UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

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

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Open-File Report 78-827

1978

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Abstract

Mount Shasta has erupted, on the average, at least once per 800 years during the last 10 000 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 10 000 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 may endanger the communities of Weed, Mount Shasta, McCloud, and Dunsmuir located on or near the flanks of Mount Shasta. This report describes the likely nature of future eruptions and the threat that they present to people and property situated around Mount Shasta; accompanying maps delineate areas likely to be affected during future eruptions in the vicinity of Mount Shasta. Future eruptions will most likely consist of 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. Mount Shasta is not likely to erupt large volumes of 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.

[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 are not statistical.

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 (fig. 1). One of the largest and highest of the Cascade volcanoes, snowclad Mount Shasta is near the southern end of the range which 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 100 000 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. 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 of Mount Shasta, the Shastina and Hotlum Cones (fig. 1), were constructed during Holocene time, which includes approximately the last 10 000 years. Holocene eruptions also occurred at Black Butte, a group of overlapping dacite domes about 13 km west of Mount Shasta (Christiansen and Miller, 1976; Miller, in press). Eruptions at these two main vents and at flank vents are the most recent activity of Mount Shasta and form 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 where 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, laharic, and fluvial debris. These fans are composed primarily of the products of successive Holocene 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

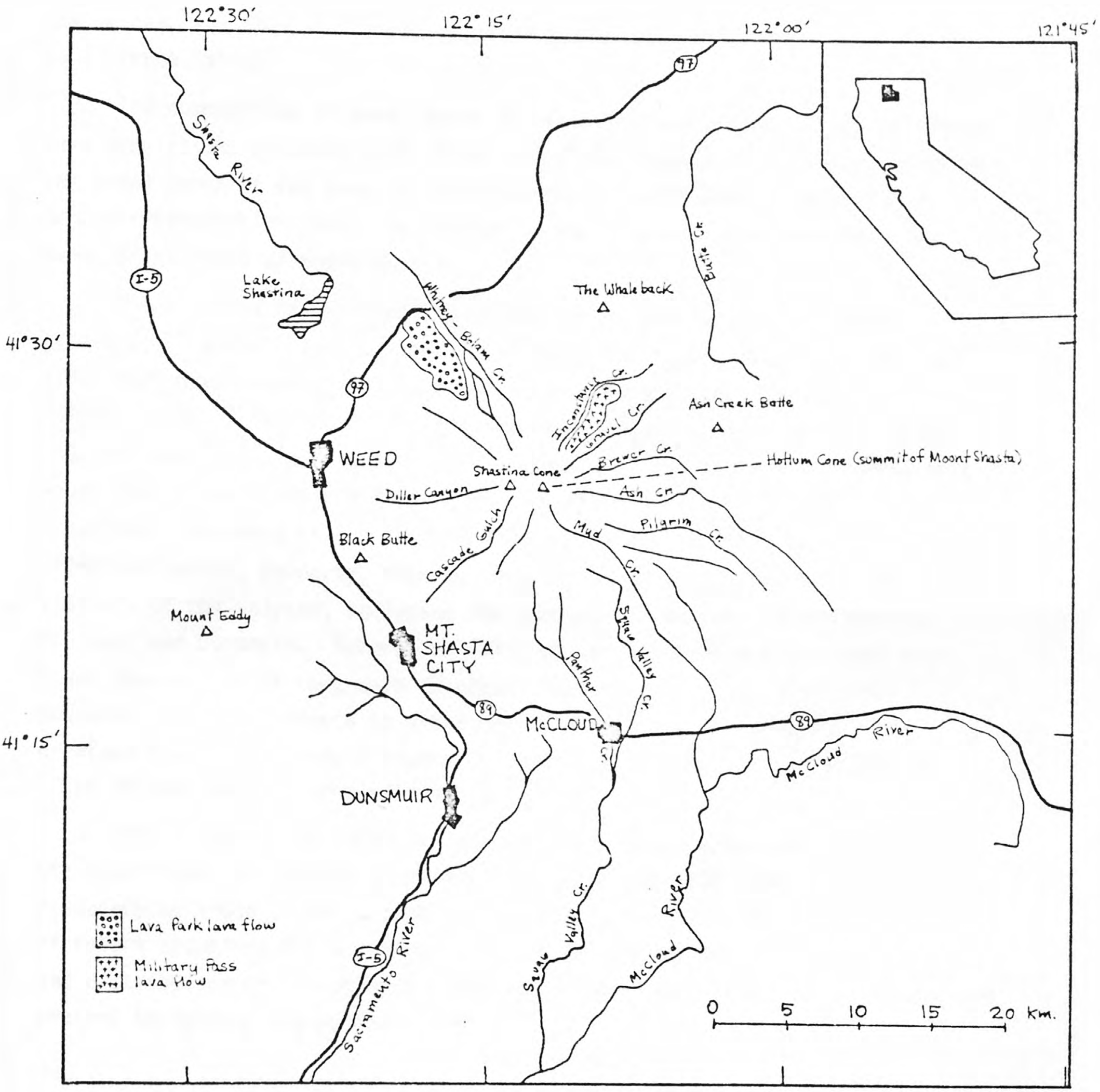

Figure 1.--Index map showing Mount Shasta and vicinity.

eruptions are concentrated and carried to distances of many tens of kilometers. At Mount Shasta, however, flowage deposits from 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 a narrow valley.

