POTENTIAL HAZARDS FROM FUTURE ERUPTIONS IN THE VICINITY OF MOUNT SHASTA VOLCANO, NORTHERN CALIFORNIA

GEOLOGICAL SURVEY BULLETIN 1503

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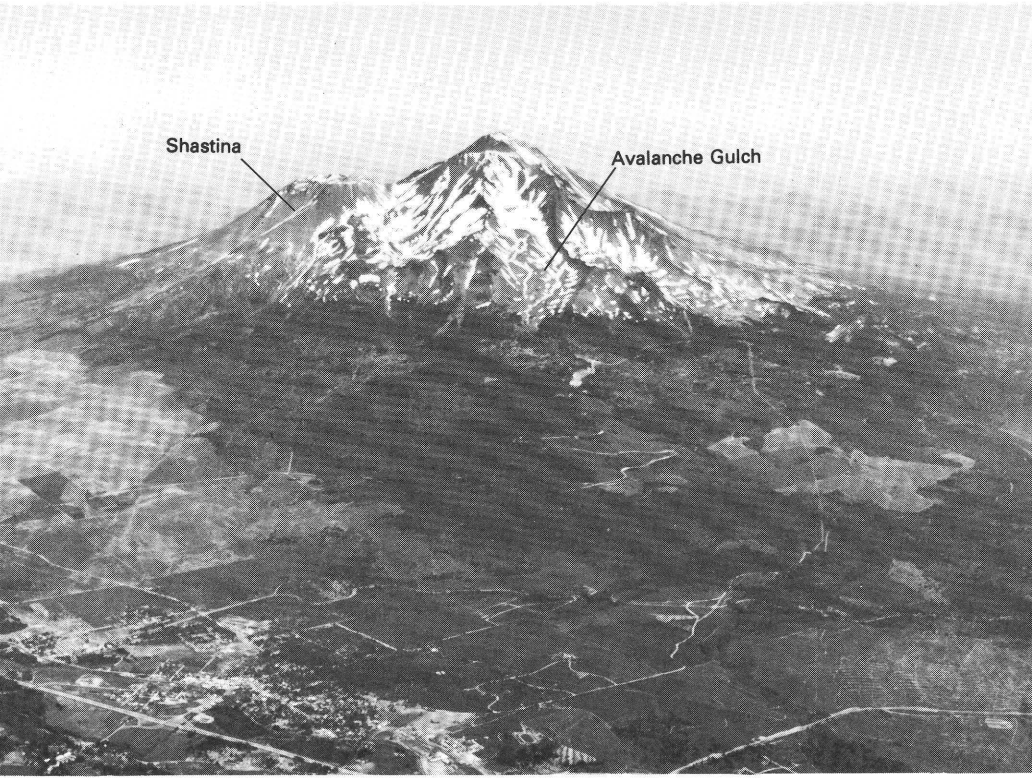

Aerial view of Mount Shasta and Shastina from the southwest. Avalanche Gulch and adjacent valleys on the southwest and south sides of Mount Shasta were glaciated during the last major glaciation; the Shastina cone is post-glacial. City of Mount Shasta visible at lower left. All photographs taken by author, except where noted.

Potential Hazards from Future Eruptions in the Vicinity of Mount Shasta Volcano, Northern California

By C. DAN MILLER

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The eruptive behavior of Mount Shasta during the last 10 000 years forms the basis for an assessment of the probable kinds and scales of future eruptions, and their potential effects on people and property

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POTENTIAL HAZARDS FROM FUTURE ERUPTIONS IN THE VICINITY OF MOUNT SHASTA VOLCANO, NORTHERN CALIFORNIA

By C. DAN MILLER

ABSTRACT

Mount Shasta has erupted, on the average, at least once per 800 years during the last 10000 years, and about once per 600 years during the last 4500 years. The last known eruption occurred about 200 radiocarbon years ago. Eruptions during the last 10000 years produced lava flows and domes on and around the flanks of Mount Shasta, and pyroclastic flows from summit and flank vents extended as far as 20 km from the summit. Most of these eruptions also produced large mudflows, many of which reached more than several tens of kilometers from Mount Shasta. Future eruptions like those of the past could endanger the communities of Weed, Mount Shasta, McCloud, and Dunsmuir, located at or near the base of Mount Shasta. Such eruptions will most likely produce deposits of lithic ash, lava flows, domes, and pyroclastic flows. Lava flows and pyroclastic flows may affect low- and flat-lying ground almost anywhere within about 20 km of the summit of Mount Shasta, and mudflows may cover valley floors and other low areas as much as several tens of kilometers from the volcano. On the basis of its past behavior, Mount Shasta is not likely to erupt large volumes of pumiceous ash in the future; areas subject to the greatest risk[1] from air-fall tephra are located mainly east and within about 50 km of the summit of the volcano. The degree of risk from air-fall tephra decreases progressively as the distance from the volcano increases.

INTRODUCTION

Mount Shasta is located in the Cascade Range in northern California about 65 km south of the Oregon-California border and about midway between the Pacific Coast and the Nevada border

[1]Risk is used in this report to denote the "possibility of loss, injury, disadvantage, or destruction," as defined in Webster's "Third New International Dictionary." Degree-of-risk evaluations stated in this report are not statistical.

(fig. 1). One of the largest and highest of the Cascade volcanoes, snowclad Mount Shasta is near the southern end of the range that terminates near Lassen Peak. Mount Shasta is a massive compound stratovolcano composed of overlapping cones centered at four or more main vents; it was constructed during a period of more than 100000 years (Christiansen and Miller, 1976; Christiansen and others, 1977). Each of the cone-building periods produced pyroxene-andesite lava flows, block-and-ash flows, and mudflows originating mainly at the central vents. (See

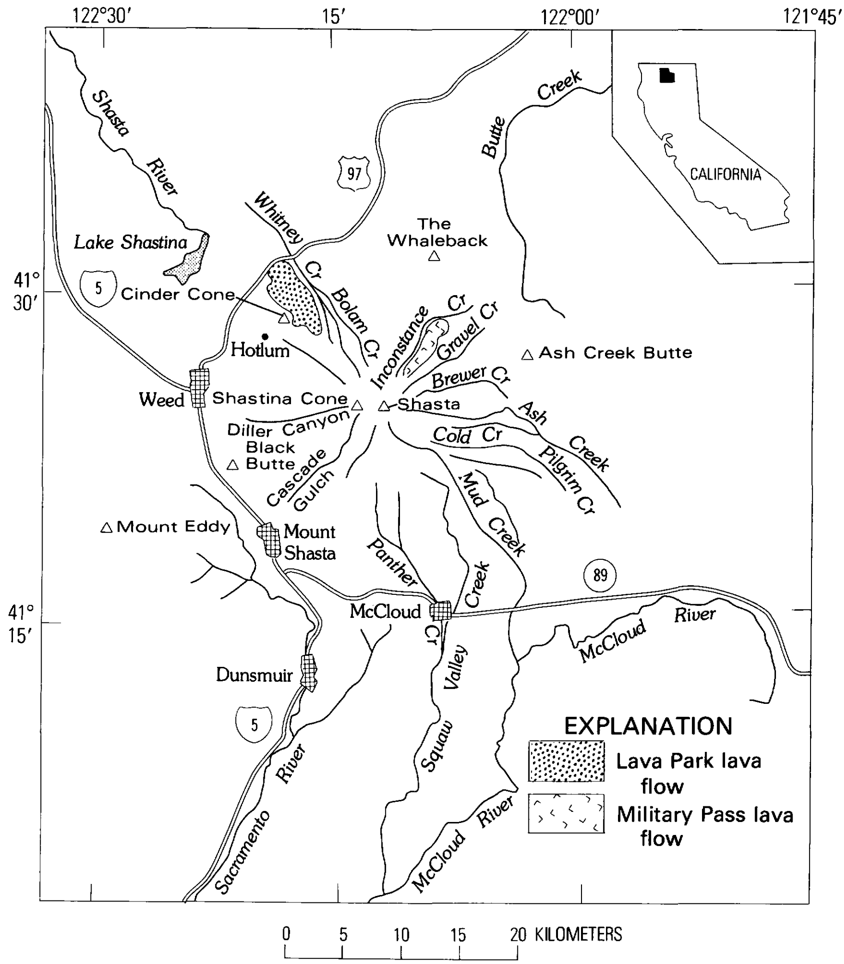

FIGURE 1.—Index map showing Mount Shasta and vicinity.

"Eruptions—their products and associated hazards" for definitions of eruptive processes.) Construction of each cone was followed by eruption of domes and pyroclastic flows of more silicic rock at central vents, and of domes, cinder cones, and lava flows at vents on the flanks of the cones.

Two of the main eruptive centers at Mount Shasta, the Shastina and Hotlum[2] cones (figs. 1, 2), were constructed during Holocene time, which includes about the last 10000 years. Holocene eruptions also occurred at Black Butte (figs. 1, 3), a group of overlapping dacite domes about 13 km west of Mount Shasta (Christiansen and Miller, 1976; Miller, 1978). Evidence of geologically recent eruptions at these two main vents and at flank vents forms the chief basis for assessing the most likely kinds of future eruptive activity and associated potential hazards.

Streams that head on Mount Shasta enter three main river systems: the Shasta River to the northwest, the Sacramento River to the west and southwest, and the McCloud River to the east, southeast, and south (fig. 1). Creeks draining the northeast flank of Mount Shasta flow into a closed depression in which fans of debris from Mount Shasta abut the pre-Shasta lava cones of The Whaleback and Ash Creek Butte (fig. 1). Many streams draining Mount Shasta are intermittent and disappear into coarse fan debris at the base of the volcano.

The lower flanks of Mount Shasta consist mostly of a broad, smooth apron of coalescent fans of pyroclastic, mudflow, and fluvial debris (fig. 4). These fans are composed of the products of successive eruptions that supplied more material than the streams could carry away. Valleys that head at many other Cascade volcanoes are deep erosional clefts in which products of eruptions are concentrated and carried to distances of many tens of kilometers. At Mount Shasta, however, flowage phenomena caused by future eruptions are likely to spread out over broad areas on and beyond the lower flanks of the volcano and thus will travel shorter distances than if they were confined to narrow valleys; their paths, however, will be less predictable.

The communities of Weed, Mount Shasta, and McCloud (fig. 1), which have populations of about 4500, 5700, and 2700 respectively, are situated on the broad apron at the base of the volcano. A fourth nearby community, Dunsmuir (population 3800), is located in the

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[2]The summit and north and northeast flanks of Mount Shasta are informally referred to here as the Hotlum cone after the Hotlum glacier on the northeast flank of the volcano.

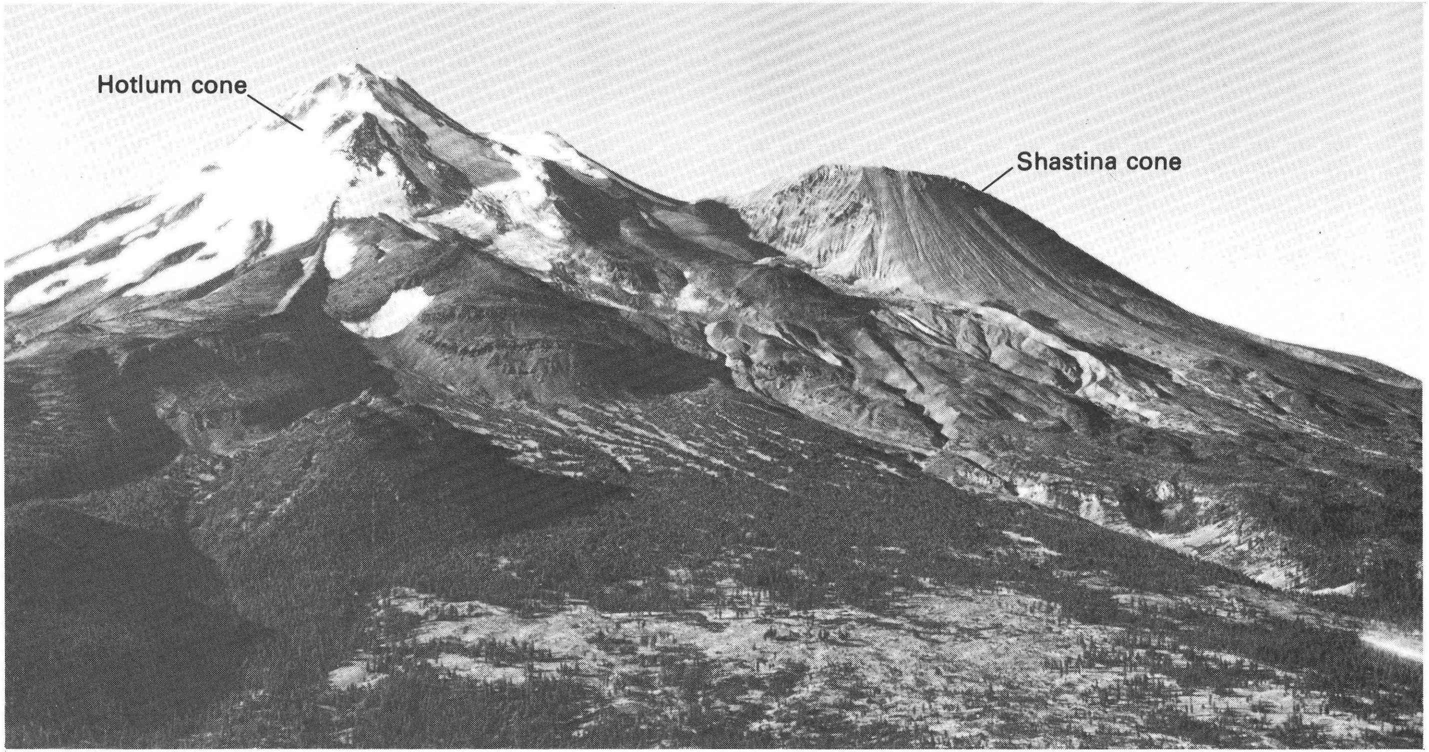


FIGURE 2.—Aerial view of Mount Shasta from the north-northeast. The Shastina cone was constructed between about 9700 and 9300 ^{14}C years ago. Much of the Hotlum cone was constructed during the last several thousand years, although eruptive activity at that vent began about 10000 years ago.

