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STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

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Rockfalls and Avalanches from Little Tahoma Peak on Mount Rainier Washington

By DWIGHT R. CRANDELL *and* ROBERT K. FAHNESTOCK

CONTRIBUTIONS TO GENERAL GEOLOGY

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A description of the deposits of seven successive rockfalls and avalanches at Mount Rainier volcano, and of their origin and manner of transport

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ROCKFALLS AND AVALANCHES FROM LITTLE TAHOMA PEAK ON MOUNT RAINIER, WASHINGTON

By DWIGHT R. CRANDELL and ROBERT K. FAHNESTOCK

ABSTRACT

In December 1963 rockfalls from Little Tahoma Peak on the east side of Mount Rainier volcano fell onto Emmons Glacier and formed avalanches of rock debris that traveled about 4 miles down the glacier and the White River valley. In this distance, the rock debris descended as much as 6,200 feet in altitude. Minor lithologic differences and crosscutting relations indicate that the rockfalls caused at least seven separate avalanches, having an estimated total volume of 14 million cubic yards. The initial rockfall may have been caused by a small steam explosion near the base of Little Tahoma Peak.

During movement, some of the avalanches were deflected from one side of the valley to the other. Calculations based on the height to which the avalanches rose on the valley walls suggest that their velocity reached at least 80 or 90 miles per hour. The unusually long distance some of the avalanches were transported is attributed to a cushion of trapped and compressed air at their base, which buoyed them up and reduced friction.

INTRODUCTION

On December 14, 1963, and probably on several subsequent occasions as well, very large masses of rock fell onto Emmons Glacier from the north side of Little Tahoma Peak on the east flank of Mount Rainier volcano (figs. 1, 2). As the rock masses struck the glacier, they shattered and formed rock avalanches that rushed as much as 4.3 miles downvalley and came to rest less than half a mile from the White River campground in Mount Rainier National Park. As snow melted during the summer of 1964, dark rock debris mantling Emmons Glacier became visible from a visitor center at Yakima Park, and clouds of dust rose almost daily from the rockfall scar. These features attracted much interest from park visitors, many of whom wondered if they were witnessing volcanic eruptions. This article discusses the avalanche deposits, their manner of transport, and what might have caused the rockfalls.

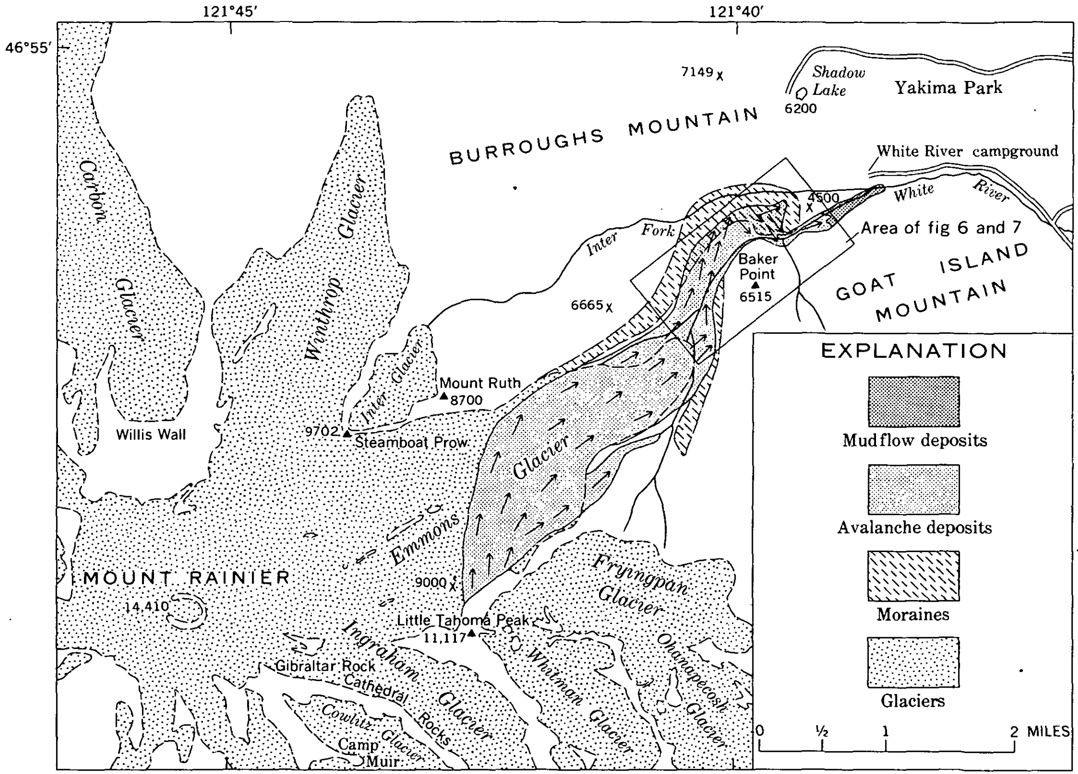

FIGURE 1.—Map of northeast side of Mount Rainier, showing area covered by avalanches from Little Tahoma Peak. Rectangular area at northeastern end of the deposits is shown in figures 6 and 7. Arrows indicate inferred direction of movement of the avalanches.

FIGURE 2.—General view of rockfall-avalanche deposits. Note avalanche debris on Emmons Glacier below Little Tahoma Peak. Wooded ridge in center of lower valley is a terminal moraine of Emmons Glacier formed between about 1700 and the early 1900's. The end of an avalanche tongue downvalley from the terminal moraine is indicated by a dashed line. Aerial photograph by Austin S. Post, U.S. Geological Survey.

The senior author currently is investigating the surficial geology of Mount Rainier National Park (Crandell and others, 1962; Crandell, 1963; Crandell and Miller, 1964); during the periods July 7–12 and August 19–September 13, 1964, he studied the avalanche deposits and the circumstances that led to their formation. He expresses his appreciation to Ranger Naturalists Arthur Haines, William Kagami, and Duane Nelson of the National Park Service, each of whom accompanied him in the field in July. The junior author, in a recent study of the White River and its flood plain, surveyed 12 profiles across the valley floor just downstream from Emmons Glacier (Fahnestock, 1963). Nine of these profiles were resurveyed in July 1964, with the assistance of David Pedersen, University of Texas, to determine the thickness of the avalanche deposits. Both of the authors wish to

acknowledge the interest and cooperation of John A. Rutter, Superintendent of Mount Rainier National Park, and his staff. The Northern Forest Fire Laboratory of the U.S. Forest Service at Missoula, Mont., provided an aircraft equipped with an infrared sensing device; this device was used to examine the north face of Little Tahoma Peak for evidence of volcanic heat. The aircraft was piloted by Eldon Down and the infrared sensing equipment was operated by Robert A. Cook, both of the U.S. Forest Service. Robert M. Moxham of the U.S. Geological Survey interpreted the results of the infrared investigation, and Austin S. Post of the Geological Survey provided aerial photographs he made of the avalanche deposits on August 20, 1964. The authors express their appreciation to J. Hoover Mackin, University of Texas, for discussions regarding the rockfalls and avalanches and for his critical reading of the manuscript.

GEOGRAPHIC AND GEOLOGIC SETTING

Little Tahoma Peak forms the highest part (11,117 ft) of a broad wedge pointing toward the top of Mount Rainier, about 2 miles to the west (fig. 1). The wedge is made up of volcanic breccia and rubble interlayered with lava flows that slope down the flank of the volcano in an easterly direction. Both the north and south sides of Little Tahoma Peak rise steeply about 2,000 feet above the flanking glaciers. The cliffs are largely the result of continuing erosion by a broad sheet of ice that flows down the east flank of Mount Rainier. This ice splits at Little Tahoma Peak into the southeast-flowing Ingraham Glacier and the northeast-flowing Emmons Glacier. Emmons Glacier now terminates about 2.5 miles downvalley from Little Tahoma Peak.

Prior to December 1963, the White River just beyond Emmons Glacier occupied a valley floor about 500 feet wide, which was flanked on the northwest by lateral moraines and stagnant ice and on the southeast by Goat Island Mountain. Farther downvalley the valley floor is constricted by a large terminal moraine which was formed at the front of Emmons Glacier between about 1700 and the early 1900's (Crandell and Miller, 1964) (fig. 2). The White River still flows through this constriction but is now about 300 feet south of its pre-avalanche course.