The communities of Weed, Mount Shasta City, 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 canyon of the Sacramento River about 23 km south of Mount Shasta.

Mount Shasta has erupted frequently during the last 10 000 years (table 1, in pocket) 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 indicates that Mount Shasta will continue to erupt intermittently in the future. Future eruptions like those of the last 10 000 years will 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 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 air-fall tephra, however, is mainly east and within about 50 km of the summit of 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 10 000 years and the present topography around Mount Shasta.

Acknowledgments

Many of the interpretations and conclusions of this study are the result 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 at a scale of 1:62 500. His work is being carried out simultaneously and in

cooperation with studies by 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, Mount Shasta City, for their enthusiastic support and help given during four summer field seasons.

Eruptions, Their Products and Associated Hazards

Stratovolcanoes like Mount Shasta erupt magma 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 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. The viscosity of lava is closely related to its composition. Generally, the greater the silica (S_1O_2) content of a magma, the more viscous it is. Relatively viscous, silica-rich dacitic and andesitic lavas generally move only short distances from their source vents as short, thick blocky flows, or pile up at the vent to produce domes. Relatively fluid, silica-poor basalt and basaltic-andesite lavas generally produce flows that move relatively slowly several kilometers downslope from vents. 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 also affects the viscosity of lava and is especially important in determining how explosive an eruption will be. If viscous lava like dacite has a high gas content, it will erupt violently, especially at the beginning of an eruption, because gas cannot readily escape. More fluid lavas like basalts and basaltic andesites tend to erupt less explosively because gases can more readily escape from them.

In the past, 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. Eruptions of basalt and basaltic andesite generally were less explosive and produced blocky lava flows as much as several kilometers long. Eruptions of lavas of intermediate composition at Mount Shasta produced either 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 such deposits, each of relatively small volume, were produced at Mount Shasta during its long history of more than 100 000 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, and tongue-shaped and probably moved more slowly than a person can walk, perhaps a few meters per hour. Most are less than 8 km in length. The distance traveled by a lava flow depends on such variables as viscosity of the lava, the volume erupted, steepness of 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 slowly and 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 path.

Most lava flows at Mount Shasta are primarily blocky flows of andesite or basaltic andesite that erupted from central vents or that issued from flank vents and flowed for several kilometers. Lava flows were erupted relatively frequently at main vents that produced the large composite cones of Shastina and the summit of Mount Shasta. Eruptions of lava from other vents on the flanks of Mount Shasta and Shastina were less frequent, but such flows are fairly common west and northwest of Mount Shasta.

Lava flows of basaltic andesite which 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, andesite and basaltic-andesite lava flows like the Lava Park flow (named by Williams, 1934; fig. 1, this report), northwest of Mount Shasta, erupted from vents located as far down the flank as 9 km from the present summit (fig. 1). Flows on the west flank of Mount Shasta, now partly buried by younger deposits, also erupted from vents about 9 km from the summit of Mount Shasta. The longest known lava flow at Mount Shasta, the 9-km-long Military Pass flow (fig. 1), flowed 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.

Eruption of lava flows at Mount Shasta in the future will probably follow other types of more explosive activity and occur 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 from hills, ridges, and other high obstacles in their paths. The degree to which they are diverted, however, depends on such factors as the viscosity of the lava mass as a whole and the slope angles involved; past lava flows at Mount Shasta have flowed up against cinder cones and domes in their paths and thickened rather than being diverted to the side. Examples of this are seen at a cinder cone, west of the upper part of the Lava Park flow, where the flow reached a height of almost 120 m on the flank of the cone (plate 1, in pocket). A similar situation is present southwest of Hotlum, where a lava stream flowed around two domes and covered the upslope side to a depth of about 120 m. Thus, future lava flows are not expected to climb 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 (fig. 1), are 110 and 146 m thick at their snouts. From this it is inferred that a maximum thickness of about 150 m would be reached only if a lava flow were ponded against a broad topographic barrier.