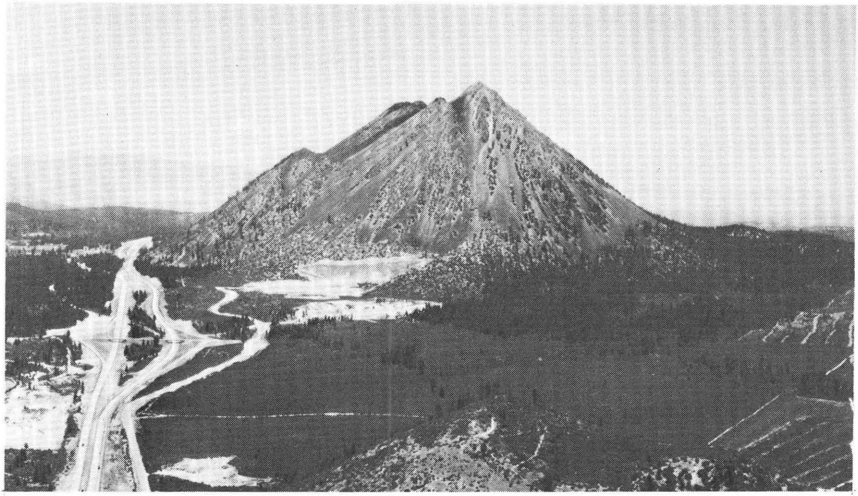


FIGURE 3.— Aerial view toward the north-northwest of the four overlapping dacite domes of Black Butte. The extrusion of the domes about 9500 years ago was accompanied by the formation of pyroclastic flows which extended more than 10 km south and 5 km north of the domes. Interstate Highway 5 on left.

canyon of the Sacramento River about 23 km south of Mount Shasta.

Mount Shasta has erupted frequently during the last 10 000 years (pl. 1) and has produced pyroclastic flows, mudflows, and lava flows that have repeatedly covered extensive areas on the flanks of the volcano; some of these products have reached distances of as much as 30 km from the summit of the volcano. This recent eruptive history implies that Mount Shasta will continue to erupt intermittently in the future. Future eruptions like those of the last 10 000 years would certainly affect human lives and health, property, manmade structures, and agriculture in the vicinity of the volcano, including the communities of Weed, Mount Shasta, McCloud, and Dunsmuir. Future pumiceous ash falls of large volume are unlikely from Mount Shasta, but if they were to occur, they could affect large areas downwind from Mount Shasta to distances of hundreds of kilometers. The greatest risk from future eruptions of tephra is from lithic air-fall tephra[3], which will fall on the flanks and within about 50 km to the east of the summit of the volcano.

[3]Tephra is used in this report to describe volcanic ejecta of any particle size (ash, cinders, lapilli, and blocks) which are erupted into the air above a volcano and fall onto the flanks of the volcano or downwind from the volcano.

This appraisal of potential hazards from future eruptions is based on the likelihood that future eruptions will be of the same general character and frequency as those of the recent past; the possible distribution and effects of future eruptions are therefore inferred on the basis of volume, character, and distribution of products of eruptions during the last 10000 years and the present topography around Mount Shasta.

FIGURE 4.—Aerial view of the southeast flank of Mount Shasta from about 30 km away showing broad, smooth apron of pyroclastic-flow, mudflow, and fluvial debris. Future pyroclastic flows and mudflows could spread out and cover almost any part of this surface.

ACKNOWLEDGMENTS

Many of the interpretations and conclusions of this study are the results of cooperative fieldwork and discussions with R.L. Christiansen of the U.S. Geological Survey. Christiansen is studying the volcanologic and petrologic evolution of Mount Shasta and is mapping the volcano and surrounding area. His work is being carried out simultaneously and in cooperation with that of the author. Radiocarbon age determinations cited in this report were made in laboratories of the U.S. Geological Survey under the supervision of Meyer Rubin and Elliot Spiker. Assistance in the field was ably provided by Slade Dingman, Jeff Grambling, and Abelardo Ramirez. Special thanks are extended to Paul H. Dawson and family, city of Mount Shasta, for their enthusiastic support and help during four summer field seasons.

ERUPTIONS—THEIR PRODUCTS AND ASSOCIATED HAZARDS

Stratovolcanoes like Mount Shasta erupt in different ways depending on many factors, including the composition and temperature of the magma, its content of volatile gases, and the size and shape of the vent. If future eruptions of Mount Shasta are like those of the past, they will produce lava flows, pyroclastic flows, domes, and relatively small volumes of predominantly lithic air-fall tephra. These eruptions may result in mudflows and floods if hot lava is erupted onto snow and ice on the flanks of the mountain. These volcanic processes and the resulting products have been described by Crandell and Mullineaux (1976) and are discussed briefly below.

The specific type of eruption that occurs at any particular time depends largely on the viscosity of the lava and its gas content and to a lesser extent on vent size and shape, interaction with ground water, and other variables. The viscosity of lava is closely related to its composition. Generally, the greater the silica (SiO_2) content of a magma, the more viscous it is. Dacitic lavas are relatively viscous and rich in silica; they generally move only short distances from their source vents as short, thick, blocky flows or pile up at the vent to produce domes. Basalt and basaltic-andesite lavas are relatively fluid and poor in silica; they generally produce flows that move several kilometers downslope from vents. Andesitic lavas are generally intermediate in viscosity and morphology between dacites and basalts. Viscosity of lava also depends on its temperature: the higher the temperature, the lower the viscosity of the lava and the more readily it flows. Gas content of a magma may affect the viscosity of lava and is especially important in determining how explosive an eruption will be. If a viscous magma like dacite has a high gas content, it may erupt violently, especially at the beginning, because gas cannot readily escape. More fluid lavas like basalts and basaltic andesites tend to erupt less explosively because of lower gas contents and the fact that gases can more readily escape from them.

In the past, at least some eruptions of dacite at Mount Shasta initially produced pumiceous pyroclastic flows and air-fall tephra, followed by eruption of lithic pyroclastic flows, and then by domes of nonvesicular dacite. Other eruptions of dacite at Mount Shasta may have formed domes early in the eruption; these then collapsed or exploded producing lithic pyroclastic flows. Eruptions of basaltic andesite generally were less explosive and produced blocky lava flows as much as several kilometers long. Eruptions of andesitic lavas at Mount Shasta produced lithic pyroclastic flows and relatively thick, short flows or domes. Few eruptions of any composition have produced pumiceous air-fall tephra deposits of large volume at Mount Shasta. Only a few pumiceous air-fall deposits, each of relatively small volume, have been produced at Mount Shasta during its long history of more than 100000 years.

LAVA FLOWS

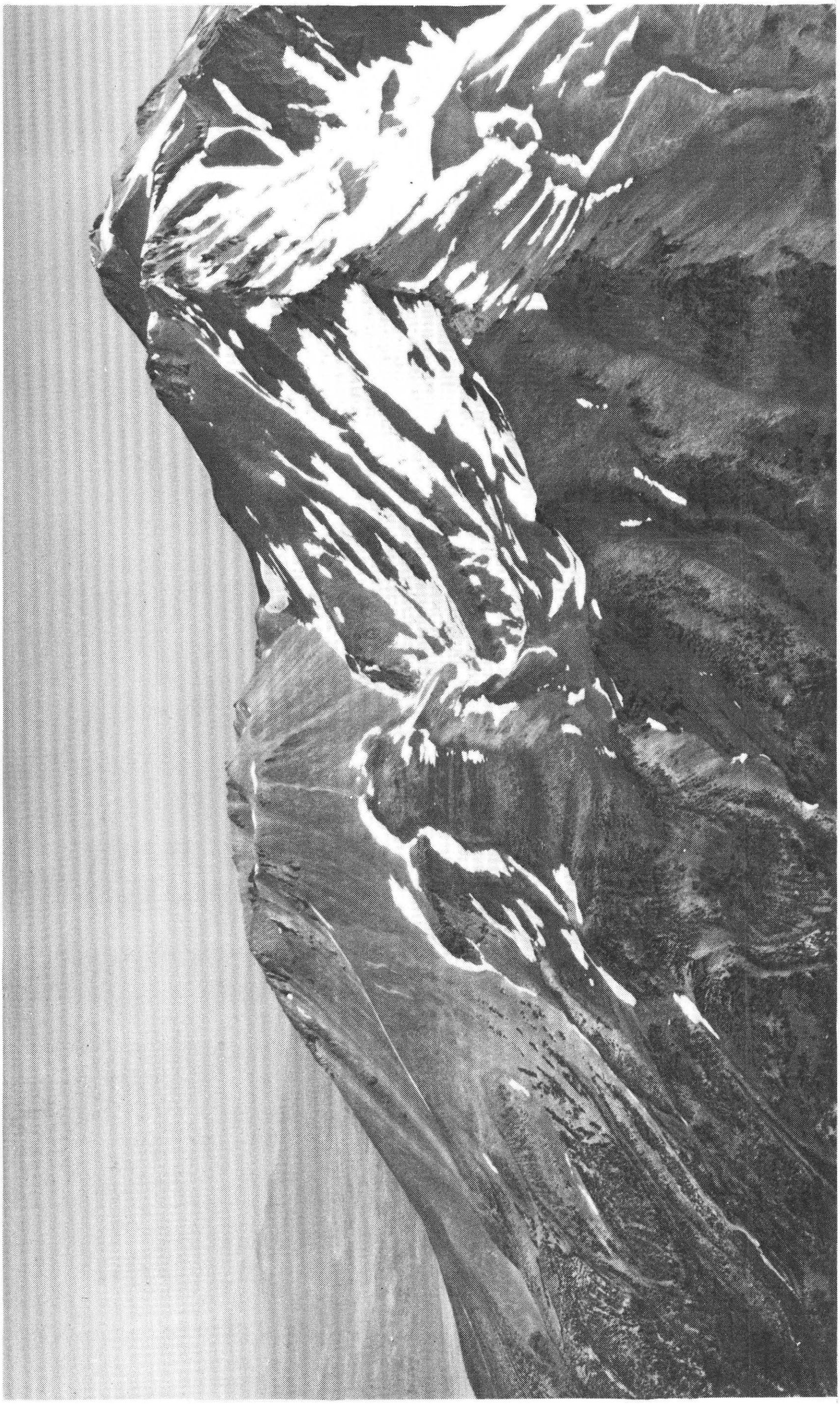
Lava flows are coherent streams of molten rock that usually issue relatively nonexplosively from a volcano and move slowly downslope. At Mount Shasta, most flows have been thick, blocky, tongue-shaped (fig. 5), and less than 8 km in length. The distance traveled by a lava flow depends on such variables as the viscosity of the lava, volume erupted, steepness of the slope, and obstructions in the path of the flow. Lava flows usually do not directly threaten people because their direction of movement can be at least roughly predicted; furthermore, they move less rapidly than a person can walk, perhaps a few meters per hour, and thus can be avoided. Lava flows are very difficult to control or stop, however, and they will flow over and destroy or burn virtually any nonmovable property in their paths.

FIGURE 5.—Aerial view of the Lava Park lava flow, northwest flank of Mount Shasta. The blocky basaltic-andesite flow erupted at a vent on the flank of Shastina and is about 6 km long and 110 m thick at its snout. The lava flow overlies a wide apron of pyroclastic-flow deposits erupted from Mount Shasta about 9700 years ago. The area shown is about 2000 m wide. Broad line crossing photograph near the bottom is U.S. Highway 97.

Most lava flows at Mount Shasta are blocky flows of andesite that were erupted from central vents or that issued from flank vents. Lava flows have been erupted relatively frequently at main vents to produce the large composite cones of Mount Shasta (fig. 6). Eruptions of lava flows from other vents on the flanks of Mount Shasta and Shastina were less frequent, but a few such flows have been identified west and northwest of Mount Shasta.

Lava flows of basaltic andesite erupted from Mount Shasta vary in maximum length from about 6 km for flank flows to about 9 km for flows that originated at the summit. During Holocene time, one andesite lava flow, the Lava Park flow (informally named by Williams, 1934; figs. 1, 5, this report), northwest of Mount Shasta, was erupted from a vent located 9 km down the flank from the present summit (fig. 1). Flows on the west flank of Mount Shasta, now partly buried by younger deposits, were also erupted from vents as far as 9 km from the summit of Mount Shasta. The longest known lava flow at Mount Shasta, the 9-km-long Military Pass flow (figs. 1, 7), moved down the steep summit cone for the first 3–3.5 km before slope angles diminished. Flank eruptions have generally occurred at locations where slopes are less steep, and the flows have therefore traveled less than 9 km from their sources.