DESCRIPTION OF AVALANCHE DEPOSITS

The avalanche deposits are a jumble of large and small rock fragments in a matrix of grayish-red sand (fig. 3). Many small cracks formed in the avalanche deposits during settling and compaction. The deposits are loose and porous and they slide and compact underfoot.

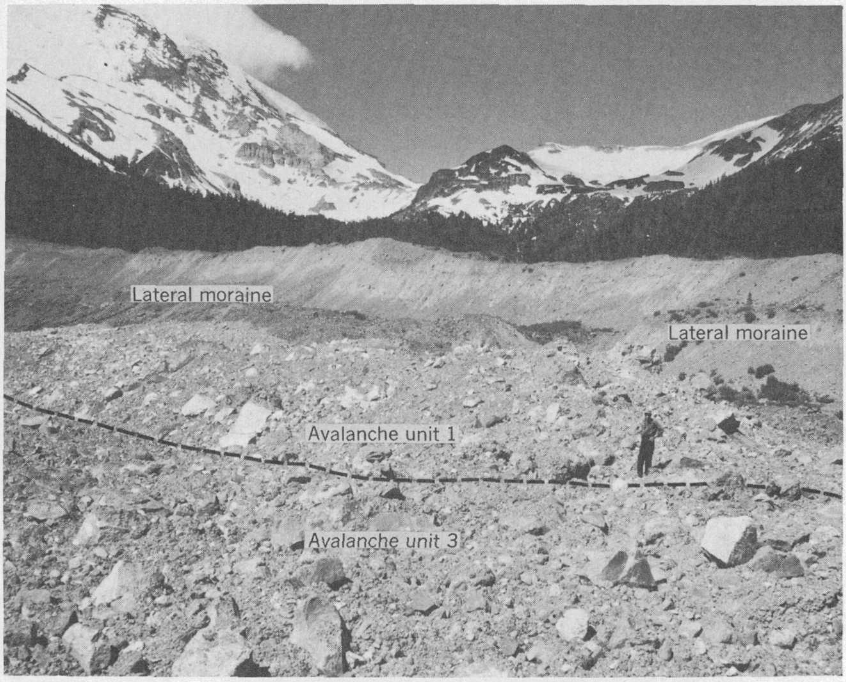

FIGURE 3.—Surface of avalanche deposits is hummocky and strewn with blocks. Deposit in front of the man is part of avalanche unit 3 (see fig. 7 and p. A10); deposit directly behind and to left of the man is part of unit 1.

Most of the rock fragments in the avalanche deposits are light-gray to dark-reddish-brown andesite. These fragments came from lava flows and from interbedded masses of breccia, both of which were erupted during the growth of Mount Rainier and are now exposed on the sides of Little Tahoma Peak (see Fiske, Hopson, and Waters, 1963, p. 73–75). In addition, the avalanche deposits contain blocks from an undetermined source. One of these blocks, 15 by 20 by 20 feet in maximum dimensions, lies on the terminal moraine near the northeastern edge of the avalanche deposits. A block of reddish-brown breccia about 1,700 feet upvalley from the terminal moraine has maximum dimensions of 24 by 30 by 46 feet (fig. 4), but the largest block in the entire deposit (fig. 5) lies on Emmons Glacier near the point where the White River flows from the glacier terminus. This rock has approximate maximum dimensions of 60 by 130 by 160 feet, and probably weighs at least 50,000 tons. Many blocks of reddish andesite breccia have disintegrated into piles of rubble since the avalanches came to rest; their poor consolidation illustrates the weakness of some rock layers in Little Tahoma Peak. Locally, the avalanche deposits lie on remnants of glacier ice downvalley from Emmons Glacier; these ice masses probably were present before the avalanche occurred. No glacier ice was seen in the avalanche deposits themselves.

Bridges formed of snow mixed with avalanche debris persisted over the White River at two places (figs. 6, 7) throughout the summer of 1964, and the river flowed beneath a third snow bridge between cross sections 10 and 12 until late July. The snow in these bridges had nearly the density of ice, and about 25 percent of the bridge material consisted of rock debris. This mixture probably was formed during one or more avalanches and indicates that snow was abundant in the debris when it came to rest.

The loose and porous fabric of the avalanche debris probably is due to the inclusion and the retention of much air and snow during transport and deposition. According to the records of the National Park Service, at White River Ranger Station (7 miles northeast of Little

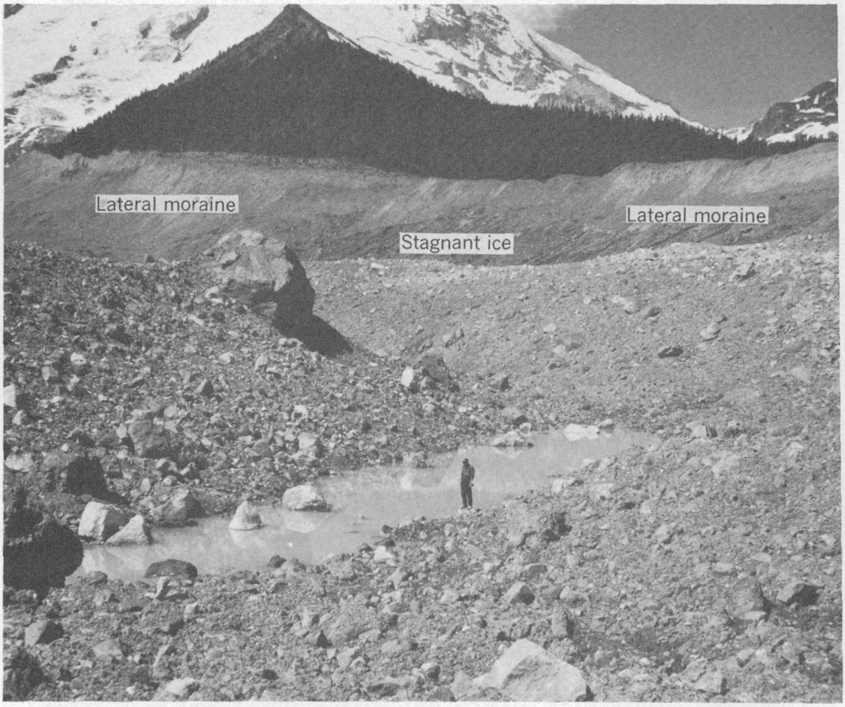

FIGURE 4.—Curved furrow in surface of avalanche unit 4. Furrow is bordered on the southwest (left) side by a long curved ridge, which may represent the front of a separate avalanche. Pond on floor of furrow drains to the left. Block on ridge is about 24 by 30 by 46 feet.

Tahoma Peak at an altitude of 3,500 ft) 13 inches of snow was on the ground on December 14, 1963. From December 15 to January 4, 1964, snow depth ranged from 7 to 15 inches at the Ranger Station, and from January 5 to the end of March, the depth ranged from 23 to 82 inches. Thus, at and subsequent to the time of the initial rockfall at least a foot of snow probably covered the area crossed by the avalanches.

The surface of the avalanche debris is very rough. If viewed from the ground, the surface between Emmons Glacier and the terminal moraine has a chaotic appearance, but if seen from above, distinct patterns are apparent. One pattern consists of a series of curved ridges and furrows between cross sections 6 and 12, just upvalley from the terminal moraine (figs. 6, 7). These ridges and furrows lie at slight angles to the trend of the valley, are in the thickest part of the deposits, and were formed as the avalanches came to rest. Another pattern lies between cross sections 3 and 6 and consists of a series of straight ridges and furrows that parallel the trend of the valley. They may have been formed by debris deposited along the margins of avalanche units 4 and 5 during movement. Shallow ponds partly occupy some of the furrows in both areas.

