more visible if outcrops are scraped with a pick or knife blade; the outcrops pictured in figures 5, 6, and 7 have been smoothed to show details of the sequence. The exposures in the alpine meadows have provided most of the evidence used to determine the sequence and features of tephra deposits in the park.

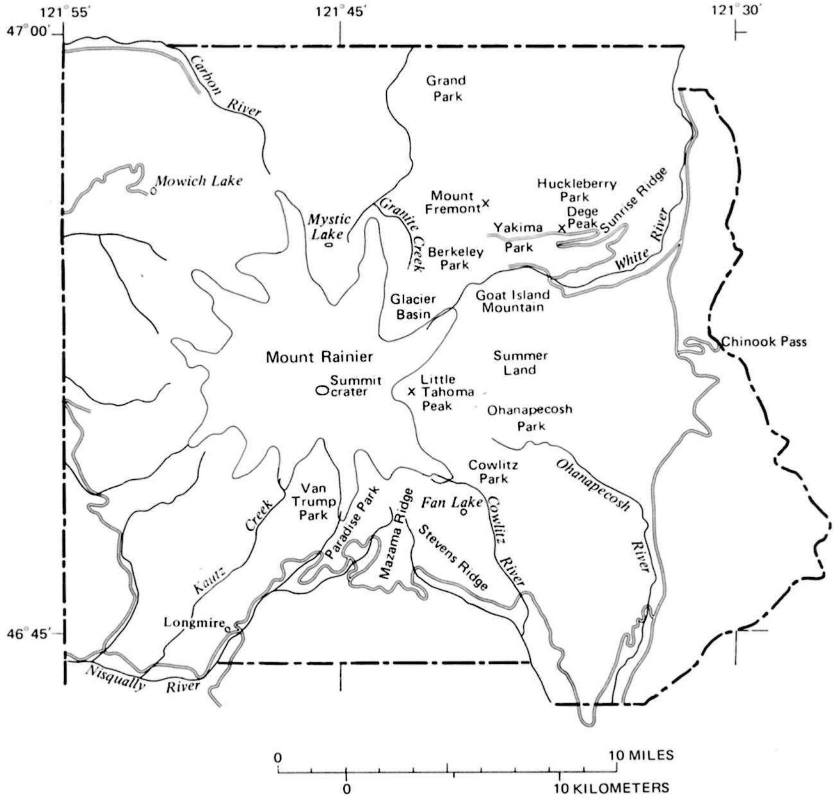
In contrast, tephra is poorly preserved on or is absent on the higher, barren slopes of rock, snow, and ice (fig. 2). Tephra that fell high on the volcano near the summit vent has been largely eroded away or is buried by snow and ice. Thus, it is likely that the thickest deposits of Mount Rainier tephra—those that fell closest to the vent—are not seen; the nearest well-preserved deposits, at altitudes of about 7,000 feet, are all at least 6 km (4 miles) horizontally from the summit.

Many exposures at altitudes lower than the alpine meadows also display tephra deposits, but the sequence of layers is usually incomplete. In most exposures, one or more layers have been eroded away, have been mixed with other sediments, or are hidden by thick mudflow or stream deposits. Tephra layers that can be identified, however, have been used to determine the ages of associated deposits, especially in the accumulations of mudflow and river deposits on valley floors.

The index map (fig. 3) shows the approximate location of several alpine meadow areas called "parks" in which tephra layers are well displayed; these are the parks mentioned most often in the report. Descriptions of the location of other sites and references to altitudes and distances refer to the Mount Rainier National Park quadrangle topographic map, scale 1:62,500, of the U.S. Geological Survey. Although most measurements in this report are given first or only in metric units, altitude is stated primarily in feet because the topographic map shows altitudes in feet only.

Brief Description Of Tephra Deposits

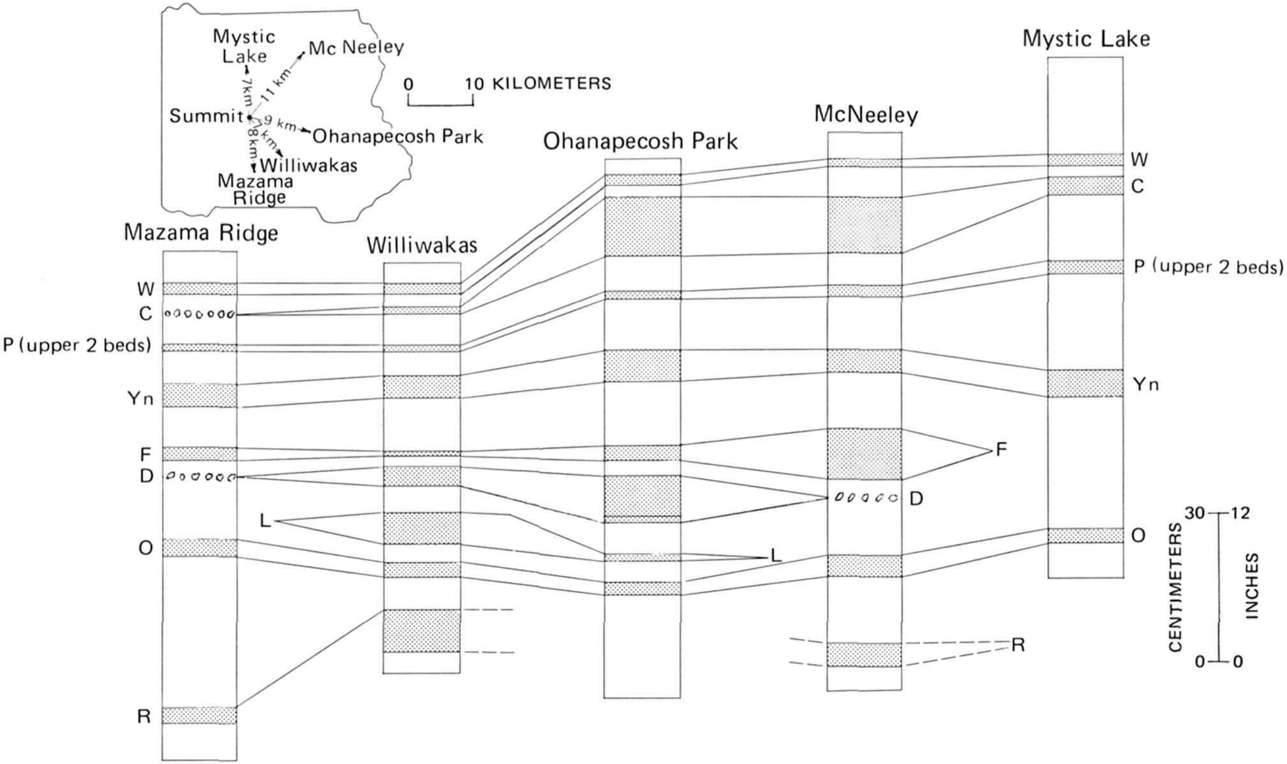
The 22 layers studied in detail are all postglacial in age, and each clearly represents an eruption. The postglacial deposits were selected



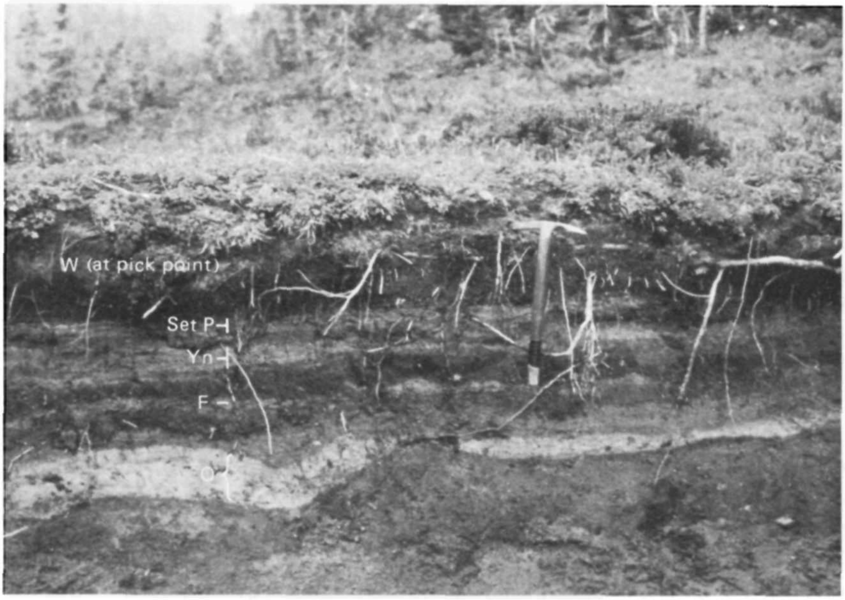
INDEX MAP of Mount Rainier National Park. (Fig. 3)

for study because these deposits are abundantly exposed and are preserved well enough to permit recognition of the sequence of layers. Outcrops of older pumice, in contrast, are too sparse to permit the sequence of older tephra to be identified in the time available. Several old pumice deposits were noted, some older and others younger than the lava flows and breccias that form the bulk of Mount Rainier volcano.

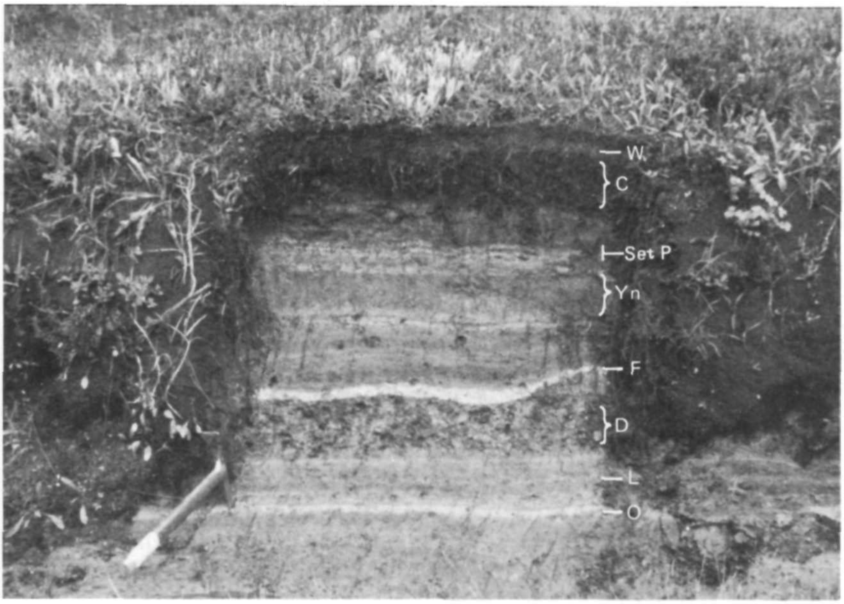
The eruptive origin of the layers selected is indicated by their distribution, in combination with their grain size, thickness, and composition. The layers form thin blankets of locally uniform size and thickness over ridges and swales alike; changes in grain size and thickness are not related to shape of the land surface, indicating that the particles fell from the air. All the tephra units erupted by Mount Rainier contain bombs or lapilli that are too large to have been picked up and carried to their present sites by wind; these show that some other agent, such as a volcanic explosion, must have thrown them into the air. Tephra deposits from other volcanoes are finer grained, but they consist of rock types that are different from those that make up



CORRELATION DIAGRAM from south, counterclockwise, around to north flank of Mount Rainier, showing thicknesses of major tephra units. (Fig. 4)



TEPHRA LAYERS ON MAZAMA RIDGE, about 1.2 km (0.75 mile) north of the park highway. (Fig. 5)



TEPHRA LAYERS IN SOUTHEASTERN PART OF OHANAPECOSH PARK, approximately 1 km (0.6 mi) northeast of Indian Bar shelter cabin. Tephra layers in the lower part of this sequence are little stained by iron oxide, and, so, layers O and F are white, rather than brown. Beds in the upper part of the sequence, especially layers C and W, are stained to a stronger brown than in most outcrops. (Fig. 6)

Mount Rainier, proving that they, too, were not merely picked up locally by wind and then redeposited.

The tephra layers studied are separated by beds of mostly darker sand- and silt-size, predominantly lithic particles (frontispiece). Some of these dark beds probably are also tephra, and, if so, they represent additional eruptions of the volcano. They were not studied in detail, however, because they could not be readily distinguished from sand and dust that actually was picked up from the volcano's slopes and redeposited by wind. A recent example of such a windblown deposit is the mantle of dust, locally as much as 2 cm thick, that fell on the east side of Mount Rainier in 1964 (Crandell and Fahnestock, 1965, p. 25). The dust resulted from rockfalls and avalanches from Little Tahoma Peak, and it was spread over the east flank of the volcano by winds.

The tephra layers selected for study have been designated by letters of the alphabet. These letters, however, do not fall in alphabetical order when the deposits are listed according to age. (See table 1.) When the most conspicuous tephra units were first studied (Crandell and others, 1962), they were known to be only a few of the many layers that are present. No orderly alphabetical sequence for all the deposits could be set up at that time, so the layers described were arbitrarily named by letters derived from some word used in field descriptions. Thus, the letter Y was used for a yellow pumice, and W for a white one.

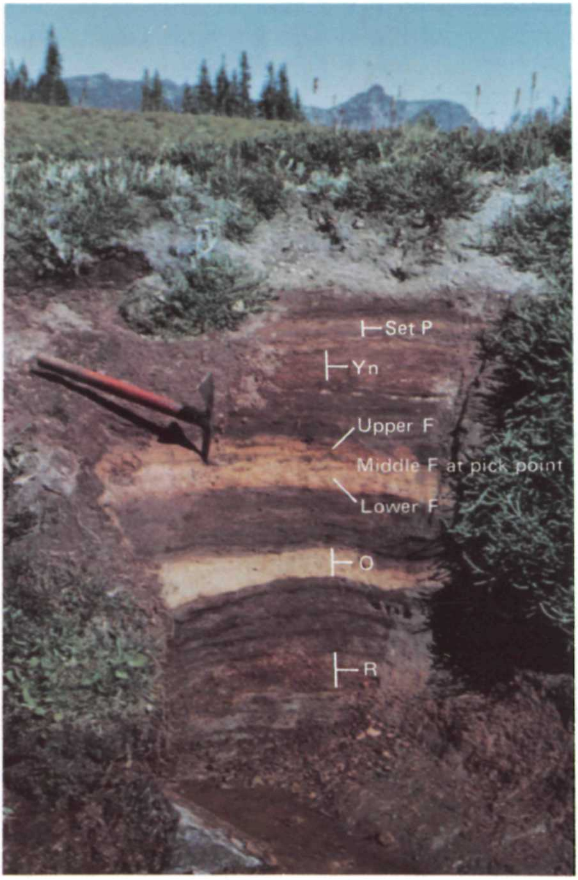
The tephra layers from Mount Rainier and two of those from other volcanos are described individually and are named by single letters. The others, all from Mount St. Helens, are grouped into two sets that also are designated by single letters. Each set contains several different beds which are similar in composition and which in many places cannot be identified one from another. Where specific beds within a set can be recognized, they are designated by adding a second letter; layer Yn, for example, is a thick distinctive bed within set Y.

The outcrop pictured in the frontispiece, on the southeast flank of Mount Rainier, shows the general appearance of almost all the layers described in the report. It also illustrates some common differences between tephra deposits from Mount Rainier and foreign tephra deposits in the park. Those from Mount Rainier are relatively dark, and locally they are thick. They are also coarse grained as compared with their thickness; most Mount Rainier tephras are no more than a few times as thick as the diameter of their large fragments. In contrast, most non-Rainier tephra units are conspicuously lighter in color, and they are fine grained as compared with their thickness. The foreign tephra beds commonly are from 10 to 100 times as thick as the diameter of the largest grains.

Comparison of the tephra beds at several sites around the volcano (fig. 4) shows the changes in thickness within short distances that are characteristic of many Rainier deposits. Units such as layers L, D, and

C that are 10 cm (4 in.) or more thick in some exposures are so thin as to be nearly unrecognizable, or are absent, only a few kilometers away. In contrast, non-Rainier tephra units, such as layers O, Yn, and W, are relatively uniform in thickness over much of the park (fig. 4). Figures 5, 6, and 7 illustrate the tephra sequence at three of the localities shown in figure 4.

Figure 8 is a diagram of a sequence of tephra that might be present in alpine meadows directly east of the summit if all the Mount Rainier tephras had been blown directly eastward, rather than in several



TEPHRA LAYERS IN AN ALPINE MEADOW (McNeeley site), 0.7 km (0.4 mi) north-northwest of Ranger Station at Yakima Park. The middle unit of layer F forms a thin gray bed that is both underlain and overlain by thicker yellowish-brown ash of the lower and upper units. Layer O ("Mazama ash") is iron stained to a yellow or brown in most places in Mount Rainier National Park. (Fig. 7)

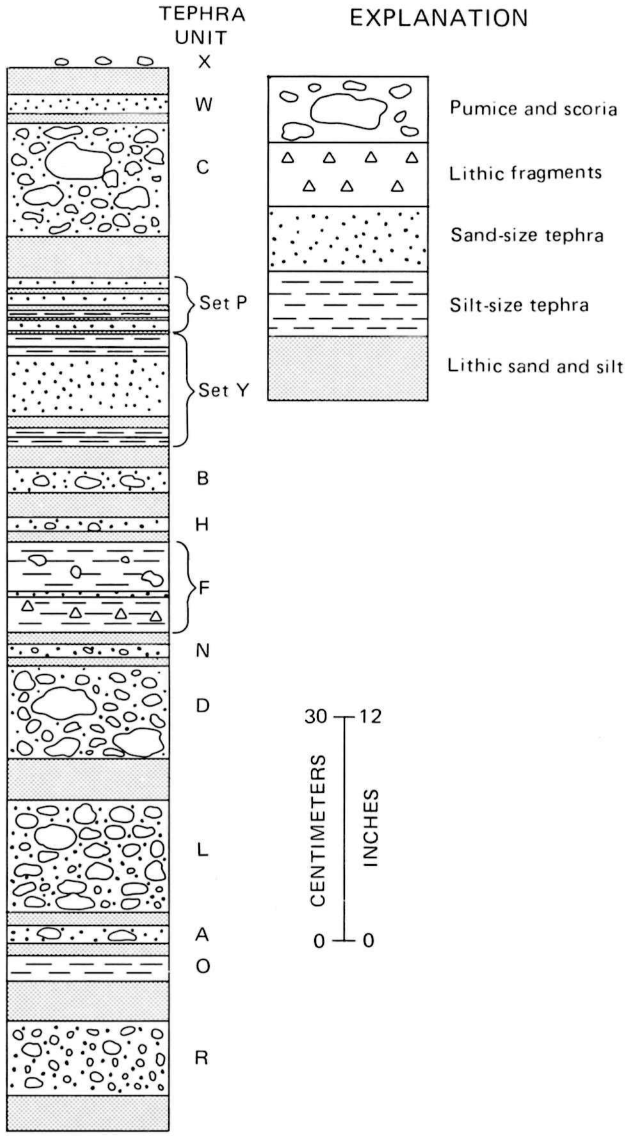


DIAGRAM OF A SEQUENCE that might be present in alpine meadows about 7 km (4 mi) east of the summit if all the Mount Rainier tephra units (except layer S) extended directly east from the summit. (Fig. 8)

different directions. The thicknesses of non-Rainier tephras and interbedded lithic sands are shown as they actually occur in those meadows. This hypothetical sequence allows a comparison of maximum thicknesses and grain sizes of the Mount Rainier tephra units at a distance of about 7 km (4 mi) from the summit. It has the disadvantage, however, of overemphasizing layer L, which is conspicuous in exposures only in a narrow lobe.

Table 3 summarizes identification characteristics of the tephra units. Few if any of these units can be recognized by any one feature. For some, color is fairly distinctive, but even in those the color does vary, and no color is unique to any one layer. Color combined with thickness and grain size are enough to identify some deposits, however, when those characteristics are compared with the values expected at a given locality. Identification is most reliable if all the layers present are considered. Not only can specific features of a given layer be evaluated, but also the position of that layer relative to all the other tephra units.

Postglacial Activity Of Mount Rainier

ERUPTIVE HISTORY

The tephra layers constitute proof of repeated eruptions of Mount Rainier at irregular intervals during the last 10,000 years. Overall, the 11 pyroclastic eruptions represented had an average frequency of about 1 every 1,000 years. However, the average does not portray the actual timing of the eruptions (table 4). For example, 8 of the 11 occurred during the period between about 6,500 and 4,000 years ago, at the relatively high rate of nearly 1 every 300 years. In contrast, the eruptions before and after that period averaged only 1 every 2,500 years. The concentration of eruptions near the middle of postglacial time is a striking feature of Mount Rainier's recent eruptive history.

Each of the average frequencies stated above is a minimum because presumably there were some pyroclastic eruptions in postglacial time that have not been recognized in the tephra sequence. For example, any eruption that ejected only lithic ash is not included in the figures. Similarly, any eruption that threw tephra only as far as the upper slopes of the volcano would not be represented. Even somewhat more extensive tephra deposits, of the size of layers A and H (table 4), might not be recognized if they were ejected in early or very late postglacial time; preservation is so poor in the deposits older than about 7,000 years and younger than about 2,000 years that thin tephra layers would be very difficult to identify.