Pyroclastic flows

Pyroclastic flows, which can travel rapidly downslope, are masses of hot, dry rock fragments mixed with hot gases. They often 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. 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). Air also may be incorporated and heated by the moving mass (Perret, 1935; McTaggart, 1960; Crandell and Mullineaux, 1973). As used here, a block-and-ash flow is a type of pyroclastic flow that consists mostly of nonvesicular rock debris, ranging widely in size, mixed with hot air or other gases. A pumice flow is a pyroclastic flow that consists largely of pumice fragments, ranging widely in 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. The latter may deposit fine ash over a wide area adjacent to the basal part of a pyroclastic flow. Pyroclastic flows can travel downslope at speeds of 50-150 km/h, their velocity depending on 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. A pyroclastic flow traveled 13 km down the northeast side of Mount Shasta about 10 000 years ago and climbed 120 m up the flank of The Whaleback. The speed of pyroclastic flows tends to diminish with decreasing slope and distance traveled; 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 may climb as high as about 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 and (or) associated hurricane-force winds. Wood and other combustible materials are commonly burned by the contact with hot debris and gases. In addition to death or injury from burns or impact from the basal flow, 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 (Macdonald, 1972). Within a few minutes, about 30 000 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 which 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 10 000 years; they have flowed down most sides of the mountain and traveled as far as 20 km from their sources (table 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 somewhat protected by the barrier formed by Shastina. 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 vent. The distribution of pyroclastic-flow deposits derived from domes at Shastina (Miller, in press) indicates that, in the future, similar pyroclastic flows from high on the volcano could travel as far as 18 km (table 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 11 km south and 5 km north of the dome complex and covered an area of about 45 km^2 (Miller, in press).

Future eruptions are very likely at vents at or near the present summit, but it is also possible that eruptions could 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 Shasta could melt a large volume of snow and ice, especially if an eruption occurred during winter months when Mount Shasta 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 many kilometers beyond the base of Mount Shasta.

Domes

Volcanic domes are masses of solid rock that are formed when viscous lava erupts slowly from a vent, often after more explosive activity has occurred. 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. 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 burial or disruption of the preexisting ground surface by the dome itself or by rock debris produced by collapse of the dome. Because of their high temperatures, domes may start fires. Domes erupt very slowly; like lava flows, they can usually be avoided by people but 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 collapse of parts of a dome. These pyroclastic flows can move very rapidly and occur without warning, endangering life and property at great distances from their source.

Explosion or collapse of dacite domes at the summit of Shastina and at Black Butte about 9500 ^{14}C years ago produced block-and-ash flows that traveled as far as 18 km and 10 km, respectively, from the domes which produced them (Miller, in press; table 1). In the future, pyroclastic flows from domes erupted in the vicinity of Mount Shasta could affect broad areas downslope and as far as 18 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" is used in this report to describe 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 hundred meters or less into the air to cataclysmic explosions that throw debris to heights of several tens of kilometers above a volcanic vent. The duration of tephra eruptions varies from single blasts which last only a few seconds to continuous outrushes of gas and particles which may last for several minutes, hours, or even days. Explosive eruptions that produce tephra can also produce pyroclastic flows when part or all of an erupted column of rock debris and hot gas collapses and flows down the flanks of a volcano.

Eruptions of air-fall tephra are usually the result of escape of gas from a magma that has been under high pressure and is suddenly erupted at the earth's surface. Expansion of gas often results in fragments of pumice, which consist of volcanic glass having many small cavities or vesicles created by gas bubbles trapped in the molten material during cooling and solidification; other tephra fragments can be bits of solid rock or mineral crystals.

Tephra eruptions can occur suddenly and often are 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 larger volumes hours or days later as the vent becomes enlarged by erosion. Eruptions generally decrease in violence with time as high-pressure gas escapes from a magma chamber. Eruption of pyroclastic flows or lava flows often follows an eruption of tephra.

Large particles erupted above a volcano fall back rapidly on or near a 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 can form a progressively thinning blanket that reaches from the volcano downwind to distances of 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 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-sized abrasive particles and the acids and gases that accompany them can cause darkness during daylight hours, can impair breathing for humans and animals, and can coat equipment and vegetation. Where particles fall, water supplies commonly become temporarily acidic and turbid; long-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 eaten 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. 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 unexpected darkness during an eruption, may disrupt normal transportation, communication, and electrical services; it could 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 tephra are less likely at Mount Shasta than are eruptions of pyroclastic flows, lava flows, and domes. Only two major eruptions of tephra have occurred during the last 10 000 years (table 1). These have been significantly smaller in volume than tephra which has been 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, in press). 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 9000 and 10 000 ^{14}C years ago (table 1) and produced a blanket of tephra that covers an area of more than 350 km^2 east of Mount Shasta (fig. 2). The eruption produced a tephra sheet with a minimum volume of about 0.1 km^3. An additional unknown volume of tephra surely lies downwind beyond the limits shown in figure 2.