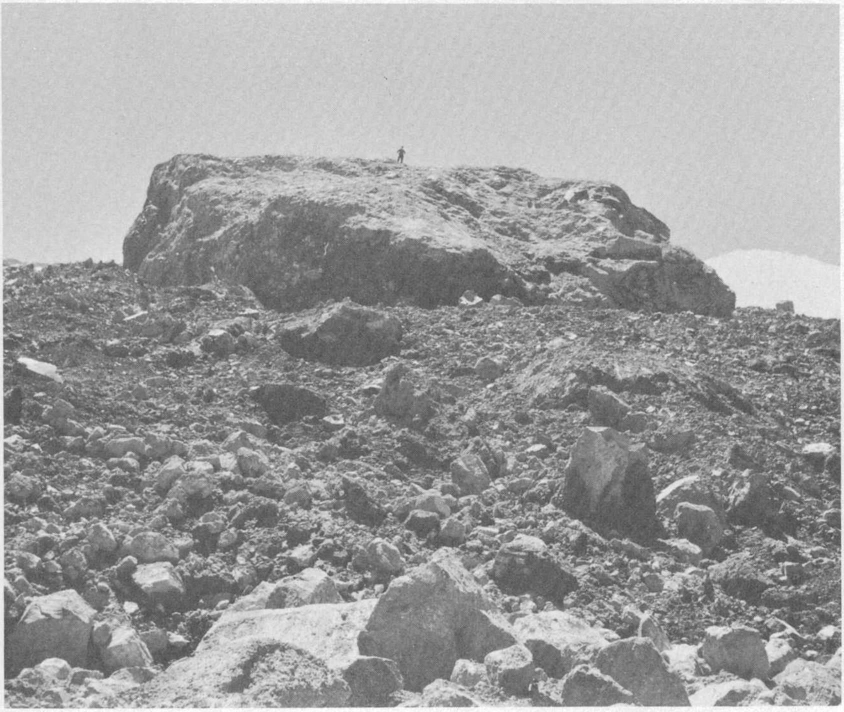

FIGURE 5.—Block of reddish breccia lying on Emmons Glacier (hidden beneath avalanche debris). The block is about 160 feet long and 60 feet high.

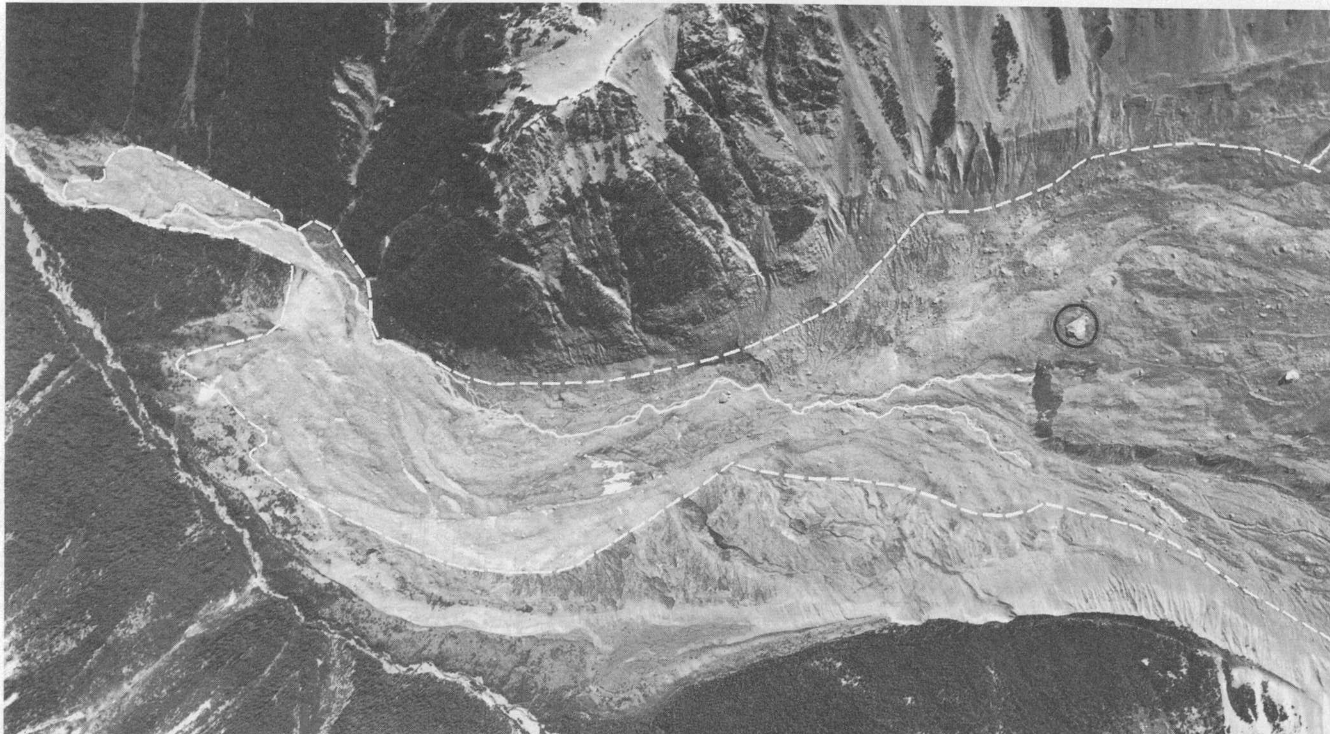

FIGURE 6.—Aerial view of downvalley part of avalanche deposits. Compare with map, figure 7. Dashed line indicates boundary of deposits. Rock fragment shown in figure 5 is circled. Photographed August 20, 1964, by Austin S. Post, U.S. Geological Survey.

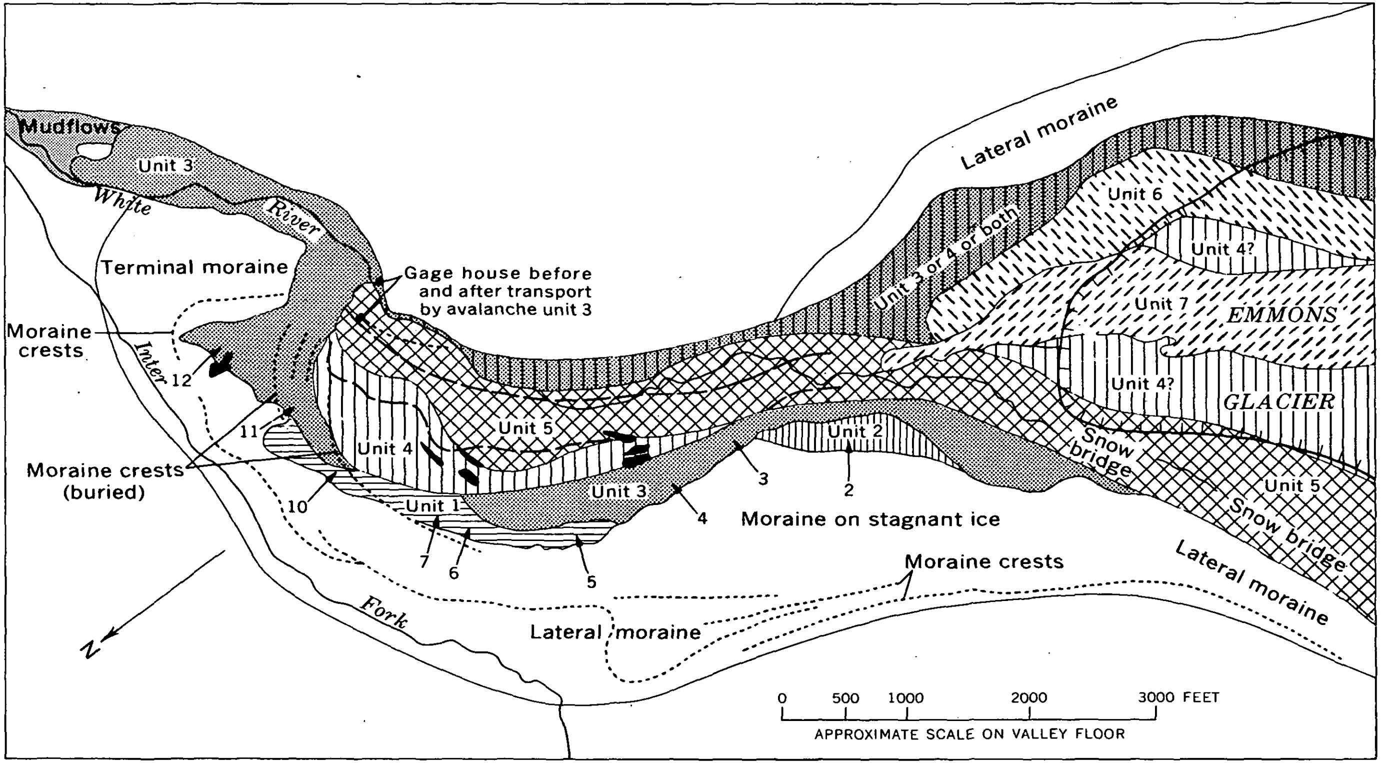

FIGURE 7.—Relation of downvalley part of avalanche deposits to moraines of Emmons Glacier and to the former flood plain of White River (heavy dashed line). Black areas are shallow ponds. Numbered arrows indicate cross sections shown in figure 10.