In the future, eruption of lava flows at Mount Shasta will probably follow other types of more explosive activity, occurring near the end of an eruptive episode rather than at the beginning. In general, future lava flows will move downslope from their vents, follow topographically low areas, and be diverted around hills, ridges, and other high obstacles in their paths. The degree to which a flow is diverted, however, depends on such factors as the viscosity of the lava mass as a whole and the steepness of the slopes encountered by the lava; some lava flows at Mount Shasta in the past have flowed up against cinder cones and domes in their paths and thickened slightly, before being diverted to the side. An example of this is seen at Cinder Cone, west of the upper part of the Lava Park flow, where the thickened flow reached a height of almost 120 m on the flank of the cone (figs. 1, 8; pl. 2). A similar situation is present southwest of Hotlum (fig. 1), where a lava stream flowed around two domes and covered the upslope sides to a depth of about 120 m. Thus, future lava flows are not expected to flow more than about 120 m up onto any obstacle if there is any topographically lower adjacent area. Two of the thickest andesitic flows, the Lava Park and Military Pass flows (figs. 1, 5, 7), are 110 and 146 m thick at their snouts. From this it is inferred that a maximum flow thickness of about 150 m would be reached only if lava were very viscous or if a lava flow were ponded against a broad topographic barrier.



◁ FIGURE 6 (facing page).—Aerial view toward the north of the southwest flank of Mount Shasta (far right) and Shastina. Lava flows of the post-glacial Shastina cone cut across glaciated valleys of Mount Shasta in the center and foreground. Overlapping dacite domes form the summit area (about 1 km across) of Shastina.

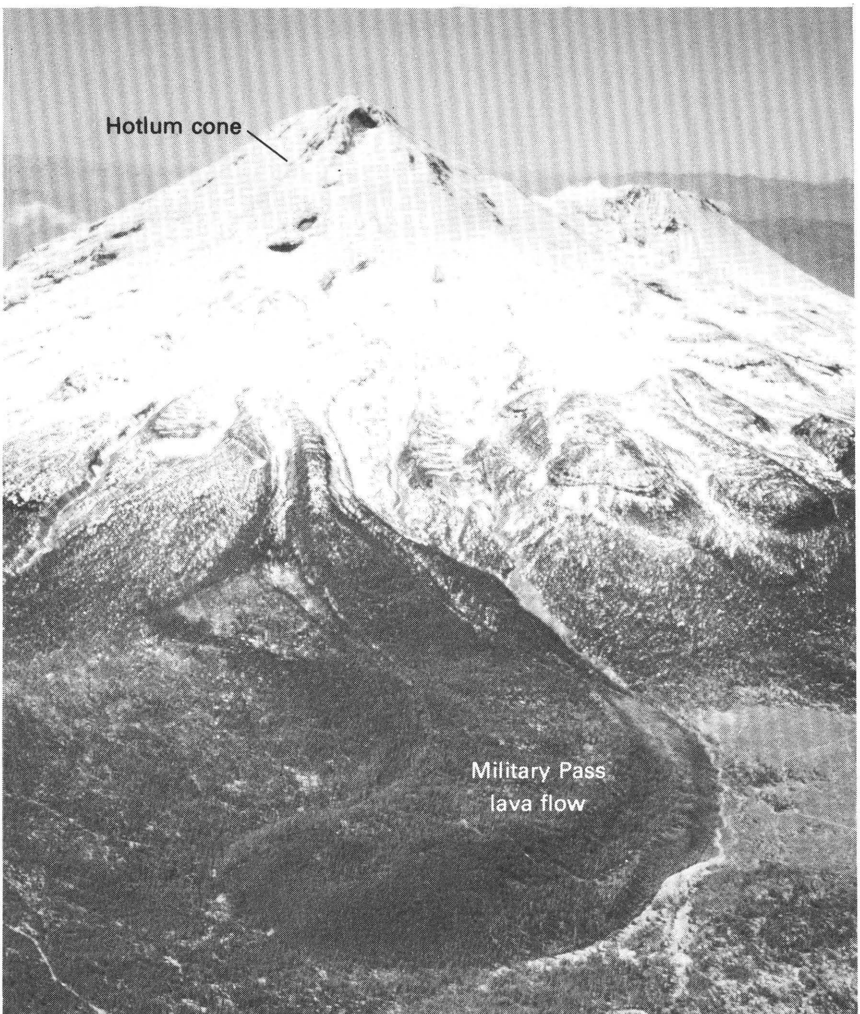


FIGURE 7.—Aerial view of the Military Pass lava flow, northeast side of Mount Shasta. The blocky lava flow originated near the summit of the Hotlum cone; it is about 9 km long and about 150 m thick near its snout. The flow overlies the Red Banks pumice and a broad fan of pyroclastic-flow deposits that were formed shortly before about 9700 years ago.

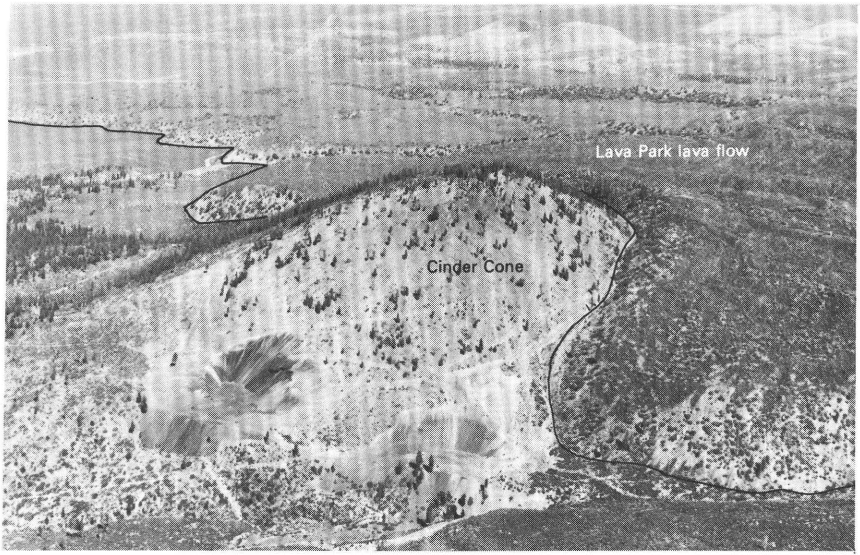


FIGURE 8.—Aerial view toward the north of the Lava Park lava flow thickening where it comes in contact with Cinder Cone. Southwest margin of Lava Park lava flow denoted by heavy line. Flow was moving right to left.

PYROCLASTIC FLOWS

Pyroclastic flows, which can travel rapidly downslope, are masses of hot, dry rock fragments mixed with hot gases. They may result from explosive eruption of molten and solid rock fragments along with gas, or from collapse or laterally directed explosion of hot rock debris from a dome or lava flow. In addition to being erupted along with the rock debris, volcanic gases in a pyroclastic flow may be emitted by the rock fragments themselves (Perret, 1935). Flowage may be sustained by air incorporated and heated by the moving mass (Perret, 1935; McTaggart, 1960). As used here, a *block-and-ash flow* is a type of pyroclastic flow that consists mostly of nonvesicular rock debris, ranging widely in grain size, mixed with hot air or other gases. A *pumice flow* is a pyroclastic flow that consists largely of pumice fragments, ranging widely in grain size, mixed with hot air or other gases.

Most pyroclastic flows consist of two parts: a basal flow of coarse fragments that moves along the ground and a turbulent cloud of finer particles that rises above the basal flow (fig. 9). Fine ash in the cloud may fall over a wide area adjacent to the basal part of a pyroclastic flow. Pyroclastic flows can travel downslope at speeds of 50 to more than 150 km/h, their velocity depending largely on

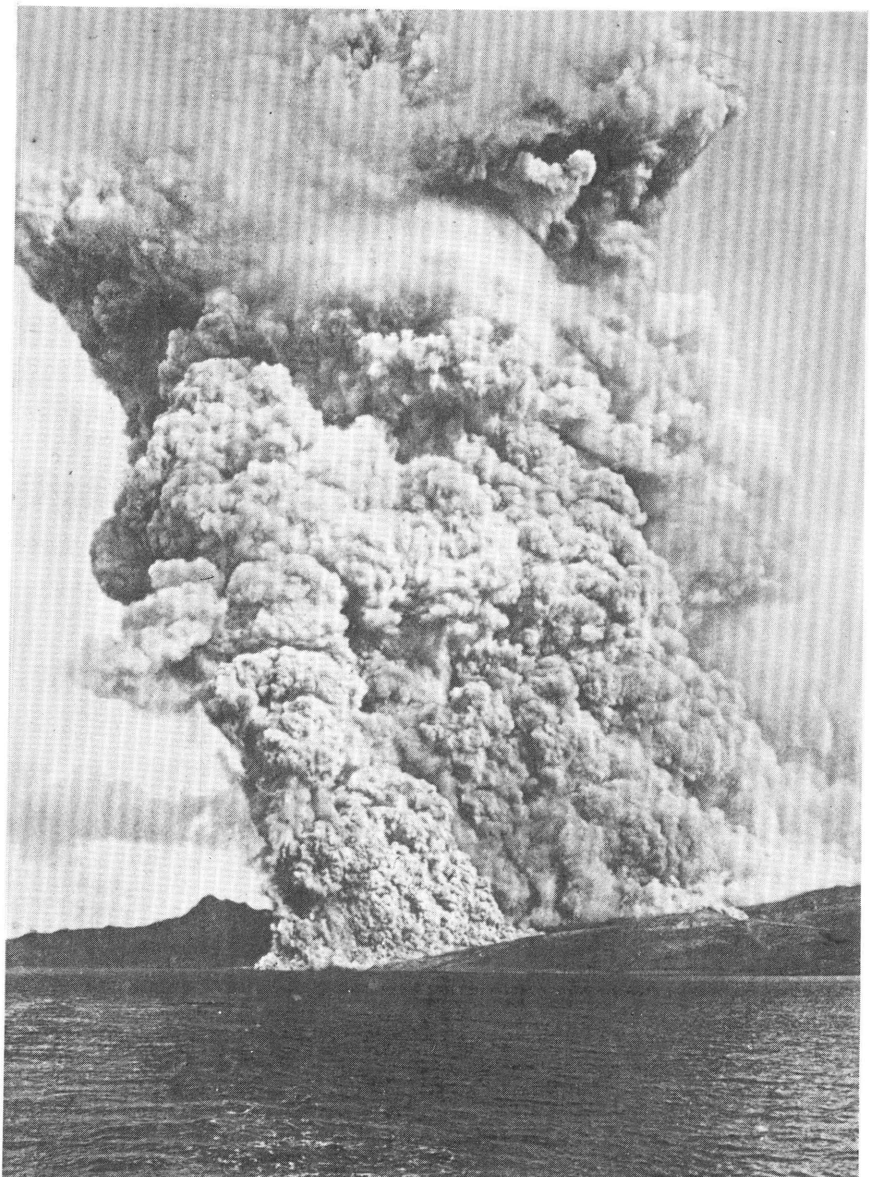


FIGURE 9.—Hot pyroclastic flow descending a valley on the north slope of Mount Pelée on Martinique. The coarse basal part of the flow is obscured by clouds of turbulent hot ash that rise hundreds of meters above it. Photograph by A. Lacroix, December 16, 1902. Published with permission of Masson, S.A., Paris.

volume and on the steepness of slopes over which they travel. Gases and rock debris in pyroclastic flows commonly have temperatures of several hundred degrees Celsius.

Pyroclastic flows generally follow valleys or other depressions but can have enough momentum to overtop hills or ridges in their paths (Aramaki and Ui, 1966; Sparks, 1976; Miller and Smith, 1977). The ability of pyroclastic flows and rock avalanches to climb up on obstacles is primarily a function of momentum. The larger the volume and faster a flow or avalanche travels, the higher it is likely to climb up on a hill in its path. About 10000 years ago a pyroclastic flow traveled 13 km down the northeast side of Mount Shasta, then climbed 120 m up the flank of The Whaleback. The speed of pyroclastic flows tends to diminish with decreasing slope and distance traveled beyond the base of the volcano; thus, pyroclastic flows at distances greater than 13 km from a vent at Mount Shasta are likely to have less momentum and thus be less capable of flowing up onto obstacles. Cold- and hot-rock avalanches described in the literature (Sparks, 1976, p. 183–184; Francis and others, 1974) have a degree of mobility similar to that of pyroclastic flows at Mount Shasta and have been reported to climb up slopes to similar heights. These examples suggest that future block-and-ash flows from Mount Shasta could climb at least as high as 120 m up slopes in their paths.

Pyroclastic flows can be extremely hazardous because of their high speeds and high temperatures. Objects and structures in their paths can be destroyed or swept away by the impact of hot debris or by associated hurricane-force winds. Wood and other combustible materials are commonly burned by the contact with hot debris and gases. In addition to the basal flow causing death or injury from burns or impact, people and animals may also be killed or burned by inhalation of hot ash and gases. During eruption of a dome at Mount Pelée on Martinique in 1902, a cloud of ash and gases with a temperature of between 700° and 1000°C swept into the town of St. Pierre traveling at an estimated speed of 160 km/h or more (fig. 9; Macdonald, 1972). Within a few minutes, about 30000 people died, most of them from inhalation of hot ash and gases. A similar explosive eruption of Mount Lamington, New Guinea, in 1951 produced clouds of hot ash that swept down the flanks of the volcano at hurricane speeds, killed about 3000 people, and destroyed nearly everything within an area of about 230 km^2 (Taylor, 1958).

