# volcanic hazards at mount rainier washington



GEOLOGICAL SURVEY BULLETIN 1238

# VOLCANIC HAZARDS
# AT
# MOUNT RAINIER
# WASHINGTON

Yellowish-orange postglacial avalanche deposit veneering gray glacial deposits at Paradise Park on the south side of Mount Rainier. The avalanche probably originated at or near the summit of the volcano.

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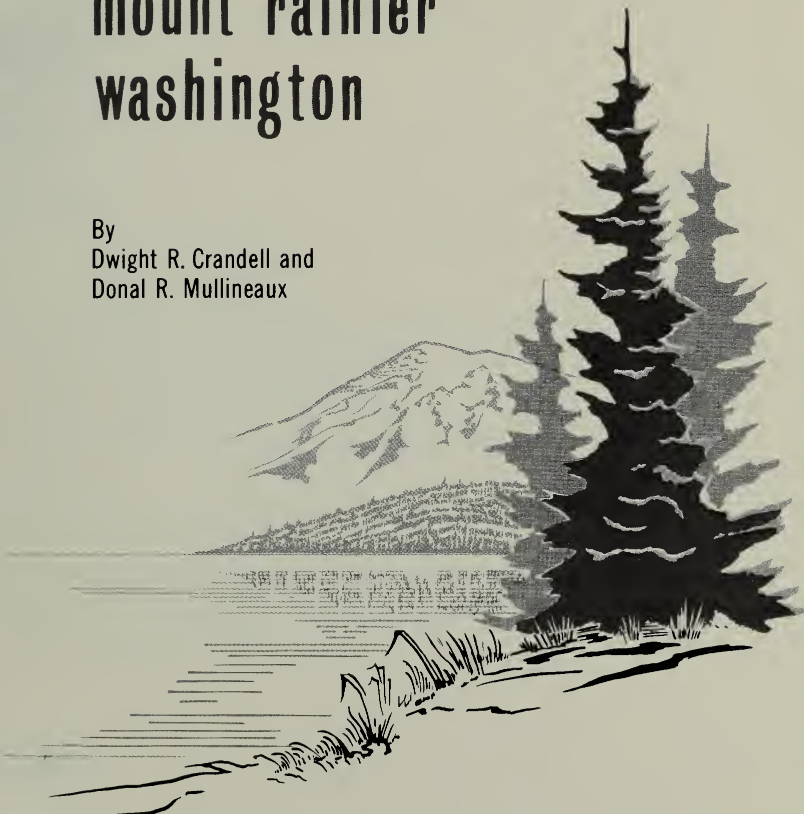

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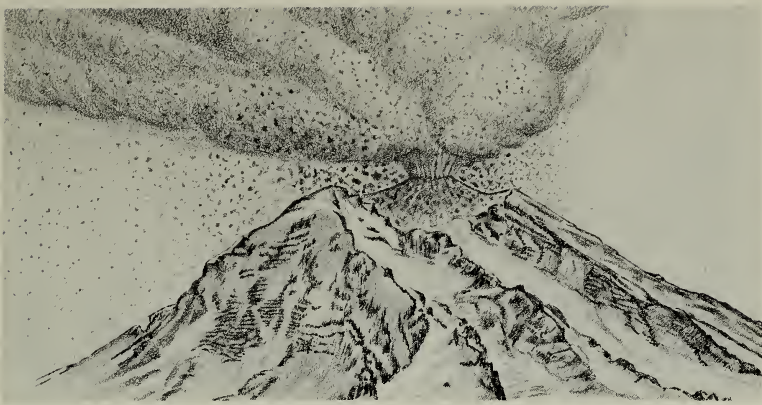


# VOLCANIC HAZARDS

## at mount rainier, washington

Mount Rainier is a large stratovolcano of andesitic rock in the Cascade Range of western Washington (fig. 1). Although the volcano as it now stands was almost completely formed before the last major glaciation, geologic formations record a variety of events that have occurred at the volcano in postglacial time. Repetition of some of these events today without warning would result in property damage and loss of life on a catastrophic scale. It is appropriate, therefore, to examine the extent, frequency, and apparent origin of these phenomena and to attempt to predict the effects on man of similar events in the future.

The present report was prompted by a contrast that we noted during a study of surficial geologic deposits in Mount Rainier National Park, between the present tranquil landscape adjacent to the volcano and the violent events that shaped parts of that same landscape in the recent past.

Natural catastrophes that have geologic causes—such as eruptions, landslides, earthquakes, and floods—all too often are disastrous primarily because man has not understood and made allowance for the geologic environment he occupies. Assessment of the potential hazards of a volcanic environment is especially difficult, for prediction of the time and kind of volcanic activity is still an imperfect art, even at active volcanoes whose behavior has been closely observed for many


LOCATION OF MOUNT RAINIER with respect to the Cascade Range and Puget Sound lowland of western Washington. The distribution of the 5,000-year-old Osceola Mudflow is shown by a pattern of large dots; that of the 500-year-old Electron Mudflow, by small dots. Many hills of glacial deposits and bedrock surrounded by the Osceola Mudflow are not shown. (Fig. 1)

years. Qualified predictions, however, can be used to plan ways in which hazards to life and property can be minimized.