There are also straight ridges and furrows in avalanche debris on the lower mile of Emmons Glacier. Farther up, the glacier is steeper and extensively crevassed, and the avalanche deposits are thin. Even in this area, however, there are parallel strips of fairly clean ice and debris-covered ice.

Still another pattern appears if the deposits are studied on the ground. Certain areas of the deposits have a distinctive color, texture, or topography. If areas of similar characteristics are mapped, it becomes apparent that at least seven separate avalanche deposits are present; these lap over each other in a series of shinglelike lobes (figs. 6, 7), which are here called avalanche units.

The earliest two avalanche units lie along the northern edge of the deposits; they are both overlapped by a third unit, but as the exposures of units 1 and 2 are 1,500 feet apart, the time relation of these two early units is not known. For convenience of reference the one farther downvalley is designated avalanche unit 1, and the other one avalanche unit 2. Avalanche unit 1 forms a ridge along the lateral moraine on the northwest side of the valley, and blocks of a distinctive light-gray andesite litter the ridge. In July a layer of compressed granular snow as much as 6 inches thick locally separated the outer margin of this unit from the underlying moraine. Avalanche unit 2 has an overall reddish appearance, and blocks of light-gray andesite are absent. This unit was recognized only in the upper part of the valley; its downvalley extent is buried by the younger avalanche deposits.

Avalanche unit 3 cuts across units 1 and 2. It has an overall reddish appearance but does not contain as many blocks of light-gray andesite as unit 1. Unit 3 represents the largest avalanche of the group. It not only reached the terminal moraine but also poured through the river gap near the southern end of the moraine and moved about 2,000 feet farther downvalley as a narrow tongue (figs. 2, 6, 7). This tongue is 300 to 500 feet wide and terminates in a lobate mass of debris 10 to 15 feet thick. On the south side of the White River, about 1,100 feet upvalley from the end of the tongue, the deposit rises abruptly about 15 feet, and farther upvalley is a series of low transverse ridges and furrows. These features may have been formed by a second pulse or wave of avalanche debris within unit 3.

On the upvalley side of the terminal moraine, trees and bushes from which bark and limbs have been partly removed flank the margin of avalanche unit 3 (fig. 8). This damage was caused by flying rock debris that now veneers the crest and flank of the moraine as much as 70 feet above the main part of the avalanche deposit. This thin veneer apparently represents an airborne curtain of sand and small rock fragments transported by a violent rush of air from beneath avalanche unit 3 as it came to rest.

FIGURE 8.—Damaged pine tree on terminal moraine. Tree has been partly stripped by airborne debris moving away from viewer. The debris forms a veneer only a few inches thick on the moraine and is visible on top of several boulders.

Another noteworthy feature of avalanche unit 3 is a scar 800 feet long that the avalanche scraped at the base of Goat Island Mountain directly opposite the terminal moraine (fig. 9). The scar is crescentic in shape if viewed from the ground, and its highest part, 140 feet above the White River, coincides with the narrowest part of the valley. To form the scar the avalanche scoured away most of the vegetation and the loose rock debris down to solid bedrock.

Avalanche unit 4 resembles unit 3 but contains fewer large blocks. Its surface is marked by a series of curved ridges; the most prominent, which is about 35 feet high (fig. 4) and 1,400 feet long, may be the front of a separate avalanche unit. Unit 5 contains more large blocks than unit 4 and cuts across the south end of the most prominent ridge in unit 4. Units 6 and 7 are differentiated by their crosscutting relation to each other and to avalanche unit 5. Neither unit 6 nor unit 7 had sufficient volume or velocity to move far beyond the terminus of Emmons Glacier.

Surveys were made in July 1964 to determine the width and thickness of the avalanche deposits (figs. 10, 11). The survey lines followed lines surveyed across the valley by Fahnestock in August 1963. Comparison of these two surveys reveals that the avalanche deposits downvalley from Emmons Glacier range in width from 900 to 1,600 feet, their broadest part coinciding with the widest and flattest part of the old valley floor. The maximum thickness of the avalanche deposits is 100 feet, at cross section 7. The greatest mass of debris lies between cross sections 10 and 12; at cross section 10, the White River is now about 50 feet higher than its pre-avalanche position and about 300 feet farther south.

The volume of avalanche debris downvalley from Emmons Glacier, estimated from the cross sections, is about 12 million cubic yards.

FIGURE 9.—Avalanche scar, about 140 feet high, at the base of Goat Island Mountain. This scar was formed when part of avalanche unit 3 moved through the narrow gap in the terminal moraine (fig. 2). The avalanche deposit downstream (left) from the scar has been partly eroded by the White River. Area of avalanche deposits is enclosed by dashed line; arrows show inferred direction of movement of avalanche unit 3.

In addition, a large volume, perhaps as much as several million cubic yards, covers an area of about 1.3 square miles on Emmons Glacier. The avalanche debris is estimated to cover a total area of about 2 square miles and to have a total volume of at least 14 million cubic yards. Although the height and the basal width of the rockfall scar are estimated to be about 1,700 and 1,800 feet, respectively, the volume of the buttress cannot be computed directly because of its irregular shape (fig. 12) and a lack of knowledge concerning its original average thickness.

MOVEMENT AND VELOCITY OF THE AVALANCHES

Prior to the rockfalls in late 1963, there was a large buttress on the north side of Little Tahoma Peak (compare figs. 12, 13); the collapse of this buttress caused the avalanches. The abundance of certain kinds of rock in some avalanche units and not in others leads the authors to conclude that different parts of the buttress fell at different times, although it is not known whether these separate falls occurred at intervals of minutes, hours, or days.

As sections of the buttress fell onto Emmons Glacier, they shattered and moved obliquely down the glacier. The avalanche debris was moving northeastward when it reached the glacier terminus. Some of the avalanches struck the shoulder of Goat Island Mountain, rose several hundred feet up its side, and then were deflected northward. The avalanches then rose 185 feet up the north lateral moraine and were deflected southeastward (fig. 10, cross sections 2–7). After avalanche unit 3 was deflected by the lateral moraine, it flowed into the gap near the south end of the terminal moraine. Here it scarred Goat Island Mountain, caromed northeastward across the valley, and rose a short distance onto the terminal moraine again before continuing downvalley.

The avalanches represent a type of dry landslide termed "rock-fragment flow." During movement, these dry flows are mixtures of rock debris and air. Their flowing motion probably is a result of buoyancy given to the mass by air trapped and compressed within and beneath the rock-fragment flow. Varnes (1958, p. 34) suggested that such a mass becomes a kind of density current[1] of high specific gravity and unusual velocity. He also stated that these dry flows of rock debris may be caused by volcanic explosions or by very large rockfalls or rockslides.

[1] Density currents are moving masses of gas or liquid (commonly mixed with pulverized solid material) which are of greater density than the gas or liquid in which they are enclosed.