Pyroclastic flows have been formed frequently at Mount Shasta during the last 10000 years; they have flowed down most sides of the mountain and have traveled as far as 20 km from their sources (pl. 1). Future pyroclastic flows from vents or domes near the summit could sweep down almost any side of the mountain, although the area west of Shastina would probably be protected by the barrier formed by the Shastina cone (figs. 6, 10). If future eruptions were to occur at new vents or domes located on a flank of the volcano, pyroclastic flows would primarily affect only those areas of the mountain downslope from the vents. The distribution of pyroclastic-flow deposits derived from domes at Shastina (Miller, 1978) indicates that, in the future, similar pyroclastic flows from high on the volcano could travel as far as 18 km (pl. 1) and cover areas as large as 65 km^2. Pyroclastic flows from vents low on the flank of, or near, Mount Shasta might spread more radially and travel in several directions from the source. Such an event occurred at Black Butte about 9500 ^{14}C years ago, when pyroclastic flows produced by collapse or explosion of dome segments of Black Butte traveled about 10 km^2 south and 5 km north of the dome complex and covered an area of about 45 km^2 (Miller, 1978).

Future eruptions are very likely at vents at or near the present summit, but eruptions could also occur at new vents almost anywhere in the vicinity of Mount Shasta. Eruption of pyroclastic flows from a vent at the summit or high on the cone of Mount

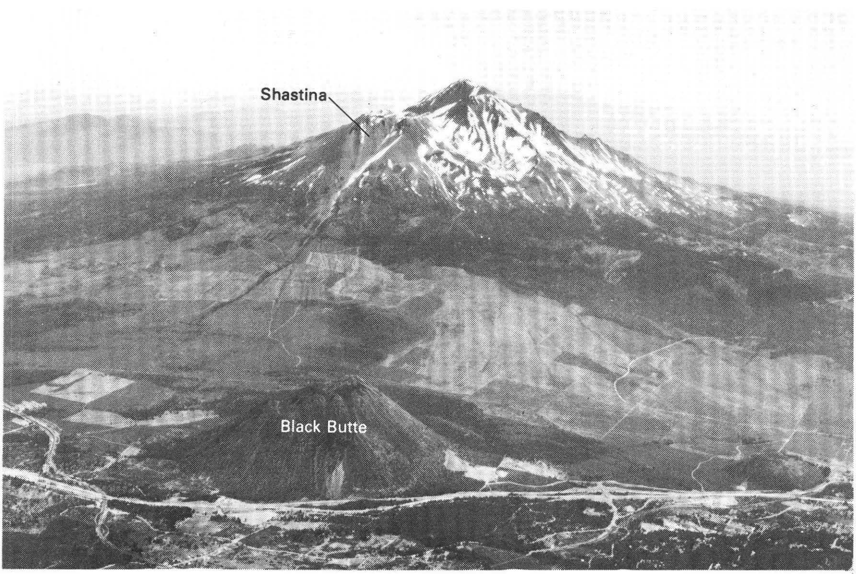


FIGURE 10.—Aerial view toward the east of Mount Shasta, Shastina, and Black Butte. The area west of Shastina (lower left half of photograph) may be shielded by Shastina from future lava flows, pyroclastic flows, and mudflows originating at or near the summit of Mount Shasta. Interstate Highway 5 crosses photograph near bottom.

Shasta could melt a large volume of snow and ice, especially if the eruption occurred during the winter when the volcano is covered by a thick blanket of snow. The resulting mudflows and muddy floods could move downslope on almost any side of the mountain and travel several tens of kilometers beyond the base of Mount Shasta.

DOMES

Volcanic domes are masses of solid rock that are formed when viscous lava is erupted slowly from a vent. If the lava is viscous enough, it will pile up above the vent to form a dome rather than flow away as a lava flow. The sides of domes are usually very steep and often are mantled with unstable rock debris formed during or shortly after dome emplacement (figs. 6, 11). Generally domes are composed of lava that has a lower gas content than the more explosive lavas erupted earlier; however, dome lavas often still contain enough gas to cause explosions or collapse of part of a dome after it is formed.

The direct effects of dome eruption include local burial or disruption of the preexisting ground surface by the dome itself or

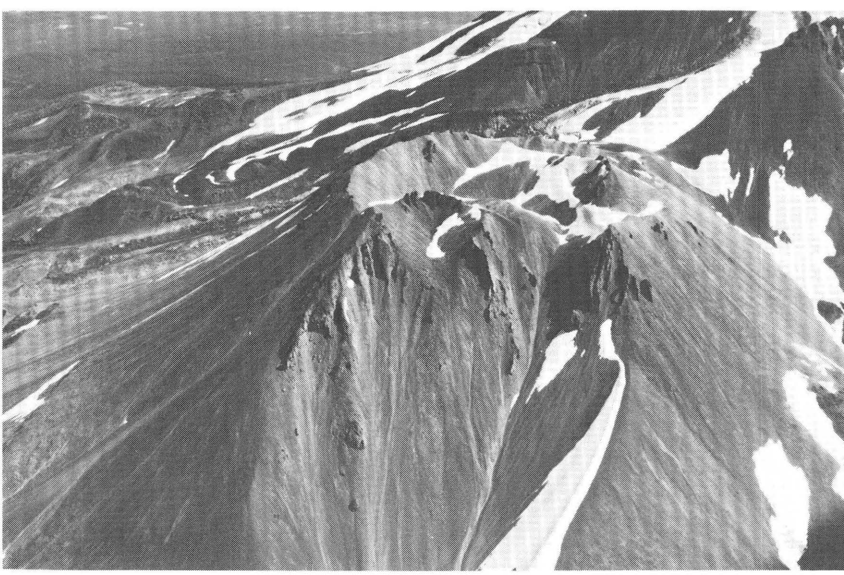


FIGURE 11.—Aerial view toward the east of multiple dacite domes which form the summit of Shastina. Steep flanks of Shastina domes are mantled with unstable rock debris formed during or shortly after dome emplacement. Circular summit area is approximately 1 km across.

more widespread burial by rock debris produced by collapse of the dome. Because of their high temperatures, domes may start fires. Domes are extruded so slowly that they can be avoided by people, but they may endanger works of man that cannot be moved. The major hazard associated with domes, however, is from block-and-ash flows produced by explosions or collapses of parts of a dome. These pyroclastic flows can occur without warning and move very rapidly, endangering life and property many kilometers from their sources.

Explosion or collapse of dacite domes at the summit of Shastina about 9500 ^{14}C years ago produced block-and-ash flows that traveled as far as 18 km down the west flank of Mount Shasta (table 1; fig. 12; Miller, 1978). Very shortly thereafter, similar events at Black Butte produced block-and-ash flows that spread about 10 km south, past the present site of the community of Mount Shasta, and about 5 km north, nearly to the present site of Weed. In the future, pyroclastic flows from domes erupted in the vicinity of Mount Shasta could affect broad areas downslope and as far as 20 km from the dome; associated ash clouds carried by high winds might affect a much larger area. In addition, lateral blasts from domes could carry steam and hot-rock fragments outward at high speed to distances of 10 km or more.

TEPHRA

The term "tephra" (Greek "ash") is used in this report for molten or solid rock particles of all sizes, from boulders to dust, which are erupted into the atmosphere above a volcano. Eruptions that produce tephra range from short-lived, weak eruptions that eject tephra only a few meters into the air to cataclysmic explosions that throw debris to heights of several tens of kilometers above a volcanic vent. Tephra eruptions vary from single blasts that last only a few seconds to continuous outrushes of gas and particles that last for several minutes, hours, or even days. Explosive eruptions that produce tephra can also produce pyroclastic flows when part or all of a vertically erupted column of rock debris and hot gas collapses and flows down the flanks of a volcano.

Eruptions of tephra are usually the result of escape of gas from a magma that has been under high pressure and is emplaced at a higher level at lower pressure or magma that erupts at the Earth's surface. Vesiculation and quenching produce fragments of pumice, which consist of volcanic glass having many small cavities or vesicles; other tephra fragments can be bits of glass, solid rock, or crystals.

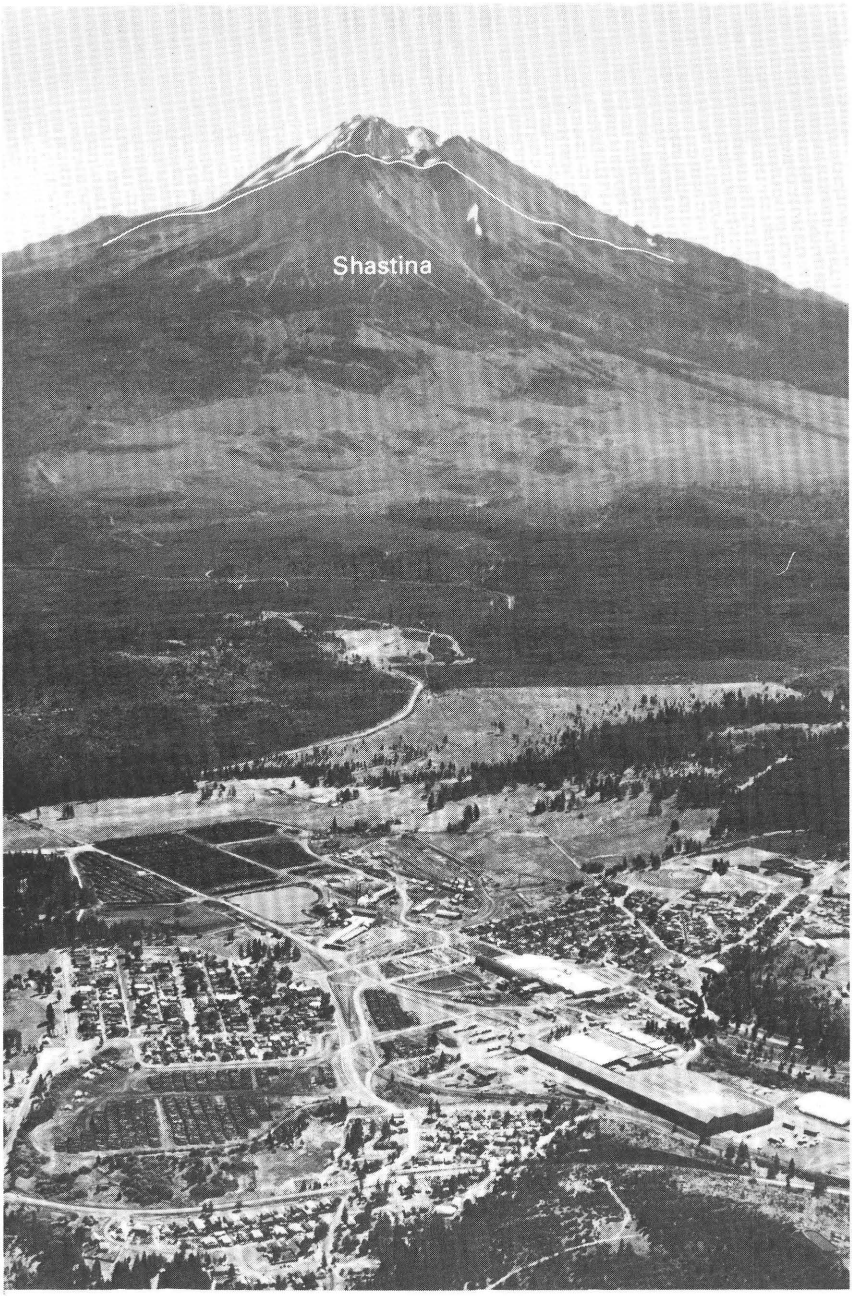


FIGURE 12.—Aerial view toward the east of the community of Weed (foreground), located on fan of pyroclastic-flow debris erupted from Shastina about 9500 ^{14}C years ago. Similar future eruptions from Shastina could endanger people and property in Weed.

Tephra eruptions can occur suddenly and may be the first or one of the first events in an explosive eruptive episode. Such eruptions often produce relatively small volumes of ash early in an eruptive episode and much greater volumes hours or days later as the vent enlarges and the eruption gains in intensity. Eruptions eventually decrease in violence as high-pressure gas escapes from a magma chamber. Eruption of pyroclastic flows or lava flows may accompany or follow an eruption of tephra.

Large particles erupted above a volcano fall back quickly on or near the volcano's flanks; but relatively small fragments can be erupted to great heights, fall slowly, and be carried great distances by winds. If a large volume is erupted, a distinct layer of tephra will accumulate. If winds are present, the falling particles will form a progressively thinning blanket that reaches from the volcano downwind for hundreds of kilometers. Such a blanket usually will be lobe-shaped and will be relatively thick near the volcano and along the long axis of the lobe. Thus, the effects of an ash fall are most severe next to the volcano and along the axis where the ash is thickest; they decrease in severity with increasing distance.