The eruptive episodes represented by the 11 recognized tephra deposits probably were short in comparison with the intervals between them. Furthermore, the eruption of each of the pumice or scoria deposits probably represents a period of only a few hours or a few days during an eruptive episode. Such an episode may have extended over a

TABLE 3.—*Characteristics useful for identification of tephra units*

Tephra unit	Source volcano (Mount)	Color	Thickness in park (cm)		Grain size[2] (cm)	Principal distribution	Iron-magnesium minerals[3]	Common field recognition features
			Average[1]	Range of average				
X	Rainier	Grayish brown	([4])	([4])	3	Northeast-east-southeast from summit.	hy, ag, hb, ol.	Scattered lapilli on young surfaces.
W	St. Helens	White	3	0-8	<1.0	Most of park	hy, hb	White sand-size ash at or near surface.
C	Rainier	Brown	15	0-30	15	Eastern two-thirds of park.	hb, ol, hy, ag.	Lapilli deposit at or near surface.
P	St. Helens	White to light gray.	≈1	0-2	<1.0	Most of park	hy, hb	Occurs as a distinct pair, coarser and more commonly preserved than others in set P.
	...do	...do	1	0-2	<0.4	...do	...do	
	...do	...do	<1	0-<1	<0.4	Eastern part of park	...do	Not distinguishable from thin beds of set Y.
	...do	Brown	≈1	0- 1	<1.0	Southeastern part of park.	...do	Relatively coarse, brown.
Y 2 beds	.do	White	[5]<1	0-<1	<0.4	...do	cm, hb	Undistinctive.
Yn	..do	Yellow, brown	8	2-30	1.0	Entire park	...do	Coarse, yellow ash, very thick west of volcano.
2 beds	..do	White	[5]<1	0-<1	<0.4	Eastern and southern parts of park.	...do	Distinguishable in field only by stratigraphic position.
B	Rainier	Reddish brown	3	0-7	5	East and southeast of summit.	hy, ol, ag	Scattered bombs and lapilli in dark ash.
H	...do	Grayish brown	1-2	0-5	1	East of summit	...do	Obscure—scattered lapilli in brown to gray ash.
F	...do	Reddish-yellow to pale yellow.	12	0-15	1	Eastern two-thirds of park.	hy, ag	Light-colored clayey ash above layer O.
S	...do	Pinkish to brownish gray.	150?	0-150	100	Northeast of summit		Angular blocks in ash.
N	...do	Reddish-brown	1-2	0-4	1	East of summit	hy, ag	Sparse lapilli in coarse ash.
D	...do	...do	12	0-15	10	Northeast to southeast of summit.	hy, hb, ag, ol.	Scoria bombs and lapilli.
L	...do	Yellowish-brown	15	0-20	5	East to southeast of summit.	hy, ag, ol	Brown pumice of relatively uniform size between dark-gray ash beds.
A	...do	Brownish gray	1-2	0-3	2	East to south of summit	...do	White pumice lapilli in brown ash.
O	Mazama	Reddish-yellow to pale yellow.	3-4	2-7	<0.4	All of park	hy, hb, ag	Oldest light-colored ash, very widespread and well preserved.
R	Rainier	Reddish-brown	10	0-15	4	Northeast to southeast of summit.	hy, ag, ol	Reddish-brown lapilli below layer O.

[1] 7 km from summit along axis of lobe (or 7 km east of summit for foreign tephra).

[2] Maximum common 7 km from summit along axis of lobe (or 7 km east of summit for foreign tephra).

[3] Hypersthene (hy), hornblende (hb), augite (ag), olivine (ol), cummingtonite (cm).

[4] Does not form a layer.

[5] Each bed.

TABLE 4.—*Tephra layers that record eruptions of Mount Rainier*

Layer	Approximate age (years)[1]	Predominant materials	Probable minimum volume (million m^3)
X	150	Pumice	1
C	2,200	Pumice, scoria, lithic fragments	300
B	> 4,000	Scoria, lithic fragments	5
H	< 5,000	Pumice, lithic fragments	1
F	5,000	Lithic fragments, pumice, crystals, and clay	25
S	5,200	Lithic fragments	20
N	5,500	Lithic fragments, pumice	2
D	6,000	Scoria, lithic fragments	75
L	6,400	Pumice	50
A	6,500	Pumice, lithic fragments	5
R	> 8,750	do	25

[1] Age of layer X was determined by tree-ring counts. All other ages are in radiocarbon years. (See p. 24-25).

period of months or years, during which time there were intermittent ash eruptions on too small a scale to be recognized in the tephra sequence.

The tephra layers suggest an overall pattern of rather short eruptive episodes separated by longer periods of relative quiet. If eruptions did occur during the relatively quiet times, they were too mild to produce recognizable tephra layers. An early postglacial eruption is recorded by layer R, after which the volcano was relatively quiet until about 6,500 years ago when the major postglacial eruptive episode began. Intermittent strong pyroclastic eruptions threw out large volumes of molten lava as pumice and scoria. These eruptions were interspersed with steam blasts that ejected fragments of previously solidified lava from the vent and crater walls that had been partly altered to clay.

During the same eruptive episode, rock avalanches and volcanic mudflows repeatedly swept down valleys heading on the volcano (Crandell, 1971). By about 4,000 years ago, the volcano had again become relatively quiet, and no other eruptions were recorded until after 2,500 years ago. Then, strong pyroclastic eruptions of large volumes of magma produced showers of pumice and scoria that form layer C. At about the same time, floods and volcanic mudflows again moved down valley floors (Crandell, 1971, p. 43). After that major episode, the volcano again returned to a relatively quiet state.

A pumice bed that was thought to be 500-600 years old by Hopson and Waters (Hopson and others, 1962; Fiske and others, 1963) and to have originated from a major eruption of Mount Rainier is much older and was erupted by Mount St. Helens. (See p. 34.) Thus, so far as the tephra record shows, the recent quiescence of Mount Rainier has been interrupted only by the ejection of layer X some time between 1820 and 1855.

The tephra sequence sheds some light on the time of formation of the young summit cone of Mount Rainier (fig. 2), a major event in the postglacial history of the peak. No thick coarse layer C has been seen on the snow-free parts of that young cone, and the cone probably is younger than layer C. In valleys below, numerous volcanic mudflows and flood deposits, perhaps started by eruptions that produced the young cone, also are younger than layer C but older than layer W (Crandell, 1971). No other major post-C eruptive episode is recorded by mudflow and alluvial deposits (Crandell, 1971) or by the tephra sequence. Consequently, it seems likely that the young summit cone formed during an eruptive episode of which layer C represents an early part and that it is on the order of 2,000 years old.

VOLUME

Another notable feature of the tephra record is the considerable difference in volume of material ejected during different eruptions. Rough calculations based on areas covered and thicknesses within the park suggest that the volume of freshly fallen tephra in layer C may have been as much as 300 million cubic meters, which is approximately one-twentieth of a cubic mile. Similar calculations suggest that layer D is the next largest Mount Rainier deposit, followed in volume by layers, L, F, and R (table 4). A few thick remnants near Dege Peak suggest that layer S conceivably might be as large as any of the last three named; so little is known of its thickness and distribution, however, that many more assumptions must be made to calculate its volume than for the other tephra deposits. The sparseness of layer X everywhere it has been found indicates that it is the smallest of the tephra layers recognized.

Even the largest Mount Rainier tephra, however, is small in volume compared with tephra deposits from Mount Mazama and Mount St. Helens. The present volume of the Mazama airfall layer of which layer O is a part has recently been calculated as 29-37 km^3 (Williams and Goles, 1968), which is roughly 100 times the volume of layer C. The volume of layer Yn indicated by data now available probably is more than 10 times the volume of layer C.

KINDS OF ERUPTIONS

The kinds of particles in the tephra deposits and their distribution and texture give some evidence of the character of the eruptions they record. The coarse highly vesicular pumice or scoria contained in most tephra units, for example, must have been molten when it was thrown from the volcano. Such particles could not have been derived from previously solidified rocks in the cone, for those rocks are solid or only slightly vesicular. Instead, the particles prove that the erupted material was still fluid or plastic enough to allow the contained gas to expand and form bubbles. Because the highly vesicular particles were molten when ejected, they record the presence of magma in the volcano before the eruption.

Eruption of molten lava, especially of a large amount, implies a kind of eruptive episode in which magma rises under and into the volcano from a considerable depth. Generally, it causes earthquakes as it rises, as well as increased heat flow and gas emission from the volcano. Small amounts of magma might possibly be formed within a volcanic cone by melting of previously formed rocks, but that would require at least the rise of abundant heat into the cone, probably accompanied by gases. Significantly, the earthquakes and increased escape of heat and gas that accompany the rise of magma under a volcano probably would be observed before a major eruption actually occurred.

An obvious property of molten lava is its heat. A small amount of fine pumice or scoria ejected high into the air might cool before reaching the ground surface, but a large volume of coarse fragments could still be very hot when it fell. Falling pumice and scoria can be hot enough to start forest fires.

Most tephra deposits from Mount Rainier contain lithic fragments as well as pumice or scoria. A high proportion of lithic particles suggests eruption of abundant volcanic gas, carrying with it fragments of previously solidified rock. These fragments may be torn from the crusts formed on the surface of magma exposed in a vent or from the vent walls, or they may be particles of rocks that have slumped down into the vent from the crater walls. Fragments that are all nearly alike, such as the abundant lithic fragments in the lower part of layer C, probably were derived from a crust formed on the magma column. Lithic particles in most other tephra deposits, however, consist of a variety of rock materials and probably represent debris derived from the walls of the vent and crater.

Tephra layer S contains no pumice or other evidence of eruption of molten lava and may have originated from an eruption of only gases, probably mostly steam. The lithic lower member of layer F may also have been ejected by a steam blast. These eruptions might represent merely one kind of event that occurred during an eruptive episode during which magma was also ejected. Such events could also occur without any rise of magma into the volcano and, therefore, without the associated events that usually precede an eruption of magma.

The great extent and good sorting of several tephra units indicate that the units resulted from strong high-angle eruptions of gases and tephra. Layers D and C, for example, occur chiefly as long tongues of well-sorted lapilli and ash that extend many kilometers beyond Mount

Rainier. Most debris in these layers probably was carried high above the volcano by powerful continuous ejection of columns of gases and fragments. The fragments were then carried downwind as they fell, and the smaller particles were carried progressively farther from the vent. However, some large bombs in layer D probably were thrown directly to their present sites by the force of an explosion, for the largest of them extend in directions different from the direction the wind-blown fragments were carried. The flight paths of similar bombs ejected during the 1935-41 eruptions of Asama volcano in Japan were calculated by Minakami (1942a). The formulas Minakami derived, applied to the 50-cm-diameter bombs on Mazama Ridge, indicate that these bombs could have reached their present sites by being ejected with an initial velocity of about 250 meters per second at an angle of near 40° to the horizontal.

Layer S appears to represent a highly explosive, but laterally directed eruption that also threw large fragments directly to their present locations. The limited overall distribution of that deposit and the presence of large blocks in ash several kilometers away from any likely vent site suggest that the mass was ejected at a high velocity and at an angle low enough that very little of it was carried and sorted by wind.

Several tephra layers that are thin, fine grained, poorly sorted, and limited chiefly to the volcano's flanks are thought to have resulted from fairly mild eruptions. They lack large fragments that might indicate a powerful explosion, and they do not show either good sorting or a strongly wind controlled distribution pattern that would suggest that they were carried high above the volcano.

Virtually all the pumice and scoria of layers L and D probably were thown from the vent during continuous eruptions. Both deposits are nearly uniform in composition and texture from bottom to top and show no evidence of significant changes in conditions of either eruption or deposition during their formation. In contrast, the changes in composition and texture from bottom to top of layer C record intermittent eruptions. A pause in the eruption that was long enough for a nonvesicular crust to form on the magma may be recorded by a concentration of lithic fragments just above the pumice and scoria in the lower part of the layer. The crust may then have been disrupted and thrown out as lithic fragments during the next eruptive pulse. The predominant pumice in the upper part of layer C differs slightly in color and texture from that in the lower part and probably represents a change in composition, though not necessarily a pause in the activity. Layer F also shows evidence of a discontinuous eruptive episode that included an initial explosion of volcanic gases, a later eruption of a small volume of crystal-rich molten material, and a final eruption of both molten and solid-rock particles.

Repeated pulses of activity are a common feature of many observed eruptions of modern volcanoes. Voluminous pumice deposits erupted by volcano Hekla in Iceland over a period of only a few days have represented only the first phase of recurring activity that, with minor interruptions, lasted months or years (Thorarinsson, 1967). Possibly, therefore, an eruptive episode that produced a tephra deposit like layer L consisted of more than the single pulse represented by the pumice. The dark lithic ash that occurs with the pumice may have resulted from minor eruptions during the same episode.

Hazards From Future Eruptions Of Tephra

The ejection of tephra described in this report is one of several ways in which volcanic eruptions can threaten lives and property. Some other kinds of hazards associated with eruptions are lava flows, explosive lateral blasts of gas and rock particles, the ejection of hot gas and rock debris to form hot avalanches, and various kinds of eruptions that initiate volcanic mudflows. The expectable danger at Mount Rainier from future tephra eruptions is greater than the direct danger from lava flows, but it is substantially less than that from volcanic mudflows and associated floods (Crandell and Mullineaux, 1967; Crandell, 1971).

KINDS OF HAZARDS

A tephra eruption can endanger lives and property by the effects of the associated volcanic gases or the tephra fragments. Various probable effects of a tephra eruption have been discussed at some length by Wilcox (1959a), who also noted that psychological factors, such as fear and possible resulting panic, might be more dangerous than physical factors in such an eruption.

Volcanic gases are hazardous largely because of the harmful effects of their acid-forming constituents, including sulfur, chlorine, fluorine, and water vapor. The chemical compounds that result are likely to irritate or damage eyes and respiratory systems if "inhaled in sufficient concentration for a sufficient length of time" (Wilcox, 1959a, p. 442). They can also severely attack cloth and metal objects, and fluorine has been regarded as responsible for the deaths of many animals after eruptions of the volcano Hekla in Iceland (Thorarinsson, 1967). The hazard from the gases decreases rapidly away from the vent, however, and probably would be relatively minor in a tephra eruption.

The tephra itself poses a danger from the direct effects of impact and inhalation, and simply by its presence where it is thick. Bombs and blocks large enough to kill or seriously injure people might conceivably reach the lower flanks of Mount Rainier at virtually any point. Layers L, D, S, and C, for example, all contain bombs or blocks large enough to be dangerous at the distance of the Paradise and Yakima Park visitor areas. Similar fragments have been thrown by eruptions of volcano Hekla to distances equal to the distance from Mount Rainier's summit to the park boundaries (Thorarinsson, 1954). A substantial risk of injury by inhalation of dust-size tephra also exists, especially if the material is hot. A wide variety of mechanical equipment that ingests air or water might also be damaged by air or water contaminated by volcanic ash.

Even if not seriously affected by impact, structures can be damaged by an accumulated load of tephra if its volume is great. Tephra accumulations can also disrupt water-supply systems, make roads impassable or dangerous, and impose severe clean-up problems. In addition, forest fires, which occasionally are started by tephra falls, could be a special problem in the park.

Other serious consequences might result from the secondary effects of a tephra eruption. Thick accumulations of tephra on steep slopes could slide and evolve into mudflows as they moved into stream channels. Mudflows or floods might also be formed if the fall of hot tephra melted snow or ice; melt water mixed with hot rock debris can form highly mobile and dangerous mudflows. Even relatively small volcanic mudflows and floods can damage or destroy bridges, highways, and other structures and can kill persons caught in their paths.

Overall, hazards mount as quantities of erupted tephra increase. If the wind direction were to change during an eruption, tephra would be spread over a wider area, and the amount deposited at a given locality might be reduced. Strong winds during a tephra eruption have a similar effect in that they spread the same amount of debris over a greater distance downwind. The hazard would also be lessened if tephra were to be erupted in small increments over a substantial period of time.

LOCATION

The areas of greatest direct hazard from an eruption of tephra are close to the vent and directly downwind from it. Risk is high close the the vent regardless of wind because large bombs and blocks can be thrown out of the crater at high velocity in any direction. As shown by Minakami (1942a), the distribution of large bombs and blocks is influenced more by the angle at which they are erupted and by the shape of the crater rim than it is by the wind. Other hazards are concentrated downwind. Figure 23 shows the distribution pattern of a tephra layer controlled chiefly by wind. The hazard is highest where the tephra is thickest near the vent, and it diminishes with decreasing thickness both downwind from the vent and across the pattern from its axis to both margins.

Most winds in this region blow generally eastward, so that the danger is substantially higher east of the vent. Figure 20, which shows the overlapping distribution patterns of the three major tephra layers from Mount Rainier, also outlines a sector of relatively high risk in the park that extends from approximately northeast to southeast of the summit. The wind does blow from other directions, however, and it should be possible to distribute tephra in a pattern similar to that of figure 23 in any direction from the volcano.

The secondary hazard of landslides is restricted to areas of heavy tephra fall, but the hazard from mudflows and floods extends down all valleys that head in those areas. The distance downvalley to which the risk extends would depend mainly on the volume and mobility of a mudflow or on the volume of floodwaters.

WARNING

A key factor in determining the severity of the hazard from an eruption—especially the hazard to life—is the probability of warning. The recognition of warning signs soon enough before an eruption could, for example, prevent any loss of human life if people in the endangered areas were evacuated. Any substantial eruption of pumice would likely be preceded by the rise of molten magma into the volcano. The movement of the magma should cause a variety of phenomena that would provide warning, including volcanic earthquakes, increase of volcanic-heat flow that would, in turn, cause an increase in steaming and melting of snow and ice, changes in the magnetic field around the volcano, and swelling of the volcano accompanied by tilting of its flanks and perhaps an increase in the number of rockfalls and landslides. Property damage and loss of life would then depend largely on the measures taken to reduce the effects of the eruption.

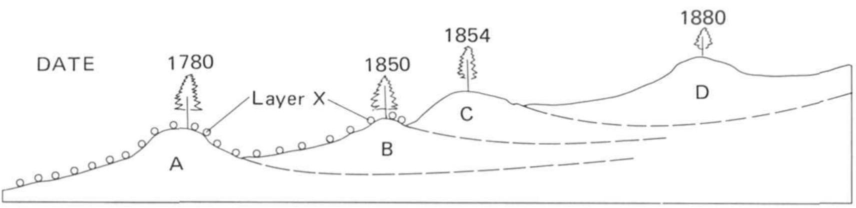
The eruption of only gases and previously solidified lithic tephra, in contrast, might occur with no such warning signs. The tephra record suggests that the probability of a steam blast of large proportions is low, but such an eruption could be highly dangerous because of the lack of a warning.

Ages Of Tephra Layers And Their Use As Marker Beds

Tephra beds extend over wide areas and, in terms of geologic history, the tephra falls everywhere at the same time. Because the tephra settles over the entire landscape, it can be preserved on, and buried by, many other kinds of deposits. Even if no date is determined for such a layer, other deposits associated with it can be correlated from place to place by the knowledge that they are either older or younger than the tephra. But usually a tephra layer can be dated at one place or another, and the date obtained is valid for that layer wherever it can be recognized. Consequently, an identifiable tephra bed marks a single time-horizon of known age in widely varied kinds of geologic deposits over a broad region.

Only rarely can the age of a tephra bed be obtained by dating material in that deposit. Instead, the age is generally obtained by determining a date that is older than the bed and another that is younger. Most of those "bracketing" or "limiting" dates at Mount Rainier have been determined from the proportion of radioactive carbon in wood samples from sediments that lie below, between, and above the various tephra layers. Other dates have been obtained by counting annual growth rings to learn the ages of trees; the tree ages can then be used to determine approximately the age of the youngest surface on which the tephra is present, and the age of the oldest surface on which it is absent (fig. 9). Both surfaces, of course, must be within the area covered by the tephra fall. The dates obtained by these methods, however, are only approximate. Radiocarbon methods give ages that probably are accurate only to within a few hundred years, and tree-ring-counting methods can give ages that are accurate to within a few tens of years.

The age assigned to a tephra layer for discussion in this report is some arbitrarily chosen even number between the closest available



EXAMPLE OF DATING TEPHRA by tree-ring counts. Sequence of moraines from older (A) to younger (D) was left by Emmons Glacier retreating from left to right. Dates are the earliest year recorded by an annual ring reached by a corer, in the oldest tree found on the moraine; the ring is close to the first-year growth ring of the tree. Layer X fell after formation of moraines A and B but before deposition of moraines C and D. It clearly is older than 1854. Studies of germination and growth of trees in Mount Rainier National Park by Sigafoos and Hendricks (1969) indicate that a maximum of 10 years should be allowed for germination of trees on moraine B after its formation, and a maximum of 20 years for growth to the height at which it was cored, which was approximately 60 cm (2 ft). Thus, moraine B probably formed in about 1820 or later, and layer X fell between 1820 and 1854. (Fig. 9) limiting dates. For example, the closest limiting dates for layer L are 6,440±250 and 6,380±250 years (table 5); these are also the only dates available from sediments that are just under and over that tephra

TABLE 5.—*Limiting dates and ages assigned to tephra layers*

Layer	Approximate age[1]	Bracketing radiocarbon samples: Sample No.	Bracketing radiocarbon samples: Radiocarbon years before 1950	Bristlecone-pine age[2]	Bracketing tree-ring counts as of 1970	Approximate calendar date[3]
					120	
X	125					A.D. 1825
					150	
		W1120	290 ± 200	500-300	435	
W	450					A.D. 1500
		W1119	320 ± 200	500-400	....	
		W1393	2,040 ± 200	2,100-1,900	....	
C	2,200					300 B.C.
		W1396	2,340 ± 200	2,400	....	
		W1394	2,460 ± 200	2,800-2,500	....	
Set P	3,000-2,500					1200-700 B.C.
		W2675	2,960 ± 250	3,300-3,200	....	
Upper beds	3,300-3,000					**1600-1300 B.C.**
		W2549	3,350 ± 250	3,600	....	
Set Y Yn	3,400					1700 B.C.
		W1115	3,500 ± 250	4,000-3,700	....	
		W1752	3,510 ± 250	4,000-3,700	....	
Lower beds	3,900-3,500					2400-2000 B.C.
		W2677	3,900 ± 250	4,500-4,400	....	
B	4,500				....	3400 B.C.
H	4,700				....	3600 B.C.
F	[4]5,000					3800 B.C.
		W2053	5,020 ± 300	5,800	....	
S	5,200					4200 B.C.
N	5,500					4400 B.C.
		W2437	5,770 ± 250	6,600	....	
D	6,000					4900 B.C.
		W2424	6,380 ± 250	7,300	....	
L	6,400					5300 B.C.
		W2423	6,440 ± 250	7,300	....	
A	6,500					5400 B.C.
		W2422	6,730 ± 250	7,600	....	
O	[5]6,600					5500 B.C.
		W951	8,750 ± 280	([6])	....	
R	>8,750					

[1] Years before 1950. Ages of layers X and W are based on tree-ring counts; all others are radiocarbon ages. Radiocarbon ages are used herein for discussion because they are in wider general use than bristlecone-pine ages.