The prediction of eruptions is handicapped because volcanism results from conditions far beneath the surface of the earth, where the causative factors cannot be seen and, for the most part, cannot be measured. Consequently, long-range predictions at Mount Rainier can be based only on the past behavior of the volcano, as revealed by study of the deposits that resulted from previous eruptions. Predictions of this sort, of course, cannot be specific as to time and locale of future events, and clearly are valid only if the past behavior is, as we believe, a reliable guide.

The purpose of this report is to infer the events recorded by certain postglacial deposits at Mount Rainier and to suggest what bearing similar events in the future might have on land use within and near the park. In addition, table 2 (page 22) gives possible warning signs of an impending eruption. We want to increase man's understanding of a possibly hazardous geologic environment around Mount Rainier volcano, yet we do not wish to imply for certain that the hazards described are either immediate or inevitable. However, we do believe that hazards exist, that some caution is warranted, and that some major hazards can be avoided by judicious planning.

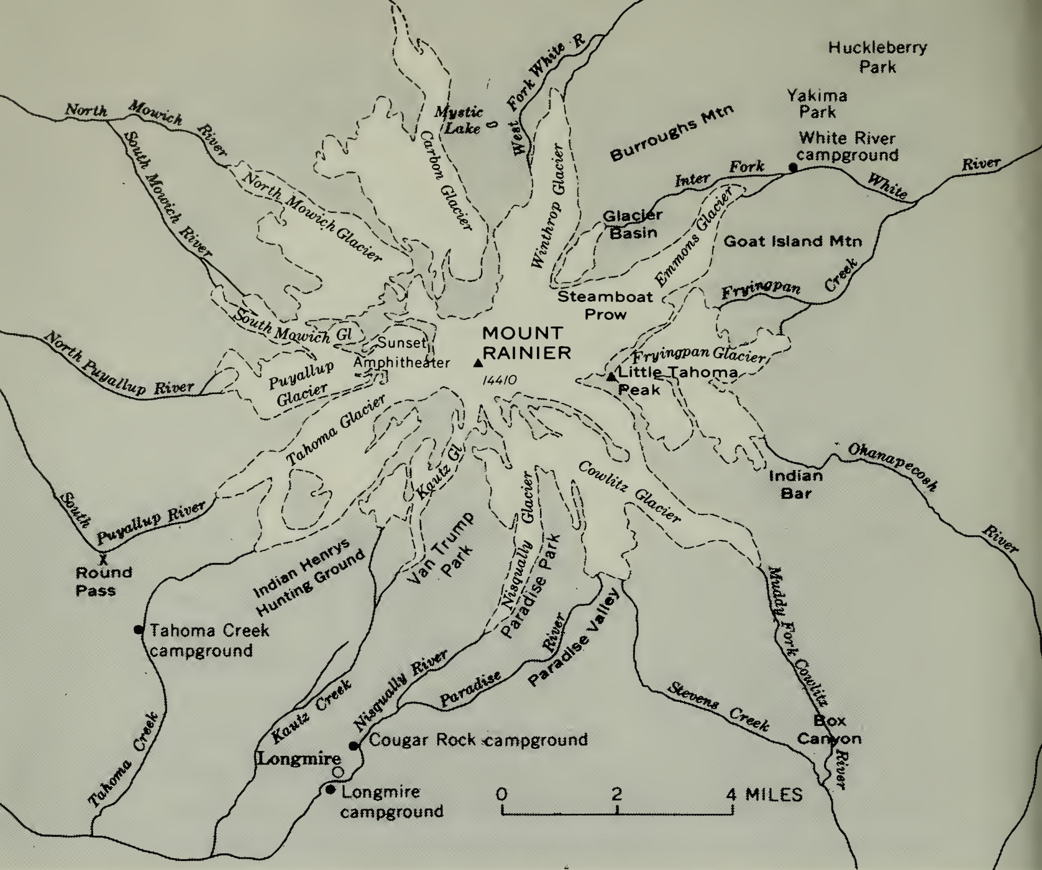
Most of the events with which we are concerned are sporadic phenomena that have resulted directly or indirectly from volcanic eruptions. Although no eruptions (other than steam emission) of the volcano in historic time are unequivocally known (Hopson and others, 1962), pyroclastic (air-laid) deposits of pumice and rock debris attest to repeated, widely spaced eruptions during the 10,000 years or so of postglacial time. In addition, the constituents of some debris flows [1] indicate an origin during eruptions of molten rock; other debris flows, because of their large size and constituents, are believed to have been caused by steam explosions. Some debris flows, however, are not related to volcanism at all.

## lava flows and pyroclastic eruptions

Most of Mount Rainier's lava flows are older than the last major glaciation (Hopson and others, 1962) and therefore are probably more than 25,000 years old. One possible exception is a lava flow in the valley of the West Fork of the White River just north of Winthrop Glacier (fig. 2; Fiske and others, 1963), whose topographic position on the valley floor suggests a relatively young age. The youngest lava flows at Mount Rainier form the present summit cone, which is indented by two overlapping craters (fig. 3). The slopes of the cone are smooth and unmodified by erosion;

---

[1] A debris flow is a mixture of rock debris and water which moves rapidly as a mass and owes its mobility to the included water. A mudflow is a variety of debris flow in which the solid component is composed of at least 50 percent sand, silt, and clay (Varnes, 1958).