Tephra eruptions can endanger human and animal lives and property by the impact of falling fragments, by depositing a layer of ash over the ground surface, and by producing a suspension of fine fragments in air and water. Dust clouds of volcanic ash and the acids and gases that accompany them can cause darkness during daylight hours, impair breathing for humans and animals, and coat equipment and vegetation. When falling particles carry absorbed acids, water supplies commonly become temporarily acidic and turbid; longer term effects can include severe crop damage over large areas. Death of livestock also can result from starvation because of the blanketing of pastureland and from poisoning of the animals by ash that is ingested with grass.

Significant damage to property from a tephra eruption can result from the weight of the tephra, especially if it is wet, as it may cause structures to collapse, particularly where the tephra is thick. Hot tephra falling near a volcano may set fire to forests and structures. In an area where ash is falling, effects of abrasion and corrosion from freshly fallen ash can be especially damaging to machinery. These effects, together with decrease in visibility and even unexpected darkness during an eruption, may disrupt normal transportation, communication, and electrical services; it can also result in psychological stresses and panic among people in an area where ash is falling, even if their lives are not directly endangered.

Based on past behavior, eruptions of appreciable amounts of pumiceous tephra are less likely at Mount Shasta than are eruptions of pyroclastic flows, lava flows, and domes. Only two major eruptions of pumiceous tephra have occurred during the last 10000 years (table 1). These have been significantly smaller in volume than those of pumiceous tephra erupted relatively frequently at Mount St. Helens, Wash., during the last 4500 years (Mullineaux and others, 1975; Crandell and Mullineaux, 1976) and at some other volcanoes in the Cascade Range during Holocene time (Crandell and others, 1979). Future eruptions of tephra, however, are possible from vents on any side of Mount Shasta, as well as from the summit. Thus, any part of the volcano or surrounding area could be affected.

The Red Banks eruption occurred between about 9600 and 9700 ^{14}C years ago (table 1) and produced a broad elliptical blanket of tephra, remnants of which cover an area of more than 350 km^2 east of Mount Shasta (figs. 13, 14). This part of the tephra sheet had a minimum volume of about 0.1 km^3, and an unknown additional volume of tephra surely was carried beyond the limits shown in figure 14. The distribution of the tephra suggests that the eruption occurred at a time of weak and variable westerly winds rather than of strong and uniform winds, which would have produced a long

FIGURE 13.—Outcrop of Red Banks tephra layer from Mount Shasta in Mud Creek about 14 km southeast of the summit of the volcano. The tephra (between heavy lines) was erupted between about 9600 and 9700 ^{14}C years ago and is about 25 cm thick at this site. The tephra layer is underlain by a mudflow and pyroclastic flow of similar age and overlain by slightly younger mudflows and fluvial deposits.

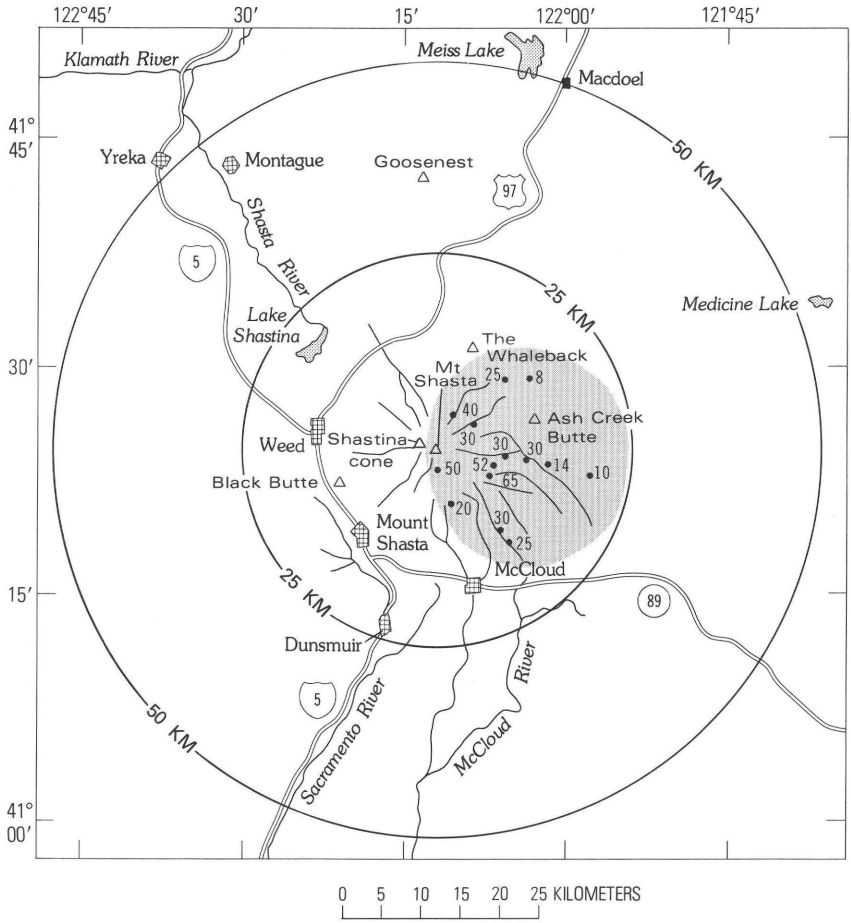


FIGURE 14.—Mount Shasta volcano and vicinity. Known distribution of the Red Banks air-fall pumice shown by stipple pattern; thickness of pumice deposit shown in centimeters. Discovery of a 2-cm-thick ash-size pumice bed, tentatively identified as Red Banks tephra, at a distance of 77 km N. 30° E. of Mount Shasta (D. R. Mullineaux, oral commun., 1979) suggests that the Red Banks tephra may extend much farther northeast than is shown here. Circles with radii of 25 and 50 km can be used with figure 16 to estimate thicknesses of compacted tephra likely to accumulate at various distances downwind from future eruptions of three different volumes. The thickness-versus-distance curves shown in figure 16 are based on tephras carried by westerly winds, which have higher velocities than easterly winds. Thus, most tephras from future eruptions of Mount Shasta that are carried westerly would be thinner than is shown in figure 16.

narrow lobe (Crandell and Mullineaux, 1976, p. 12; fig. 15). Thus the distribution of Red Banks tephra is representative of the

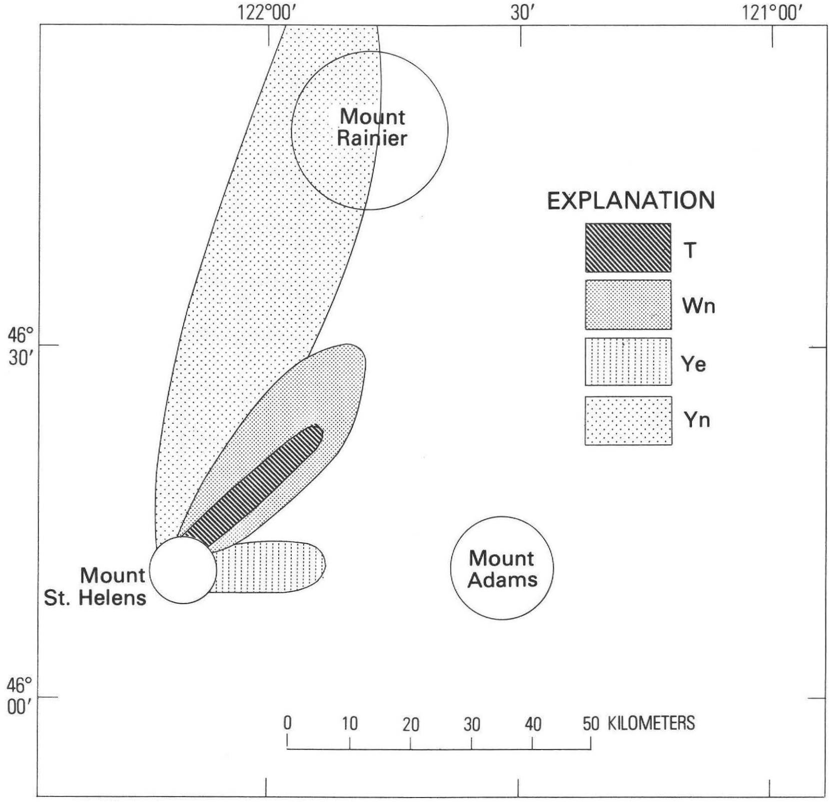


FIGURE 15.—Orientation and width of four tephra lobes (T, Wn, Ye, and Yn) from Mount St. Helens, Wash. Each lobe consists of air-fall tephra 20 cm or more thick from a single eruption (from Crandell and others, 1979).

distribution expected from some, but not the most far-reaching, future tephra eruptions from Mount Shasta. Eruptions during periods of strong winds are likely to produce long and narrow, but relatively thick, bands of tephra that extend far downwind from the volcano.

At Mount St. Helens, tephra layer T has an estimated volume of about 0.1 km^3 (Crandell and Mullineaux, 1976); it can be used as a model of the probable variation in thickness with distance for tephra from most future eruptions of similar volume at Mount Shasta (fig. 16). Also shown in figure 16 is the variation in thickness with distance of tephra from the Red Banks eruption and from eruptions of Mount St. Helens that are both larger and smaller than the Red Banks eruption. Layer Yn has a volume estimated to be between 1 and 3 km^3 (D.R. Mullineaux, oral commun., 1978), whereas the unnamed tephra erupted at Mount St.

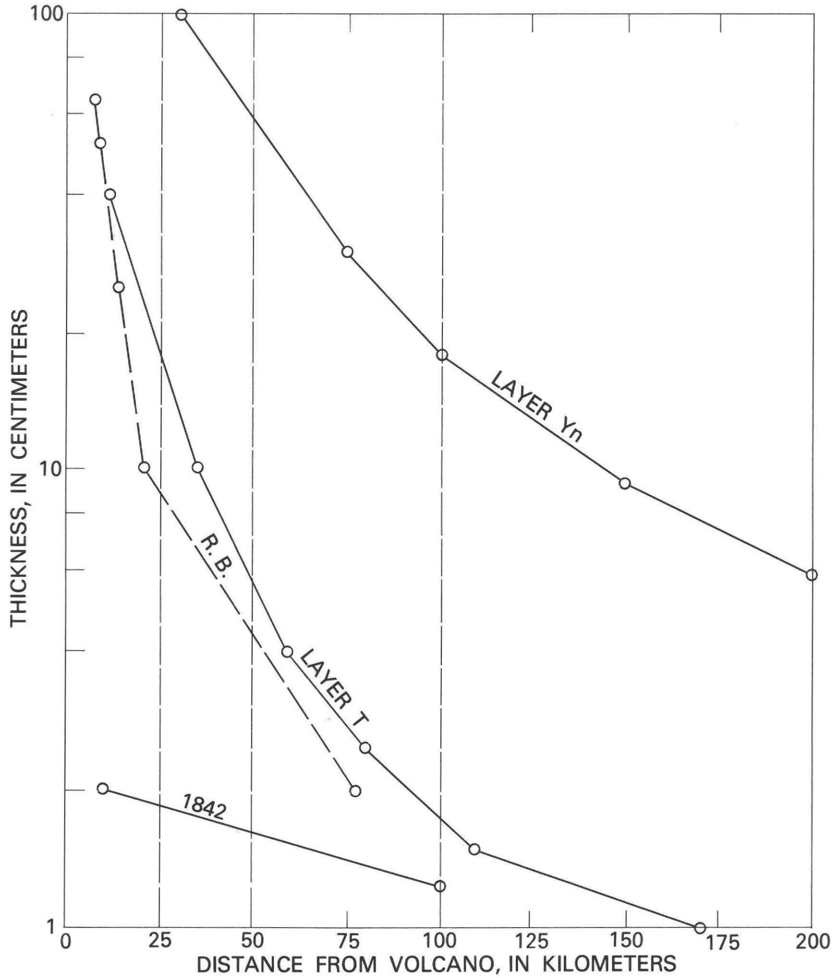


FIGURE 16.—Relation between distance from volcano and the present thicknesses of tephra preserved locally along the thickest parts of lobes. (The tephra layers may have been as much as twice as thick when they were first deposited.) The solid lines represent three tephra deposits of different volumes from Mount St. Helens: layer Yn, layer T, and an unnamed layer deposited in 1842. These are estimated to have volumes of approximately 1-3, 0.1, and 0.01 km^3 respectively (modified from Crandell and Mullineaux, 1976). The heavy dashed line represents the Red Banks (R.B.) tephra layer from Mount Shasta, which has a volume of approximately 0.1 km^3.

Helens in 1842 has a volume of about 0.01 km^3 (Crandell and Mullineaux, 1976). Figure 16 shows diagrammatically how deposits from these four eruptions decrease in thickness downwind from their source vents at very different rates. Future eruptions of tephra from Mount Shasta are not likely to be identical to or even as large as some from Mount St. Helens, but the Mount St. Helens eruptions serve as good examples of possible distributions and thicknesses of tephra from future eruptions of Mount Shasta.

Eruptions of tephra much smaller than layer T or the Red Banks tephra are likely to occur more frequently at Mount Shasta than are larger eruptions. Past history suggests that eruptions as large as the Red Banks tephra will probably occur very infrequently at Mount Shasta. Tephra eruptions as large as the one that produced the Yn tephra at Mount St. Helens are not known to have occurred at Mount Shasta during its long history of more than 100000 years, and such eruptions therefore seem unlikely in the future.

MUDFLOWS

A mudflow is a mass of water-saturated rock debris that flows downslope as a fluid because of the force of gravity. Mudflows consist of material varying widely in size from clay to blocks several tens of meters in maximum dimension. When moving, they resemble masses of wet concrete and tend to flow downslope in channels or stream valleys.