Pumice from the Red Banks eruption forms a broad elliptical blanket east of Mount Shasta (fig. 2). The distribution of 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 narrow lobe (Crandell and Mullineaux, 1976, p. 12; fig. 3). Thus the distribution of Red Banks tephra is representative of the 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) and 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. 4). Also shown in figure 4 is the variation in thickness with distance of tephra from the Red Banks eruption and from eruptions of Mount St. Helens that are significantly 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. Helens in 1842 has a volume of about 0.01 km^3 (Crandell and Mullineaux, 1976). Figure 4 shows diagrammatically how deposits from these four eruptions decrease in thickness downwind from Mount St. Helens 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

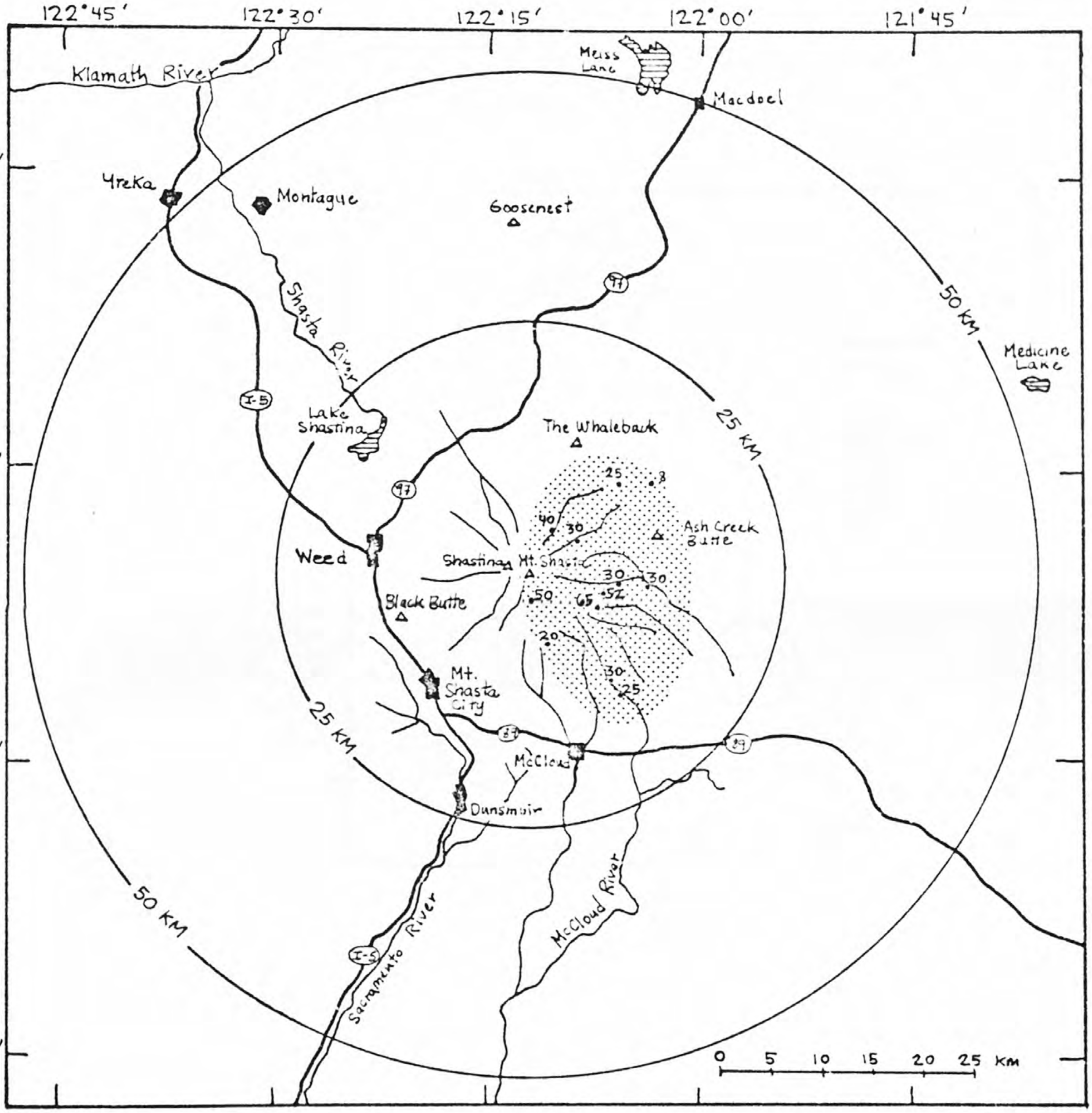

Figure 2.--Mount Shasta volcano and vicinity. Known distribution of the Red Banks air-fall pumice shown by stipple pattern; thickness of pumice deposit shown in centimeters. Circles with radii of 25 and 50 km can be used with figure 4 to estimate thicknesses of compacted tephra likely to accumulate at various distances downwind from future eruptions of three different volumes.