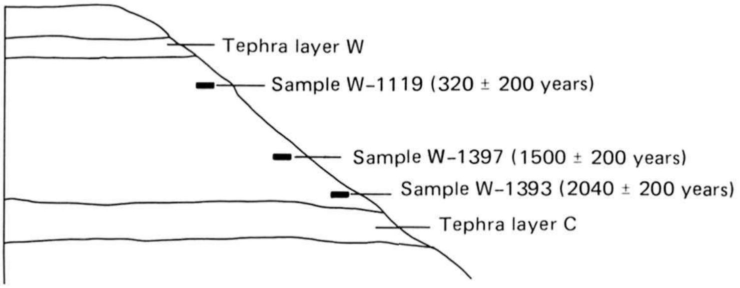
[2] Based on comparison of radiocarbon dates to bristlecone-pine tree-ring dates (Suess, 1970; and H. Suess, oral commun. to Meyer Rubin, 1972) in years before 1950. Fluctuation in atmospheric radiocarbon concentrations in the past can cause one radiocarbon age to be equivalent to a range of bristlecone-pine ages.

[3] Calendar dates are derived from bristlecone-pine ages and differ from radiocarbon ages in this table by as much as 900 years, because of fluctuation of atmospheric radiocarbon concentrations in the past.

[4] Based on several radiocarbon dates. (See Crandell, 1971, p. 24.)

[5] Based on several radiocarbon dates. (See p. 29.)

[6] No date available.



STRATIGRAPHIC POSITIONS of selected radiocarbon samples from sediments between layers C and W. (Fig. 10)

layer. The assigned age of 6,400 years is an obvious choice of an even number within that range. Table 5 lists the dates that have been used to assign ages to all the tephra deposits. Only the closest limiting dates available for each tephra unit, however, are listed in table 5. For example, more than two dates have been obtained from sediments in various stratigraphic positions between tephra layers C and W (fig. 10). The oldest of these (sample W-1393) is most useful for dating layer C, and the youngest (W-1119) is most useful for dating layer W; other available dates do not need to be listed in the table.

The tephra beds most useful as marker beds for dating or correlation of other deposits are those which are widespread, well preserved, conspicuous, and easy to identify. In Mount Rainier National Park, the tephras from volcanoes other than Mount Rainier meet those requirements best. Those from Mount Rainier that are thick are highly useful, however, and even thin beds can be valuable tools where conditions are suitable.

In the park, tephra beds have been used to date other deposits, but have been used more to subdivide and correlate deposits from one place to another. They have been especially valuable for use in correlation of glacial deposits on the uplands, and of sequences of volcanic mudflows (lahars) and river deposits (alluvium) on the valley floors (Crandell, 1971). For example, layer O, the most conspicuous and widespread of the tephras, is so widely preserved that it is almost invariably present on moraines of the last major glaciation and, so, distinguishes them from the younger Neoglacial moraines. The presence of layers Yn, L, D, or F, each of which is widespread and distinctive, can also be used to distinguish the older moraines from the Neoglacial ones. Layer C, however, was erupted after the earlier of two Neoglacial episodes but before the younger (Crandell and Miller, 1964). The presence of the widespread and distinctive layer C thus differentiates the moraines of the older Neoglacial episode from those of the younger, on which no layer C is present. The younger Neoglacial moraines can be further subdivided by the presence of layer W into those that are older and younger than about 450 years (Crandell, 1969a, p. 30).

Lahars and associated alluvium of various ages are highly similar but can be subdivided into units younger and older than various tephra deposits. Layers O, Yn, and W are particularly valuable for such work because they are noticeably different in composition from the materials derived from Mount Rainier volcano. The use of these tephras to subdivide valley-floor deposits is illustrated by the sequence in the Nisqually River valley (Crandell, 1971). The sequence there includes at least 12 lahars and 8 fluvial deposits, and those deposits are subdivided into lahar and alluvium assemblages of 4 ages that are interbedded with the tephra units, as follows (Crandell, 1971, p. 32):

Lahar assemblage D
Pyroclastic (tephra) layer W
Lahar assemblage C
Pyroclastic layer Yn
Lahar assemblage B
Pyroclastic layer O
Lahar assemblage A

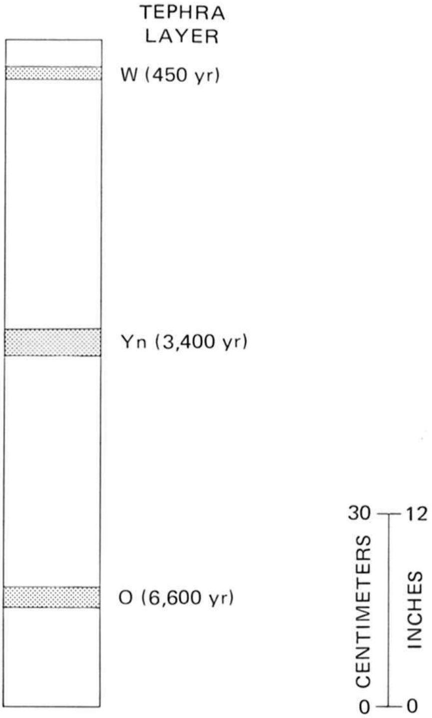
These particular tephra layers generally can be identified in the field, and the various lahar assemblages could be identified fairly readily wherever the tephra deposits are interbedded with them. Similarly, deposits that are about the same age can be identified from one valley to another by their relation to those tephra layers (Crandell, 1971, p. 11).

Tephra From Distant Volcanoes

The non-Rainier or exotic tephra layers are generally fine grained and light colored and are rarely more than a few centimeters thick. They stand out in outcrops as thin white or light-colored bands that contrast with the darker and duller colors of the Mount Rainier tephra. Layers O, Yn, and W are the most widely preserved and readily recognized and are therefore the most important marker beds. All the foreign tephra beds described here except layer O are from Mount St. Helens volcano, which is 80 km (50 miles) south-southwest of Mount Rainier. Layer O was erupted by prehistoric Mount Mazama at the present site of Crater Lake, Oreg., about 440 km south of Mount Rainier.

TEPHRA LAYER O (MAZAMA ASH)

Layer O in the park is a thin yellowish-orange to pale-brown fine ash that occurs near the base of the tephra sequence (fig. 11). It is widespread and probably the most visually striking ash in the park (frontispiece, figs. 5, 7). Locally it is interbedded with peaty material



REPRESENTATIVE STRATIGRAPHIC POSITIONS, thicknesses, and ages, in radiocarbon years, of layers O, Yn, and W, relative to the postglacial tephra sequence as a whole. (Fig. 11)

and is white (fig. 6), but at most places it is strongly colored. Although most of it is no more than 5 cm (2 in.) thick, it is remarkably well preserved. It is found not only in alpine meadows, but also on steep valley walls, and on valley floors, where it is commonly interbedded with river sediments and mudflow deposits.

Individual ash particles, most of which are too small to be seen with the naked eye, are chiefly crystal fragments and highly vesicular pumice. The larger pumice grains appear silky under a microscope because their vesicles are drawn out into tiny elongate tubes. The pumice is not strongly weathered, even though individual particles have rusty coatings that give the layer its color. These coatings may consist largely of noncrystalline clay material and iron oxide; no more than a trace of crystalline clay minerals was detected by X-ray-diffraction analyses of six samples of the ash (p. 72).

DISTRIBUTION, THICKNESS, AND GRAIN SIZE

The tephra of layer O fell throughout the park and far beyond its boundaries. No consistent trends in thickness were noted within the park, and layer O is 1-5 cm (½-2 in.) thick nearly everywhere. The deposit consists mostly of silt-size fine ash, with lesser amounts of coarser grains as much as 0.5 mm across. The median grain size of samples of this layer at 10 sites within the park ranged from approximately 0.015 mm to 0.035 mm. No trends in grain size were evident in the field, but laboratory analyses show that the deposit is slightly coarser in the southern part of the park than in the north.

Considerable local thinning and thickening can be seen in this layer, and locally its original thickness appears to have been as much as 8-10 cm (3-4 in.). The layer is much thicker where it was washed into ponds that existed along streams when the tephra fell. Thicknesses of 25 cm at such sites are not unusual, and the thickest deposit of layer O seen is slightly more than 50 cm thick. The ash has been segregated into conspicuously coarse and fine fractions in some of the pond deposits. The median grain size of one such coarse zone in a deposit near Mystic Lake is about 0.2 mm, about 10 times the average median diameter of the 10 airlaid samples analyzed.

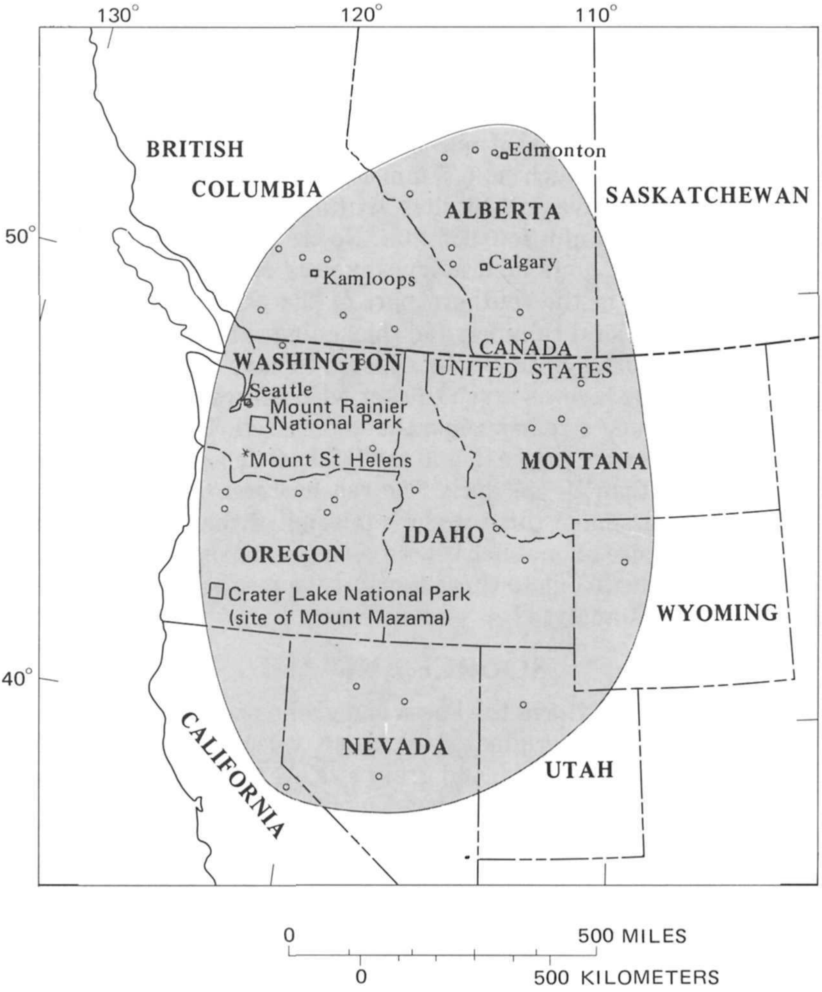
SOURCE AND AGE

The relatively uniform thickness and grain size of layer O across the park imply that it originated at some volcano other than Mount Rainier. Its age, thickness, and grain size are all consistent with what would be expected in this region for the Mazama ash, which covers much of the Pacific Northwest (Powers and Wilcox, 1964), and Wilcox (oral commun., 1962) has confirmed that it is petrographically similar to the Mazama ash. Thus, layer O is regarded to be a part of the Mazama tephra blanket that is near the western limit of distribution now recognized for that tephra (fig. 12).

Organic material from just above layer O in the park has been dated as 6,730±250 years old (table 5). Radiocarbon ages for the Mazama ash elsewhere vary by several hundred years; a commonly used age of 6,600 years is based largely on a date of 6,640±250 years for charred wood from within the layer near Crater Lake and on dates of 6,600±400 and 6,630±400 for peat below and above the ash, respectively, near Seattle, Wash. (Rubin and Alexander, 1960, p. 161, 164).

DISTINCTIVE FEATURES

This ash bed can generally be distinguished from other tephras in the park by its color and nearly uniform grain size and thickness (table 3).



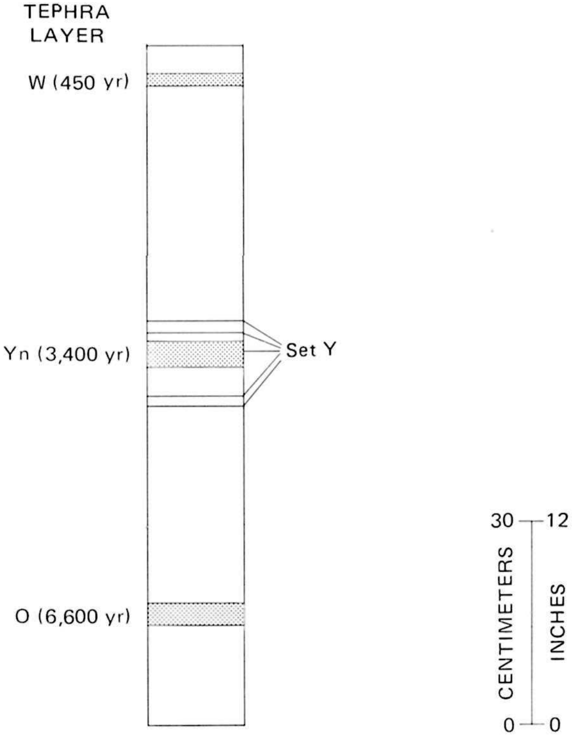
MINIMUM EXTENT OF MAZAMA ASH (patterned) in the Western United States and Canada. Circles mark sites where ash layer has been identified. From Powers and Wilcox (1964), Westgate, Smith, and Nichols (1970), and Wilcox, R. E. (oral commun., 1971). (Fig. 12)

At some places, it is similar in appearance to layer F (figs. 6, 7), but the latter contains a different suite of iron-magnesium minerals (table 3) and is limited to the eastern part of the park. Layer O also differs in that it contains no more than traces of clay minerals, whereas layer F locally is rich in montmorillonite and kaolinite (p. 72).

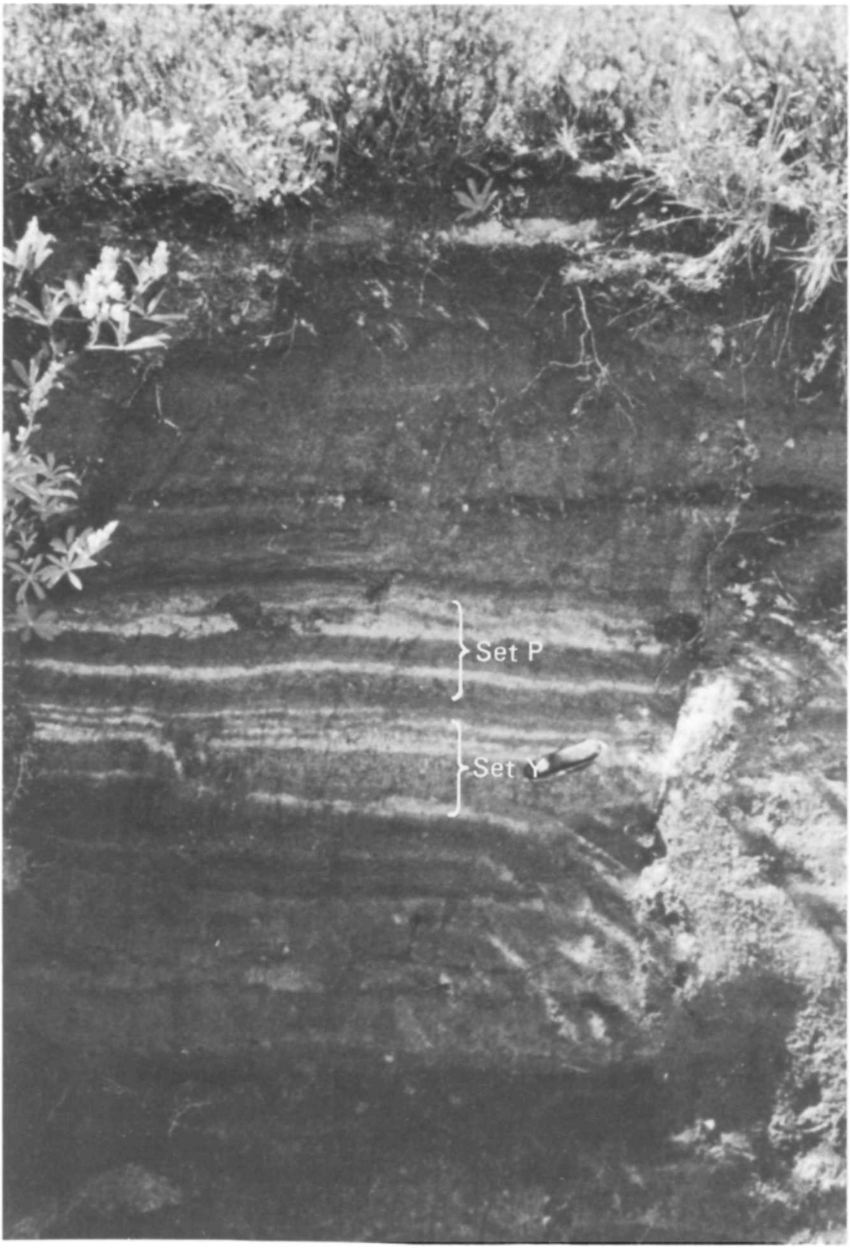
TEPHRA SET Y

One thick and several thin tephra layers that are characterized by a cummingtonite-hornblende iron-magnesium mineral suite constitute the parts of tephra set Y (Mullineaux, Hyde, and Rubin, 1972) that reached Mount Rainier. Only the one thick bed (layer Yn), however, is individually traceable across the park, for the others are not only thin but discontinuous. Nearly complete tephra sequences commonly show one and locally two beds below and two more above layer Yn (figs. 13, 14). Above these upper two set-Y beds are two other thin beds which are similar in appearance but which contain abundant particles probably derived from Mount Rainier. It is not clear whether these last two are primary ash layers of set Y that were contaminated by dust-size Mount Rainier debris or are merely layers of dust derived from set-Y tephra and local rocks on the flanks of Mount Rainier.

The thin ash beds of set Y are white or light gray, less than 1 cm (½ in.) thick, and composed of silt and sand-size particles. All consist chiefly of crystals and particles of milky nonvesicular to vesicular glass. They generally are not distinguishable from each other and are not readily separable from some tephra beds in the overlying set P except by laboratory examination of mineral content. Although locally



STRATIGRAPHIC POSITION of thin ash beds in set Y at Mount Rainier. (Fig. 13)



APPEARANCE OF THIN ASH BEDS in set Y and set P at Mount Rainier. (Fig. 14)

set-Y tephra beds have been seen both above and below layer Yn on the north and west flanks of Mount Rainier, they are common only in the southern and eastern parts of the park.

In some places these beds have an admixture of fine pyroclastic or windblown material derived from Mount Rainier, but elsewhere Mount Rainier detritus is absent, showing that the deposits must have come from a distant volcano. Their source is regarded to be Mount St. Helens because they are lithologically similar to pumice beds in set Y at that locality, and because layer Yn can be traced to that volcano. The age of set Y has been determined at Mount St. Helens to be between about 4,000 and 3,000 years (Mullineaux, Hyde, and Rubin, 1972).

TEPHRA LAYER Yn

Layer Yn is a yellow to brown deposit of pumice ash and small lapilli (figs. 6, 7) that is about 2 cm (1 in.) to more than 30 cm thick within the park. It is well preserved and is conspicuous where thick because it consists of loose, nearly uniformly sized grains that are small as compared with the thickness of the bed. These grains roll, slide, and wash down the slopes and cutbanks so that the layer appears to be thicker than it is. Although the pumice is white to colorless on fresh surfaces, the particles commonly have a yellowish-brown surface stain or alteration that colors the entire deposit. Lithic fragments are sparse, and crystals are abundant only in the ash-size fraction. The only iron-magnesium minerals in the pumice fragments are hornblende and cummingtonite; hypersthene, which is present in almost all other tephra deposits at Mount Rainier (table 3), is absent.

DISTRIBUTION, THICKNESS, AND GRAIN SIZE

Layer Yn pumice forms a long narrow tongue of tephra that extends from Mount St. Helens north-northeastward across Mount Rainier National Park into Canada (fig. 15). It is the most voluminous tephra within the park boundaries. The thickest and coarsest axial part of its long lobe lies west of the park boundary; as a result, the pumice becomes progressively thinner and finer grained toward the northeast (fig. 16). From an average thickness of slightly more than 30 cm (12 in.) in the southwest corner, it decreases to about 20 cm in the northwest corner and to about 2 cm along the eastern boundary. Lapilli as large as 2 cm across are common in the southwest corner, where the median grain size is about 1 mm. The median decreases to about 0.7 mm near the northwest corner and to 0.5 mm along the eastern boundary.

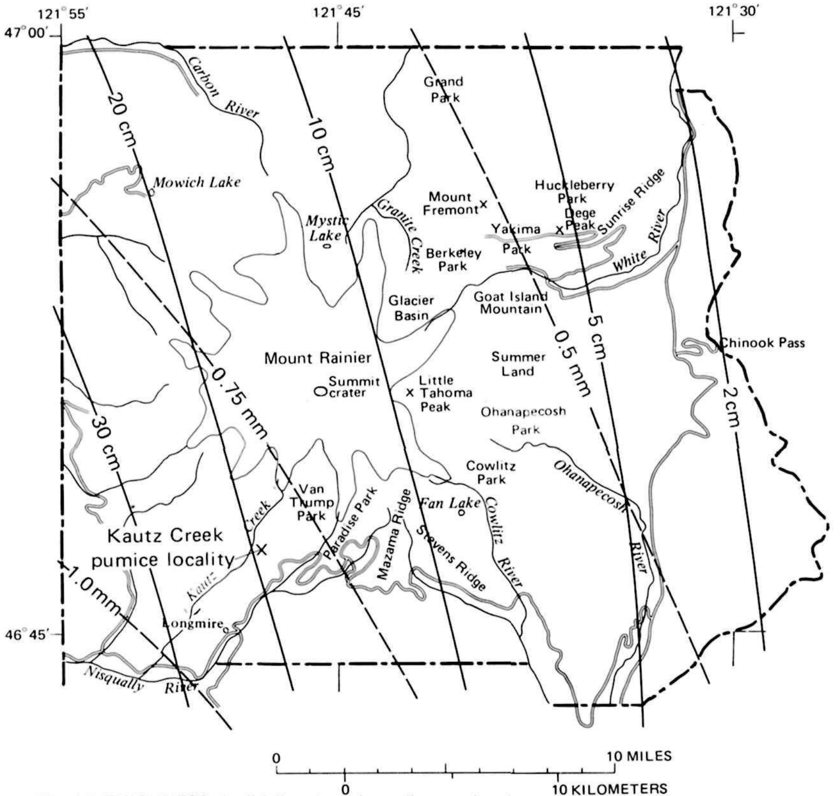
Abrupt local variations in thickness are common. This pumice fall produced a deep loose deposit of small lightweight particles, which probably blanketed and destroyed much vegetation, so the grains were easily reworked by wind and water. Accumulations of pumice several times the estimated original airfall thickness are common. Deposits as much as 1 m (3 ft) thick have been found within the park, a layer at

MINIMUM EXTENT OF LAYER Yn (patterned). Dashed line marks thick coarse axial zone. From Crandell, Mullineaux, Miller, and Rubin (1962); Fulton and Armstrong (1965); Nasmith, Mathews, and Rouse (1967); and Westgate, Smith, and Nichols (1970). (Fig. 15)

least 1.5 m thick is known northeast of the park, and a bed that is as much as 3 m thick lies just outside the northwest corner of the park.