Mudflows are formed when loose masses of unconsolidated debris, such as glacial deposits, pyroclastic-flow debris, or rock-avalanche debris, are saturated with water and become unstable. Water may be supplied by rain, by melting snow or ice, or by overflow of a crater lake. Mudflows may be formed directly if lava or a hot pyroclastic flow is erupted onto snow or ice. They may be either hot or cold, depending on their manner of origin and the temperature of their constituent debris.

Hydrothermal activity on a volcano can alter adjacent volcanic rocks to form clays and other minerals. If the increase in water and clay content is extensive enough, the rock in large areas on a volcano can become weakened. Such areas are relatively unstable and can collapse and produce very large and highly mobile mudflows—a process that has occurred several times at Mount Rainier, Wash. (Crandell, 1971).

Mudflows can travel great distances down valleys, and depending on slope and fluidity, fronts can move at high speeds—as much as 85 km/h. Mudflows produced during an eruption of Cotopaxi volcano in Ecuador in 1877 traveled more than 320 km down one valley at an average speed of about 27 km/h (Macdonald, 1972, p. 174). Mudflows moving swiftly down valleys may climb valley walls on the outsides of bends, and their momentum may also carry them over obstacles in their path. Mudflows confined in narrow valleys or by constrictions in valleys can temporarily deepen and fill valleys to heights of 100 m or more.

The major hazard to human life from mudflows is that of burial or impact by boulders and other debris. People and animals also can be severely burned by mudflows carrying hot debris. Buildings and other property in the path of a mudflow can be smashed, completely buried, or carried away. Because of their high viscosity, mudflows can move and even carry away vehicles and objects of tremendous size and weight, such as bridges.

Mudflows have occurred frequently during the last 10000 years at Mount Shasta (pl. 1) and have included both hot and cold varieties. Many mudflows have traveled more than 20 km from the summit, and some have gone more than 30 km (fig. 17). Most of the large mudflows probably resulted from eruptions of hot lava or pyroclastic debris that melted snow or ice high on the mountain, producing hot mudflows of large volume. Some pyroclastic flows originating at the summit of Mount Shasta probably changed into hot mudflows at some point down on the flanks after being mixed with water from rivers or melted snow. At Mount Shasta, many mudflows are confined to channels high on the cone, but at the base of the mountain they leave the channels and spread out to cover much broader areas on fans.

Small mudflows, not caused directly by eruptions, are common at Mount Shasta. They occur because past volcanic activity has

FIGURE 17.—View toward the north of Mount Shasta and flat-topped fill in Squaw Valley Creek (foreground) from a point 26 km south of Mount Shasta. Upper several meters of valley fill consist of mudflows originating at Mount Shasta during about the last 4000 years. Similar future mudflows could pass through the community of McCloud.

built a high, steep cone largely veneered with loose fragmental debris. Relatively small but frequent mudflows have been produced historically, and probably prehistorically, by accelerated melting of glaciers on Mount Shasta during warm summer months. Rapid melting of the Konwakiton Glacier on the south side of Mount Shasta produced mudflows during the summers of 1924, 1926, and 1931 (Hill and Egenhoff, 1976). Mudflows that occurred during the summer of 1924 covered an area of more than 6 km^2 near the community of McCloud with an estimated 5.4 million m^3 of mud; an additional but undetermined volume of debris entered the McCloud River and subsequently flowed into the Sacramento River (Hill and Egenhoff, 1976).

During the summer of 1977, rapid melting of glaciers on Mount Shasta following a very light winter snowfall produced small mudflows that swept down most canyons which head at glaciers. Mudflows traveled more than 20 km down Ash Creek, Mud Creek, and the Bolam and Whitney Creek valleys (fig. 18). The mudflows were contained within deep canyons on the cone, but spread out on fans at the base of the mountain; successive mudflows covered different parts of the smooth fans before coming to rest.

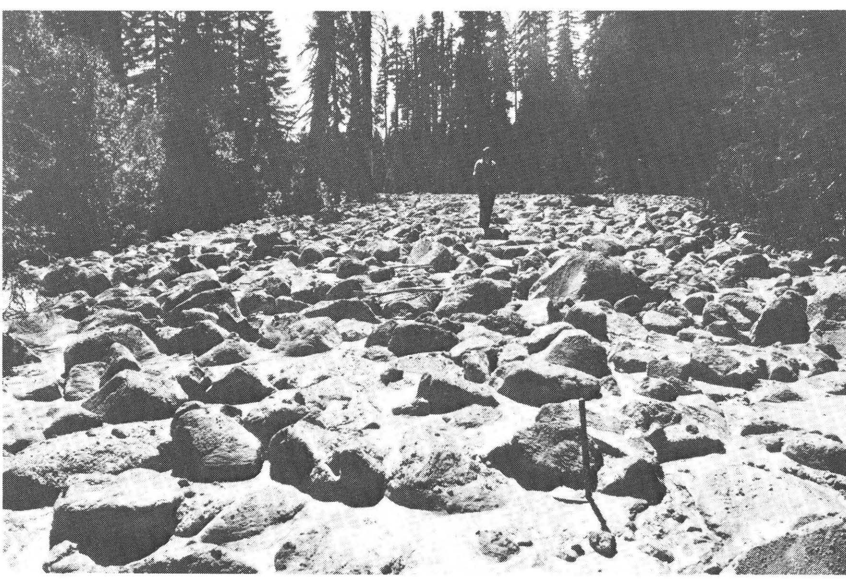


FIGURE 18.—View of deposit from mudflow which moved down Ash Creek on the east side of Mount Shasta during summer 1977. At this locality, about 9 km from the summit of the volcano, the mudflow is as much as 5 m thick. The mudflow traveled more than 20 km from the volcano and apparently was produced by rapid melting of Wintun Glacier owing to a combination of a light snowpack during the previous winter and high summer temperatures. Similar mudflows moved down most canyons on Mount Shasta that head at glaciers. Army shovel in right foreground for scale.

FLOODS

Floods commonly are produced by melting of snow and ice during eruptions of ice-clad volcanoes like Mount Shasta or by heavy rains which may accompany eruptions. By incorporating river water as they move down valleys, mudflows may grade into muddy floods (slurry floods) carrying unusually large amounts of rock debris. Such floods can leave thick deposits of sand and gravel on fan surfaces and valley floors whenever the carrying power of the flood decreases for any reason. Eruption-caused floods can occur suddenly and can be of large volume. If floods caused by an eruption occur when rivers are already high because of heavy rainfall or snowmelt, floods far larger than normal can result. Streams and valley floors around Mount Shasta could be affected by such floods as far downstream as Shasta Lake on the Sacramento River, and as far as the Shasta River valley (fig. 14) and possibly the Klamath River northwest of Mount Shasta. The danger from floods caused by eruptions is similar to that from floods having other origins, but floods caused by eruptions may be more damaging because of a higher content of sediment which would increase the bulk specific gravity of the fluid.

VOLCANIC GASES

Volcanic gases are emitted from small vents called fumaroles on many and perhaps most stratovolcanoes in the world, whether they are active or dormant. Gases are also erupted, along with molten or solid rock fragments, from main vents during eruptions. Emission of sulfur compounds and other gases, usually accompanied by hot water or steam, often precedes an eruption; and gases can issue from fumaroles for hundreds or thousands of years after an eruption has ended. Eruptions are often preceded not only by increased fumarolic activity, but also by increased gas temperatures or a change in the composition of the gases emitted; such changes do not, however, guarantee that an eruption is imminent. Fumarolic activity increased significantly in Sherman Crater on Mount Baker, in the northern part of the Cascade Range, in March 1975 (Frank and others, 1977); it continued at a relatively high level of activity through the winter of 1980. However, no other phenomena which usually precede eruptions have occurred as of the present writing (January 1980).

Volcanic gases emitted at stratovolcanoes usually consist predominantly of steam, followed in abundance by carbon dioxide and compounds of sulfur and chlorine. Minor amounts of carbon monoxide, fluorine and boron compounds, ammonia, and several other compounds of lesser abundance are found in some volcanic gases. Fumarolic emissions also deposit incrustations of various minerals where they issue from rock.

Distribution of fumarolic gases is mostly controlled by the wind; concentrated gases near a vent become diluted rapidly downwind. Such gases, even if very dilute, can have a noticeable odor and can be harmful to plants many tens of kilometers downwind from a vent.

Volcanic gases can be dangerous to life and health as well as property. Acids and ammonia and other compounds present in volcanic gases can damage peoples' and animals' eyes and respiratory systems, and accumulation in closed depressions of gases heavier than air, like carbon dioxide, can suffocate people or animals that wander into such basins. Other harmful effects of volcanic gases on plants and animals, and corrosion of metals and other property, can be severe near and downwind from especially active fumaroles.

On Mount Shasta fumarolic activity is restricted at present to two small areas on the summit dome. Both areas contain numerous small fumaroles, and one has a small acidic hot spring. Fumarole temperatures measured in July 1975 were about 84°C, which is approximately the boiling temperature of water at an altitude of 4270 m. Evidence of alteration of rock and deposition of minerals elsewhere around the summits of Mount Shasta and Shastina indicates that fumarolic activity has been considerably greater and more widespread at various times during the past than at present. Future increase of fumarolic activity would be most likely at the summits of Mount Shasta or Shastina, but could occur anywhere on the flanks or even around the base of the volcano.

VOLCANIC HAZARD ZONES AROUND MOUNT SHASTA

Areas subject to risk from future eruptions of Mount Shasta have been divided into zones that delineate the estimated degree of risk from each type of eruptive phenomenon (pls. 2, 3). The zones of risk are to a great extent arbitrary and gradational; that is, risk does not necessarily decrease sharply or disappear at most outer zone boundaries, but generally decreases gradually across entire zones and from one zone to the next. The specific positions of some boundaries may indicate a relatively sharp decrease in risk, like that denoting the upper limit of lava-flow risk on a hillside, but most boundaries drawn are diagrammatic and show general areas of successively lower risk.

LAVA-FLOW HAZARD ZONES

Potential hazard zones for future lava flows erupted at and in the vicinity of Mount Shasta, shown on plate 2, are based on the vent locations of past lava flows, the areal extents of those lava flows, and their behavior. (Lava flows older than about 10000 years were not considered in determining the location and extent of lava-flow hazard zones.)

Many more lava flows have erupted from central vents at the summits of the Shastina and Hotlum cones than from individual flank vents. Thus it seems likely that most future eruptions of lava also will occur at the central vents rather than on the flanks of the volcano. Some future lava flows could, however, be erupted at flank vents located as far as 9 km downslope from the present summit of Mount Shasta, and individual flows may travel as far as 9 km downslope from their sources. On the basis of these inferences, the outer limit of potential hazard from lava flows is placed at a distance of 18 km from the summit[4] (pl. 2), excluding areas within 18 km of the summit that are more than about 120 m above the surrounding fan surface or any adjacent low areas.

The 18-km extent of this zone is based on the assumption that future lava flows will be of andesite or basaltic andesite and of similar viscosity and volume to those erupted in Holocene time. If future flows are more fluid or more copious than those of the past, they could conceivably travel much farther than 9 km downslope from a vent.

The area of potential hazard from lava flows is divided into three concentric zones. In general, within this 36-km-diameter area, the risk is greatest near the present summit, where eruptions of lava have been most frequent in the past, and decreases with distance outward, reaching a minimum beyond the outer edge of zone C. Zone A extends from the summit outward 6 km in all directions and includes the main vents that were active during Holocene time and their associated cones. Most future lava flows are likely to erupt within zone A, and this therefore constitutes the zone of greatest potential hazard from lava flows (table 1). Zone B consists of a ring-shaped area that extends from 6 to 12 km from the summit. It is a zone into which lava flows from the Hotlum and Shastina central vents have flowed. In the northwest and west sectors, it is also a zone in which lava flows have been erupted from flank vents

[4]An old lava flow west of the Lava Park flow extends toward Lake Shastina beyond the 18-km boundary; however, this flow is older than about 25000 years and was not considered in determining the extent of lava-flow hazard zones.

during Holocene time; thus, it might be affected by future lava flows from both main- and flank-vent eruptions. The outer zone, zone C, is a ring extending generally from 12 to 18 km from the summit. No known lava flows have been erupted from vents in zone C during Holocene time; however, this zone has been affected by flows that were erupted from vents in zone B and flowed into zone C. Lava flows are not likely to erupt from vents in zone C in the near future, but vents closer to Mount Shasta may erupt lavas that could flow into this zone. Thus, some degree of this type of hazard exists to property and manmade structures within zone C, which includes the communities of Mount Shasta, Weed, and McCloud (pl. 2).