LOCATION OF MOUNT RAINIER. The extent of glaciers shown is that of about 1910. (Fig. 2)

this condition may be partly due to volcanic heat which hinders the accumulation of deep snow and ice on the flanks of the cone. Even so, the lack of erosion suggests that the summit cone is no more than a few thousand years old, and possibly the cone is only a few hundred years old. The two craters of the summit cone most likely were formed during a single episode of volcanic activity. Fumaroles are present today on the slopes and along the rims of both craters, although the highest apparent temperatures are associated with the east crater (Moxham and others, 1965). The overlapping relation of the craters probably represents only a small eastward shift of the eruptive conduit near the summit of the volcano.

Future lava flows limited to the summit cone would not be direct hazards, although rapid melting of snow and ice by

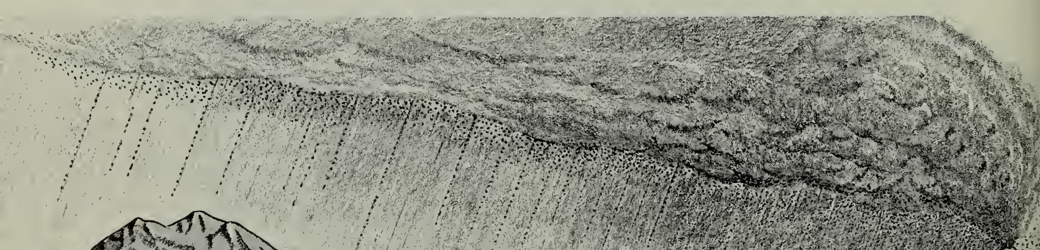
SUMMIT CONE OF MOUNT RAINIER shown here is indented by two overlapping craters; the left one is about 1,300 feet in diameter. Aerial view southeastward toward Mount Adams volcano; photographed September 3, 1964. (Fig. 3)

lava could cause disastrous floods and debris flows on valley floors. Lava flowing from the flanks of the volcano would threaten existing campgrounds in the valleys of the Nisqually and White Rivers and Tahoma Creek if the flows reached a distance of 5 miles beyond the base of the volcano, but they should present a minimal direct hazard because their relatively slow rate of movement would permit ample warning. Such flows could, however, also cause disastrous floods and debris flows if the lava were erupted onto glaciers or snowfields.

Pyroclastic eruptions at Mount Rainier have included the ejection of both molten and solid rock, which formed, respectively, deposits of pumice and dense rock fragments. Although pumice is readily recognized as a product of an eruption, it is so easily transported by wind that care must be taken to determine whether or not a specific deposit was actually erupted by Mount Rainier volcano. For example, some layers of pumice in the park were erupted by Mount Rainier, but others were brought in by wind from other Cascade volcanoes (table 1). Air-laid deposits consisting of large fragments of volcanic rock are also evidence of eruptions, but fine-grained deposits of similar material can also originate as windblown sediment derived from moraines and alluvium and from dust clouds that accompany large rockfalls.

The various pyroclastic deposits form thin but widespread layers that are interbedded locally with organic material and elsewhere with other deposits such as debris flows. Radiocarbon age determinations of the organic material permit age bracketing of the pyroclastic deposits by absolute dates. Some debris flows have been dated directly by radiocarbon; others, by their stratigraphic relation to pyroclastic deposits that have been dated elsewhere.

The most extensive and youngest known pumice layer erupted by Mount Rainier is layer C (table 1), which is widely distributed east and northeast of the cone. Crandell, Mullineaux, Miller, and Rubin (1962) estimated its age to be 1,000–3,000 years. Subsequently, wood fragments from above and below the layer near Mystic Lake (fig. 2) were found to have radiocarbon ages, respectively, of about 2,000 and 2,450 years. (All the radiocarbon age determinations cited in this report were made in the laboratories of the U.S. Geol. Survey under the supervision of Meyer Rubin.) In addition, wood fragments from above and below the layer at Huckleberry Park were found to have ages, respectively, of



about 1,500 and 2,350 years. Thus, layer C is approximately between 2,000 and 2,350 years old. Crandell and Waldron (1956) described the layer in a measured section on the northeast side of Mount Rainier as brown and light-gray pumiceous cinders, and others (Hopson and others, 1962; Fiske and others, 1963) have described it as coarse-grained tawny-brown to light-gray pumice that crunches underfoot.

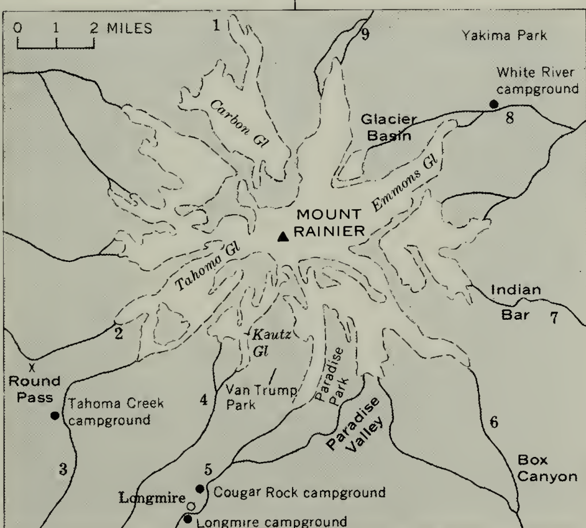
Layer C forms a mantle as much as a foot thick at the northeast base of the volcano; it diminishes in grain size and thickness northward and eastward and extends beyond the boundaries of Mount Rainier National Park. The layer contains pumice lapilli as large as 2×3×4 inches, at the east end of Burroughs Mountain, as well as angular fragments of dense gray andesite 1–2 inches in diameter that apparently were erupted at the same time. Fragments of pumice as large as 1 foot in diameter have been found near the west end of Goat Island Mountain. On the south and west sides of Mount Rainier, layer C is limited to the immediate flanks of the cone—a distribution that suggests southwesterly winds during the pumice eruption.