SOURCE AND AGE

Layer Yn increases in grain size and thickness progressively southwestward from Mount Rainier to the base of Mount St. Helens, where it consists of more than 1 meter of lapilli and bombs of pumice; farther southwest, however, it is absent. On Mount St. Helens itself the layer is buried by younger deposits. Layer Yn is bracketed by



AVERAGE THICKNESS (solid lines) and median grain size (dashed lines) trends of layer Yn within Mount Rainier National Park. Thicknesses estimated from field observations; grain size determined by mechanical analysis in the laboratory. (Fig. 16)

radiocarbon-dated samples from near Mount Rainier that are about 3,500 and 2,900 years old and by other samples from near Mount St. Helens that are about 3,500 and 3,350 years old. It is assigned an arbitrary age of 3,400 years (table 5).

Layer Yn is the layer Y of Crandell, Mullineaux, Miller, and Rubin (1962). It is also the deposit described by Hopson and his coworkers as the characteristic layer of sand- to granule-size pumice that is the "main ash fall" that "constitutes the major part of the youngest ash blanket from Mount Rainier" (Hopson and others, 1962, p. 641). The cummingtonite content, thickness, and grain size of that sand and granule-size pumice layer, including the deposit at the critical Kautz Creek locality (Crandell and others, 1962, p. D67; Hopson and others, 1962, p. 641; fig. 16, this report), however, demonstrate that the sand- and granule-size pumice is part of layer Yn, rather than a pumice erupted by Mount Rainier.

The date of 500-600 years old obtained by Hopson and his colleagues for the pumice at the Kautz Creek locality was derived from tree-ring counts that showed a minimum age of 550 years and a radiocarbon sample whose maximum age was interpreted to be about 500 years (Hopson and others, 1962, p. 641, 643). The radiocarbon sample was taken from a tree stump on the streambed of Kautz Creek; the bouldery deposit in which the stump grew was held to be the same deposit as that which underlies the sand- and granule-size pumice in the nearby streambank (Hopson and others, 1962, p. 642). The stump was, therefore, judged to be older than the pumice. It seems certain that the two bouldery deposits are not the same, however, inasmuch as other limiting dates for the pumice show that it is much older than 500-600 years.

DISTINCTIVE FEATURES

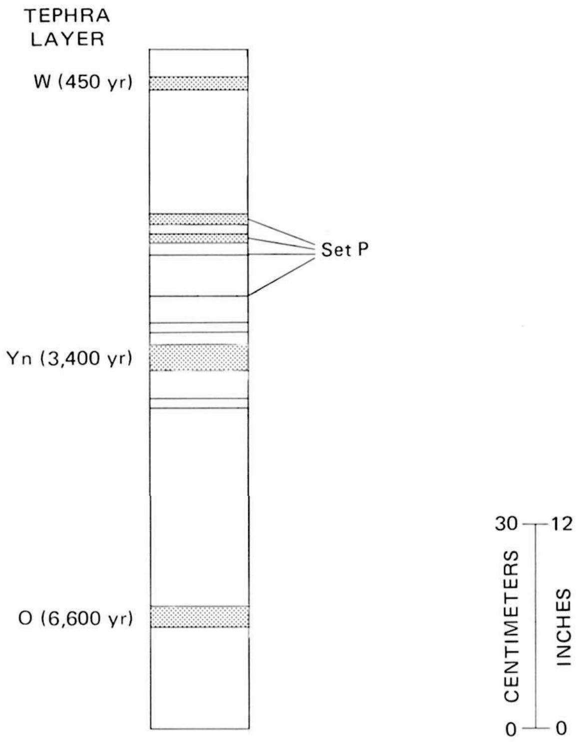
Layer Yn is the only tephra in Mount Rainier National Park that forms a thick yellow to brown pumice deposit of coarse ash and small lapilli size (table 3). Where it is thin, microscopic identification of its mineral content can be used to distinguish layer Yn, because no other coarse granular pumice in the park contains the same group of minerals (table 3).

TEPHRA SET P

At least four thin ash beds compose tephra set P (Mullineaux, Hyde, and Rubin, 1972) in Mount Rainier National Park. All are white to light gray except the lowest, which commonly is brown. All are less than 1 cm (½ in.) thick, and all consist of crystals and milky, largely nonvesicular glass particles. Some of these beds are not distinguishable in the field from thin beds in set Y, but the two sets can be separated by laboratory examination of their iron-magnesium mineral suites (table 3). Locally, the two lower beds of this set contain fragments of cummingtonite and rock derived from set-Y tephra and Mount Rainier lavas, whereas the upper two are nearly free of such particles.

The four beds, which are seen only in relatively complete tephra sequences, include the brown sand-size ash at the base, which is overlain by a thin silt-size ash and then by two light-gray sand-size beds at the top (fig. 14, 17). The lowest bed has been found only in the southeastern part of the park, but the silt-size ash is common over most of the eastern part. The upper two beds have been found everywhere except in the northwest corner of the park; there, only one, probably the uppermost, has been seen.

The uppermost of these beds is widely preserved and is a useful marker bed. It is nearly identical to the set-P ash bed just below it, though somewhat browner and slightly coarser, but apparently very



STRATIGRAPHIC POSITION of set-P ash beds at Mount Rainier.
(Fig. 17)

close to the same age. It is somewhat similar in appearance to layer W, but in most places is separated from that deposit by coarse brown pumice of layer C from Mount Rainier. Where necessary, set-P tephra can be distinguished from layer-W tephra by the refractive index of the mineral hypersthene. (See p. 69.)

These four tephra beds are fairly uniform in thickness and grain size wherever they are found in the park and must have come from a volcano other than Mount Rainier. Although they have not been traced to Mount St. Helens, they are similar lithologically to set-P beds that are known to originate at, and extend far northeast from, that volcano; for the present, they are regarded as part of the Mount St. Helens set-P tephra. At Mount St. Helens, the oldest set-P tephra is about 3,000 years old (Mullineaux, Hyde, and Rubin, 1972), and all set-P tephra at Mount Rainier are older than about 2,460 years (table 5).

TEPHRA LAYER W

Layer W is a thin white, locally light-brown bed of loose sand-size pumiceous and crystal ash. It is the youngest tephra at Mount Rainier that forms a distinct bed, and it locally makes a conspicuous band at or near the ground surface (frontispiece). In some other places, it occurs as a white sand spread over the surface.

Pumice and crystals compose almost the entire deposit. The pumice generally is white and is not noticeably weathered, but in some places the entire bed is stained brown. Dark minerals and a few lithic fragments are conspicuous enough in a few places to give the bed a "salt-and-pepper" appearance.

DISTRIBUTION, THICKNESS, AND GRAIN SIZE

Layer W forms a long lobe that trends northeast from Mount St. Helens; its thickest and coarsest axial zone passes through the southeast corner of the park, where its average thickness is 5-8 cm (2-3 in.). It becomes thinner and finer to the west and north and is absent in the northwestern part of the park (fig. 18). The deposit is generally well preserved, and reworked accumulations seldom are more than twice the average thickness. The largest particles are lapilli about 8 mm across, and the median grain size in the southeast corner of the park is 0.4-0.5 mm. The median size decreases to about 0.3 mm at the north boundary of the park and at the western limit of the well-defined bed of ash.

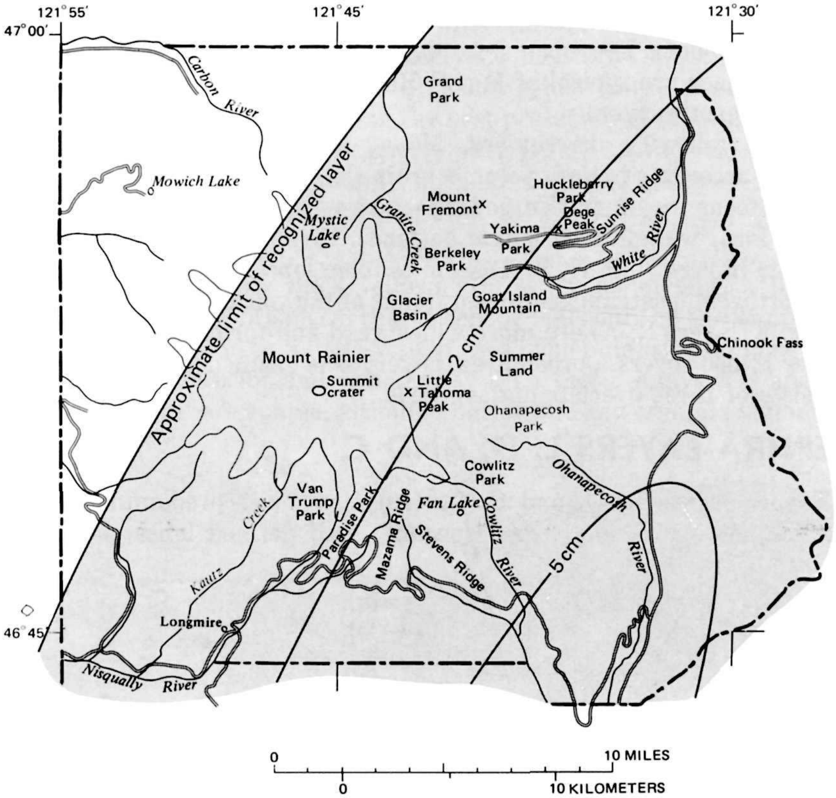
SOURCE AND AGE

Like layer Yn, this deposit increases in thickness and grain size southwestward from Mount Rainier and can be traced to Mount St. Helens. It forms a thick deposit of pumice lapilli and blocks on the flanks of that volcano, but thins and abruptly becomes absent farther southwest.

Near Mount Rainier, the layer is underlain and overlain by wood fragments, whose radiocarbon content indicates ages of about 320 and 290 years, respectively (Crandell and others, 1962). The calendar age of wood having that radiocarbon content can be about 300 or 450 years (Stuiver and Suess, 1966). Because trees as much as 435 years old are growing on terraces near Mount Rainier that are younger than layer W (Crandell, 1971, p. 12), the layer is regarded to be about 450 years old.

DISTINCTIVE FEATURES

Layer W is distinguished from most other ash layers in the park by its white color and sand-size pumice grains (table 3) and by its position at or not far below the surface. Where necessary, it can be distinguished from set-Y and set-P tephra by laboratory examination to determine identity and refractive index of its iron-magnesium minerals. (See table 3; p. 69.)



DISTRIBUTION AND AVERAGE THICKNESS of layer W within Mount Rainier National Park. (Fig. 18)

Mount Rainier Tephra Deposits

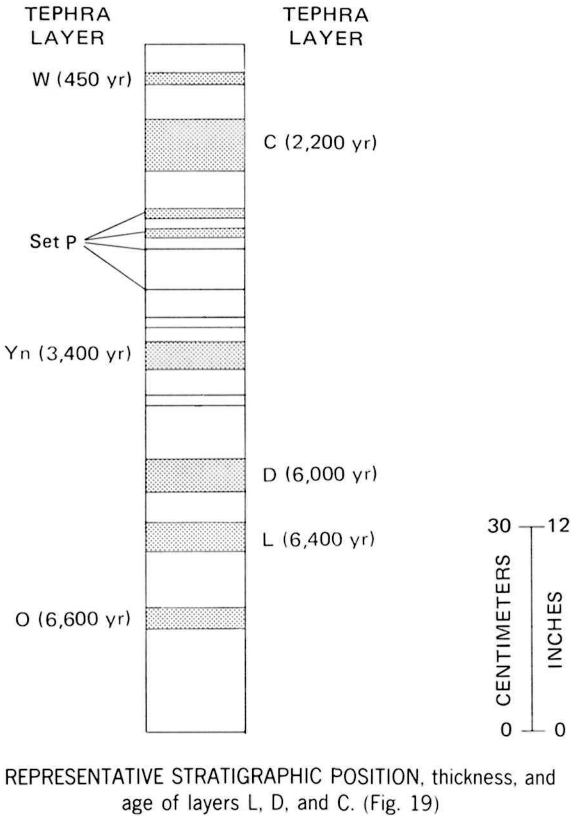
Certain features are common to nearly all the tephra layers from Mount Rainier and locally distinguish those layers in the field from the exotic tephra beds and interbedded sands. Coarse grain size is the most distinct feature: all the Rainier tephra beds described include lapilli-size fragments; and some layers, especially on the volcano's flanks, consist mostly of lapilli and bombs or blocks. In contrast, lapilli are absent or sparse in the exotic tephras. Mount Rainier tephra also is commonly moderate brown to grayish brown, and the brown color is emphasized by reddish-brown weathering products. Their color generally is darker than that of the exotic tephra beds, yet is lighter or browner than the gray to brownish-gray of many of the interbedded sands. (See frontispiece.)

Mount Rainier tephra layers also are mostly limited to areas east of the volcano. Westerly winds during most eruptions concentrated the tephra in elongate lobes downwind from the vent. Grain size and thickness decrease rapidly downwind, and also from the axis to the sides of the lobes. These rapid changes in grain size and thickness from place to place are typical of Mount Rainier tephra layers, in contrast with the exotic layers.

In the following descriptions, Mount Rainier tephra deposits are grouped according to their volume, grain size, and the kinds of distribution patterns they form. Three large coarse-grained deposits (layers L, D, C), form well-defined lobate patterns. Five smaller, finer grained deposits (layers N, S, H, B, X) seem to form lobes that are confined to the northeast, east, and southeast flanks of the volcano. Two additional deposits (layers R, A) are more widespread and form indistinct lobes. Layer F also covers a broad area, is very fine grained, and apparently consists of three overlapping ash beds.

TEPHRA LAYERS L, D, AND C

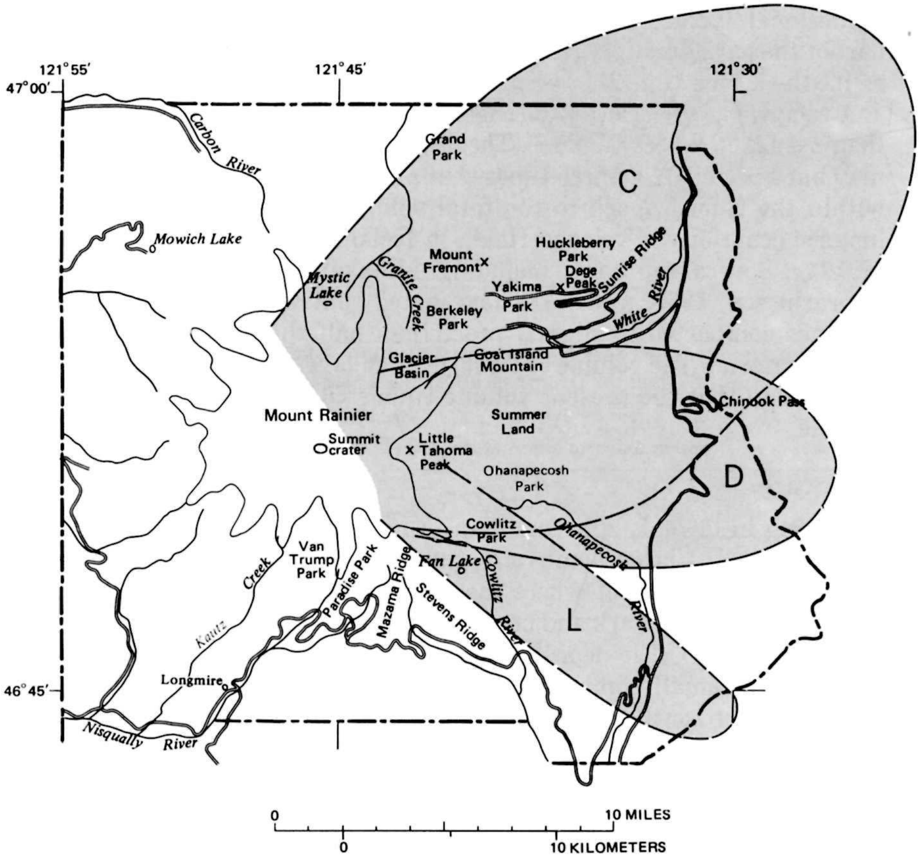
Tephra layers L, D, and C (fig. 19) all consist predominantly of pumice and scoria and form especially well defined lobes that lead



REPRESENTATIVE STRATIGRAPHIC POSITION, thickness, and age of layers L, D, and C. (Fig. 19) southeast, east, and northeast away from Mount Rainier, respectively (fig. 20). All locally are at least 15 cm (6 in.) in maximum thickness, contain bombs or blocks, and make conspicuous brown, coarse deposits where they are more than about 2 cm thick. These deposits have resisted erosion well, are among the best preserved of all tephra units, and are the easiest of the Rainier tephra layers to find and identify. They are the most commonly preserved Mount Rainier tephras between alluvial and mudflow deposits on valley floors.

LAYER L

Layer L is a locally thick yellowish-brown layer of pumice lapilli, bombs, and ash (frontispiece) that is conspicuous only on the southeast flank of the volcano in a little-visited area. The pumice fragments are more uniform in color and vesicularity than those in layers D and C, and lithic lapilli are sparse, although both lithic and crystal fragments



GENERALIZED DISTRIBUTION PATTERNS of layers L, D, and C where they are more than 5 cm thick. Limits are highly approximate. (Fig. 20) are abundant in the ash-size fraction. Pumice lapilli are commonly somewhat weathered on their outer surfaces but the weathering rinds are thin.

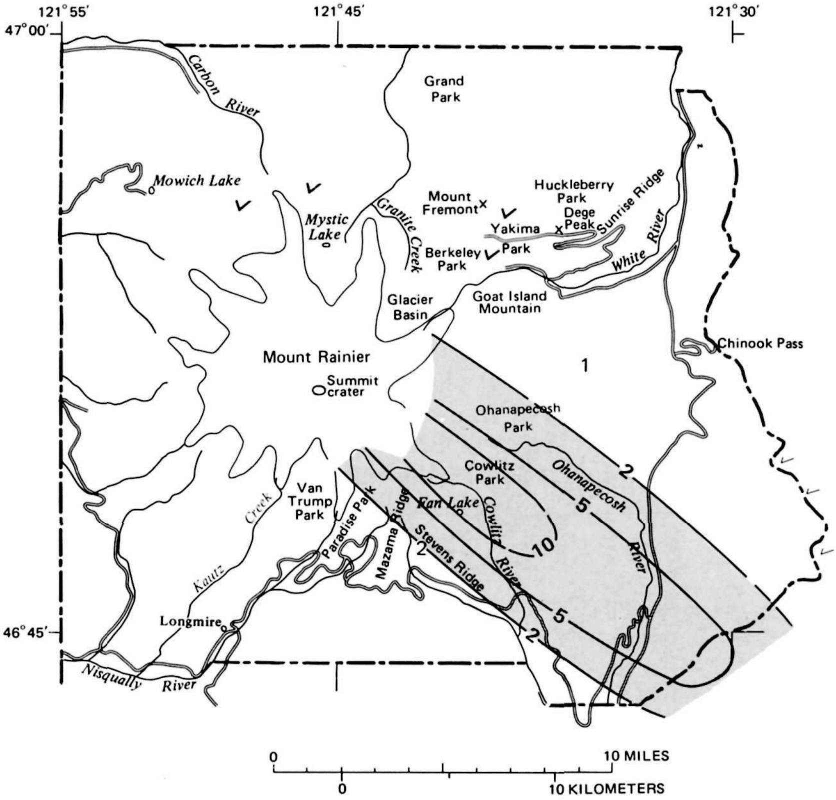
Distribution, thickness, and volume

Layer L occurs widely in the eastern half of the park, but it is thick only in a narrow southeast-trending tongue (fig. 21). It is thickest in Cowlitz Park, where locally its undisturbed thickness is 25 cm (10 in.). It is at least 15 cm thick in many other exposures in Cowlitz Park and on the next ridge to the southwest near Fan Lake. Although exposures are poor farther southeastward, thicknesses of 8 cm are common 10 km (6 miles) to the southeast in the Ohanapecosh River valley. The thickness diminishes more rapidly across the lobe to the northeast and southwest; in Ohanapecosh Park and on Stevens Ridge, at the same distance from the summit as Cowlitz Park, the layer is no more than 2 cm thick. Although thickness changes are rapid, they seem to be gradational. Layer L occurs discontinuously but widely in the northern part of the park, but apparently is absent beyond a short distance south of its thick lobe (fig. 21).

A volume has been calcuated roughly for the part of layer L that is more than 2 cm (1 in.) thick (table 6). The original volume of the entire deposit may have been two or three times that amount; such a ratio for volume within the 2-cm isopach to the total volume has been calculated for historic eruptions of volcano Hekla in Iceland (Thorarinsson, 1967, p. 48, 94). Several authors, including Minakami (1942b, p. 95) and Thorarinsson, 1967, p. 34, 48) have noted that with time the tephra becomes compacted to slightly more than half the volume of freshly fallen material. The volume of freshly fallen layer L is estimated on the assumption that the present volume equals 60 percent of the original volume.

Grain size

Sorting in layer L is better than in most other tephra layers from Mount Rainier—large bombs are not common in lapilli deposits, and lapilli are not abundant where the layer is chiefly ash. The deposit is coarsest in Cowlitz Park and near Fan Lake in the areas where it is also thickest (fig. 21). The deposit consists chiefly of lapilli in those areas but contains small bombs as much as 5 cm (2 in.) across. Ten km (6 miles) farther southeast along the axis of the tephra lobe, the deposit still is chiefly lapilli and commonly contains lumps as much as 3 cm across. The grain size decreases more rapidly across the lobe to the northeast and southwest. In Ohanapecosh Park and on Stevens Ridge, only about 3 km from Cowlitz Park, most of the largest fragments are less than 2 cm across.