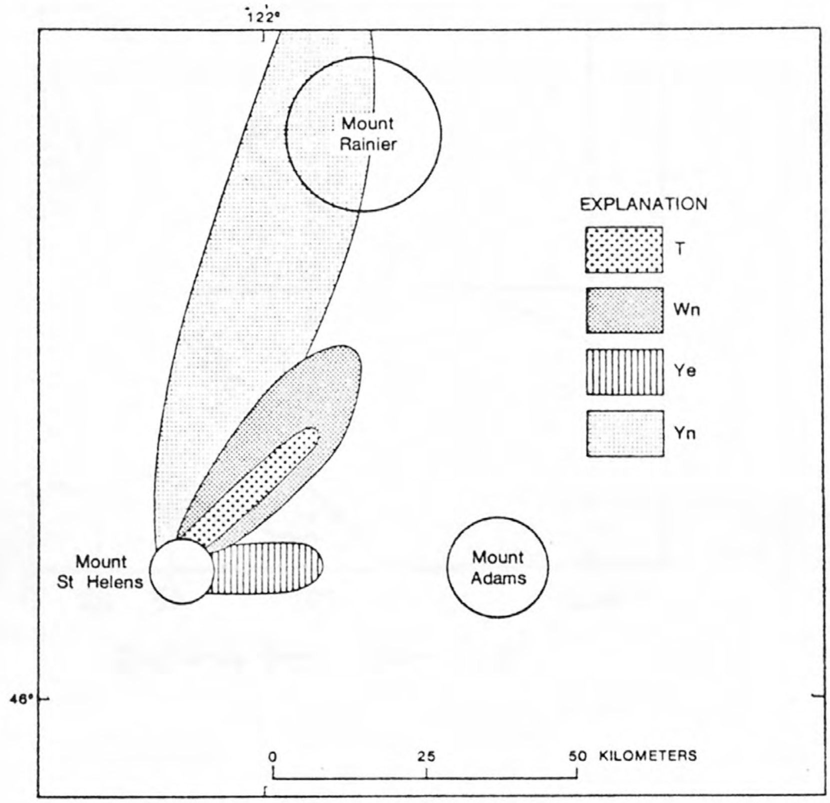

Figure 3.--Orientation and width of four tephra lobes (T; Wn; Ye; and Yn) from Mount St. Helens, Wash. Each lobe consists of air-fall tephra 20 cm or more thick from a single eruption (from Crandell and others, in press).

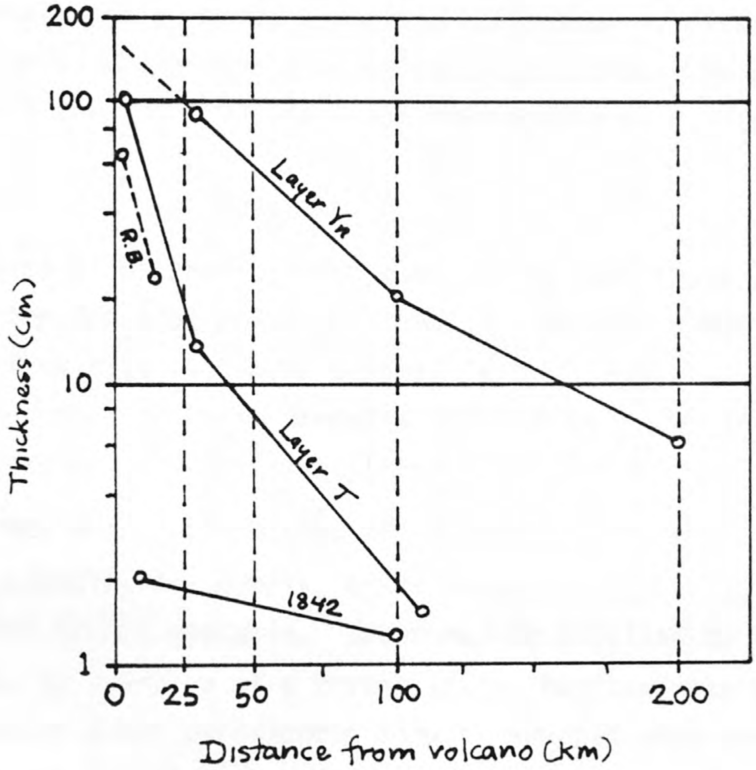

Figure 4.--Relation between distance downwind from volcano and the estimated average present thickness of tephra along the thickest parts of lobes. The tephra layers may have been as much as twice as thick when they were first deposited. The solid lines represent three tephra deposits of different volumes from Mount St. Helens: layer Yn, layer T, and an unnamed layer formed in 1842. These are estimated to have volumes of approximately 1-3, 0.1, and 0.01 km^3 respectively (after Crandell and Mullineaux, 1976). The dashed line represents the Red Banks tephra layer from Mount Shasta, which has a volume of approximately 0.1 km^3.

St. Helens, but such past eruptions serve as good examples of likely distribution 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. Eruptions as large as the Yn from Mount St. Helens have apparently never occurred at Mount Shasta during its long history of more than 100 000 years and 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 of a wide variety of sizes from clay to blocks several tens of meters in maximum dimension. When moving, they resemble masses of wet concrete and generally flow downslope in any channels or stream valleys that are present.

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 also be formed directly if lava or a hot pyroclastic flow is erupted onto snow or ice. Mudflows 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 process is extensive enough, the rock in large areas on a volcano can become weakened as water and clay content increase. 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 move at high speeds--as much as 85 km/h--depending on slope and fluidity. 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 outside 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 like bridges.