Layers D, L, and R (table 1) also were erupted by Mount Rainier and seem from preliminary field and laboratory studies to be similar to layer C in thickness, grain size, and mineral content. Layers D and L are thickest and most extensive directly east and southeast, respectively, of the volcano. Layer R seems to have nearly the same pattern of distribution as layer C but is not nearly so widespread.

At some time between 5,000 and 6,600 years ago, as dated with respect to the Osceola Mudflow and layer O (table 1), the Yakima Park area (fig. 2) was blanketed by a few inches to as much as 3 feet of explosion rubble that consists of angular rock fragments in a matrix of reddish-brown sand and silt (fig. 4). The fragments are as large as 1.5 feet in diameter and are derived from the volcano. A thin rubble of comparable rock type lies on the summit and upper flanks of Goat Island Mountain. The distribution and composition of the rubble, plus the fact that no new pumice or scoria seems to be associated with it, indicate that the rubble probably originated in one or more steam explosions that blew out part of the northeast flank of Mount Rainier.

| Years ago | Eruptions that produced summit cone of Mount Rainier and main pyroclastic deposits in park | 1<br>Carbon River valley |
|---|---|---|
| | **Layer W** erupted by Mount St. Helens 400-500 yr ago. Covered park to maximum depth of 3 in. | |
| 1,000 | ?— **Lava flows erupted to form present summit cone of Mount Rainier.** —? | |
| 2,000 | **Layer C** erupted by Mount Rainier 2,000-2,300 yr ago. Covered NE and E part of park to maximum depth of 1 ft. | |
| 3,000 | **Layer Y** erupted by Mount St. Helens 3,000-3,500 yr ago. Covered park to maximum depth of 20 in. | **Debris flow** extended at least 5 miles downvalley from Carbon Glacier between 3,000 and 6,600 yr ago. |
| 4,000 | | |
| 5,000 | **Explosion rubble** erupted by Mount Rainier 5,000-6,600 yr ago. Rubble as much as 3 ft thick deposited at Yakima Park. | |
| 6,000 | **Layers D and L** erupted by Mount Rainier 5,000-6,600 yr ago. Layer D is as much as 12 in. thick on E flank, layer L as much as 6 in. thick on SE flank of volcano. | |
| 7,000 | **Layer O** erupted by Mount Mazama at Crater Lake, Oreg., 6,600 yr ago. Covered park to maximum depth of 3 in. | |
| 8,000 | | |
| 9,000 | **Layer R** erupted by Mount Rainier more than 8,700 yr ago. As much as 1 ft thick in NE part of park. | |

| 2<br>South Puyallup River valley<br>(study incomplete) | 3<br>Tahoma Creek valley | Years ago |
|---|---|---|
| **Avalanche** of rock debris extended to end of Tahoma Glacier less than 100 yr ago.<br>**Electron Mudflow** *extended 40 miles downvalley about 500 yr ago.* | **Debris flow** *was at least 200 ft deep at Tahoma Creek campground 400–500 yr ago. Extent not known.*<br>**Debris flows** twice extended at least as far as Tahoma Creek campground more than 500 yr ago. | 1,000 |
| **Mudflow** *extended at least 15 miles downvalley about 2,000 yr ago.*<br>**Hot debris flow** of ash and bombs extended to park boundary about 2,350 yr ago. | **Mudflow** *covered Round Pass between 500 and 3,500 yr ago. Reached thickness of at least 800 ft in valleys within park. May be correlative with 2,000-yr-old mudflow in South Puyallup River valley.* | 2,000 |
| | | 3,000 |
| | | 4,000 |
| | | 5,000 |
| | | 6,000 |
| | | 7,000 |
| | | 8,000 |
| | | 9,000 |



| Years ago | 4<br>Kautz Creek valley | 5<br>Nisqually River valley |
|---|---|---|
| 1,000 — | **Debris flows** extended to Nisqually River in 1947.<br>**Debris flows** twice extended at least 4 miles beyond Kautz Glacier within the last 500 yr.<br>**Debris flows** extended at least 3 miles beyond Kautz Glacier at least three times between 500 and 3,500 yr ago. | **Debris flow** covered area of Longmire and Longmire campground about 300 yr ago.<br>**Debris flow** covered area of Cougar Rock campground and extended at least as far downvalley as Tahoma Creek between 500 and 3,500 yr ago. |
| 2,000 — | | **Debris flow** *probably several hundred feet deep within park extended at least 25 miles downvalley from Nisqually Glacier between 500 and 3,500 yr ago.* |
| 3,000 — | **Debris flow** occurred more than 3,000 yr ago; extended more than 4 miles beyond Kautz Glacier. | |
| 4,000 — | | |
| 5,000 — | | **Avalanche** *of rock debris covered Paradise Park and Paradise Valley about 5,000 yr ago. Resulting debris flow was several hundred feet deep at site of Longmire and extended at least 18 miles downvalley.* |
| 6,000 — | | **Debris flows** *twice extended at least 20 miles downvalley more than 6,600 yr ago.* |
| 7,000 — | | **Avalanche** of rock debris covered Van Trump Park more than 6,600 yr ago. |
| 8,000 — | | |
| 9,000 — | | |