DISTRIBUTION AND AVERAGE THICKNESS, in centimeters, of layer L. Checks mark sites where layer has been found but is less than 1 cm thick. (Fig. 21)

TABLE 6.—*Volume of layer L, in millions of cubic meters*

	Total volume within 2-cm isopach	Minimum total volume
In present state	15	30
As freshly fallen	25	50

Source

Progressive increases in thickness and grain size in the narrow tongue of layer L point to a vent at the summit of Mount Rainier as its specific source. The narrow band of thick and coarse tephra also indicates that a consistent northwest wind blew while most of the material was being erupted. The spotty, thin deposits of layer L tephra in the northern part of the park, on the other hand, suggest that southerly and perhaps variable winds blew during ejection of a small part of the tephra, perhaps during one or more pulses of the waning stage of the eruption.

Distinctive features

On the southeast flank of the volcano, thickness and coarse grain size distinguish layer L from all tephras except layers D and C. Layer L consists of lighter colored fragments than layer D, it is noticeably lower in the tephra sequence than layer C, and it contains fewer lithic fragments than either of the other two coarse tephras. It also differs in mineral content from the other two. Where layer L is thin and fine grained, its stratigraphic position between the prominent layers O and D is the most helpful field criterion for identification. Layer L usually is underlain and overlain by thin beds of dark-gray ash, whereas layer A, the only other pumiceous tephra in that stratigraphic position, is not. Laboratory examination of the refractive index of olivine also helps to distinguish layer L from layer A.

LAYER D

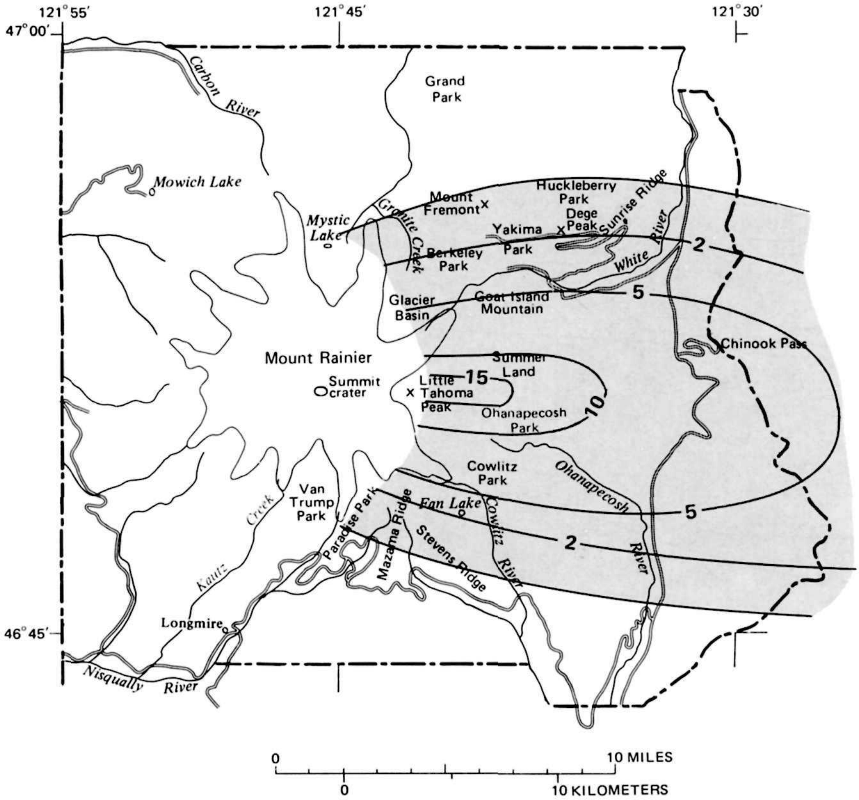
Layer D is a conspicuous thick yellowish- to reddish-brown deposit (fig. 22) that consists mostly of scoria and pumice lapilli. Its striking features are (1) a relatively strong color, (2) abundant dark-gray scoria, (3) scattered bombs that are much larger than the average fragment size, and (4) abundant hornblende in both scoria and pumice. The pumice, usually pale brown, is not nearly as abundant as the darker scoria. Lithic fragments are common though they usually are masked by reddish-brown weathering products. These products, probably derived largely from the scoria, generally stain the entire layer. Large scoria lapilli have visible weathered rinds, and some small lapilli are weathered enough to be soft all the way through. The weathered rinds are soft, and smear easily to a brown gritty clay. The alteration products have formed chiefly from volcanic glass, for the crystals are firm. Layer D is more weathered than most other tephra deposits, probably because of its more basic composition (table 10).

Distribution, thickness, and volume

Layer D forms a well-defined lobe that extends eastward from Mount Rainier to far beyond the park boundary (fig. 23). It forms a somewhat thinner but broader main lobe than does layer L (fig. 19).

The average thickness of the deposit is greatest in the northern part of Ohanapecosh Park and at Summer Land (fig. 23). The maximum thickness of undisturbed tephra in those areas is about 15 cm (6 in.). Thicknesses of 10 cm are common elsewhere in and near Ohanapecosh Park, and at the eastern park boundary the layer still is as much as 8 cm thick (fig. 23). To the north and south across the lobe, it thins more

TEPHRA SEQUENCE in the southwestern part of Ohanapecosh Park, showing the color, grain size, and thickness of layers D, N, F, and B (at pick point). Most pumice and scoria layers from Mount Rainier here show strong brown colors that distinguish them from the interbedded gray to brownish-gray lithic ash beds. Layer B, however, typically is gray; and lapilli of layer C that are exposed at the ground surface, as they are here, are typically light brown or gray. Compare with figure 7. (Fig. 22)



DISTRIBUTION AND AVERAGE THICKNESS, in centimeters, of layer D (Fig. 23)

rapidly, to less than 8 cm thick in a distance of only about 5 km (3 miles). Variations from the average thicknesses, however, are common. Although the deposit seldom is completely eroded away at sites where other tephra deposits are well preserved, reworking of small lapilli into thick wind-drift or fluvial accumulations is fairly common. At one site southeast of the summit, an accumulation 60 cm thick was found where the average thickness is less than 10 cm.

The volume has been calculated roughly for the part of layer D that lies within the 2-cm isopach and the total present and freshly fallen volumes have been estimated (table 7) in the same manner as for layer L. (See p. 42.)

Grain size

Layer D consists chiefly of lapilli throughout its extent in the park. Overall, it is coarsest grained directly east of the volcano's summit, where it is thickest. In Ohanapecosh Park and at Summer Land the

TABLE 7.—*Volume of layer D, in millions of cubic meters*

	Total volume within 2-cm isopach	Estimated minimum total volume
In present state	23	45
As freshly fallen	38	75

largest bombs are about 15 cm (6 in.) across, and others more than 5 cm across are abundant. At the eastern boundary of the park, a few bombs are as large as 5 cm across, and lapilli as large as 2 cm in diameter are common. Even at the mapped margins of this bed, the bed consists chiefly of lapilli rather than ash.

The largest bombs, however, do not lie in the thickest part of the layer. The largest ones found, about 50 cm (20 in.) across, are on Mazama Ridge southeast of the volcano summit where layer D is less than 2 cm thick. Other bombs as much as 15 cm across have been found on Stevens Ridge, as well as at Ohanapecosh Park and Summer Land, but none that big was seen in Cowlitz Park. The large bombs seem to lie in two different sectors, one approximately east and the other southeast of the summit.

Source and origin

The marked decrease in grain size and thickness away from Mount Rainier points to a summit vent as the source of layer D. The eastward distribution of lapilli and small bombs probably was controlled by a steady wind from the west at the time of eruption. Because there is no evidence of change in wind direction during that time, it seems likely that the eruption was of relatively short duration.

Some factor other than wind, however, must be responsible for the projection of large bombs southeastward from the summit. It seems likely that they were ejected at high velocities with such a strong horizontal component that their flight was little affected by the wind. Studies by Minakami (1942a) of the 1935 and 1941 eruptions of Asama volcano in Japan show that large bombs fell over a much wider arc than small ejecta. There, the bombs that traveled farthest from the vent were those that had the lowest possible angle of emission that permitted escape over the crater wall. A low saddle in the southeastern part of the crater wall of Mount Rainier during eruption of layer D could have allowed the projection of large bombs onto Mazama Ridge.

Distinctive features

Layer D can be recognized readily in most places east of the volcano because it is relatively thick and coarse grained. In addition, its abundant scoria generally distinguishes it from all other tephra deposits. Where field criteria are not adequate, layer D can be identified under the microscope by its abundant hornblende.

LAYER C

Layer C is a thick coarse brown bed of lapilli, blocks, and bombs that commonly lies at or near the ground surface. It is the largest and most widespread of the Mount Rainier tephra deposits and contains brown to nearly white pumice, dark-gray scoria, and lighter gray lithic fragments. Some large bombs of pumice and scoria enclose white pumice lapilli and also angular lithic fragments.

Layer C varies somewhat in proportion of rock types, both vertically within the layer and horizontally from place to place. Dark scoria, for example, is concentrated at the base and on the north flank of the volcano. Gray lithic fragments are most abundant near the base but above the scoria and on the northeast and east flanks of the mountain. Brown pumice occurs vertically throughout the layer but constitutes most of the middle and upper parts, and it is also most common on the northeast and east flanks. These vertical and horizontal variations seem to record either more than one eruptive shower or, possibly, changes in type of material erupted and in wind direction during a continuous eruption.

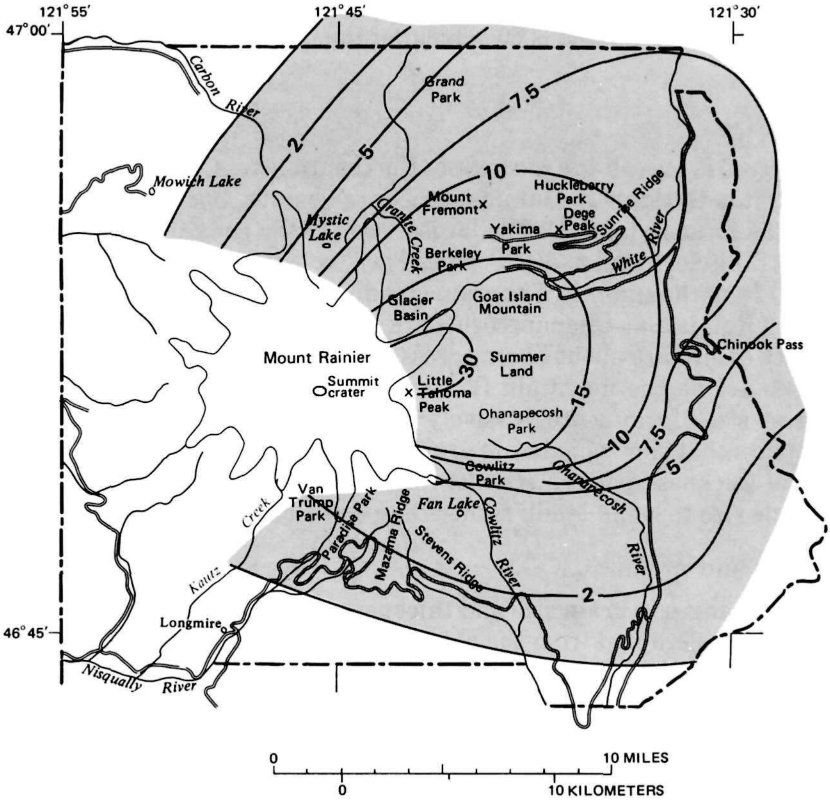
Two thin beds of brown pumice lapilli in the stratigraphic position of layer C are separated by a few centimeters of ash in several outcrops on the southeast flank of the volcano. No other evidence of a time interval between the two pumice beds was seen, however, and a separation of layer C into two beds is not evident in most outcrops in that area.

Fragments in layer C are not strongly weathered; most pumice lapilli are firm, and weathering is limited to a thin zone at the surface of the lapilli. The deposit appears unweathered and unstained where it lies at the ground surface though it commonly is stained brown where it is buried (fig. 6).

Distribution, thickness, and volume

Layer C occurs in a wide northeasterly trending lobe that extends over much of the park and beyond its boundaries to the north and east (fig. 24). The thickest airfall deposit seen is at Summer Land, where it is about 30 cm (12 in.) thick. The layer is at least 15 cm thick over a wide area that includes Ohanapecosh Park and that reaches nearly to Yakima Park (fig. 24). At the northeast boundary of the park, it is still 8 cm thick at a distance of 25 km (15 miles) from the summit. Layer C is equally thick over a wide arc near the volcano—the isopach for a thickness of 10 cm, for example, outlines a very broad lobe. Farther away, however, the thick part narrows markedly and the isopachs for lesser thicknesses outline more elongate lobes to the northeast (fig. 24).

Variations from average thicknesses are relatively unimportant and indicate only minor reworking of this layer. Layer C rarely is absent within the distribution shown in figure 24 where other tephra layers are preserved. Thicker accumulations from wind drift and stream



DISTRIBUTION AND AVERAGE THICKNESS, in centimeters, of layer C. (Fig. 24)

deposition also generally are less than twice the airfall thicknesses in the same area. The thickest reworked accumulation seen is at one site in Yakima Park, where the deposit is nearly 30 cm thick, about twice the airfall thickness at that locality.

Layer C is the largest of the Mount Rainier tephra layers, and most of it lies outside the park boundaries. Calculation of even the volume lying within the 2-cm (1 in.) isopach (table 8) requires projection of isopachs considerably beyond the park. The estimates of the total and freshly fallen volumes (table 8) are based on the assumptions that the

TABLE 8.—*Volume of layer C, in millions of cubic meters*

	Total volume within 2-cm isopach	Minimum total volume
In present compacted state	90	180
As freshly fallen	150	300

total volume is at least twice the amount within the 2-cm isopach and that the present volume is 60 percent of the freshly fallen volume. (See p. 42.)

Grain size

Layer C is overall the coarsest of the tephra layers, and it is coarsest where it is thickest. It contains some large bombs, but they are not as large as those in layer D. The largest seen, 25-30 cm (10-12 in.) across, are at Summer Land and at Cowlitz Park, at distances of about 8 km (5 miles) from the summit. The grain size diminishes rapidly farther from Mount Rainier; at Ohanapecosh Park, 9-10 km from the summit, the largest bombs are about 15 cm across. The large bombs are spread over a wide arc on the mountain flanks, whereas at greater distances the largest sizes form a progressively narrower northeast-trending lobe. Contours that show maximum grain size form nearly the same pattern as the thickness pattern (fig. 24). Layer C decreases in predominant particle size to small lapilli rather than ash along the lateral margins.

Source and origin

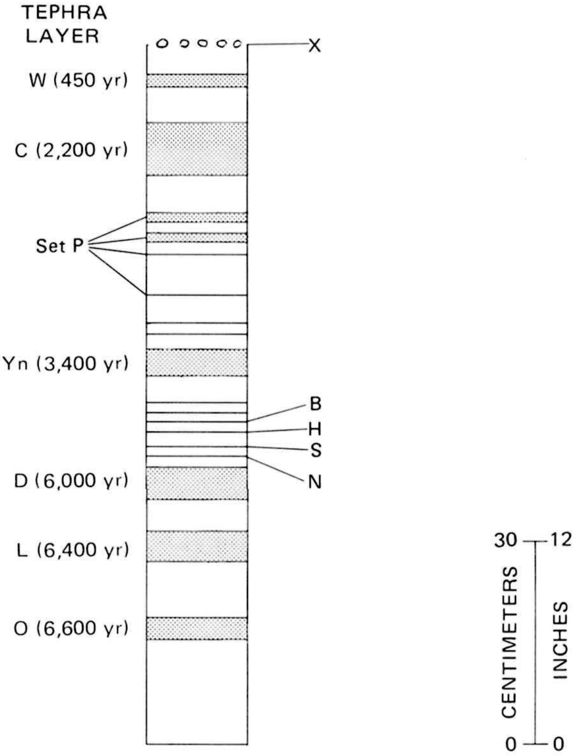
The changes in grain size and thickness within the park suggest that layer C was erupted from the central vent at Mount Rainier's summit. Horizontal and vertical variations of rock types, however, indicate that the material was ejected in more than one shower, under changing wind conditions. Dark scoria from an explosion early in the eruptive episode was blown chiefly to the north, then lithic fragments from a subsequent explosion were carried chiefly to the northeast and east. Later, a much larger volume of pumice buried the scoria and lithic fragments and spread far to the northeast, implying a southwesterly wind. No evidence has been seen of a long period of time between the successive eruptions.

Distinctive features

Layer C is so thick and coarse that it is not likely to be confused with any layer other than L or D, and with them only south or east of the volcano. Its prominent brown pumice distinguishes it from layer D, and its dark scoria and lithic fragments should separate it from layer L. In the laboratory, the presence of hornblende helps distinguish layer C from most other tephra deposits from Mount Rainier, and the sparseness of that mineral shows that it is not layer D.

TEPHRA LAYERS N, S, H, B, AND X

Five deposits that seem to form small lobes east of Mount Rainier's summit are designated, from oldest to youngest, layers N, S, H, B, and X (fig. 25). Each of these has been recognized only in a small area east

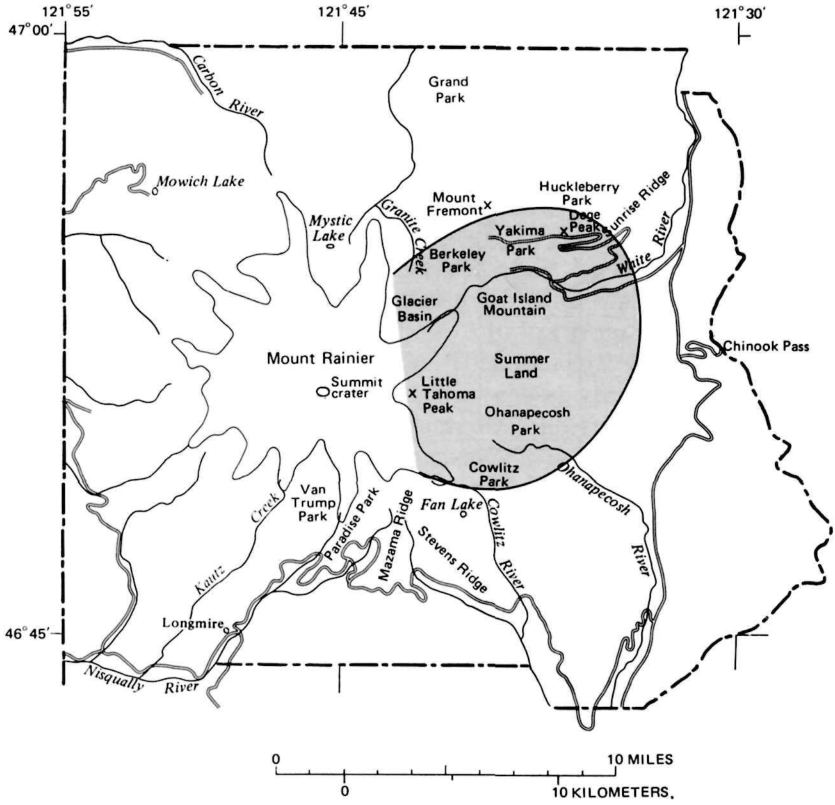


STRATIGRAPHIC POSITIONS of layers N, S, H, B, and X. (Fig. 25)

of the volcano. Three layers (N, H, B) consist of lithic and pumice or scoria lapilli in thin ash; one layer (X), where found, consists only of pumice and scoria lapilli, and the other (S) consists of lithic blocks and lapilli in lithic ash. All but layer S are too thin to be readily recognized anywhere but in the alpine meadows, or, as for layer X, on glacial deposits that are so young that no other tephra deposits lie on them.

LAYER N

Layer N is a thin inconspicuous gray to reddish-brown layer of small lapilli and relatively coarse ash (fig. 22). It consists chiefly of lithic fragments but locally includes abundant brown pumice and brown to gray scoria. The proportions of these constituents vary considerably from place to place; most of the larger particles are brown pumice in Yakima Park, scoria or lithic fragments in Ohanapecosh Park, and lithic fragments in Cowlitz Park. In many places the layer is stained yellowish or reddish brown, yet individual lapilli are not strongly weathered.



MINIMUM EXTENT of layer N. Limit is highly approximate. (Fig. 26)

Layer N is distinct from Yakima Park south to Cowlitz Park (fig. 26). Scattered lapilli in the same stratigraphic position that probably are part of this deposit also occur a few kilometers north of Yakima Park and as far east as the park boundary. The layer is thickest and best preserved in Ohanapecosh Park, but even there it is typically less than 2 cm thick. The largest lapilli, most no more than 1 cm in diameter, are in the same area. Lapilli, however, make up only a small part of the layer, which is chiefly ash.

Only a very rough estimate of the volume of the layer can be made because so little is known of its thickness and extent. An estimated volume of tephra as freshly fallen, based on an average thickness of 2 cm in a lobe that reaches Ohanapecosh and Cowlitz Parks, is 2-3 million m^3.

The limited distribution of layer N east of the volcano and its lithologic similarity to other tephra from Mount Rainier indicate that it was erupted by Mount Rainier. Its pumice and scoria lapilli lack

RUBBLE OF LAYER S above undisturbed continuous layer O. Roadcut is 3 km (2 miles) east of Ranger Station at Yakima Park.(Fig. 27)

hornblende, showing that it was not derived from the underlying layer D but represents a different, younger eruption.

The variety of rock types from place to place and the broad extent of such a thin deposit suggest that layer N may have originated from more than one eruptive pulse. The kind of ash ejected and also the direction of the wind, though generally westerly, probably changed during the eruptive episode.

Layer N is not distinctive in the field, and it is identified chiefly as a yellowish-brown layer between the more conspicuous layers D and F. Its principal minerals are the same as those in several other tephra deposits from Mount Rainier, but the lack of even minor amounts of olivine seems to distinguish it from all but layer F (table 3). It differs from layer F in its generally duller color, its coarser ash fraction on the east flank of the volcano, and its lack of clay.

LAYER S

Layer S is a reddish-gray to reddish-brown deposit of large angular blocks and lapilli in ash that is as much as 1.25 m (4 ft) thick (fig. 27). This coarse rubble consists almost entirely of red and gray lithic fragments; pumice and scoria are absent. The lithic fragments are pieces of Mount Rainier lava, and they seem unweathered.