Mudflows have occurred frequently during the last 10 000 years at Mount Shasta (table 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. 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 leave the channels and spread out to cover much broader areas on fans at the base of the mountain.

Small mudflows, not caused directly by eruptions, are common at Mount Shasta. They occur because past volcanic activity has produced 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. 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 relatively small mudflows that swept down most canyons which head at glaciers. Mudflows traveled more than 20 km down Ash Creek, Mud Creek, and Bolam-Whitney Creek valleys. 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.

Floods

Floods commonly are produced by melting of snow and ice during eruptions of ice-clad volcanoes like Mount Shasta. By incorporating river water as they move down valleys, mudflows caused by eruption may grade into muddy floods carrying unusually large amounts of rock debris. Such floods can leave thick deposits of sand and gravel on fan surfaces and valley floors wherever 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 Shasta River Valley (fig. 2) 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.

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 associated with 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, but such changes are no 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), and has continued at a relatively high level of activity through the spring of 1978. However, no other phenomena which usually precede eruptions have yet occurred.

Volcanic gases 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 the rock.

Distribution of fumarolic gases is mostly controlled by the wind; emitted gases are concentrated near a vent, but become diluted rapidly downwind. Such gases, even if they are 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 and carbon monoxide, can suffocate people or animals who 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.

Fumarolic activity on Mount Shasta is restricted to two main 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. The zones of risk are arbitrary to a great extent 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 position of some boundaries may indicate a relatively sharp decrease in risk, like that denoting the upper limit of lava-flow risk on a hill, but most boundaries are diagrammatic, to 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 1 (in pocket), are based on the vent locations of past lava flows, areal extents of those lava flows, and their behavior[1].

Many more lava flows have erupted from central summit vents like the Shastina and Hotlum vents, building composite cones at those locations, than from individual flank vents (see p. 6). Thus it is likely that most future eruptions of lava will occur at main vents rather than on the flanks of the volcano. Past evidence suggests that some future lava flows could, however, occur at flank vents as far as 9 km downslope from the present summit, and individual flows may travel as far as 9 km downslope from their sources (see p. 6). On the basis of these assumptions, the outer limit of potential hazard from lava flows is placed at a distance of 18 km from the summit of Mount Shasta[2] (plate 1), except for 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 zone is based on the assumption that future lava flows will be of andesite or basaltic andesite, like those erupted in Holocene time. If future flows are more fluid 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 ring-shaped 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 near the outer edge of zone C. Zone A extends from the summit outward 6 km in all directions and includes the main vents and associated cones which were active during Holocene time. Zone A is the one in which most future lava

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[1] Lava flows older than about 10 000 years were not considered in Determining the location and extent of lava-flow hazard zones.

[2] 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 25 000 years and was not considered in determining the extent of lava-flow hazard zones.

flows are likely to erupt and therefore constitutes the zone of greatest potential hazard from lava flows (table 2). 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 main vents have flowed and in which flank vents have also erupted lava flows during Holocene time; thus it will likely 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 erupted from vents in zone C during Holocene time; however, this zone has been affected by flows that 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 future, but vents closer to Mount Shasta may erupt lavas that could flow into this zone, and thus there exists some degree of hazard to property and manmade structures within zone C.

During future eruptions, only a very small part of the lava-flow hazard zones will be affected by a single lava flow. Any one eruption is likely to produce a single flow or flows that would cover no more than about 10 km^2. (The Lava Park flow on the northwest side of Mount Shasta (fig. 1), 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 fairly accurately and only the areas downslope will be directly affected.

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

The communities of Mount Shasta, Weed, Mount Shasta City, and McCloud are located at least partly within the area of potential hazard from lava flows (plate 1).

Pyroclastic-flow and mudflow hazard zones

The boundaries of pyroclastic-flow and mudflow hazard zones shown on the map are based primarily on the frequency and extent of pyroclastic flows and mudflows that have affected those areas during the last 10 000 years (plate 2, in pocket).

Areas within zone 1, which is centered on the volcano, have frequently been affected by pyroclastic flows and mudflows during the last 10 000 years (tables 1, 2). Future eruptions like those of the past will affect this zone more frequently than any other area around Mount Shasta. In general, the

Table 2.--*Approximate percent of hazard zones around Mount Shasta that have been affected at least once by eruptions during the last 10 000 years, and the estimated average frequency of certain future hazardous events in each zone*

[Values are approximate and are based on the known distribution of deposits and on the frequency of the events listed in table 1. 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" did not occur at regular intervals, however, but were clustered in episodes that were separated by quiet intervals of variable length. Refer to plates 1 and 2 for locations and limits of hazard zones. "Large" mudflows as defined here cover areas greater that about 10 km^2. "Small" mudflows are those which cover less than about 10 km^2. Symbol / means "per," and symbol < means "less than."]