TABLE 1.—*Approximate percentage of hazard zones around Mount Shasta that have been affected at least once by eruptions during the last 10000 years, and the estimated average frequency of certain future hazardous events in each zone.*

Values, based on the known distribution of deposits and on the frequency of the events listed on plate 1, are approximate. Individual pyroclastic flows and mudflows were counted as single "events" for determining the "estimated average frequency of future hazardous events"; however, a single lava-flow "event" includes multiple lava flows erupted over a period of tens to hundreds of years. These "events" have not occurred at regular intervals, however, but are clustered in episodes separated by quiet intervals of variable length. Refer to plates 2 and 3 for locations and limits of hazard zones. "Large" mudflows as defined here cover areas greater than about 10 km^2. "Small" mudflows are those which cover less than about 10 km^2. Leaders (......) indicate not applicable. Symbol / means "per," and symbol < means "less than"]

Hazard zones	Lava flow (pl. 2)			Pyroclastic flow and mudflow (pl. 3)				
	Zone A	Zone B	Zone C	Zone 1	Zone 2	Zone 3	Zone 4, northwest part	Zone 4, south part
Area of zone affected at least once during the last 10000 years (in percent)	50	25	<5	100	60	25	<10	40-60(?)
Estimated average frequency of future hazardous events in zone (in years):								
Lava flows	1/3000-4000	1/5000	1/10000	......	......	......	......	......
Pyroclastic flows	......	......	......	1/800	1/1500	1/10000	None expected	None expected
"Large" mudlfows	......	......	......	1/600	1/600	1/2000	1/5000	1/5000
"Small" mudflows	......	......	......	1/10	1/10	1/25(?)	None expected	None expected

During any one future eruption, a single lava flow is expected to affect only a very small part of a lava-flow hazard zone. One eruption is likely to produce a single flow or a few flows that would cover no more than about 10 km^2. (The Lava Park flow on the northwest side of Mount Shasta (figs. 1, 5,), one of the largest, covers about 13 km^2.) When an eruption begins and the location of the vent is known, the direction of flow can be predicted at least approximately, and only the areas downslope from the vent will be directly affected.

Flank eruptions of lava have occurred during Holocene time chiefly on the west and northwest sides of Mount Shasta; however, the specific locations of future flank vents cannot be predicted, and eruptions could occur anywhere within lava-flow hazard zones A and B.

PYROCLASTIC-FLOW AND MUDFLOW HAZARD ZONES

Plate 3 shows areas of pyroclastic-flow and mudflow hazard, based primarily on the frequency and extent of pyroclastic flows and mudflows that have affected those areas during the last 10000 years.

Parts of zone 1, centered on the volcano, have frequently been affected by pyroclastic flows and mudflows during the last 10000 years (pl. 1, table 1). Future eruptions like those of the past will affect this zone more frequently than any other area around Mount Shasta. In general, the degree of hazard within this zone decreases outward in all directions from a maximum at the summit. Although all parts of zone 1 probably will be affected by pyroclastic flows at some time in the future, the greatest hazard from mudflows is in deep canyons. Mudflows tend to follow valleys; some may cross zone 1 confined within deep canyons, such as those along Mud Creek, Ash Creek, and Whitney Creek, and may not spread out until they reach fan surfaces in zone 2 (fig. 19). Pyroclastic flows and mudflows coming down smooth flanks of Mount Shasta or down small stream courses would be expected to spread more widely and cover broader surfaces within zone 1.

Hazard zone 2 is a zone of irregular shape between 10 and 20 km from the summit of Mount Shasta that has been affected less frequently by pyroclastic flows and mudflows than zone 1 (table 1). The outer boundary is based on the maximum distance at which pyroclastic-flow deposits younger than 10000 years have been found. The general ring shape of hazard zone 2 is strongly modified by topography; areas thought to be topographically too high to be affected by pyroclastic flows or mudflows as they descend the flanks of Mount Shasta have been excluded. These areas, however, may be affected by ash clouds associated with pyroclastic flows. Within 20 km of the summit, the limit of pyroclastic-flow hazards around Mount Shasta has been drawn about 120 m vertically above the bases of hills within hazard zones 1 and 2, on the basis of

FIGURE 19.—View of upper Ash Creek and the terminus of Wintun Glacier, east side of Mount Shasta. Future lava flows, pyroclastic flows, and mudflows originating high on the cone may be concentrated in deep canyons such as this one within hazard zone 1 (pl. 3) before spreading out in zones 2 and 3. The mudflow shown in figure 18 originated at the terminus of the Wintun Glacier and produced the light-colored trimline (arrows) visible in the creek bottom at lower left.

the height to which pyroclastic flows climbed on the southeast flank of The Whaleback.

In hazard zones 1 and 2 (pl. 3), future mudflows are not likely to climb as high as pyroclastic flows on topographic obstructions or valley sides because of their lower speed. Mudflows are likely to cover wide areas of zone 2, especially where they move across broad, smooth fans such as those on the northwest and southeast flanks of Mount Shasta (figs. 4, 20). Elsewhere in this zone, mudflows may be confined or directed by valley walls or other topographic barriers. In general, risk from mudflows in zone 2 decreases gradually with increasing distance from the summit and more abruptly with increasing height above a fan surface or valley bottom.

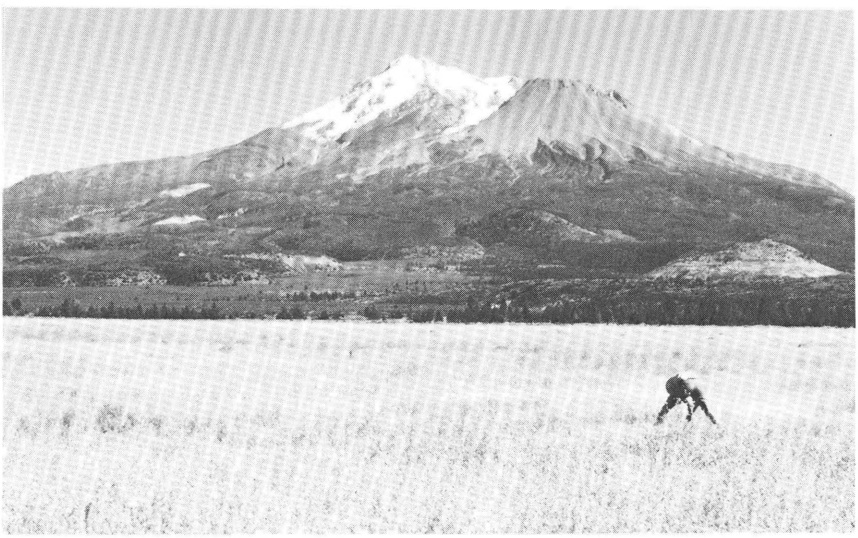


FIGURE 20.—View of Mount Shasta (left), Shastina, and the Whitney Creek fan (foreground) from about 21 km northwest of the summit of the volcano. The broad flat fan surface has been covered by successive mudflows during the last few decades and probably centuries. Mudflows that came down Whitney and Bolam Creeks during the summer of 1977 reached within about 2 km of this site.

Zone 3 includes areas between 20 and 30 km from Mount Shasta that, during the last 10000 years, are known to have been affected only by mudflows, but that also could be affected by very large and infrequent pyroclastic flows from Mount Shasta (table 1). The limit of 30 km for the largest expectable pyroclastic flow from Mount Shasta is based on a hypothetical pyroclastic flow, which could descend from near the present summit and have a mobility similar to that exhibited by the most mobile pyroclastic flow that has occurred in the Mount Shasta area during the last 10000 years.

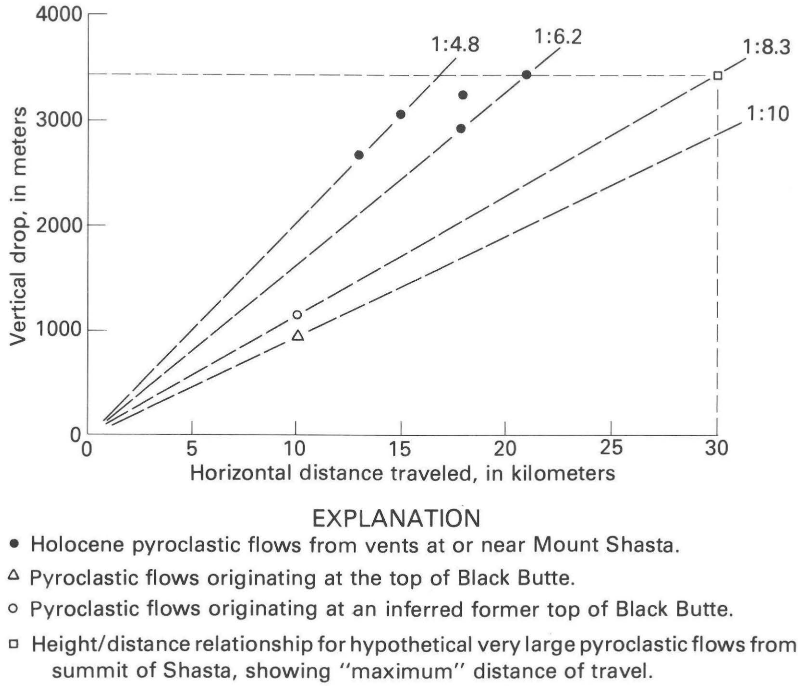


FIGURE 21.—Relationship between the vertical height dropped and horizontal distance of travel for pyroclastic flows from vents at or near Mount Shasta (long dashed lines) and for hypothetical, very large pyroclastic flows from Mount Shasta (short dashed lines).

Figure 21 is a plot of vertical drop versus distance traveled for six pyroclastic flows from vents at or near Mount Shasta. Five of the six have a ratio of vertical to horizontal distance between 1:4.8 and 1:6.2 (table 2, fig. 21). A pyroclastic flow that originated by explosion or collapse of dacite domes at Black Butte traveled a distance that is 10 times the vertical drop (fig. 21). A possibly more realistic ratio can be obtained for this pyroclastic flow by projecting the slopes to reconstruct the original height of the partly collapsed domes at Black Butte. Using this value, the ratio of vertical drop to distance traveled for the Black Butte pyroclastic flow is 1:8.3 (fig. 21). Even this lower ratio suggests that this pyroclastic flow was more mobile than the other five. If it is assumed that a pyroclastic flow from the summit could descend one of the flanks northwest or southeast of Mount Shasta through a vertical distance of about 3400 m and move with a vertical to horizontal ratio of 1:8.3, the maximum possible distance traveled would be about 30 km (fig. 21). The volume of a pyroclastic flow is also a factor determining the distance that a pyroclastic flow can travel, but it has not been considered in this analysis. Thus this

TABLE 2.—*Mobility of selected lithic pyroclastic flows from Mount Shasta, Shastina, and Black Butte*

Location of vent	Altitude of vent (m)	Altitude of lower limit of pyroclastic-flow deposit (m)	Vertical drop, V (m)	Horizontal distance of travel, H (km)	V:H
Summit of Hotlum cone	4300	1600	2700	[1]13	1:4.8
Do	4300	1200	3100	[1]15	1:4.8
Do	4300	1000	3300	[1]18	1:5.5
Do	4300	900	3400	[1]21	1:6.2
Summit of Shastina cone	3800	900	2900	18	1:6.2
Summit of Black Butte	1900	900	1000	10	1:10
Reconstructed summit of Black Butte	2100	900	1200	10	1:8.3

[1]Value shown is maximum known distance traveled; pyroclastic flow may have gone farther.

"calculated" outer limit of risk from pyroclastic flows defines a zone which probably will be affected only by very large pyroclastic flows from Mount Shasta.

No known pyroclastic flows have reached distances of more than 20 km from Mount Shasta. Even if a pyroclastic flow did reach that far, it should be moving more slowly than on the volcano's upper slopes and thus should be less able to climb much above the surface on which it is moving. The limits of hazard from mudflows and pyroclastic flows beyond 20 km are therefore arbitrarily drawn close to the bases of most hills or obstructions.

Mudflows are likely to cover broad areas in zone 3 as often as several times per century (table 1). The risk from mudflows is greatest on smooth fans and topographic depressions near major valleys like those of Ash Creek, Mud Creek, and Whitney Creek, which head on Mount Shasta. Risk from mudflows in zone 3 decreases downvalley and with increasing height above surfaces on which they flow. Hills within zone 3 northwest of Lake Shastina probably will not be affected by mudflows, but possibly will be affected by ash clouds.

Hazard zone 4 consists of areas that, during the last 10000 years, have been affected only by mudflows and that are beyond the limit of the largest predictable pyroclastic flows. The zone reaches from 30 km to as far as 70 km south from Mount Shasta; it includes part of the broad Shasta Valley northwest of Mount Shasta and narrow river canyons like those of the McCloud and Sacramento Rivers to the south. Future mudflows may extend many tens of kilometers south along major drainages and may reach Shasta Lake, about 70 km to the south. Future mudflows may also spread out in Shasta Valley northwest of Mount Shasta and could cover wide areas of the valley floor. The degree of risk in hazard zone 4 also decreases gradationally with increasing distance downvalley and more rapidly with increasing height above valley floors.

Plate 3 shows a shaded area west of and including the summit of Shastina. This area has been affected by mudflows and pyroclastic flows only from Shastina and Black Butte during the last 10000 years. It is not likely to be affected by pyroclastic flows or mudflows originating at vents near the summit or on the north, east, or south flanks of Mount Shasta, because the area would probably be shielded from such flowage deposits by the cone of Shastina (fig. 10). However, this area may be affected by air blasts and ash clouds associated with pyroclastic flows (fig. 9) originating near the summit or on the north, east, or south flanks of Mount Shasta. The area shown is also likely to be affected by eruptions of Shastina or, in part, by eruptions from Black Butte or any new vent west of Shastina.

Mudflows caused by eruptions are less likely to occur in the shaded area than in other areas around Mount Shasta (except in winter), because Shastina has no glaciers or permanent snow cover and no large source of water except for winter snow.