*and avalanches at Mount Rainier*—Continued

| 6<br>Muddy Fork of the Cowlitz River valley | 7<br>Ohanapecosh River valley | Years ago |
|---|---|---|
| **Debris flow** extended at least as far downvalley as Box Canyon between 500 and 3,500 yr ago. | **Debris flow** extended at least 6 miles beyond Ohanapecosh Glacier between 500 and 3,500 yr ago. | 1,000 |
| | | 2,000 |
| | | 3,000 |
| | **Debris flow** extended at least 6 miles beyond Ohanapecosh Glacier between 3,000 and 6,600 yr ago. | |
| | | 4,000 |
| | | 5,000 |
| | | 6,000 |
| | **Debris flow** covered valley floor at Indian Bar more than 6,600 yr ago. | 7,000 |
| | | 8,000 |
| | | 9,000 |

TABLE 1.—*Postglacial eruptions, debris flows, and avalanches at Mount Rainier*—Continued

| Years ago | 8<br>Inter Fork and White River valleys | 9<br>West Fork of the White River valley |
|---|---|---|
| 1,000 | **Avalanche** of rock debris from Little Tahoma Peak in 1963 extended 4.3 miles downvalley.<br>**Debris flows** occurred at least three times between 500 and 3,500 yr ago; one extended at least 18 miles beyond Emmons Glacier. | **Debris flows** twice extended at least 18 miles downvalley from Winthrop Glacier less than 500 yr ago.<br>**Debris flow** extended at least 15 miles downvalley from Winthrop Glacier between 500 and 3,500 yr ago. |
| 2,000 | | |
| 3,000 | | **Debris flow** extended at least 15 miles downvalley from Winthrop Glacier between 3,000 and 5,000 yr ago. |
| 4,000 | | |
| 5,000 | **Avalanche** *of rock debris covered Glacier Basin and Emmons Glacier about 5,000 yr ago. Resulting* **Osceola Mudflow** *was at least 500 ft deep at site of White River campground. Extended at least 65 miles downvalley.* | **Avalanche** *of rock debris covered Winthrop Glacier about 5,000 yr ago. Resulting* **Osceola Mudflow** *merged with flow in White River valley.* |
| 6,000 | **Debris flow** containing volcanic bombs reached downvalley at least as far as 1 mile beyond White River campground more than 5,000 yr ago. | |
| 7,000 | **Debris flow** *extended at least 30 miles downvalley between 5,000 and 6,600 yr ago. Was at least 400 ft deep at N boundary of park.* | |
| 8,000 | | |
| 9,000 | Note: The North Puyallup River valley and the North and South Mowich River valleys have not yet been studied. Italics indicate debris flows of very large volume, as shown by long distance of travel or by temporary filling of valley to depth of hundreds of feet. Dating of most ash layers is based on radiocarbon age determinations by Meyer Rubin, U.S. Geological Survey, of interbedded organic deposits (Crandell and others, 1962). Age of other events is based on the stratigraphic relation of their deposits to pyroclastic deposits and to the Osceola Mudflow | |


PYROCLASTIC DEPOSITS exposed in a roadcut at Yakima Park. Man is standing on glacial drift directly overlain by layer R, which originated at Mount Rainier more than 8,750 years ago. The thin light-colored band is layer O, which has been identified as ash that was erupted at Crater Lake, Oregon, about 6,600 years ago. The layer of rock fragments above layer O is an explosion rubble derived from Mount Rainier. (Fig. 4)

Layer Y, which is locally nearly 2 feet thick and is the most voluminous postglacial pumice deposit in Mount Rainier National Park, came not from Mount Rainier but from Mount St. Helens volcano, 50 miles to the south-southwest (Crandell and others, 1962; Mullineaux, 1964). Layer Y underlies layer C and is between about 3,000 and 3,500 years old. Layer Y apparently is the sand- to granule-size pumice deposit that was described by Hopson, Waters, Bender, and Rubin (1962, p. 641) as the main ash fall that forms the "major part of the youngest ash blanket from Mount Rainier"; they believed this deposit to be no more than 600 years old. Our interpretation that layer Y is a product of Mount St. Helens is based chiefly on the fact that this deposit coarsens and thickens to the south-southwest toward that volcano. A few miles northeast of Mount St. Helens the layer, as much as 10 feet thick, consists of pebble- and cobble-size pumice lumps.

Layer W (table 1), like layer Y, coarsens and thickens to the south-southwest, its thickness ranging from 1–3 inches at Mount Rainier to more than 10 feet on the north flank of Mount St. Helens. The pumice of layer W also originated at Mount St. Helens volcano.

Layer O, which forms a discontinuous blanket a few inches thick over the whole park, was erupted by Mount Mazama at Crater Lake, Oregon, about 6,600 years ago (Wilcox, 1965). The deposit from Mount Mazama is the most widespread postglacial ash layer in the Pacific Northwest, blanketing the region from western Washington and Oregon eastward to Montana (Powers and Wilcox, 1964). Wide distribution of the ash from Mount Mazama makes it particularly useful as a marker horizon in postglacial deposits in the park as well as elsewhere in the region.