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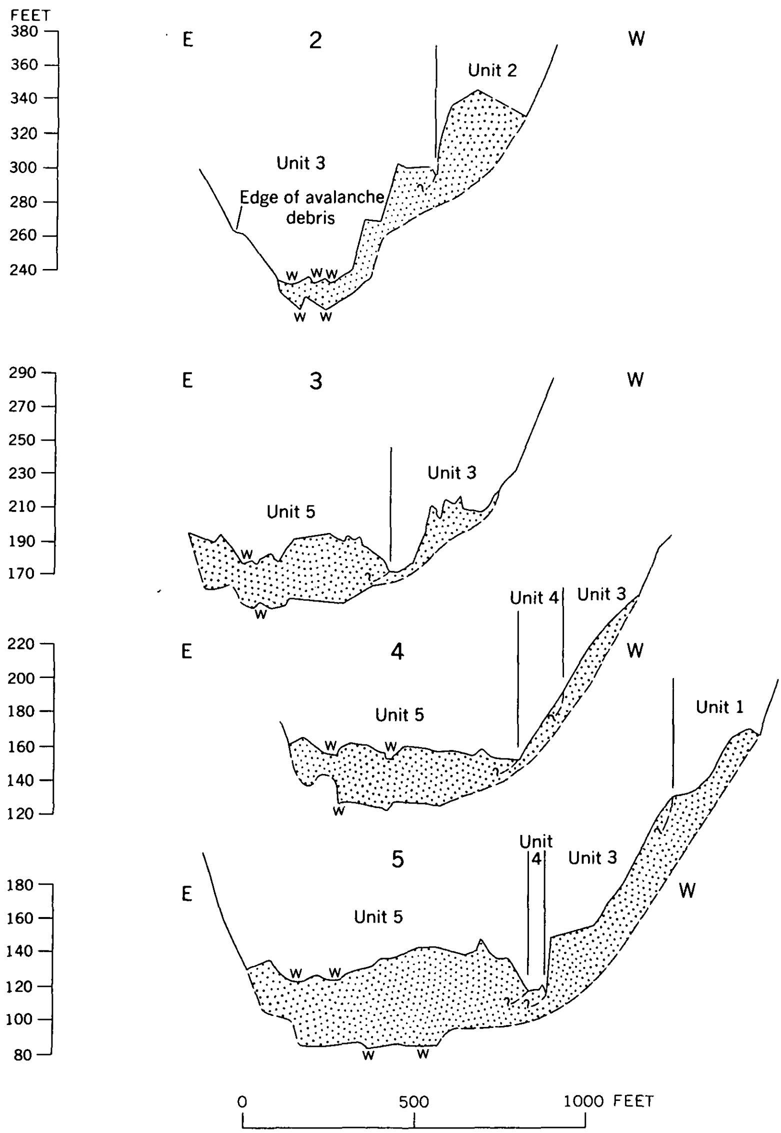
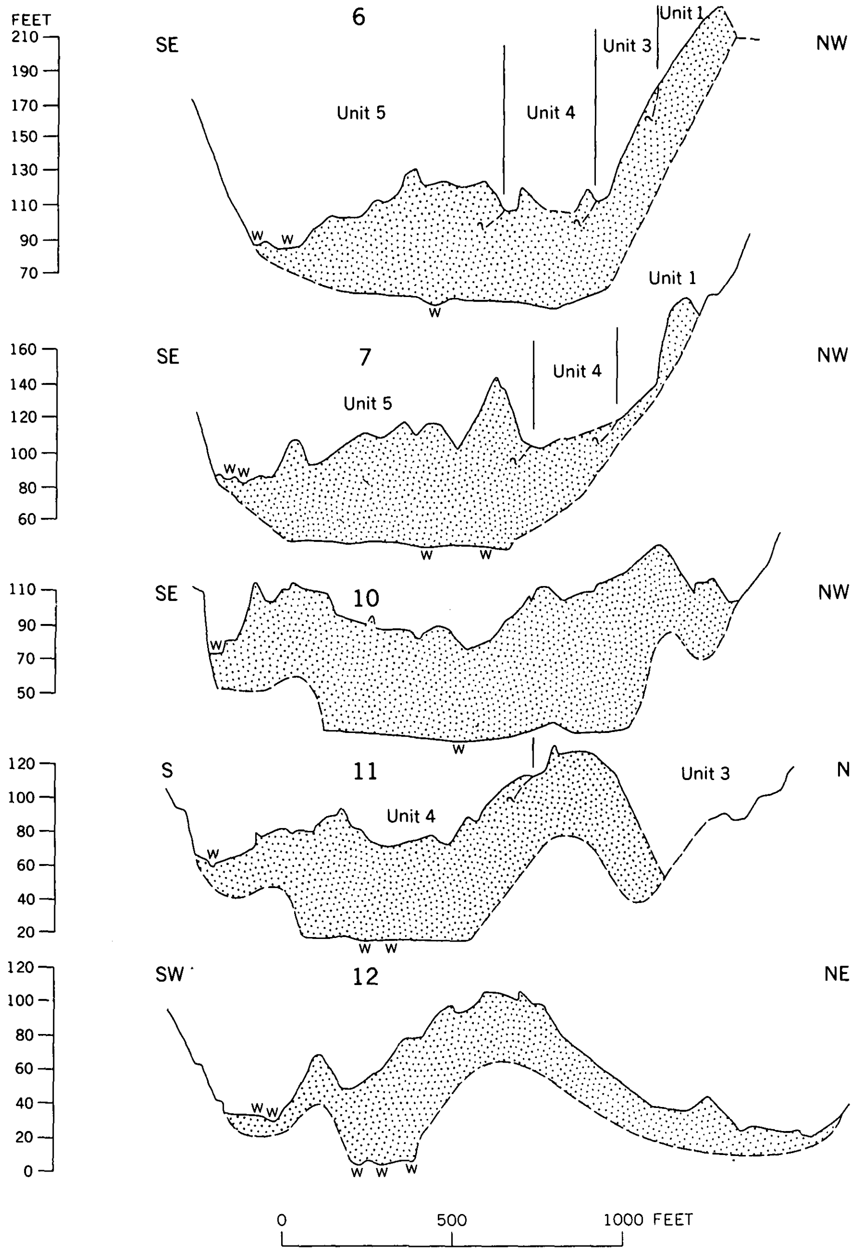


FIGURE 10.—Transverse cross sections of avalanche deposits. Position of Whi
avalanche topography is based on a survey made by Fahnestock in Augu
scale is referred to an arbitrary datum. Verticle exaggeration is ×



ver before and after the avalanches is indicated by the letter w. Pre-
3. Locations of the cross sections are shown in figure 7. The vertical

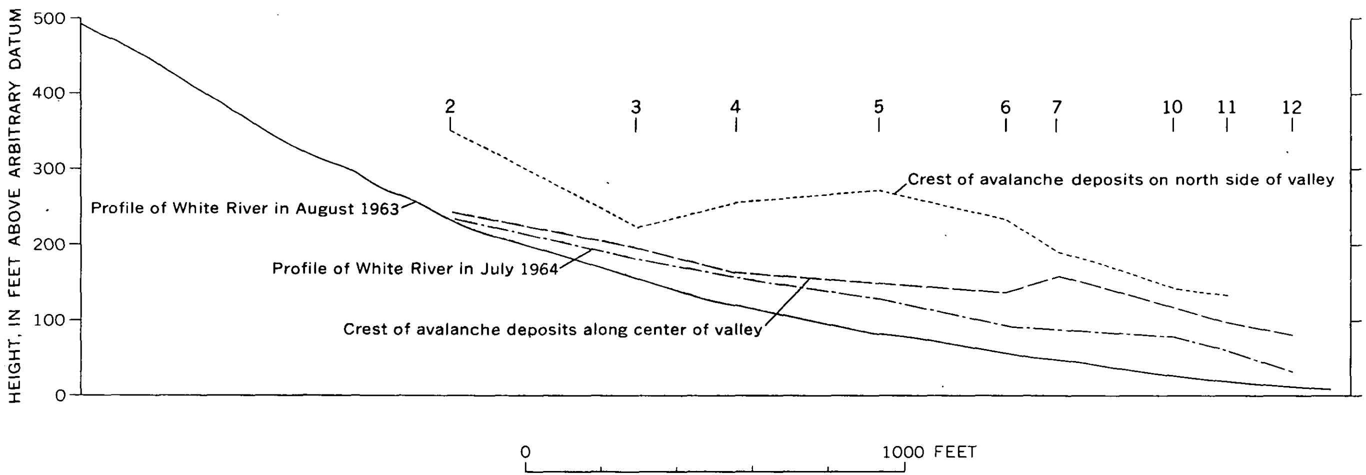


FIGURE 11.—Longitudinal section of avalanche deposits, showing the height of the deposits above the former and present flood plain of the White River. Preavalanche profile is based on a survey made by Fahnestock in August 1963. Numbers 2 to 12 indicate position of sections shown in figure 10.

Eyewitnesses of rock-fragment flows tell of a cloud of rock debris pouring like a liquid over the land surface, filling depressions and being deflected by obstacles. A steam explosion that blew out a large part of Bandai-san volcano in Japan in 1888 formed a tremendous rock-fragment flow that devastated an area of 27 square miles. Sekiya and Kikuchi (1889, p. 109 and 106–107, respectively) believed that the greater part of the rock-fragment flow was dry during movement, and they surmised that its movement was similar to that resulting from a large rockfall which they observed in the crater of Bandai-san some time after the steam explosion. They described the rockfall as follows:

> One day, while we were at work in the crater, a huge slice of the precipitous wall of rock that had been bared by the explosion fell suddenly and crashed with a tremendous uproar down the steep incline beneath. This slab fell from a place about 300 mètres high. The great masses of earth and rocks were shattered as they fell, and broken up into pieces, ever growing smaller as they descended. The behaviour of this pulverized mass resembled the rush of a headlong torrent. Although boulders measuring 10 mètres or more in diameter were mixed up with finer matter, as a whole the movement approximated to that of a fluid. No words can describe the fierceness and force of that impetuous downpour—its mad surgings this way and that, and the bold leaps with which it would now and then bound over low ridges that hindered its progress, and shoot onward down the neighbouring depression.