The rubble of layer S has been found interbedded with other tephra deposits only on the ridge from Yakima Park east to Sunrise Ridge. Large blocks of similar Mount Rainier lava that lie on the crest of Goat Island Mountain may also be part of the deposit, but their relation to other ash layers was not seen there. Thin lithic ash that probably is part of layer S has been found in Huckleberry Park north of Yakima Park.

The thickest and coarsest bed of layer S that lies between other tephra deposits can be seen in roadcuts at the switchback of the highway to Yakima Park that is directly south of Dege Peak. There, the deposit is 50-125 cm (20-50 in.) thick and contains blocks as much as 45 cm across. From that locality the layer thins abruptly and becomes finer grained to both the west and the east along the ridge. It is only 2-5 cm (1-2 in.) thick near the Ranger Station at Yakima Park, and the largest fragments are about 2 cm across. The ash in Huckleberry Park, to the north, is less than 2 cm thick. The deposit is absent at Summer Land, south of Goat Island Mountain.

Too little of layer S is seen to caculate its volume even roughly, but it may have been larger than all but a few other Mount Rainier tephra deposits. If it originally was a minimum of 50 cm thick between outcrops of that thickness and either a summit or a flank vent, for example, the volume probably was at least 20 million m^3.

Layer S seems to have been erupted from Mount Rainier inasmuch as it consists of Mount Rainier rock types and has a very limited distribution. The decreases in thickness and grain size along the ridge from Dege Peak westward toward Yakima Park, however, suggest that layer S may not have been erupted from a central summit vent. Its pattern of grain size and thickness could have resulted from ejection of a very narrow lobe of coarse debris from a summit vent or of a somewhat broader lobe from a point lower on the east flank of the volcano.

Layer S is described as tephra because of (1) the size and extent of its large blocks and lapilli, (2) its rock types, and (3) its position between other tephra layers. Its blocks and lapilli of Mount Rainier lava mantle the area from Yakima Park to Sunrise Ridge and they were laid down over easily eroded ash layers without significantly disturbing them. The rubble is not avalanche debris or talus, for there is no adequate source of Mount Rainier lava higher on that slope. They are not frost-heaved blocks, for the underlying ash beds are not disturbed; and they cannot be glacier deposits because they lie far beyond the limits reached by glaciers of Holocene age (D. R. Crandell, oral commun., 1971). They must have been airlaid, but they obviously were not windblown. Thus, the evidence seems to require that the rubble of layer S was distributed by a pyroclastic eruption, and the lack of pumice or scoria suggests that the eruption was one or more steam explosions (Crandell and Mullineaux, 1967, p. 7).

This deposit is similar only to some rock-avalanche deposits that locally are interbedded with tephra. It differs from other tephra layers in its content of large angular lithic blocks and in the absence of pumice or scoria.

LAYER H

Layer H is a thin obscure gray to brown bedded ash that contains scattered pumice and scoria lapilli whose diameters locally are greater than the thickness of the ash. White pumice lapilli generally occur at the base of the ash, whereas brown scoria lie slightly higher. Both the pumice and scoria contain hypersthene, augite, and olivine, but the refractive index of olivine differs from one to the other (fig. 33). Ash-size particles are lithic fragments and crystals and smaller amounts of the pumice and scoria.

Lapilli of layer H have been identified only in alpine meadows from Summer Land south to Cowlitz Park (fig. 28), in ash that typically is less than 2 cm (1 in.) thick. The largest lapilli, about 2 cm in diameter, were found in Cowlitz Park. The largest seen in Ohanapecosh Park and at Summer Land are about half that size. Layer H is one of the smallest and least known tephra deposits; the meager evidence available suggests that its original volume was only on the order of 1 million m^3.

The limited distribution, content of large lapilli, and similarity to other tephra deposits from Mount Rainier indicate that layer H was derived from that volcano. Lithologic differences indicate that the tephra was not derived from underlying layers F, N, and D; thus, layer H represents an eruption of the volcano. Minor differences in stratigraphic position and character of the white and brown lapilli may indicate that the deposit represents more than one small eruption.

Neither the lapilli nor the ash is conspicuous or distinctive in the field. The deposit is identified by its scattered lapilli and their position relative to the more distinctive layers F and B (fig. 22). Under the microscope, the lapilli differ in mineral content from those in the underlying layers F, N, and D (table 3).

LAYER B

Layer B is a medium- to dark-brownish-gray deposit of scattered lapilli and small bombs in thin, dark-gray ash (fig. 22). Almost all lapilli and small bombs are brown to gray scoria, though a few lapilli are lithic. These scoria contain a larger proportion of olivine crystals than the other tephras. Ash-size particles consist mostly of the same rock types, but some particles are crystal fragments and grains of black scoria. Scoria lapilli and bombs commonly appear weathered for a few millimeters inward from their surfaces, and many particles in the deposit are covered with a yellowish-brown coating.

Lapilli or bombs in layer B have been found only in or near Ohanapecosh and Cowlitz Parks on the east and southeast flanks of the volcano (fig. 28). Bombs are abundant only in the southern part of Ohanapecosh Park, where they reach 8 cm (3 in.) in diameter, about twice the size of the largest fragment seen in Cowlitz Park. In most places, the associated ash is no more than 2 cm thick, and the maximum thickness seen is about 5 cm. Although the lapilli have been found only in a very limited area, dark ash that is at the same horizon in the ash sequence and that may have resulted from the same eruptive episode is present from the northeast flank clockwise around to the south flank of the volcano.

Although the distribution of layer B is not well enough known to permit calculation of its volume, a rough estimate of its freshly fallen volume is about 5 million m^3.

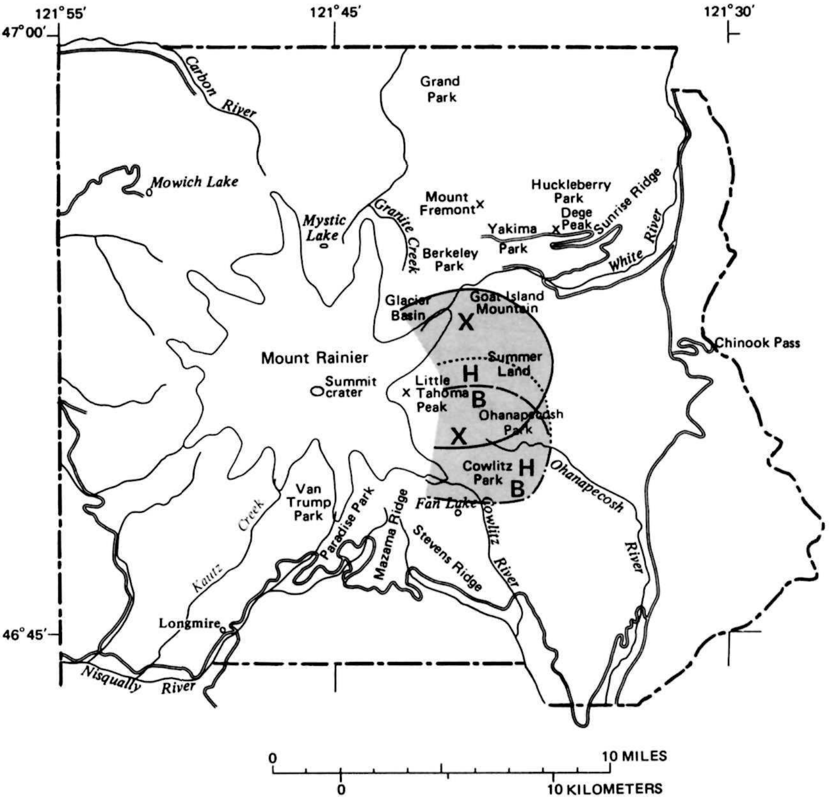
The presence and location of bombs in layer B leave little doubt of its origin at Mount Rainier. The restriction of the bombs and lapilli to the east and southeast flanks of the volcano suggests a significant west to northwest wind during their eruption. On the other hand, the wide extent of ash that apparently is associated with the bombs suggests that wind directions changed during eruption of the finer material.

This deposit is distinguished from most other tephra layers by its content of scoria bombs and lapilli. Only layers D and C contain similar fragments, and both are thicker and coarser overall than layer B in Ohanapecosh and Cowlitz Parks. Under the microscope, layer B is distinguished from layers D and C chiefly by the absence of hornblende, and by the abundance and refractive index of olivine (fig. 33).

LAYER X

Layer X consists of sparse pumice and scoria lapilli that have been identified only on a few young glacial moraines. The lapilli do not form a continuous layer; they are found scattered on the surface of barren moraines in alpine areas, or nearly hidden in surficial duff on lower, forested moraines. The deposit is inconspicuous even on some of the barren moraines where only a few lapilli per square meter might be found. In addition, the lapilli are unevenly distributed and locally may be absent even in the area generally covered by the tephra deposit. Pumice and scoria are the only materials recognized; any lithic material that might have fallen has not been distinguished from the lithic fragments in the underlying moraines. Though most of the lapilli are brown, some are white or various shades of gray.

Layer X has been found on moraines in three places on the northeast and east flanks of the volcano—in Glacier Basin below Inter Glacier, in



MINIMUM EXTENT of lapilli-bearing parts of layers H, B, and X. (Fig. 28)

the White River valley below Emmons Glacier, and in the Ohanapecosh River valley below Ohanapecosh Glacier (fig. 28). The lapilli do not seem to be significantly more abundant in one place than another. Fragments are somewhat larger on the moraines of Emmons Glacier, however, where they reach 5 cm (2 in.) in diameter. In contrast, the general maximum diameter on other moraines is about 3 cm. Ash-size pumice or scoria is not abundant; ash-size particles might be sparse because they have filtered down into the loose moraine, or because very little ash-size material was produced by the eruption.

The sparseness of layer X lapilli suggest that the layer is the smallest of the tephra deposits, and probably is considerably less than 1 million m^3 in volume.

The size and distribution of layer X lapilli, along with the similarity of the lapilli to those in other Mount Rainier tephra, show that Mount Rainier is the source of the tephra. Their relation to glacial moraines proves that they are very young; they resulted from the most recent eruption that is recorded by a recognized tephra deposit. In the White River valley, they occur on moraines that, as indicated by the age of trees growing on them, probably formed as late as 1820, and they are absent on moraines formed before 1854 (Mullineaux, Sigafoos, and Hendricks, 1969). Thus, layer X tephra apparently was erupted in the first half of the last century.

Layer X cannot be distinguished lithologically from layer C at this time. Where layer C underlies a surface at shallow depth, fragments from it work to the surface, where they mingle with any layer X lapilli that are present. Consequently, layer X has been recognized only on deposits, such as moraines, where layer C is absent.

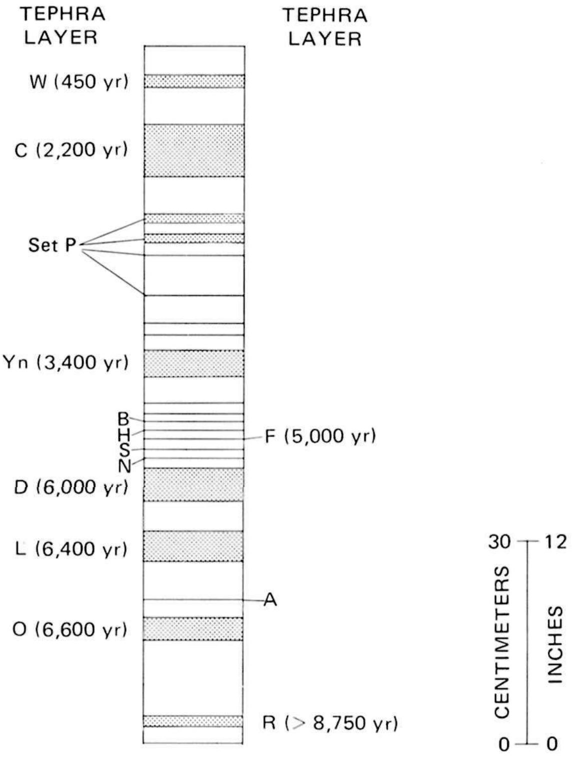
Tephra lapilli described here as layer X were initially regarded as part of a deposit called layer G by Crandell, Mullineaux, Miller, and Rubin (1962). Finer grained materials that were described as parts of layer G are so variable in composition from place to place that they are no longer regarded as parts of a single definable tephra deposit.

TEPHRA LAYER R

Layer R, the oldest postglacial ash recognized (frontispiece, fig. 29), is a reddish-brown deposit of ash and lapilli that occurs widely in the eastern part of the park in small lenses or in a thin, discontinuous layer. Northeast of the volcano, however, it is several inches thick and contains abundant large lapilli. These lapilli are mostly brown pumice or dark-gray scoria. Pumice and scoria are also common as ash-size grains, but the ash includes abundant lithic particles, and, on the southeast side of the volcano, consists mostly of such particles. Layer R lapilli do not contain hornblende as was previously reported (Crandell and others, 1962). The earlier description resulted from my misidentification of a bed of layer D lapilli in an outcrop as layer R, before layer D was recognized as a separate deposit.

Layer R is relatively strongly weathered, and the entire deposit typically is stained. Weathered rinds several millimeters thick have formed in most pumice and scoria lapilli, and some small lapilli are weathered and soft all the way through. Lithic fragments are coated with weathering products but are not otherwise obviously affected. The weathering seems to be limited mostly to the glassy parts of the fragments, for the mineral crystals are firm. Examination of the weathered material by X-ray diffraction methods showed the presence of only amorphous clayey material rather than crystalline clay minerals.

More than one bed of pumice lapilli in this deposit, interbedded with stream deposits, has been seen in several places. These multiple beds suggest that products of more than one eruption might be included in

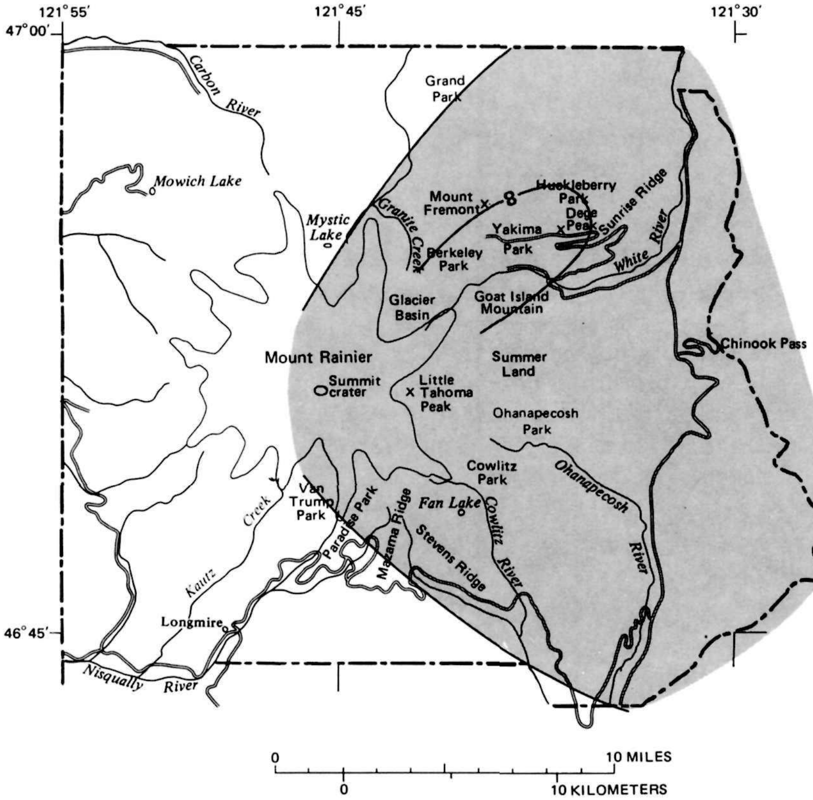


STRATIGRAPHIC POSITION of layers R, A, and F. (Fig. 29)

layer R as described here, but no multiple beds were seen in sequences of only airlaid material.

Layer R probably covered nearly all the park east of Mount Rainier's summit and extended well beyond the park boundaries (fig. 30). It is preserved so sparsely, however, that its extent and thickness are not well defined. It seems to be no more than 2 cm (1 in.) thick over most of the area where it has been recognized. Lapilli are common in the deposit everywhere except southeast of the volcano, but they generally are not more than 1 cm in diameter. The deposit is significantly thicker and coarser only in the vicinity of Yakima Park and Grand Park northeast of the summit. A northeast-trending lobe that extends to Yakima Park is consistently at least 8 cm thick (fig. 30). Large lapilli are common in this vicinity, and the largest lumps are nearly 5 cm in diameter.

Layer R has been completely eroded away in many localities where it would be expected and where other tephra layers are preserved, and accumulations several times the average thickness of the layer, locally including multiple beds of lapilli, are common. Those accumulations,



MINIMUM EXTENT of layer R, and area in which deposit averages more than 8 cm thick. (Fig. 30)

however, seem to consist chiefly of lapilli that have been eroded from slopes and redeposited along stream channels. One such fluvial accumulation, along Huckleberry Creek in Huckleberry Park, is 25 cm (10 in.) thick. Another, in Berkeley Park, west of Yakima Park, includes four separate lapilli beds.

A rough calculation, based on an estimated average thickness of 1 cm over most of the eastern part of the park and an average thickness of 10 cm in the lobe extending from the summit of Mount Rainier to Yakima Park, indicates a minimum volume of 25 million m^3 of layer R tephra as freshly fallen.

The large fragments northeast of the volcano and their petrographic character strongly indicate that layer R came from Mount Rainier. The limited distribution of large fragments also suggests that a southwesterly wind blew during the major part of the eruption. Conversely, the widely dispersed smaller lapilli and ash indicate changing wind directions during other, less voluminous episodes of the eruption. The very spotty preservation of the deposit may have resulted from its deposition largely on ice, snow, and barren ground that were present at the time, which may have been during the waning stages of the last major glaciation.

Layer R is not significantly different from several other tephra deposits from Mount Rainier, but it is the only pumiceous layer that is below the highly distinctive layer O and, so, is not likely to be confused with other tephra deposits.

TEPHRA LAYER A

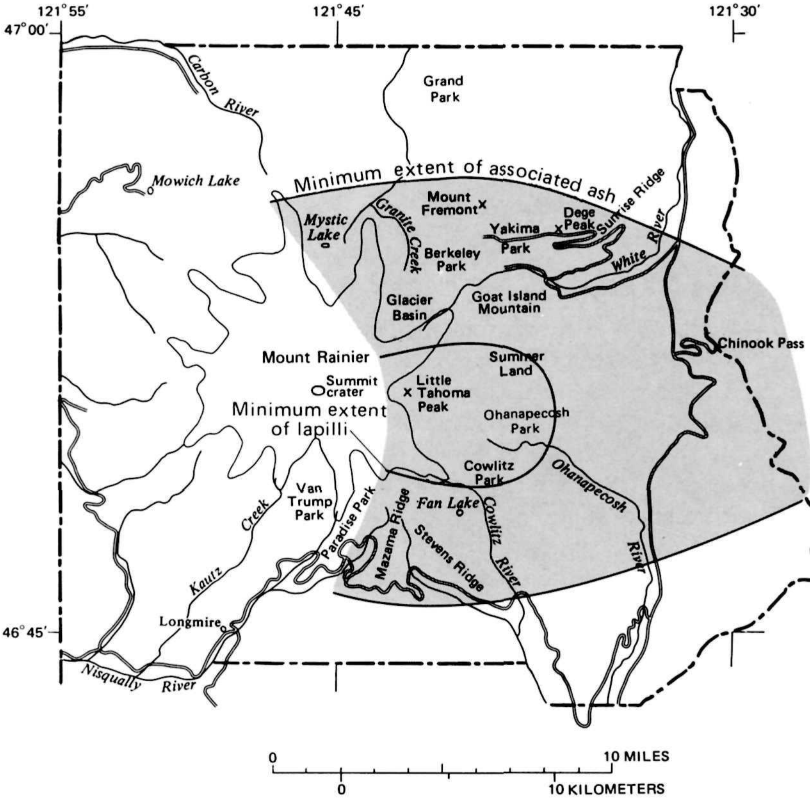
Layer A (fig. 29) is a thin inconspicuous bed of brown ash that is marked by scattered white and brown pumice lapilli. The largest of these lapilli are white, and their diameters are locally much greater than the thickness of the associated ash. Typically, they form a discontinuous line of white lapilli in an outcrop that is more noticeable than the ash bed (fig. 22). Brown pumice lapilli in the layer generally are smaller. Pumice is abundant in the ash, but less so than mineral crystals and lithic particles. The brown lapilli seem somewhat weathered, and the white ones are stained brown, but weathering of the layer is not enough to color the bed strongly; consequently, it is not conspicuous in outcrops.

This deposit crops out widely from the north flank of Mount Rainier clockwise around to the southeastern slopes, and locally along the east boundary of the park (fig. 31). Lapilli are common only east of the summit, where the layer is also thickest. The thickest deposit seen, however, is less than 5 cm (2 in.) thick, and the largest lapilli are slightly less than 5 cm across. In most places, the ash is much less than 2 cm thick. The layer apparently has been completely stripped from many sites, but no thick fluvial or wind-drift accumulations of it have been seen.

The volume of layer A is calculated roughly as at least 5 million m^3.

The inference that layer A was erupted from Mount Rainier is based on the presence of large lapilli on the flanks of the volcano and on the similarity of the tephra to that in other deposits which clearly were erupted from Mount Rainier. The distribution of layer A suggests that a predominantly west wind blew during eruption, but that the wind was gentle or variable enough to allow wide dispersal of ash.

Layer A ash is identified chiefly by its sparse content of large white lapilli and its position relative to other tephra layers. The ash is not conspicuous in color or size, but its occurrence in a group of grayish-brown volcanic sand beds just above layer O and below noticeably darker sands (fig. 22) seems to be typical. The pumice of layer A is not different in mineral content from that in several other tephra beds. The refractive index of its olivine, however, seems to separate it from layers R and L that are also in the older part of the tephra sequence (fig. 33).