Future eruptions of pumice from Mount Rainier, even on the largest scale recorded by postglacial deposits, would be troublesome but not catastrophic. This does not mean that a larger eruption could not occur—at least once during the time just preceding the last glaciation, for example, a much more voluminous eruption of pumice did occur at Mount Rainier. Nevertheless, the absence of any large pumice eruption in postglacial time and the similarity of recurring small pumice eruptions suggest that a disastrous event of this nature is not likely.

If a future volcanic explosion caused an eruption of previously solidified rock on a scale similar to that represented by the explosion rubble at Yakima Park and Goat Island Mountain, it would be a serious hazard to life within a radius of perhaps 5 to 8 miles from the summit of the volcano. Such an explosion would probably be strongly directional and would affect only a small sector of the volcano.

## debris flows

Debris flows are one of the most common and devastating geologic phenomena in the postglacial history of the volcano. The largest debris flows from Mount Rainier probably originated in volcanic explosions that caused large-scale avalanching of rock debris. Other debris flows were caused by such factors as heavy rainfall and rapid snowmelt, which are unrelated to volcanism; their occurrence at Mount Rainier results from the availability there of large quantities of loose rock debris on steep slopes.

A few debris flows have constituents that clearly indicate an origin during volcanic eruptions. Such a debris flow is exposed in roadcuts in the South Puyallup River valley directly north of Round Pass (fig. 2). It contains breadcrust bombs as well as wood fragments that have been wholly converted to charcoal, the implication being that the flow was hot. One piece of charcoal has a radiocarbon age of about 2,350 years. A similar debris flow that contains unmodified breadcrust bombs as large as 10 feet in diameter underlies the Osceola Mudflow near White River campground. We found no wood, so we do not know whether the bombs were hot or cold when they were incorporated in this deposit. These deposits probably resulted from eruptions that ejected hot ash, bombs, and rock fragments onto snowfields and glaciers. Rapid melting of snow and ice could then have provided large volumes of water to flush the rock debris down the slopes of the volcano and into the stream valleys.

Even though they apparently were cold, some debris flows were of such large volume that a volcanic eruption is the most likely process by which adequate quantities of rock debris could be set in motion down the flanks of the volcano. It is possible, however, that some flows resulted from avalanches caused not by volcanism but by earthquakes or by collapse of oversteepened parts of the volcano.

The largest postglacial mudflow, which is estimated to have had a volume of nearly half a cubic mile, is the 5,000-year-old Osceola Mudflow (Crandell and Waldron, 1956). This clay-rich mudflow probably originated from the avalanching of rock, previously altered partly to clay by steam, from the summit and upper slopes of the volcano (Crandell, 1963a, b). Others (Fiske and others, 1963) have proposed, instead, that the mudflow was formed by "the collapse and flowing out of a thick fill of water-saturated sediments in the upper part of the White River valley." However, the source of the mudflow was above rather than within the valley of the White River, as is clearly shown by remnants of the Osceola deposit higher on the flanks of the volcano at Steamboat Prow, to the west of Winthrop Glacier, and on the ridge crests at the head of Inter Fork valley (Crandell and Waldron, 1956; Crandell, 1963a). Thus, the distribution of the mudflow on the northeast side of Mount Rainier, inferred from detailed mapping of its remnants, indicates an origin at or near the former summit. The avalanches that caused the mudflow may have resulted from one or more steam explosions.

During its movement, the Osceola Mudflow submerged the White River valley at the site of White River campground beneath at least 500 feet of mud and rock debris. It traveled 40 miles downvalley to the mountain front, then spread out in a lobate mass that covered 65 square miles in the Puget Sound lowland. There it buried the sites of the present communities of Enumclaw and Buckley under as much as 70 feet of mud and probably extended at least as far northwest as the present town of Auburn (fig. 1).

At about the same time, a similar avalanche and debris flow swept down and across Paradise Park and Paradise Valley on the south side of the volcano (see frontispiece) and temporarily filled the Nisqually River valley at the site of Longmire to a depth of at least several hundred feet (Crandell, 1963a).

Another very large mudflow originated less than 3,500 years ago on the west side of the volcano. It temporarily filled the valleys of Tahoma Creek and the South Puyallup River to a depth of more than 700 feet, so that mud spilled from one valley into the other through Round Pass. At the pass, remnants of the mudflow as much as 15 feet thick overlie pumice of layer Y. This mudflow also buried the northern part of Indian Henrys Hunting Ground (fig. 2), which is 800 feet above the adjacent valley floor. It is possibly the same mudflow as that exposed at the junction of the Mowich and Puyallup Rivers (fig. 1), from which wood about 2,200 years old has been obtained (Rubin and Alexander, 1960). Because of the large size of the mudflow, its distribution, and the apparent lack of any other source of adequate volume, we think it had an origin similar to that of the Osceola Mudflow.

A younger mudflow, which has been named the Electron Mudflow, originated on the west side of Mount Rainier within the Puyallup River drainage basin; the flow extended about 40 miles downvalley to the outskirts of Sumner (fig. 1) and buried the floor of the Puyallup River valley at Orting under 15 feet of rock debris and mud (Crandell, 1963b). Wood from this mudflow has been radiocarbon dated as about 500 years old.

A debris flow between 400 and 500 years old temporarily flooded the valley floor at Tahoma Creek campground to a depth of at least 200 feet. This flow contains clay and fragments of altered rock similar to that cropping out in Sunset Amphitheater (Fiske and others, 1963) and probably originated in avalanches at that locality.