HAZARD ZONES	APPROXIMATE PERCENT OF AREA OF ZONE AFFECTED AT LEAST ONCE DURING THE LAST 10 000 YEARS	ESTIMATED AVERAGE FREQUENCY OF FUTURE HAZARDOUS EVENTS IN ZONE (IN YEARS)		
Lava flow:			Lava flows	
Zone A	50		1/3000-4000	
Zone B	25		1/5000	
Zone C	< 5		1/10 000	
Pyroclastic flow and mudflow			Mudflows	
		Pyroclastic flows	"Large"	"Small"
Zone 1	100	1/800	1/600	1/10
Zone 2	60	1/1500	1/600	1/10
Zone 3	25	1/10 000	1/2000	1/25(?)
Zone 4				
Northwest part	<10	None expected	1/5000	None expected
South part	40-60(?)	None expected	1/5000	None expected
Zone 5	70	1/5000	None expected	(?)

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. Because 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. 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 2). The outer boundary is based on the maximum distance at which pyroclastic flow deposits have been found. The basic ring shape of hazard zone 2 is strongly modified by topography. The modifications exclude areas within 20 km of the summit, which are thought to be topographically too high to be affected by pyroclastic flows or mudflows as they descend the flanks of Mount Shasta; however, these areas 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 up on hills within hazard zones 1 and 2. This is based on the height to which pyroclastic flows climbed on the side of the southeast flank of The Whaleback (p. 8).

Future mudflows at Mount Shasta are almost certain to remain within the limits shown for hazard zones 1 and 2 on plate 2, but because of their lower speed they are not likely to climb as high as pyroclastic flows on topographic obstructions or valley sides. Mudflows are likely to cover wide areas of zone 2, especially where there are broad, smooth fans such as on the northwest and southeast flanks of Mount Shasta. Elsewhere in this zone, mudflows may be confined or directed by valley walls or other topographic barriers. In general, risks from mudflows decrease with increasing distance from the summit and with increasing height above a fan surface or valley bottom.

Zone 3 includes areas between 20 and 30 km from Mount Shasta that have been affected only by mudflows during the last 10 000 years, but could be affected by very large and infrequent pyroclastic flows from Mount Shasta (table 2). A 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 erupted in the Mount Shasta area during the last 10 000 years. Figure 5 shows 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 (H) to horizontal distance (D) between 1:4.8 and 1:6.2 (table 3; fig. 5). A pyroclastic flow which originated by explosion or collapse of dacite domes at Black Butte traveled a distance that is 10 times the vertical drop (fig. 5). 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. 5), which also 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. 5). This "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.

There are no known examples of pyroclastic flows having reached distances of more than 20 km from Mount Shasta. Even if a pyroclastic flow did reach that far, it should be moving relatively slowly and have a reduced capability of climbing much above the surface on which it is moving. The limit of risk from mudflows and pyroclastic flows beyond 20 km is arbitrarily drawn close to the base of most hills or obstructions.

Mudflows are likely to cover broad areas in zone 3 as often as several times per century (table 2). The risk from mudflows is greatest on smooth fans and topographic lows near major valleys like 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 may be affected by ash clouds.

Hazard zone 4 consists of areas that have been affected only by mudflows during the last 10 000 years and that are beyond the limit of the largest predictable pyroclastic flows. The zone reaches from 30 km to as far as 70 km

Table 3.--*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, H (m)	Distance of travel, D (km)	H/D
Summit of Hotlum Cone----	4300	1600	2700	[1]13	1:4.8
Summit of Hotlum Cone----	4300	1200	3100	[1]15	1:4.8
Summit of Hotlum Cone---	4300	1000	3300	[1]18	1:5.5
Summit of Hotlum Cone----	4300	900	3400	[1]21	1:6.2
Summit of Shastina-------	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.