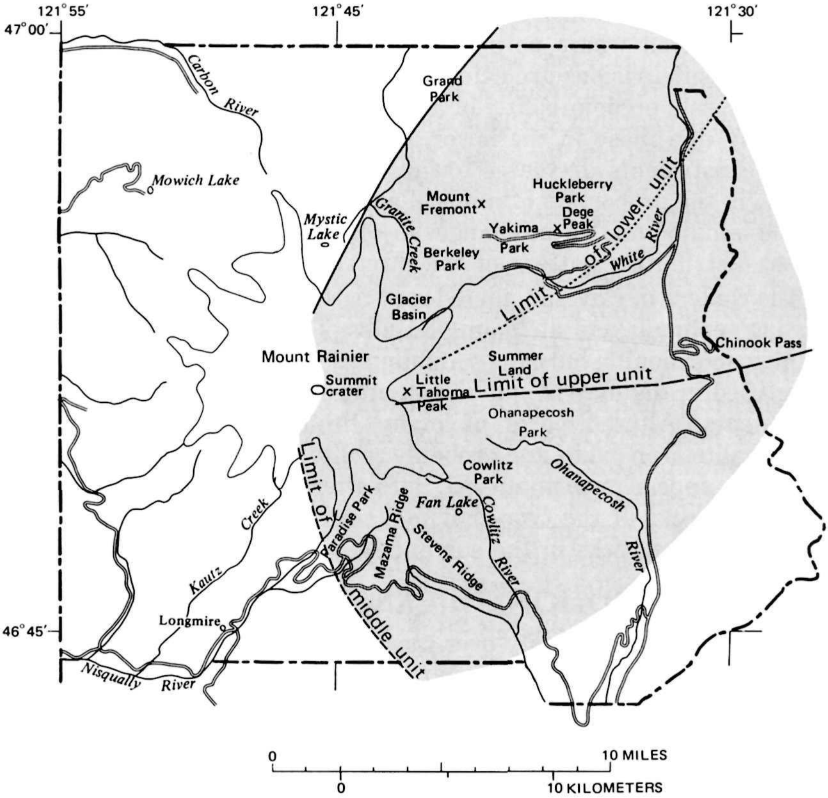


DISTRIBUTION of layer A. (Fig. 31)

TEPHRA LAYER F

Layer F is a thin, locally brown but more commonly bright-reddish-yellow to yellow clay-rich ash (figs. 7, 22), that is especially conspicuous in the northern and eastern parts of the park. It consists of widely varying proportions of altered and unaltered lithic fragments, pumice, crystals, and clay; the variations seem to be related to the distribution of three stratigraphic units in the layer that are distinctly visible in only a few exposures in and near Yakima Park and Berkeley Park (fig. 32). The lower and upper of these units extend north and east from the volcano, and they consist mostly of partly altered lithic fragments and clay; almost all particles in the deposit in those areas are coated with clay and iron oxides that give the layer its conspicuous color. The middle unit extends from northeast to south of the mountain, and it consists chiefly of pumice and crystal grains.

Layer F appears weathered because of its color and content of partly altered particles and of clay minerals. However, the alteration and for-



INFERRED DISTRIBUTION of three units that make up layer F. Northwestern boundaries of the three units are approximately the same. (Fig. 32)

mation of clay minerals occurred before the materials were ejected to become part of layer F, and they do not represent weathering of this deposit since its formation.

COMPOSITION

The three stratigraphic units recognized differ markedly in proportions of the various constituents. The lower one consists chiefly of lithic fragments, about half of which are partly altered to clay, in a matrix of clay minerals. Mineral crystals, scoria, and pumice grains are minor components. The middle unit of ash, in contrast, consists almost entirely of mineral crystal and pumice grains and contains only a few lithic fragments and no clay. The upper limit is like a mixture of the lower two: it contains abundant clay and altered and fresh lithic fragments, and its coarse ash fraction includes abundant crystal and pumice grains.

The layer may consist of more than one of the three units just described, even where no subdivisions can be seen. In some places where no subdivisions are evident at Berkeley and Yakima Parks, the layer consists predominantly of altered and unaltered lithic fragments and clay like those in the lower and upper units. The proportion of those constituents decreases toward the east and south with the increase in the proportion of mineral and pumice grains that are typical of the middle unit. These changes in composition are attributed to the offset distribution pattern of the three units (fig. 32).

The content of clay and altered-rock particles in this deposit is unique among tephra layers at Mount Rainier. The clay minerals are chiefly montmorillonite, but minor amounts of illite and kaolinite have been identified in the matrix and also in altered zones within discrete rock fragments. Altered parts of many lithic fragments also contain cristobalite, iron oxide, and probably zeolite and opal. Other fragments, however, appear to be unaltered. Both altered and unaltered fragments are from rocks of the type that make up Mount Rainier rather than from the older rocks in the surrounding mountains.

DISTRIBUTION, THICKNESS, AND VOLUME

Layer F is spread thinly over most of the eastern part of the park, and it extends well beyond the park boundaries (fig. 32). The layer is 1-2 cm (½-in.) thick over most of its area of distribution. It is substantially thicker only on the northeast flank of the volcano; near Yakima Park and Berkeley Park, the thickness probably averages as much as 10 cm. It varies markedly in thickness over short distances, however, and is absent at many outcrops where other tephra layers are well preserved. It also locally has been reworked into thick accumulations; the thickest such deposit found, along Granite Creek, is as much as 40 cm thick.

The volume of the deposit probably was originally at least 25 million m^3.

GRAIN SIZE

Layer F is predominantly a silt- and sand-size ash that contains from about 5 to 25 percent clay-size particles. The lowest of the three stratigraphic units within layer F consists of lapilli in ash that includes only about 5-10 percent of clay. At one locality in Yakima Park, lapilli make up as much as 30 percent of that unit and are as large as 2 cm (1 in.) across. The middle ash unit is better sorted and contains very little clay- or lapilli-size material. The uppermost unit seems to have fewer lapilli and more clay than the lowest one.

As a whole, the deposit shows a decrease in proportions of both clay and lapilli from Yakima Park southward. The largest lapilli seen, however, are at Ohanapecosh Park, where pumice fragments are as much as 5 cm in diameter.

SOURCE AND ORIGIN

The composition and extent of layer F show that it came from Mount Rainier. Its broad sheetlike distribution demonstrates that it was air-laid, whereas the lapilli-size fragments and the montmorillonite clay show that it was not merely detritus picked up and redistributed by wind. The abundance of pumice and glass-encrusted crystals, especially in the middle unit, verifies that molten material was erupted during formation of this layer.

The origin of the abundant clay is of special interest, inasmuch as no more than a trace of crystalline clay mineral was found in any of the other postglacial tephra layers. The clay minerals in layer F must have been formed elsewhere before their deposition as part of that tephra layer rather than in place by weathering afterward. Their restriction to certain stratigraphically well defined beds in layer F and the occurrence of both fresh pumice and partly altered lithic fragments in the same beds provide strong evidence that the clay minerals formed before they were emplaced in the tephra. Clay minerals are abundant in the lower and upper units of layer F, yet absent in the middle unit and in other ash layers and volcanic sands below and above layer F. At the McNeeley site near Yakima Park (fig. 32), for example, the proportion of montmorillonitic clay in the clay-size fraction of samples from the upper and lower units is at least 80 percent (table 10). No montmorillonitic clay was detected by the same technique in samples from the middle unit of layer F or from the other beds immediately below and above layer F. Restriction of clay minerals to the two separate units in layer F indicates that the clay minerals did not form as a part of a clay-rich surficial-weathering profile.

In addition, delicate pumiceous glass exists along with lithic fragments that are altered partly to clay in the upper unit of layer F and elsewhere in the undivided layer. The glass would be expected to be altered more easily by weathering than the lithic fragments. Thus, survival of the glass implies that surficial weathering did not form the clay minerals that occur with it.

Iron-stained crusts within the tephra sequence were cited by Fiske, Hopson and Waters (1963, p. 85) as evidence of formation of clays by weathering of tephra. Iron-stained crusts that probably result from leaching occur under layer F at several localities, but they also occur under ash deposits that do not contain clay. In addition, they are absent in many places where layer F is rich in clay minerals. Thus, the iron-oxide crusts probably demonstrate the occurrence of leaching, but they do not record the formation of clay minerals.

The most probable origin of the clay seems to be by hydrothermal alteration of solid rock within the volcano, and the ejection of that altered material by later pyroclastic eruptions. Such an origin was proposed for the clayey component of the Osceola Mudflow, a large clay-rich Holocene mudflow that originated on the northeast flank of Mount Rainier (Crandell and Waldron, 1956). The "airlaid facies" of the Osceola described by Crandell and Waldron is the clay-rich layer F northeast of the summit. The eruptions envisioned by Crandell and Waldron as the cause of the Osceola Mudflow could easily have thrown enough altered material into the air to form the clayey component of layer F.

Layer F, then, is regarded as having resulted from three or more pyroclastic eruptions. The sequence of events that formed layer F is visualized as follows:

1. A violent steam eruption threw lapilli- and ash-size fragments of previously solid, partly altered rock onto areas mostly northeast of a vent that presumably was at or near the summit of Mount Rainier.
2. A subsequent eruption ejected crystals and molten material along with a small proportion of solid rock fragments, depositing a crystal and pumice ash over a broad area east of the summit.
3. Eruption of some molten material continued or was repeated but was accompanied by ejection of a much larger proportion of fragments of partly altered rock so that a second shower of clay-rich ash was deposited north and east of the summit.

No evidence of a time interval separating the three units of layer F was found, and all three could have been deposited within a short time, perhaps within a few hours or days.

AGE

The age assigned to layer F (table 1) depends in part on its correlation with the Osceola Mudflow, which has been dated as slightly less than 5,000 radiocarbon years old (Crandell, 1963a). Layer F is younger than a bed of peat in Cowlitz Park that has been dated as 5,020±300 years old. (See table 5.) The ash has not been found above the Osceola Mudflow, despite careful searches in areas where the ash is thick and well preserved on ridges next to the mudflow; thus, the ash evidently is at least as old as the mudflow. The close correspondence of age as well as the clay content of layer F and the Osceola indicates that they are correlative.

ORIGIN OF THE OSCEOLA MUDFLOW

The composition of layer F seems to bear on two aspects of the origin of the Osceola Mudflow: the place of formation of the clay minerals in the mudflow, and the manner in which the mudflow was initiated. Crandell and Waldron (1956) and Crandell (1963a; 1963b; 1971) inferred that the montmorillonitic clay minerals in the mudflow came from altered rock within Mount Rainier, and that the mudflow probably was caused in some way by an eruption. Crandell (1963b, p. B139) suggested that a phreatic explosion had caused a large part of a former summit to avalanche and form the mudflow. These hypotheses require that the clay minerals in the "airlaid facies of the Osceola" (layer F of this report) were formed before they were deposited.

Fiske, Hopson, and Waters (1963), however, held that the clay component of the Osceola originated by postglacial weathering of pyroclastic sediments in thick valley fills and in thin upland ash deposits like the "airlaid facies." The brown iron-stained crusts within the tephra sequence were regarded as evidence of long-continued oxidation and leaching of ash after its deposition (Fiske and others, 1963, p. 85). They proposed that the mudflow was formed by mobilization of a thick valley fill of partly altered pumiceous sediments. They, too, suggested that a volcanic eruption was a possible—though not necessary—cause of the mudflow.

Evidence in the tephra sequence adequately demonstrates that the clay minerals in layer F (the "airlaid facies" of the Osceola) were formed before deposition of the tephra rather than after. (See p. 65.) The fact that montmorillonitic clays have not been identified in other postglacial tephra deposits suggests that no large amount of clay was formed in pumiceous materials in valley fills after the last glaciation. Thus, surficial weathering seems to have been inadequate to provide the large amount of clay that is present in the mudflow. A more likely source of the clay was the altered rocks within the volcano, where the clay formed before both layer F and the mudflow.

The evidence provided by layer F also supports the proposal that the Osceola Mudflow originated during an eruption. There seems to be no question that layer F and the Osceola are related and that layer F records multiple pyroclastic eruptions that included ejection of molten material during that episode. The Osceola Mudflow thus probably was initiated during a complex eruptive episode which included pyroclastic eruptions. It cannot be proved that the Osceola was caused directly by an eruptive event, yet the timing suggests strongly that it was triggered by one. Either of the explosions that produced the lower and upper units of layer F might have forcefully ejected rock particles and clay into the air to form layer F and might have also dislodged the massive amounts of material that formed the Osceola Mudflow.

Petrography And Chemistry

Laboratory determinations of the composition of tephra have proved to be useful supplements to field criteria for identification of tephra layers. Mineral and element content also may suggest correlations or comparisons with other known units, and thereby point to a possible source or age of a layer. For example, the presence of cummingtonite in several thin ash beds invites comparison with layer Yn and suggests the possibility that Mount St. Helens was their source, and a high silica content for a tephra layer in the park at least suggests a source volcano other than Mount Rainier.

All the letter-designated tephra deposits except layer S contain pumice or scoria fragments whose abundant constituents are volcanic glass, plagioclase, opaque minerals, and iron-magnesium minerals; the same constituents make up the ash-size particles. In addition, the tephra deposits include very small amounts of other minerals, such as apatite and zircon. Mineral content, refractive index of iron-magnesium minerals, refractive index of glass, clay-mineral analyses, and a few whole-rock chemical analyses were tried as aids to identification. Of these properties, the mineral content and refractive indices of iron-magnesium minerals proved to be the most useful.

IRON-MAGNESIUM-MINERAL CONTENT

The iron-magnesium minerals that occur in the tephra layers are listed in table 9; they are the predominant nonopaque grains that were obtained by crushing lapilli or coarse-ash-size pumice or scoria. The minerals listed for deposits that lack coarse debris are ones that occur as discrete crystals that are at least partly mantled by vesicular glass. Three mineral associations are evident: (1) hypersthene and augite, with or without olivine or hornblende, (2) hypersthene and hornblende, and (3) cummingtonite and hornblende. The hypersthene-augite combination is found in all Mount Rainier tephra deposits; absence of olivine seems to distinguish two of the Rainier layers, presence of minor amounts of hornblende marks two more, and abundance of hornblende marks only one. The cummingtonite-hornblende suite marks the older Mount St. Helens tephras, and the hypersthene-hornblende suite marks the younger ones.

Some differences in mineral content, such as the absence or abundance of hornblende or the contrast between hypersthene and cummingtonite as principal constituents, can be used to help distinguish tephra layers in the field. For example, the abundant hornblende in crushed lapilli of layer D commonly is distinct enough to be identified with a hand lens. With practice, one can also differentiate enough between the color of cummingtonite in layer Yn and that of hypersthene in layer W to help differentiate those two deposits. Concentrates of heavy minerals can be prepared conveniently in the field by crushing and panning pumice or scoria lapilli with a small mortar and pestle.

Most Mount Rainier tephra layers are similar in mineral content to Mount Rainier lava flows, which repeatedly have been described as remarkably uniform in composition (Hague and Iddings, 1883; Coombs,

TABLE 9. —*Content and proportions of iron-magnesium minerals in heavy-mineral fractions*

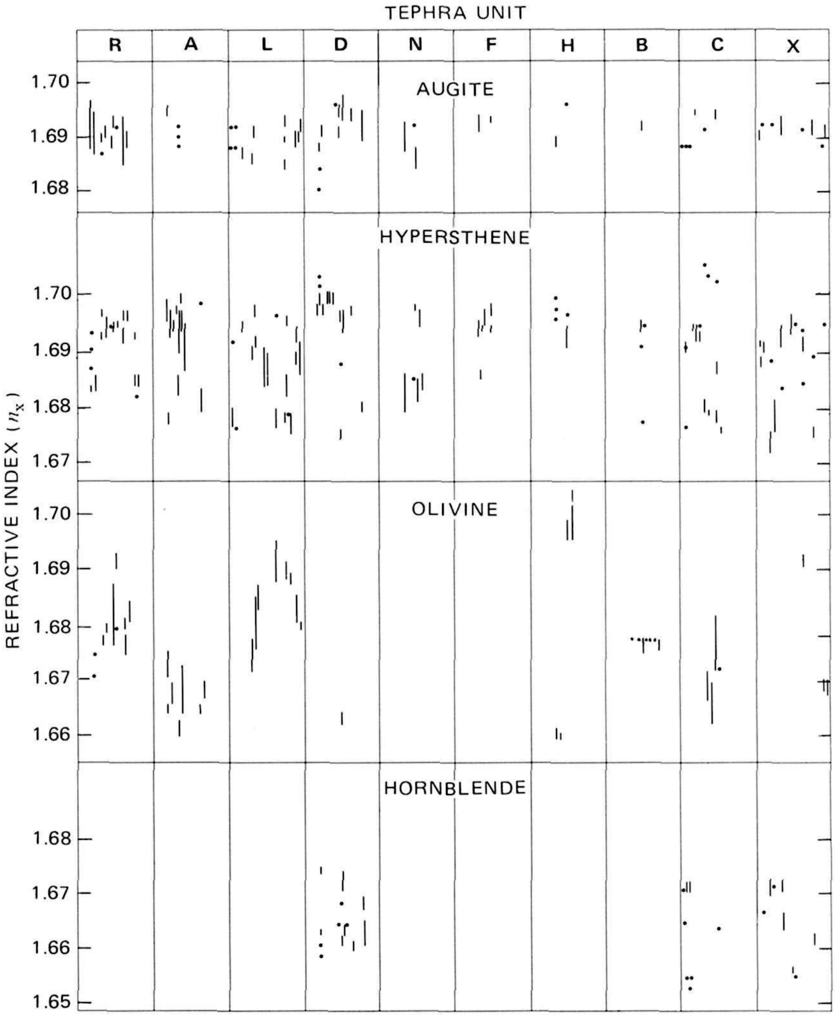
[Queried minerals are those that may have been derived from previously solidified rocks rather than from pumice or scoria]

Tephra layers	Principal constituents (>30 percent)	Secondary constituents (2-30 percent)	Minor constituents (<2 percent)
Mount Rainier			
X	Hypersthene	Augite	Hornblende, olivine.
C	...do	...do	Do.
B	...do	Augite, olivine	None.
H	...do	Augite	Olivine.
F	...do	...do	None.
N	...do	...do	None.
D	Hypersthene, hornblende	...do	Olivine.
L	Hypersthene	...do	Do.
A	...do	...do	Do.
R	...do	...do	Do.
Volcanoes other than Mount Rainier			
W	Hypersthene	Hornblende	None.
Set P:			
Upper two.	Hypersthene, hornblende	None	None.
Lower two.	..do	None	Cummingtonite (?), augite (?).
Set Y:			
Upper two.	Hornblende, cummingtonite	None	Hypersthene (?), augite (?).
Yn	..do	None	None.
Lower two.	..do	None	Hypersthene (?), augite (?).
O	Hypersthene	Hornblende, augite	None.

1936; Fiske and others, 1963). Only in layer D does a tephra mineral suite differ strikingly from that of the flows. Because hornblende is considered to be stable under high water pressure, its presence may indicate that the magma of layer D was brought up relatively rapidly from depths at which hornblende was stable and was ejected before the hornblende was altered or resorbed.

REFRACTIVE-INDEX MEASUREMENTS

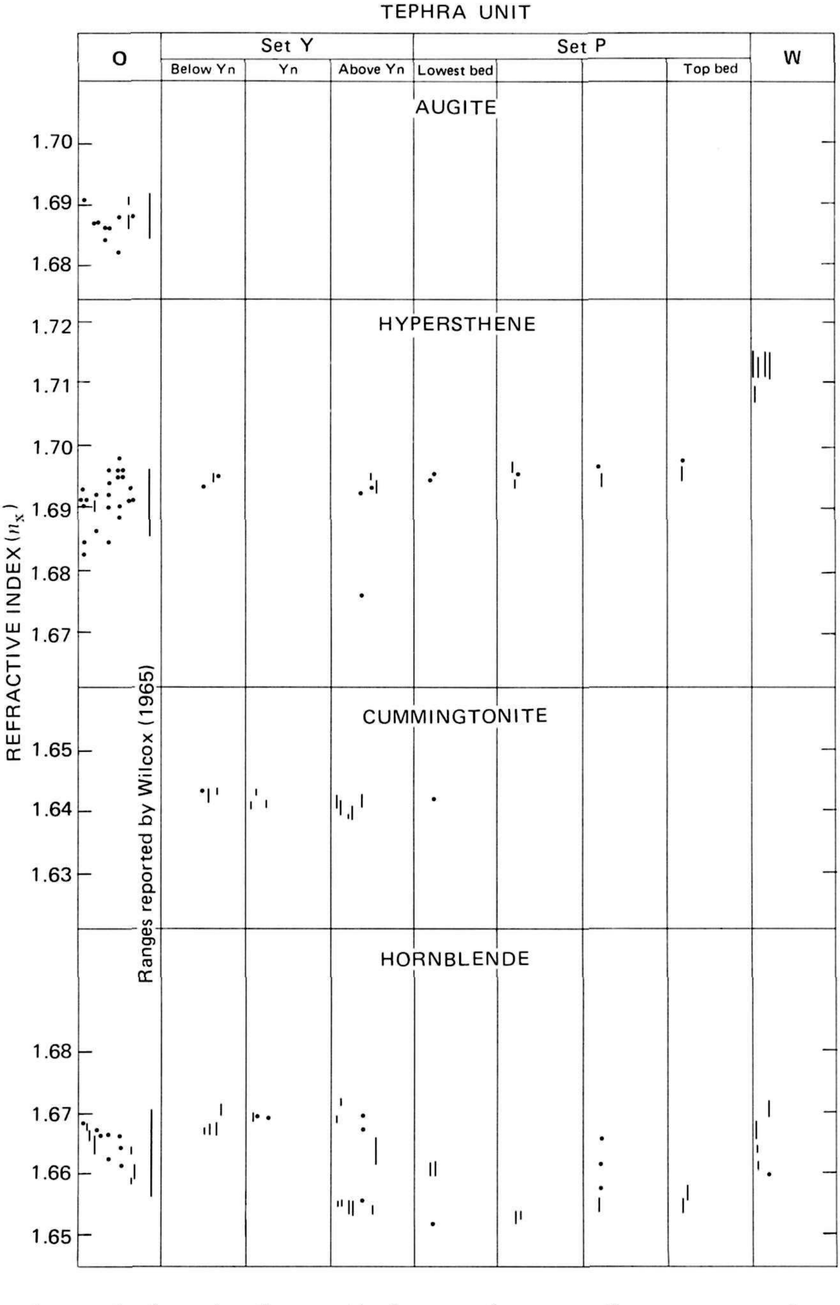
Refractive index (R.I.) values of iron-magnesium minerals provide additional help in identifying some tephra layers that are similar in mineral content (fig. 33). For example, the R.I. values of olivines in



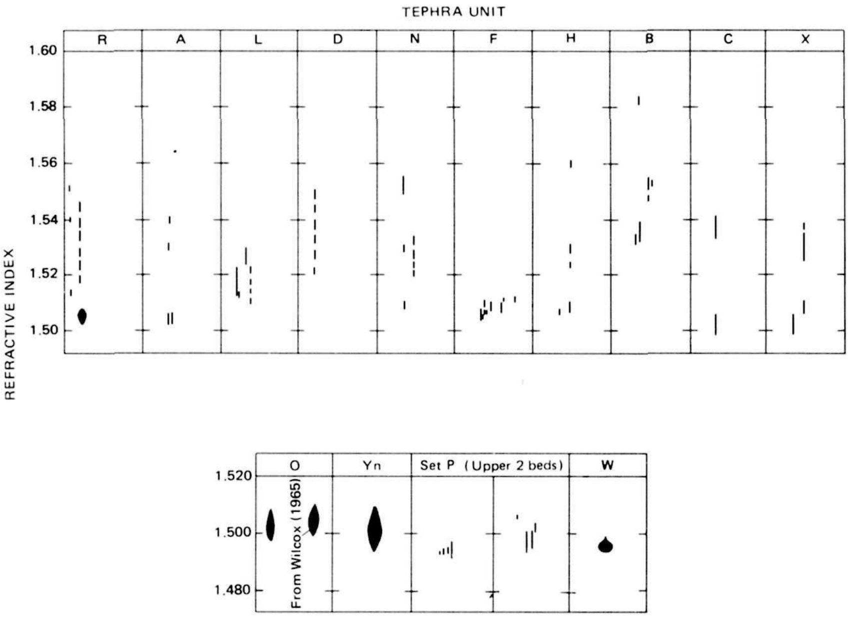
REFRACTIVE INDICES of iron-magnesium minerals. Each dot or vertical line represents the index or range of index measured for a single fragment. (Fig. 33, above and facing page)

layer A are different from those in layer L. Similarly, the high R.I. of hypersthene distinguishes layer W from the otherwise similar layer P.