That the Little Tahoma avalanches moved in a manner like that of a fluid is inferred from the way the debris caromed from one side of the valley to the other during movement. The heights the avalanches reached on the lateral moraine and on Goat Island Mountain are thus explained by centrifugal force, which caused the flowing debris to rise higher on the outer side of its curving path.

The path followed by avalanche unit 3 required that the debris move at high velocity; some of the speed was attained as masses of rock fell vertically as much as 1,700 feet from Little Tahoma Peak. Within a distance of 1.3 miles from the base of the rockfall scar, the avalanche descended an additional 2,400 feet. It had by then attained enough velocity to travel 3 miles farther across the more gentle slope of the lower glacier and valley floor to its present resting place.

That a high velocity was attained by avalanche unit 3 is indicated by the fact that some of the highest points on the terminal moraine were buried by debris and by the fact that the avalanche debris rose high on the outside of valley bends (fig. 10). At several places the direction of movement of the avalanche was nearly at right angles to the valley walls, and debris was deposited high on the valley sides. Two tongues of debris ran up on Goat Island Mountain to estimated

FIGURE 12.—Little Tahoma Peak as viewed from Mount Ruth in 1956.

heights of 250 to 300 feet above the adjacent valley floor, and, farther downvalley, the tongue of debris that moved through the gap in the terminal moraine reached a height of 140 feet on Goat Island Mountain.

If it is assumed that the energy of avalanche unit 3 on the valley floor was wholly kinetic energy $\frac{(\text{mass} \times \text{velocity}^2)}{2}$ which was completely transformed into potential energy (mass × gravity × height) without frictional loss, a velocity may be computed for the avalanche from the height to which it rose on Goat Island Monutain. This computation is made by the following equation, in which g represents the

FIGURE 13.—Little Tahoma Peak as viewed from Mount Ruth July 9, 1964. Small cloud in front of the peak is formed by water vapor rising from the lower right side of the rockfall scar. (See fig. 16.)

value of the acceleration of gravity (32 ft per sec per sec), v=velocity, m=mass, and h=height:

$$\frac{mv^2}{2}=mgh$$

$$v^2=2gh$$

$$v=\sqrt{2gh}$$

If h=300 feet, v=139 feet per second, or 95 miles per hour;
if h=250 feet, v=127 feet per second, or 87 miles per hour;
if h=140 feet, v=95 feet per second, or 65 miles per hour.

The velocities indicated are probably too small because friction caused loss of energy as the debris rose on the flanks of Goat Island Mountain. Furthermore, there must have been a substantial downvalley component of movement that would have caused the avalanche to travel faster than the computed velocities indicate. If the height is decreased by 50 feet to allow for the thickness of the avalanche, velocities should be decreased by roughly 15 feet per second, or by about 10 miles per hour. It is interesting to compare these calculated velocities with those of other avalanches. For example, the 1881 rockfall avalanche at Elm, Switzerland (Heim, 1932, p. 93), had an average velocity of about 100 miles per hour, and the 1962 avalanche of ice and rock debris from the northwest face of Nevado Huascarán in Peru traveled 9 miles in 7 minutes at an average velocity of 77 miles per hour (McDowell and Fletcher, 1962). The estimated minimum speed of avalanche unit 3 from Little Tahoma Peak also is similar to that computed for other rockfall and rockslide avalanches in North America (table 1), using the formula described above.

TABLE 1.—*Comparison of Little Tahoma rockfall-avalanche deposits with others in the United States and Canada*

[Thickness of the avalanche deposits is not taken into consideration in computation of velocity]

Location and Reference	Year	Volume of debris (millions of cu yds)	Maximum distance of movement (miles)	Approximate maximum vertical drop (feet)	Maximum runup (feet)	Velocity of avalanche (mph) [1]
Madison Canyon, Mont. (Hadley, 1964)	1959	37.0	1.0	1,300	430	[2] 112
Gros Ventre, Wyo. (Alden, 1928)	1925	50.0	1.2	2,100	350	102
Frank, Alberta (McConnell and Brock, 1904)	1903	47.8	2.5	2,860	400	109
Little Tahoma Peak, Wash. (this paper)	1963	14.0	4.3	6,200	140 300	65 95

[1] Calculated from $v=\sqrt{2gh}$.
[2] A maximum velocity of 100 mph was estimated by Hadley.

The maximum velocity of a rockfall and the subsequent rate of descent of an avalanche on Emmons Glacier can be crudely estimated from the acceleration of gravity. A mass of rock falling from a height of 850 feet, half the height of the rockfall scar, would have attained a velocity of about 160 miles per hour just before it struck Emmons Glacier, assuming free fall. The avalanches probably also accelerated throughout their first 7,000 feet of travel downglacier, as they descended about 2,400 feet. Although a loss of velocity must have occurred as falling rock masses struck the glacier, as a cross-glacier component of movement occurred after impact, and as sliding on the glacier produced frictional resistance, it seems likely that an avalanche would have been traveling at a speed of 100 to 300 miles per hour when it left the end of Emmons Glacier.

Some of the avalanches probably were aided in their movement beyond the glacier by a cushion of air trapped beneath them which buoyed them up; this cushion reduced friction and permitted the avalanches to be transported a much greater distance than if they had traveled in actual contact with the valley floor.

The formation of a cushion of air beneath moving rock debris has been analyzed by Shreve (1959), who studied a large prehistoric rock-fragment flow at the northern edge of the San Bernardino Mountains in southern California. The deposit is about 2 miles wide and extends over a piedmont slope for a distance of about 5 miles beyond the mountain front. Shreve suggested that the rock-fragment flow was caused by a large rockslide or rockfall on the northern face of Blackhawk Mountain and that, after initial impact, the flow was launched laterally into the air from a rock step near the base of the mountain. Lateral movement was at such a high velocity, the maximum was estimated to be 250 miles per hour, that air became entrapped and formed a cushion beneath the sheet of rock debris. Escape of air along the margins of the rushing mass permitted its outer edges to drop to the underlying surface, where they formed marginal ridges that hindered further escape of trapped, highly compressed air.

Preservation of a fragile thermograph shelter about 1.5 feet high in the gap near the south end of the terminal moraine suggests that a cushion of air was trapped beneath avalanche unit 3. Although this avalanche did not damage the shelter in passing over it, the shelter was subsequently crushed by a 10-inch boulder that rolled down the front of avalanche unit 5. A pile of boards that lay on the ground near the shelter also was not disturbed by avalanche unit 3 but was buried by a few inches of avalanche debris. A protective layer of snow seemingly cannot account for the lack of damage, for if the avalanche had been traveling in contact with the ground, the leading part should have scraped away the snow, and the trailing part should then have destroyed the thermograph shelter. Evidently the base of the avalanche was not in contact with the ground when it crossed this site. A 6-foot-high plywood gage house, less than 10 feet from the shelter, was removed by avalanche unit 3. This gage house was transported about 300 feet southward in a direction nearly at a right angle to the trend of the valley and now lies at the upstream end of the scar opposite the terminal moraine (fig.7). This scar (fig. 9), produced by the scouring action of the avalanche as it struck the side of the valley and caromed back to the northeast, suggests the nature of erosion that should have occurred everywhere at the base of the avalanche if a cushion of air had not been present.

The existence of an air cushion beneath avalanche unit 3 is also suggested by the distance, about 9,500 feet, the avalanche moved beyond the end of Emmons Glacier. Regardless of its velocity as it left the glacier, the avalanche should have struck the valley floor within a time interval determined by the acceleration of gravity through the vertical distance between the top of the glacier and the valley floor at the point of impact. If the avalanche had struck the valley floor at the calculated point of impact, 2,000 feet or less from the end of the glacier (fig. 14), it seemingly could not have traveled in contact with the valley floor as much as 7,500 feet farther downvalley, nor have risen on the side of the lateral moraine and on Goat Island Mountain, nor have made a nearly right-angle turn through the gap in the terminal moraine. Therefore, it seems unlikely that the avalanche debris struck the valley floor within a few thousand feet from the glacier and this circumstance can be explained only by the supposition that the avalanche was buoyed up by a cushion of compressed air at its base.