It should be noted that the larger debris flows from Mount Rainier apparently did not form permanent fills in valleys to the maximum height of their remnants on the valley walls. Instead, these remnants probably mark transient flow crests, analogous to those of stream floods.

The formation of a large debris flow depends partly on the availability of a large source of water. A potential source on the flanks of the volcano and in the craters is the extensive cover of snow and ice, parts of which would melt during an eruption. Heat production at the summit craters (Moxham and others, 1965) even now probably is adequate to convert part of the snow and ice to water. In this regard, Flett (1912) stated that a member of a climbing party descended about 85 feet into an ice cave along the rim of the eastern crater, threw stones farther down into the cave, and heard splashes as the stones fell into a body of water. More recently, Louis W. Whittaker (oral commun., Aug. 5, 1966) of Tacoma, Wash., and his brother James W. Whittaker of Seattle descended into the east summit crater along an ice cave on a summer day in the mid-1950's. Using oxygen masks, they climbed down along the crater wall, which had a slope of 30° or less and was studded with fumaroles and areas of hot rock. When they reached a depth of about 450 feet vertically below the crater rim, they threw stones farther down the ice cave and heard splashes as the stones struck a body of water.

A significant increase of heat caused by molten rock rising in the volcano could further melt the ice and snow in the summit craters to form lakes perhaps several hundred feet deep. Such lakes in the two craters could contain several hundred million gallons of water. If this water were expelled during an eruption, it would most likely spill down the east, south, or west side of the volcano, pick up loose rock debris on the flanks and on valley floors, and create floods and large debris flows.

Some debris flows form during very heavy rainfall or rapid melting of snow; others are caused by outbursts of water from within, under, or on top of glaciers. Flows of these kinds are not directly connected with any kind of volcanic activity, unless they result from excessive melting of ice due to volcanic heat. Debris flows caused directly by heavy rainfall pick up rock debris mainly from masses of loose glacial drift. Although these flows are of rather limited size, they occur more often than the vastly larger flows such as the Osceola and Electron. Debris flows occurred in October 1947 in the Kautz Creek valley during a period of very heavy rainfall. As runoff from valley sides and Kautz Glacier swept downvalley, it formed a series of debris flows that came to rest in a broad fan at the lower end of the valley (see sketch, p. 15). Grater (1948) estimated that 50 million cubic yards of rock debris was carried by the debris flows. Deposits of at least six previous but similar debris flows are exposed in the banks of Kautz Creek.

Even though they do not result in debris flows, some large rockfalls and avalanches of rock debris from high parts of the volcano are also a potential hazard on the slopes of the volcano and on adjacent valley floors. Avalanches that


AVALANCHE DEBRIS (outlined by dashed line), which covers parts of Emmons Glacier and the valley floor, originated in rockfalls at Little Tahoma Peak in December 1963. Maximum distance of movement of the avalanches was a little more than 4 miles. Photograph by Austin S. Post, U.S. Geological Survey. (Fig. 5) resulted from rockfalls at Little Tahoma Peak in December 1963 moved as much as 4.3 miles and stopped only 2,000 feet from White River campground (fig. 5). These rockfalls may have been triggered by a small steam explosion on the north side of Little Tahoma Peak (Crandell and Fahnestock, 1965).

## anticipation of debris flows and eruptions

Debris flows and eruptions have occurred sporadically since the last major glaciation. If this pattern continues with no significant change, both phenomena must be expected in the future. The best available guide to the possible variety, frequency, and location of future events is table 1, which shows all known postglacial debris flows and eruptions. This tabulation goes beyond the short time span of direct observation of Mount Rainier volcano, which embraces little more than 100 years. Discretion must be used, however; for such a tabulation not only "mixes" deposits formed in different ways but also has the effect of telescoping time; from it one might conclude that disaster is imminent. For better perspective, it is helpful to examine the relative frequency and location of each kind of event (table 2). It can be seen from tables 1 and 2 that some volcanic events (lava flows) have occurred perhaps not more than once in 10,000 years; others (small-scale steam explosions), as often as once each century and perhaps as often as once each decade. Records of the National Park Service indicate that from 1932 to 1961, five debris flows and floods not caused by volcanic activity occurred in the Kautz Creek and Nisqually River valleys alone; thus, for the entire park, these phenomena probably have occurred at a rate of one in 3–10 years. It is clear that valley floors are the localities most often affected and that some valleys are affected more often than others.

We conclude that debris flows are by far the greatest hazard because of their frequency and possibly very large size and because they travel along valley floors where highways, dwellings, and other works of man are concentrated.

Furthermore, we believe that any future major eruption of Mount Rainier, and even some minor ones, will be accompanied by passage of debris flows down one or more valleys that head on the volcano. If a flow as large as the Osceola Mudflow were to occur today, it doubtlessly would result in wholesale destruction and death, perhaps on a scale comparable to that accompanying some large mudflows caused by volcanic eruptions in Japan and Indonesia within the last century. Flows of this kind could result from steam explosions or possibly from processes unrelated to volcanism and could thus occur without warning. Fortunately, however, debris flows of extremely large volume are infrequent. Debris flows of relatively small volume, which may not be accompanied by volcanic activity and which are a rather common occurrence in many of the valleys, also present a definite hazard to the roads and recreational facilities that have been developed on valley floors adjacent to the volcano.