Broad areas within and beyond the limits of hazard zones 1-3 can be affected by clouds of hot ash and air blasts associated with pyroclastic flows. The width of the area that could be affected by these phenomena may extend as much as several kilometers beyond the margin of the pyroclastic flow. Ash clouds and associated air blasts will not be restricted to topographic depressions as pyroclastic flows and mudflows will be, but could affect all areas within several kilometers of pyroclastic flows (fig. 9).

RISK FROM TEPHRA

Eruptions of pumiceous tephra from Mount Shasta have been rare and of small volume in the past 10000 years. Only one widespread pumiceous tephra layer, from the Red Banks eruption (pl. 1), has been found around Mount Shasta. Assessment of hazards from tephra around Mount Shasta is based in part on the volume of this eruption and on comparison to the volumes and distributions of tephra originating at Mount St. Helens in Washington.

Figure 14 shows circular rings that have radii of 25 and 50 km around Mount Shasta. By analogy with eruptions at Mount St. Helens, the expected maximum thicknesses of compacted tephra from future eruptions at various distances from Mount Shasta might be as shown in figure 16. Inasmuch as the severity of effects from ash fall decreases generally with decreasing thickness of the deposit, the risk from tephra decreases as the distance from the summit of Mount Shasta increases.

Significant ash-fall thicknesses from a single eruption are likely to cover only a narrow band downwind from the vent if winds are strong and unidirectional during the eruption. A review of wind records from the last 21 years at Medford, Oreg., about 110 km north-northwest of Mount Shasta, indicates that high-altitude winds in this region blow much more frequently and at higher speeds toward the east-northeast and east than toward the west. Figure 22 shows that winds at altitudes between 3000 and 16000 m blow into a sector between and including north-northeast and south-southeast about 82 percent of the time, while winds blow toward the west into a sector between and including northwest and southwest only about 5 percent of the time.

Modern prevailing westerly winds above Medford, Oreg., appear to be similar in speed and direction to the winds at similar altitudes near Mount St. Helens in Washington during the last several thousand years (Crandell and Mullineaux, 1976, p. 16–17). More than 90 percent of the known young tephra deposits from Mount St. Helens lie in quadrants east of the volcano, and only 1 of more than 10 relatively large tephra deposits lies to the west of that volcano (D. R. Mullineaux, oral commun., 1978). These data suggest that risk from tephra should be considerably less west of Mount Shasta than toward the east and that ash from about 90 percent of the future tephra eruptions may be expected to fall east of the mountain.

It is possible, of course, that an eruption of tephra could occur during a time of light and variable winds, or when winds are blowing toward the west or southwest. In this situation ash could be deposited on the communities that lie generally west, southwest, and south of Mount Shasta (fig. 14). In fact, tephra erupted about 1100 ^{14}C years ago at Little Glass Mountain, about 50 km east-northeast of Mount Shasta, was carried toward the west and deposited on the northeast flank of Mount Shasta. While such an event is probably infrequent, it does indicate the possibility that a future eruption at Mount Shasta could deposit ash on the populated areas west and southwest of the volcano. Depending on wind speeds and directions, an eruption from Mount Shasta with the volume of layer T of Mount St. Helens or of the Red Banks eruption could deposit more than 50 cm of ash on communities like Weed and Mount Shasta (fig. 16). A larger eruption, while very unlikely, could deposit considerably more ash at similar distances if the wind were blowing toward the west during the eruption.

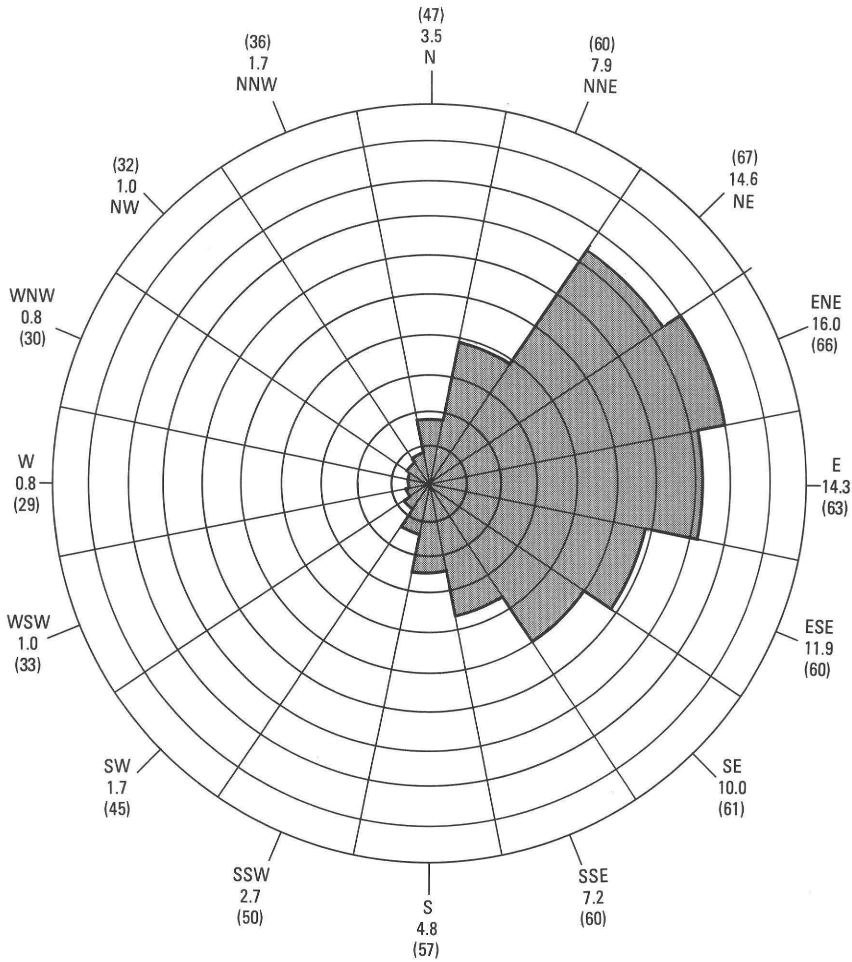


FIGURE 22.—Percentage of time annually that the winds at elevations between 3000 and 16000 m blow toward wedge-shaped sectors along principal compass directions over Medford in southern Oregon (indicated by stippled pattern). Average wind speeds in kilometers per hour (rounded off to the nearest whole number) for winds blowing in each direction are shown in parentheses. Directions and speeds are averaged from 21-year records at Medford, Oreg. (Winds Aloft Summary of the Air Weather Service, U.S. Air Force, available from the National Climatic Center, Asheville, N.C.)

FUTURE ERUPTIONS AND MITIGATION OF THEIR EFFECTS

Future eruptions of Mount Shasta are virtually certain to occur and can be neither prevented nor stopped. Diversion or control of lava flows, pyroclastic flows, mudflows, and other products of eruptions from volcanoes like Mount Shasta is generally not feasible. Instead, reduction of loss of life and damage to property requires that the products of eruptions be avoided when possible and that plans be made to reduce the effects when and where they cannot be avoided. Monitoring Mount Shasta to detect signs of an approaching eruption and developing contingency plans to deal with the next eruption should help reduce the loss of lives and loss or damage to property from future eruptions.

PLANNING FOR THE NEXT ERUPTION OF MOUNT SHASTA

In order to help mitigate the results of an eruption, certain actions must be taken before it occurs. Local, State, and Federal agencies should now develop contingency plans that include the following:

1. Procedures to be followed by the populace in potentially hazardous zones around Mount Shasta during eruptions.
2. Limit of access to and use of potentially hazardous areas if an eruption seems imminent and possibly evacuation of such areas.
3. Evaluation of the possible effects of tephra and other eruptive products on transportation routes, communication systems, water supplies, and other critical utilities.
4. Development of emergency communication systems that could be used to warn people in potentially hazardous areas to evacuate or to take other precautions.
5. Preparation of a pamphlet or other means of describing official plans and procedures for dealing with various aspects of a volcanic eruption. Such a pamphlet should be distributed to the populace around Mount Shasta if an eruption seems imminent and should include information on the kinds of events that might occur, their probable ranges in severity, the expected effects of those events, and what people should do if an eruption does occur. All people in the vicinity of Mount Shasta should be aware of official plans to cope with an eruption and what warnings, if any, can be expected.
6. Installation of an adequate geophysical monitoring system around Mount Shasta to determine the location and frequency of small earthquakes, ground tilt, and possibly other events that

might precede and accompany the movement of magma into the volcano.

7. Careful evaluation of plans for future land use and development around Mount Shasta considering the probable effects of future eruptions.

Once such plans are prepared, they should be modified as necessary when land-use patterns around Mount Shasta change and more information becomes available on the thermal and seismic state of the volcano. Plans like those described above may not be needed or utilized during the next few years or decades, but could conceivably be needed in the near future. For maximum effect, they must be made before an eruption occurs.

MONITORING

Most volcanoes like Mount Shasta provide various types of warnings before eruptions begin. Although an explosive eruption could occur at Mount Shasta without warning, it is more likely that some premonitory events will precede the next eruption. The success of a monitoring system depends on the detection and interpretation of such events in time to evacuate people from threatened areas and to initiate other measures to mitigate the effects of the eruption.

The most effective means of monitoring are instrumental and include a variety of geophysical and geochemical techniques. Seismometers are widely used to detect earthquakes associated with the rise of magma into a volcano. Such movement of magma may result in swelling of the volcano and may produce outward tilting of the flanks. Swelling can be measured using tiltmeters or other precision instruments that are capable of measuring minute changes in slope, distance, or elevation at the ground surface.

Other techniques involve measurement of changes in heat flow at a volcano. This can be done by repeated infrared measurements taken from the ground or air, or by direct measurements of hot-spring or fumarole temperatures and activity. Changes in the composition or relative abundances of fumarolic gases and in their temperatures may precede eruptions. These changes can be monitored by repeated examinations of gas samples or by continuously operating probes. Many other types of instrumental monitoring techniques may be useful in detecting warning signs of an impending eruption (Unesco, 1972).

In the absence of adequate monitoring systems, people living near volcanoes may notice premonitory events before an eruption. Both the frequency and magnitude of felt earthquakes commonly increase before eruptions begin. Eruptions may also be preceded by increased steaming or fumarolic activity and increased melting of snow and ice.

Although monitoring systems may be very useful in providing a warning that volcanic activity may be on the way, they unfortunately do not indicate the kind or scale of an expected eruption, the areas that might be affected, or even its certainty.

The first visible signs of an eruption, if it begins on a small scale, might include one or more of the following:

1. Clouds of white or gray "steam" and "smoke" rising above the volcano.
2. Glow in the night sky above the volcano.
3. Loud rumbling or thunderlike noises.
4. Darkening of snow on the volcano's flanks by fallen tephra.

EXPECTATIONS FOR FUTURE ERUPTIONS AND ERUPTIVE EVENTS

Mount Shasta has erupted on more than 13 separate occasions during the last 10000 years and at least 8 times during the last 4500 (pl. 1). Although data on plate 1 indicate that additional eruptions occurred, several of the events listed there may have been parts of a single eruptive episode. I have therefore grouped some of the dated eruptions into single eruptive periods. Thus, Mount Shasta has erupted, on the average, at least once per 800 years for the last 10000 years and once per 600 years during the last 4500 years. These eruptions did not occur at regular intervals, however, but were clustered in episodes separated by quiet intervals of variable lengths, some as long as about 2000 years (pl. 1). The duration of the present dormant interval cannot now be predicted.

Mount Shasta erupted last about 200 radiocarbon years ago (pl. 1). The eruption may have been observed from the Pacific Ocean by La Perouse in 1786 (Finch, 1930). So recent an eruption, along with the thermal and hot-spring activity that continues near the summit, suggests the possibility that magma still exists within or beneath Mount Shasta. However, the presence or location of magma has not yet been verified by geophysical or other evidence. The past record suggests that Mount Shasta will erupt again, conceivably in the near future, but as yet there is no known way to predict when the next eruption will occur.

Once an eruptive episode begins it could include many kinds of events, and various types and scales of activity could extend over many weeks or months. Future eruptive episodes will probably begin with small tephra eruptions, as have been described by Harris (1976) in his fictional account of an eruption of Mount

Shasta. Later events could include lava flows, pyroclastic flows, and mudflows. Eruptions may not follow a predictable sequence, however, and the kind and timing of events generally cannot be reliably predicted even after an eruption has begun.

WHAT TO DO IF AN ERUPTION BEGINS OR APPEARS IMMINENT

If signs of an impending eruption appear, its effects on people and property may be minimized if certain contingency plans are put into effect in time. It is suggested that the following actions be taken as soon as possible if an eruption begins or seems imminent.

1. Notify local, State, and Federal authorities including County Sheriff Offices, State Police, State Division of Emergency Services, and District Ranger, U.S. Forest Service.
2. Inform the populace by suitable means about potential hazards that could be associated with an eruption, as well as areas of possible danger, and about official plans to deal with an eruption.
3. Put into effect official contingency plans to limit access to and use of potentially hazardous areas as well as plans for possible evacuation of such areas.
4. Put into effect an emergency communication system that could be used to warn people in potentially hazardous areas of the likelihood of an eruption and to direct them.
5. Establish a volcano watch to observe the volcano from the ground and air on a regular basis and to monitor the volcano using various geophysical, and perhaps geochemical, techniques.

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