The initial impact of a rockfall would not itself create an air cushion; the formation of this cushion may require lateral launching of a broad sheet of debris into the air parallel to the underlying surface so that the debris as it starts to settle can trap air quickly and compress it. Further requirements would be previous pulverization of the rock mass to form a sheet of debris and sufficient thickness and impermeability of the debris to prevent substantial upward escape of air. Air passing upward through the debris, however, would tend to fluidize the mass by reducing friction between rock particles and thus would increase mobility.

Pulverization of the rock masses from Little Tahoma Peak occurred when they struck Emmons Glacier. Sheets of rapidly moving debris then descended the glacier and probably were launched laterally into the air as they left the terminus of the glacier, which is 200 to 300 feet high. Formation and preservation of a cushion of air beneath the avalanches in the valley would have been aided by the confining valley sides. Marginal ridges comparable to those of the Blackhawk landslide described by Shreve (1959) are not conspicuous, although they may be represented by ridges along the north side of the deposits at the locations of cross sections 2, 4, 5, and 6.

Because of the distance and the inferred nature of their movement downvalley, avalanche units 1, 3, 4, and 5 are thought to have moved as rock-fragment flows, probably riding on air cushions. Avalanche units 6 and 7 stopped only short distances beyond the glacier and may have moved as debris slides in contact with the underlying surface throughout most of their distance of transport. The nature of movement of avalanche unit 2 cannot be inferred because of its limited area of outcrop.

MUDFLOWS

An interesting side effect of the avalanches was the formation of mudflows; they head at channels in the avalanche deposits and traveled at least as far downstream as White River campground. The mudflows thin downstream from about 6 feet to a few inches. Although they have fairly smooth surfaces, some mudflows a foot or

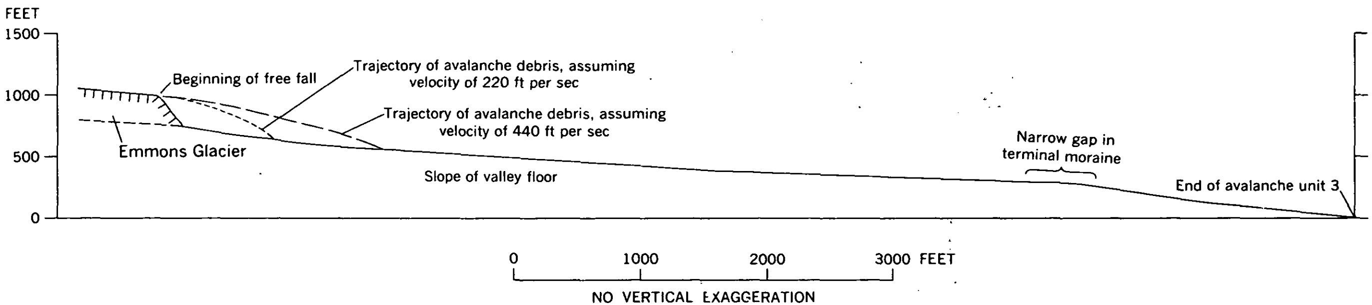


FIGURE 14.—Diagram showing expectable points of impact of avalanche unit 3 on valley floor if avalanche had not been buoyed up by a cushion of air. A speed of 300 miles per hour (440 ft per sec) was the probable maximum velocity of the avalanche debris at the end of the glacier, although 150 miles per hour (220 ft per sec) may be a more reasonable estimate. The glacier slope was estimated to be 10 percent, and the velocities of 150 and 300 miles per hour were assumed to be parallel to the slope of the glacier.

two thick are dotted with many low mounds, a few inches to a foot high and a foot to several feet in diameter (fig. 15). Several mounds were excavated, and a large boulder was found beneath each one. If the mudflows had come to rest on a layer of snow, the mounding and the cracking might have occurred as the supporting snow melted and the mudflow settled over the underlying boulders.

The mudflows downvalley from the tongue of avalanche unit 3 consist of sand and of rock fragments as large as several feet in diameter. In addition, several very large blocks lie on the surface of some of these mudflows. The largest of these is a mass of gray andesite that has maximum dimensions of 9 by 11 by 16 feet; this mass was transported by a mudflow about 4 feet thick. It and other blocks like it are excellent evidence of the remarkable ability of mudflows to transport large rock fragments.

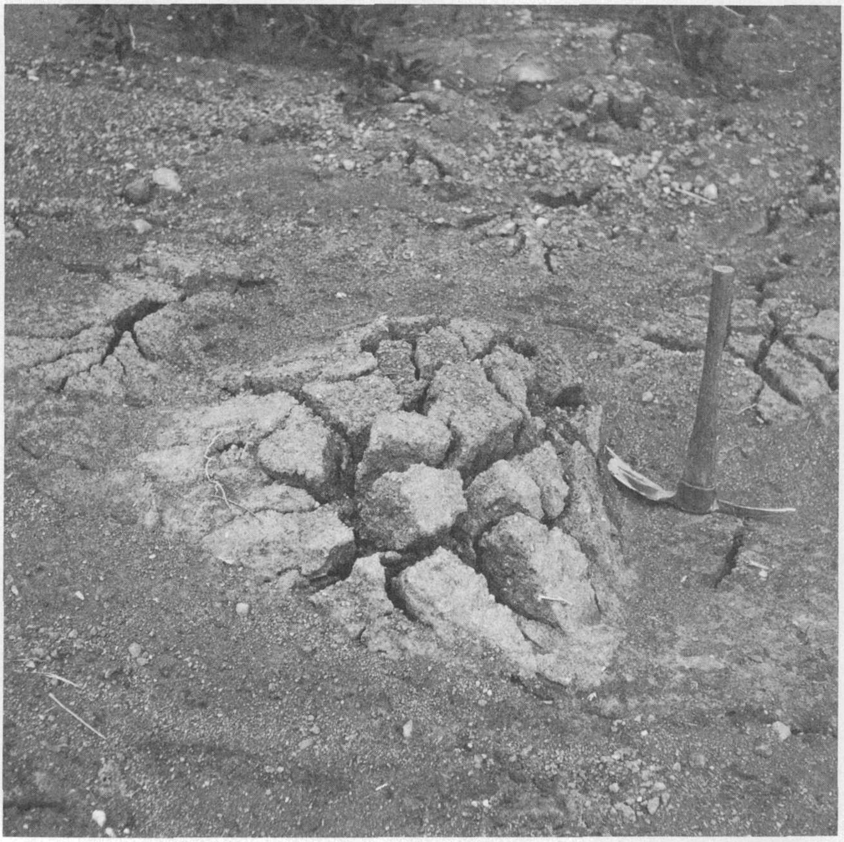


FIGURE 15.—Cracked mounds on surface of mudflow deposit, probably formed as a layer of snow melted under mudflow, permitting mudflow to settle around buried boulders.

The mudflows resulted from the White River spilling over temporary dams of avalanche debris in the narrow gap through the terminal moraine and probably upstream from the moraine as well. As the water ran across the debris it quickly became loaded with loose material and formed masses of bouldery mud that flowed downvalley. The paths of the mudflows through the avalanche deposits were subsequently followed by clearer water that cut flat-bottomed channels and partly eroded the mudflow deposits (fig. 9).

DUST CLOUDS

Dust clouds frequently veiled the north face of Little Tahoma Peak during the winter, spring, and summer months of 1964. These clouds were caused by rocks bounding from the rockfall scar onto a long dusty apron of debris that bordered the scar base and reached onto Emmons Glacier. The rocks apparently were dislodged from the scar by freeze and thaw, by melt water from a hanging glacier perched on the east side of Little Tahoma Peak, and by wind currents. At times, winds would sweep the dust clouds upward and eastward, causing the surface of Fryingpan Glacier to become unusually dirty. Although rocks continued to fall from the scar during late August and early September, dust clouds became rare after this period because frequent rains and snows dampened the rockfall debris at the base of the cliff.

These dust clouds were small and insignificant in comparison with the great palls of dust that accompanied the avalanches. The effects of those clouds were still to be seen in July 1964 on the southern slope of Mount Ruth, where conifers were still mantled with nearly an inch of silt and fine sand that had settled out of the air. Much of this sand and silt had been washed off by rains before the following September.

CAUSE OF THE ROCKFALLS

The topography and geology of Little Tahoma Peak form an ideal setting for rockfalls; in fact, it is surprising that large rockfalls are not more common there. Yet, one is led to wonder whether some specific event might have triggered the first rockfall from the peak, which apparently occurred about noon on December 14. Although perhaps not the largest of the series of falls, this first rockfall probably was the most important for it almost certainly removed support from other masses of rock, leaving them highly unstable.