A second conclusion reached from inspection of table 1 is that debris flows are more common in some valleys than in others. The reasons for this are not fully understood, but two important factors are the presence of masses of altered and weakened rock on the volcano at some valley heads and the availability of large volumes of loose glacial drift on some steep valley sides. If, as we believe, the largest debris flows from Mount Rainier in the past did originate in avalanches of altered rock from high parts of the volcano, the largest avalanches and debris flows in the future probably will originate in similar areas. The most extensive known mass of altered rock near the summit of the volcano is in the east wall of Sunset Amphitheater. At least four large avalanches and debris flows probably have originated in Sunset Amphitheater during the last thousand years or so, and similar phenomena will very likely occur there again.

Table 1 implies that debris flows have become more frequent with the passage of time, but this may be only because younger deposits are relatively well preserved and readily seen, whereas some older ones may have been either removed by erosion or buried.

Although future volcanic eruptions are expectable, prediction of such events is not possible in terms of a specific time, place, or scale. Not only do we lack knowledge of the events that preceded eruptions of the past, but these events

TABLE 2.—*Types of eruptions that have occurred at Mount Rainier in the future, and possible warning*

[The flanks of the volcano include

| | Volcanic activity not necessarily associated with the rise of new magma | Types of volcanic activity associated with rise of new magma |
|---|---|---|
| | Steam explosion (generally on small scale) | Steam explosion (may be on small to very large scale) |
| Direct effects | Formation of small-scale rockfalls and avalanches. Effects confined chiefly to flanks of volcano and valley floors immediately adjacent. | Formation of rockfalls and avalanches which grade down-valley into debris flows. Effects confined chiefly to flanks of volcano and valley floors.<br>Formation of air-laid rubble deposits whose distribution would be limited to flanks of volcano and areas closely adjacent. |
| Indirect effects | Possible floods and (or) debris flows caused by damming of rivers by avalanche deposits. Principal effects probably would be limited to valley floors within and closely adjacent to park. | Very large avalanches of moist altered rock on flanks of volcano grading directly into debris flows on valley floors.<br>Debris flows may be very long, extending tens of miles beyond park boundaries. |
| Possible warning signs of impending activity | Appearance of steam jets and clouds of water vapor, possibly accompanied by explosions and rockfalls.<br>Abnormal melting of glaciers at hot spots; appearance of melt pits in glaciers. | |
| Indicated possible frequency | 1 in 10 to 100 years-------- | 1 in 2,000 years--------- |

*postglacial time, anticipated effects and frequency of similar eruptions in*
*signs of an impending eruption*

an area within 4 or 5 miles from the summit]

| Types of volcanic activity associated with the rise of new magma—Con. | | |
|---|---|---|
| Pumice eruption | Eruption of bombs and (or) block-and-ash avalanches | Eruption of lava flows |
| Fall of pumice on flanks of volcano; widest distribution beyond flanks in a downwind direction, thus probably greatest to the northeast, east, or southeast. Thickness probably will be less than a foot beyond 5-mile radius of summit. Anticipate thin ashfall over broad area without regard for topography. | Fall of hot to incandescent bombs, ash, and rock fragments. Distribution chiefly on flanks of volcano, but avalanches may extend into valleys. | Distribution probably limited to flanks of volcano. Major effects expectable only in immediate vicinity of flow. |
| Extensive melting of glaciers possible, caused by internal volcanic heat and by steam moving toward outside of volcano. Expected result: floods and debris flows on valley floors. | | |
| Ejection of water from summit craters in early stage of eruption. Possible result: floods and debris flows on valley floors. | | Ejection of water from craters if flows occur at summit of volcano. |
| Debris flows may result from extensive downslope movements of pumice onto valley floors. | Possible floods and debris flows caused by eruption of hot debris onto snow. | Extrusion of lava flow beneath or onto glacier might cause catastrophic floods. |
| Increase in frequency and magnitude of local earthquakes.<br>Large increase in stream discharge unrelated to meteorological conditions.<br>Appearance of clouds of water vapor associated with steam jets, possibly accompanied by small steam explosions and rockfalls.<br>Increase in fumarolic activity and increased melting of snow at summit cone.<br>Abnormal glacier melting at hot spots; appearance of melt pits in glaciers.<br>Increase in temperature of fumaroles.<br>Increase of sulfur and chlorine in fumarolic gases. | | |
| 1 in 2,500 years | 1 in 5,000 years | 1 in 10,000 years. |

might not necessarily be identical during each successive eruption. Our inability to predict specifics of future activity leaves two principal methods by which destructive effects might be minimized: careful site selection for future construction away from areas likely to be affected, and recognition of signs of an impending eruption. Special importance should be attached to the recognition of phenomena which, if correctly evaluated, might warn of an impending eruption. Eruptions preceded by the rise of molten rock into the volcano might thus be anticipated (table 2), even though some kinds of steam explosions could occur with little or no warning.

## summary

During postglacial time Mount Rainier volcano apparently was characterized by long quiet periods punctuated by brief episodes of activity; thus, its present dormant state cannot be regarded as a reliable sign that the volcano is now extinct. If the pattern of past activity continues, a substantial steam, pumice, or lava eruption might occur on an average of once each 500–1,000 years.

The direct hazard presented by future eruptions of lava, pumice, or steam is not regarded as great, but such eruptions may cause devastating floods and debris flows. Whatever their origin, debris flows are regarded as a major hazard because of their frequency and their movement along valley floors where works of man are concentrated. Their destructive effects can be minimized by careful land-use planning on valley floors.

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