Refractive-index measurements of glass have proved to be less useful for identification (fig. 34). A few measurements showed a very wide range in R.I. values for glass in most tephra deposits from Mount Rainier. The indexes seem to correlate closely with (and are not more useful than) the more easily observed color of the fragments. R.I.



values of glass in the exotic layers show smaller ranges and are generally lower than R.I. values for glass in Rainier tephras. The values for most exotic layers, however, overlap the values measured for



REFRACTIVE INDICES of glass. (Fig. 34)

Rainier tephra (fig. 34), so use of this property for identification would require measurement of a large number of grains.

CLAY MINERALS

Layers O, N, and F, and weathered rinds from pumice and scoria lapilli in layers R and D were examined for clay minerals by X-ray diffraction methods. No crystalline clay minerals were detected in the weathered rinds or in layer N. Neither were any crystalline clay minerals detected in six samples of layer O from several sites around the volcano, except for a trace of possible mixed-layer montmorillonite-mica in one sample (table 10). In contrast, crystalline clay minerals were found in each of five samples from the upper and lower units of layer F, and in two whole-layer samples of that deposit from the northern and northeastern parts of the park. In these samples the clay-mineral proportion ranged from approximately 50 to 90 percent of the clay-size fraction and from about 1 to 25 percent of whole samples. Montmorillonite is by far the most abundant clay mineral detected; it occurs as a relatively pure mineral and in mixed-layer assocation with mica. Discrete mica and kaolinite were detected in four of the seven samples from layer F. Clay minerals were not detected in whole-layer samples of layer F from Ohanapecosh and Cowlitz Parks nor in a single sample of the middle unit of layer F from northeast of the volcano.

TABLE 10.—*Crystalline clay minerals in tephra layers*

Layer	Locality	Field No.	Clay minerals[1]
F (whole layer)	Ohanapecosh Park	9-12-67-23	None detected.
	Chinook Pass	8-27-61-6	Montmorillonite, 1; mixed layer, 1.
	North of Mount Fremont	40-6	Montmorillonite, 4; mica, 2; kaolinite 2.
	Cowlitz Park	8-12-67-25	None detected.
F (upper unit)	"McNeeley" site	7-5-63-16	80 percent mixed layer (montmorillonitic)
F (middle unit)	"McNeeley" site	7-5-63-17	None detected.
F (lower unit)	"McNeeley" site	7-5-63-18	80-90 percent montmorillonite.
	Yakima Park	7-6-63-3	Montmorillonite, 2; mixed layer, 5; kaolinite, less than 1.
	...do	9-23-65-9	Montmorillonite, 6.
	...do	9-23-65-9a	Montmorillonite > kaolinite.
O	Van Trump Park	17-6-28a-3	None detected.
	...do	17-6-27	Mixed-layer montmorillonite-mica (?), trace.
	Mowich Lake	8-22-61-4	None detected.
	Ohanapecosh Park	8-14-62-6	Do.
	"McNeeley" site	7-5-63-21	Do.
	Longmire	8-18-63-3	Do.

[1] Proportion in clay-size fraction, relative abundance or parts in 10.

CHEMICAL COMPOSITION

Chemical analyses of pumice and scoria have been made of whole samples from three of the major Mount Rainier tephra layers (table 11). All the fragments analyzed are andesitic, with SiO_2 values of approximately 55-60 percent. The fragments included a single piece of brown pumice from layer L, a dark scoria fragment from layer D, and three lapilli from layer C. One of the lapilli from layer C was a sample of the predominant brown pumice; the others were not identified as to type, but they are very similar chemically to the one identified. The lowest silica content reported in these samples was for the hornblende-rich scoria of layer D; thus, at Mount Rainier, as at Mount Mazama (Williams, 1942, p. 145-146), abundant hornblende is associated with scoria rather than with the more silicic pumice. Even the highest silica content measured in the tephra, for layer-C lapilli, is lower than the silica contents reported previously for Mount Rainier lava flows (table 11). The tephra samples analyzed, however, probably do not represent either the most mafic or most silicic rocks in the tephra beds from Mount Rainier. The very pale color and low refractive index of glass in some pumice lapilli within layer C and in a few other layers suggest that these fragments are as silicic as the lava flows.

The variation of R.I. values implies a wide range of silica contents for glass in various tephra deposits. Silica contents of glass alone seem to range considerably above and below those recorded by the bulk chemical analyses of whole-rock samples of either tephra or flow rocks. Curves that relate silica content to refractive index of glass (fig. 35) indicate that some of the glass in layers A, F, C, and X whose R.I. is near 1.50 probably have silica contents of 70 percent, or even more. Conversely, some glass in layer B, whose R.I. is about 1.58, apparently contains as little as about 50 percent silica.

The refractive-index values also suggest that most of the glass within specific tephra units is, as would be expected, more siliceous than the rock as a whole. A silica content of about 70 percent in glass of the predominant brown pumice of layer C, indicated by its R.I. value of about 1.50 (fig. 35), is considerably more than the silica content of whole-rock samples of layer C. Yet, other glass in scoria lapilli from layer C (R.I. as high as 1.54) probably has a silica content of slightly less than 60 percent (fig. 35), virtually the same as that in whole-rock samples of layer C. Glass in scoria in layer D (R.I., 1.52-1.55) probably ranges in silica from 65 percent down to about 55 percent; the latter is

TABLE 11.—*Chemical analyses, in percent, of tephra and of lava flows in Mount Rainier National Park*

[Whole-sample analyses of layers L, D, C, Y, and W done in U.S. Geological Survey laboratories under direction of Leonard Shapiro, L. C. Peck, and W. W. Brannock by methods described in U.S. Geol. Survey Bulls. 1144-A and 1036-C, supplemented by atomic absorption analyses]

MOUNT RAINIER ROCKS

	Layer L	Layer D		Layer C		Lava flows (4 andesite flows)[1]
Field No	9-23-65-22	9-23-65-21	7-11-62-1	C-971	LT-4	
SiO_2	57.3	54.7	59.4	59.77	59.8	60.53-63.57
Al_2O_3	17.6	19.3	17.2	17.36	18.3	17.01-17.25
Fe_2O_3	2.6	3.9	1.7	1.59	1.7	1.17-2.12
FeO	3.6	3.0	4.0	3.74	3.5	3.32-3.85
MgO	3.4	3.1	3.6	3.51	2.5	2.78-3.47
CaO	5.5	6.3	5.8	5.71	5.6	5.11-5.80
Na_2O	3.7	3.6	4.0	3.97	4.3	4.01-4.21
K_2O	1.4	1.1	1.5	1.71	1.6	1.58-1.84
H_2O-	1.4	1.7	.32	0.32	1.1	.09-.25
H_2O+	1.4	1.7	.53	0.76		.04-.12
TiO_2	1.0	1.0	1.0	0.89	0.84	.18-.95
P_2O_5	.29	.32	.26	0.20	0.28	.25-.85
MnO	.09	.10	.10	0.09	.09	.08-.10
CO_2	<.05	<.05	<.05	0.02	.05	....
Sum	99	100	99	100	100	....

TABLE 11.—*Chemical Analyses, in percent, of tephra and of lava flows in Mount Rainier National Park*— Continued

EXOTIC TEPHRA DEPOSITS

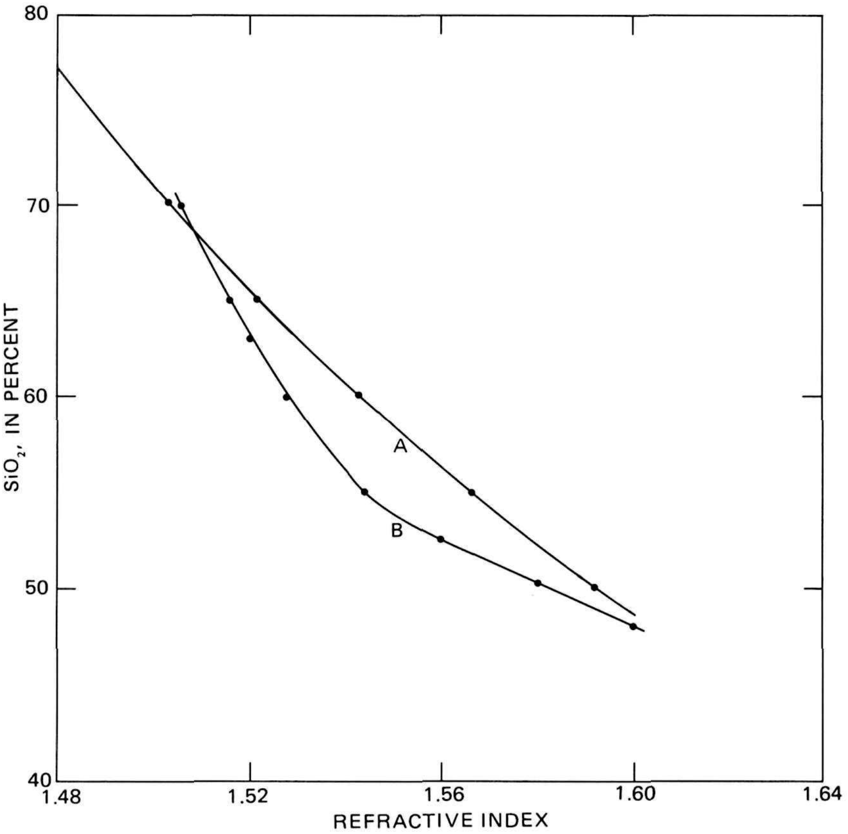
	Layer O (Mount Mazama)		Layer Y (Mount St. Helens)		Layer W (Mount St. Helens)
	Whole sample[2]	Glass (avg. 58 samples)[1]	Whole sample	Glass (avg. 9 sample)[3]	Whole sample
Field No			8-27-61-14		8-15-64-2
SiO_2	68.56	72.59	63.4	75.02	67.5
Al_2O_3	14.22	14.42	17.2	14.51	16.2
Fe_2O_3	1.42	2.08	1.6	1.4	1.3
FeO	1.49		2.3		2.1
MgO	0.83	0.54	1.3	0.48	.99
CaO	2.35	1.71	4.1	1.85	3.6
Na_2O	5.18	5.15	4.3	4.40	4.8
K_2O	2.47	2.70	1.2	1.98	1.6
H_2O-	3.32	....	.76	....	.14
H_2O+			2.3		1.0
TiO_2	0.58	0.48	.51	0.16	.44
P_2O_5	0.10	0.06	.17	0.04	.12
MnO	0.03	0.04	.08	0.03	.06
CO_2	......	....	.05	....	.05
Sum	101		99		100

[1] Reported by Coumbs (1939) and cited in Fiske and others (1963).
[2] Mount Mazama whole-sample analysis from Moore (1937, p. 159). Analyst, J. J. Fahey.
[3] From Westgate, Smith, and Nichols (1970).

approximately the same proportion as was measured for the whole-rock sample from that layer.

In several Mount Rainier tephra deposits, dark and light fragments of different chemical composition seem to occur together vertically throughout the layers rather than to be concentrated in distinct lenses or beds. Evidence of compositional stratification was seen only in layer C. That evidence consists of the stratigraphic zones in which certain rock types are concentrated: (1) Dark scoria is concentrated in, though not restricted to, the lower third of the deposit, and (2) brown pumice is predominant in the middle and upper parts of the layer, although some also occurs in the lower part.

Thus, several tephra deposits show evidence of eruption of magma of slightly different chemical composition at the same time, and layer C shows evidence of a distinct shift in chemical makeup of ejecta during an eruption. These compositional differences lead to the inference that the magmas that were available for eruption were not homogeneous. The eruption of such probably inhomogeneous magmas has been



RELATION OF SiO_2 content to refractive index of volcanic glass. Curve A is for glasses produced by fusion of natural volcanic rocks (Huber and Rinehart, 1966); curve B is for natural volcanic glasses (George, 1924). (Fig. 35)

described at Parícutin volcano in Mexico by Wilcox (1954) and at the volcano Hekla in Iceland by Thorarinsson (1967).

The light and dark tephra deposits from Mount Rainier are more variable in composition than the lava flows have been reported to be by Coombs (1936) and by Fiske, Hopson, and Waters (1963). The tephra layers are uniform in the sense that they are mostly andesitic, but they exhibit both mineral and chemical differences in detail. The lava flows might show a comparable range of mineralogical and chemical character on closer examination, but it seems likely at present that the tephra layers actually are marked by greater variety.

Chemical analyses of pumice lumps from exotic layers O, Yn, and W show that they generally are more silicic than tephra from Mount

Rainier (table 11). Layer Yn, for example, which has the lowest measured silica content of the three, is higher in silica than any of the Mount Rainier tephra samples analyzed. An overlap in range of silica content might be found if more Rainier tephra were analyzed, for the silica content of layer Yn does overlap the range reported for Mount Rainier lava flows. However, the silica content reported for layer Yn may be relatively low mainly because the analysis was made of pumice lapilli that included abundant iron-magnesium minerals. Comparison of layer Yn and layer O analyses indicates that whole samples of layer Yn are less siliceous than those from layer O, but that glass from layer Yn is at least as siliceous as glass from layer O (table 11).

Exotic tephra at Mount Rainier would be expected to have a generally higher silica content even if their source volcanoes were not, overall, any more silicic than Mount Rainier. Because most eruptions of siliceous magma are more explosive than eruptions of mafic magma, siliceous tephra is spread farther from the source volcano. Only the more siliceous tephra from the source volcano would reach a second, distant volcano. At the distant volcano, the siliceous tephra becomes interbedded with locally derived tephra deposits that include beds of relatively low silica content.

Measured Sections

SECTION A.—*Streambank on Mazama Ridge about 1.2 km north of the park highway*

	Thickness (cm)
Sand, dark-gray to brown, and organic material	6
Layer W; ash, pumiceous, gray to brown	2
Sand, brown; contains zone of layer-C fragments	9
Sand, dark-brownish gray	2
Set P; 3 gray ash beds, separated by thin sand and silt beds	4
Sand, brown, strongly iron-stained	1
Set Y; two ash beds, gray, and interlayered thin sand beds	3
Layer Yn; ash, coarse, brown	5
Sand, dark-brownish-gray	1
Set Y; single ash bed, gray to white	<1
Sand, dark-brownish-gray; contains roots	5
Layer F; ash, crystals and glass, pale brown	3
Sand, grayish-brown; contains scattered lapilli of layer D	5
Avalanche deposit at Paradise (Crandell, 1969b, p. 36); gray, angular pebble-, granule-, and sand-size fragments in silt and clay matrix	7
Sand, fine, grayish-brown	4
Layer O; ash, grayish yellow	4
Sand, purplish-brown; contains organic material	32
Layer R; ash and scattered lapilli, reddish brown	3
Sand and silt, layered brown and gray	55

SECTION B.—*Bank of small creek in an alpine meadow between Williwakas Creek and Cowlitz River valley, 0.6 km north of the Williwakas Creek falls noted on topographic map, at altitude of about 5,900 feet (1,800 m) on the southeast flank of Mount Rainier*

	Thickness (cm)
Silt, sand, and organic material mixed	4
Layer W; ash, gray	2
Sand and silt, brown	2
Layer C; lapilli and ash, brown	2
Sand and silt, brown	3
Sand and silt, gray	3
Set P; three ash beds and intervening thin silt beds	2
Set P; lowest ash, brown, sand size	<1
Sand, gray	1
Set Y; two gray ash beds and intervening sand beds	3
Layer Yn; ash, brown; swells and pinches out locally	5
Silt, gray	2
Set Y; ash, very light gray	<1
Sand, medium- to dark gray	1
Sand, grayish-brown	2
Set Y; ash, very light gray	<1
Sand, medium- to dark-gray	3
Sand and silt, gray and brown, laminated	4
Layer F; ash	1
Silt and sand, brown	2
Layer D; lapilli and ash, brown	4
Sand, dark-gray	2
Silt and sand, pale-grayish-brown	1
Sand, gray, contains scattered lapilli	3
Layer L; lapilli and ash, yellow brown	7
Sand and silt, dark-gray	2
Sand and silt, brown, laminated	1
Layer O; ash, reddish yellow; 1-7 cm thick, average	3
Sand and silt, reddish-gray; contains organic material	7
Layer R; stream accumulation	9
Sand, gray, contains lithic fragments	4

SECTION C.—*Bank of intermittent stream, southeast part of Ohanapecosh Park, 1 km north of Wauhaukaupauken Falls*

	Thickness (cm)
Silt, sand, and organic material	3
Layer W; ash, pale brown	2
Sand, silt, and organic material	3
Layer C; lapilli and ash, reddish brown	12
Sand, silty, gray, brownish at top	7
Set P; three beds, ash, gray, and interbedded sand	3
Set P; lowest ash bed, brown	<1
Sand, silty, gray	3
Set Y; ash, gray, and interbedded silt and sand	2
Layer Yn; brown	5-10
Sand, gray-brown	<1
Sand, gray	1
Layer B; ash and scattered lapilli, brownish gray	1-2

SECTION C.—*Bank of intermittent stream, southeast part of Ohanapecosh Park, 1 km north of Wauhaukaupauken Falls*—Continued

Sand, dark-gray	1-2
Sand, brownish-gray	5
Sand, dark-gray	2
Sand and silt, brown	1
Layer F; ash, yellowish white	3
Sand and silt, disturbed (?)	3
Layer D; lapilli and ash, grayish brown	10
Sand, dark-gray, pale-brown bed in middle	6
Layer L; coarse ash, brown	1
Sand, dark-gray	2
Layer A; ash, brown; contains scattered lapilli	1
Sand, grayish-brown	1
Layer O; ash, pale yellowish gray	2
Sand and silt, gray and brown, interbedded	20

SECTION D.—*Bank of creek 0.7 km north-northwest of Ranger Station at Yakima Park ("McNeeley site")*

	Thickness (cm)
Mixed sand, silt, and ash; includes grains from layer W	10-15
Layer C; lapilli and coarse pumiceous ash, brown	13
Sand, gray to brown	5-10
Set P; pumiceous and crystal ash, very pale brown	1
Sand, fine, silty, dark-reddish-gray to brown	1.5
Set P; pumiceous and crystal ash, white	0.5
Silt, gray to brown	1.5
Set P; silt-size ash, light gray	0.5
Sand and silt, brown; iron stained to reddish brown in upper 0.5-1 cm	6
Reworked ash (?), silt-size, light-gray	1
Silt, brown	0.5
Set Y; ash, silt size, light gray	0.5-2
Silt, brown	0.5
Layer Yn; ash, coarse, pumiceous, brown	4
Sand, brown	1
Set Y; fine sand- and silt-size ash, light gray	0.25-.5
Bedded sand and silt, brown to gray; contains granules near top	8
Sand, silty, dark-gray	1
Layer F, upper unit; ash, clayey, lithic, pale brown; darker in upper part	3
Middle unit; ash, crystal and pumiceous, grayish brown	0.5-2
Lower units; ash, clayey, lithic, yellowish brown; contains lithic lapilli as much as 7 mm across	6
Sand and silt, bedded, pale-brown to reddish-gray; contains lapilli of layer D	11
Sand, bedded, dark-gray to pale-brown; zone of pumiceous coarse ash in middle	4
Sand, interbedded, pale-brown and gray; scattered pumice lapilli in upper part	2
Layer O; ash, pumiceous and crystal; grades finer from bottom to top; very pale brown	5-6
Sand, silty, brownish-gray to brown; includes carbonaceous zones (source of radiocarbon sample W-951) and thin granule zones	16
Layer R; ash and small lapilli, reddish brown	7
Sand, silty, brownish-gray	5

SECTION E.—*Composite section along bank of stream 0.2 km northwest of Mystic Lake*

	Thickness (cm)
Silt, sand, roots and other organic matter	20
Layer W; ash, gray	1-2
Sand and silt	2
Layer C; small lapilli and ash	3
Sand and silt, brown	8
Sand, coarse, dark-gray	1
Silt and sand, ash (?), light-gray	< 1
Sand, brown	3
Set P; sand- and silt-size ash, gray	1
Sand and silt, purplish-brown	2
Set P; ash, gray	< 1
Sand, brown	1
Set P; silt-size ash	< 1
Sand, brown, apparently disturbed, pumiceous	16
Set Y; silt-size ash	< 1
Sand and silt, brown	2
Layer Yn; brown	5-10
Peat; minor amount of silt and sand	5
Set Y; ash, light gray	< 1
Peat and silt	15
Sand, gray	5
Layer O; locally in thick pond deposit	3-25
Sand and angular rubble	> 5

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