A sound heard at the time the first mass of rock is believed to have fallen suggests that a steam explosion may have occurred at Little Tahoma Peak. On December 14, Benjamin E. Cottman (oral commun., Aug. 25, 1964) and Richard J. Allen (oral commun., Aug. 17, 1964), Forest Rangers of the U.S. Forest Service, were at the Crystal Mountain ski area, about 12 miles northeast of Little Tahoma Peak. Shortly before noon they both heard a very loud, sharp boom in the direction of Mount Rainier. Jet aircraft were not heard before or after the loud noise, and Cottman and Allen concluded that the noise had originated in some way at Mount Rainier rather than as a sonic boom. Although the noise possibly resulted from the rockfall itself, the fact that it was a single sharp boom may suggest that it originated from an explosion rather than from a rockfall and avalanche. Visibility was poor at the time because of clouds and snow, but as the clouds lifted from time to time during the afternoon of the 14th, Cottman and Allen observed that a large part of Emmons Glacier had become covered with dark rock debris below Little Tahoma Peak. According to Allen, fresh rock debris also fell from the peak onto new snow several times during the following 2 months, but the size of the later rockfalls is not known.

If an earthquake had occurred just before or at the same time as the first rockfall, one might conclude that the shock triggered the fall. According to Prof. Norman Rasmussen (written commun., July 17, 1964) of the Department of Geology at the University of Washington, the most recent quake that preceded the rockfall was recorded on a seismograph at Longmire, 8.5 miles south of Little Tahoma Peak, on December 13, at about 8:20 a.m. This earthquake had a duration of about 40 seconds and occurred at an estimated distance of about 11 miles from Longmire in an undetermined direction. No earthquake was recorded on the seismograph near noon on December 14, when the initial rockfall apparently occurred; however, according to Professor Rasmussen, at 4:40 p.m. on that day the seismograph recorded "a disturbance not containing the usual character of an earthquake. This event is of very small amplitude and short period suggesting a local disturbance and may be from sliding rock against rock * * *." This small seismic disturbance may have been caused by one of the rockfalls and avalanches that followed the initial rockfall, possibly by avalanche unit 3, the largest of the group. There is no evidence that an earthquake shock was directly responsible for the initial rockfall.

Another possible trigger might have been freezing and thawing of ice in cracks in the rock, either of which would have caused a slight weakening of the rock. At White River Ranger Station, the maximum temperature was 34° on December 14 and the minimum 28°F. It seems unlikely that the temperature reached above freezing on that day at altitudes of 9,000–11,000 feet on Little Tahoma Peak. Although repeated freeze and thaw undoubtedly contributed to progressive weaking of the rock over many years, these processes probably were not the immediate cause of the rockfall on December 14.

A third way in which the inital rockfall might have originated could have been by a small steam explosion at or near the base of Little Tahoma Peak, caused by water beneath the surface coming into contact with hot rock in a confined space.

If one or more steam vents had been active between December 14 and the end of January, they probably would not have been observed because of the generally cloudy weather during this period; however, William Pope and Ross Gregg (oral commun., July 1964), residents of Crystal Mountain ski area, observed clouds at Little Tahoma Peak from Crystal Mountain on clear days during the winter of 1963–64. Some of these appeared to be dust clouds because of their grayish-brown tinge; others were thought to be clouds of water vapor.

Clouds of "steam" also were frequently reported at Little Tahoma Peak during July and August 1964 by observers at Yakima Park and Burroughs Mountain, but owing to the distance of these points from Little Tahoma Peak it was not possible to be sure that these clouds were water vapor rather than the dust plumes that were a daily feature of the rockfall scar during those months.

On the afternoon of July 9, Crandell and Ranger Naturalist Arthur Haines observed the rockfall scar on Little Tahoma Peak through binoculars from a point near Mount Ruth. Plumes of water vapor could be seen rising from near the base of the west side of the rockfall scar (figs. 13, 16), forming a small white cloud that hovered along the north side of the peak all afternoon. Meanwhile, no water vapor could be detected coming from other obviously moist parts of the scar, and no other clouds were visible in the sky. On the basis of this observation, Crandell concluded that an unusual source of heat was present at that time near the base of Little Tahoma Peak, and that this source of heat might have caused a steam explosion in December 1963.

In the late summer, the U.S. Forest Service was asked to conduct an aerial examination of Little Tahoma Peak with infrared heat-sensing equipment that is normally used to detect and outline the extent of forest fires. The investigation was made on September 3 and 4, 1964, and the results indicated that the temperature of the rockfall scar was then no warmer than normal. Furthermore, snow that fell in late August and early September seemed to disappear from all parts of the scar at the same rate, indicating approximately equal temperatures throughout. Thus, if a source of heat did exist near the base of the peak from December 1963 to July 1964, it apparently had disappeared by late August or early September.

Small steam explosions probably are not unusual occurrences on Mount Rainier, but owing to the inaccessibility of most of the volcano during much of the year, they are rarely observed. Such an explosion, however, occurred during the summer of 1961. Luther G. Jerstad

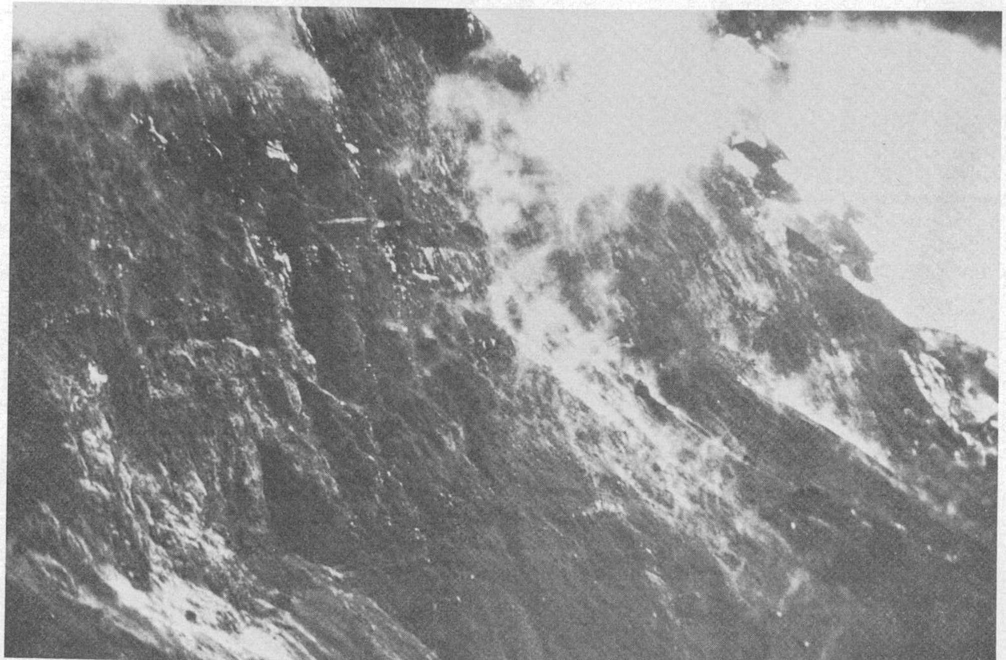


FIGURE 16.—Water vapor issuing from western base of rockfall scar on July 9, 1964. White area at upper right is a glacier. (See fig. 13.)

(written commun., Sept. 16, 1964) of Eugene, Oregon, was at that time guiding parties to the summit. According to Jerstad, he was awakened one night at Camp Muir (fig. 1) by a loud noise and shaking of the ground. There was bright moonlight, and a great cloud of dust could be seen at the south end of Gibraltar Rock, caused by continuing rockfalls which could be plainly heard. The next morning, Jerstad observed rock fragments strewn over the surface of Cowlitz Glacier for a distance of at least three-quarters of a mile below Gibraltar Rock, and in the southern side of Gibraltar Rock there was a fresh scar about 150 feet wide, 150 feet deep, and 100 feet high. Steam was spouting 200 feet into the air from a vent in the scar, apparently under great pressure, and making a noise like a high wind. According to Jerstad, the steam continued to issue from the vent all summer, although it seemed to decrease in volume and pressure over a period of about 5 weeks. It was no longer active by the summer of 1962.

This example demonstrates that small steam explosions are normal and expectable phenomena on the flanks of Mount Rainier. Such explosions in unstable areas undoubtedly have contributed substantial quantities of rock debris to glaciers on the volcano in the past. Although the evidence is not conclusive, the rockfalls and avalanches from Little Tahoma Peak possibly were initiated by such a mild steam explosion.

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