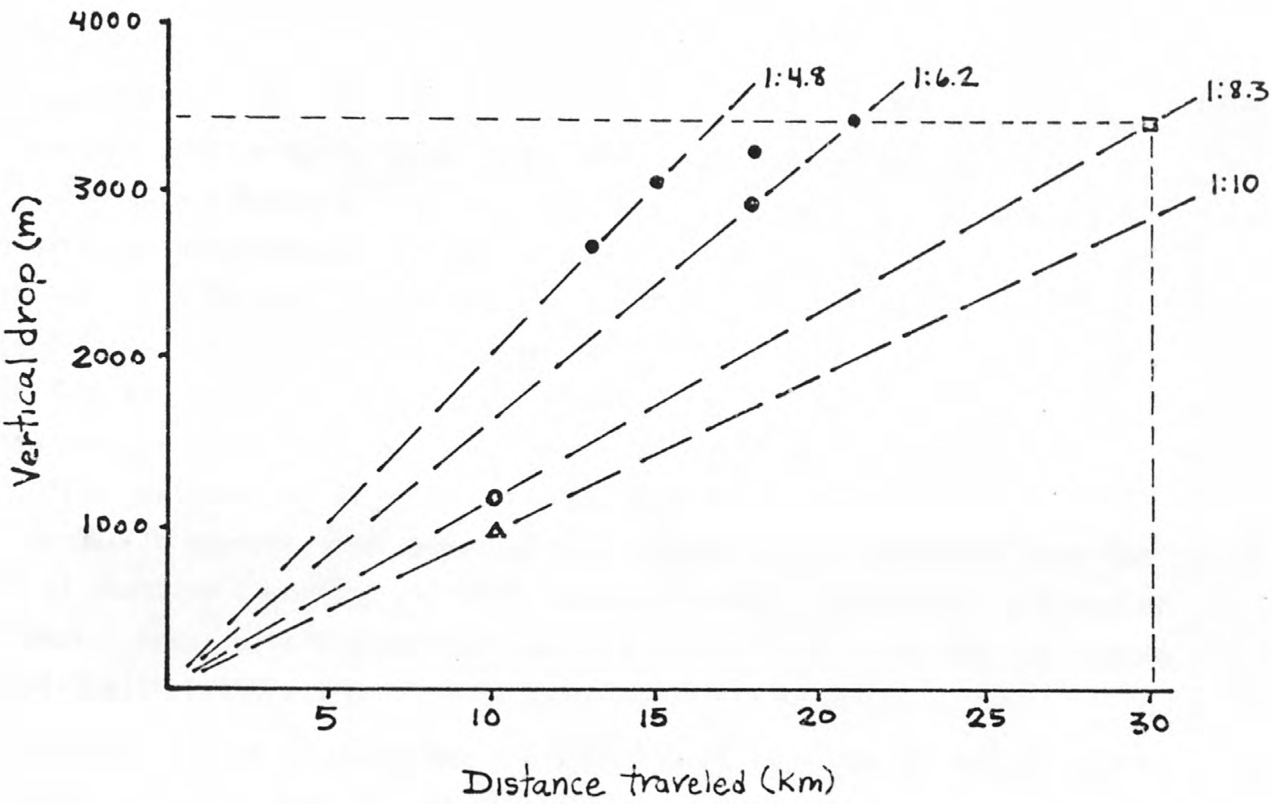

Figure 5.--Relationship between the vertical height dropped and the horizontal distance of travel for pyroclastic flows from vents at or near Mount Shasta and for hypothetical, very large pyroclastic flows from Mount Shasta. ●, Holocene pyroclastic flows from vents at or near Mount Shasta. △, Pyroclastic flows originating at the top of Black Butte; ○, pyroclastic flows originating at an inferred former top of Black Butte; □, height/distance relationship for hypothetical very large pyroclastic flows from summit of Shasta, showing "maximum" distance of travel.

south from Mount Shasta; it includes part of the broad Shasta Valley northwest of Mount Shasta and narrow river canyons like 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 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 with increasing height above valley floors.

Hazard zone 5 is a zone west of and including the summit of Shastina. This zone has been affected by mudflows and pyroclastic flows only from Shastina and Black Butte during the last 10 000 years. Zone 5 is not likely to be affected by pyroclastic flows or mudflows originating at vents near the summit or on the flanks of Mount Shasta, because the area within zone 5 is shielded from such flowage deposits by the cone of Shastina. Zone 5 can be affected by eruptions of Shastina or in part by eruptions from Black Butte or any new vent west of Shastina. Pyroclastic flows and associated ash clouds and mudflows originating at such vents may locally flow from zone 5 into zones 1, 2, or 3. In general, the degree of risk within zone 5 decreases from the summit of Shastina downslope and with increasing height above fan surfaces or streambeds. Areas within zone 5 may be affected by high winds and ash clouds associated with pyroclastic flows originating within zones 1, 2, or 3.

Mudflows caused by eruptions are less likely to occur in zone 5 than in other zones, 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 and hazard zone 5 can be affected by clouds of hot ash and high winds associated with pyroclastic flows. The width of the area that could be affected by such phenomena may extend as much as several kilometers beyond the margin of a pyroclastic flow. Ash clouds and associated high winds 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.

Risk from tephra

Eruptions of tephra from Mount Shasta have been rare and of small volume in the past. Only one widespread tephra layer, from the Red Banks eruption (table 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 also on the volume and distribution of tephra layers erupted at Mount St. Helens in Washington.

Figure 2 shows circular tephra-hazard zones with radii of 25 and 50 km around Mount Shasta. On the basis of eruptions at Mount St. Helens, the expected maximum thicknesses of compacted tephra from future eruptions at various distances from Mount Shasta, are shown in figure 4. The degree of risk from ash fall decreases with decreasing thickness of the deposit; thus the risk from tephra decreases as the distance from the summit of Mount Shasta increases.

Ash fall from a single eruption is 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 Medford, Oreg., about 110 km north-northwest of Mount Shasta, indicates that high-altitude winds in this region annually blow much more frequently and at higher speeds toward the east-northeast and east than toward the west (fig. 6). Figure 6 shows that winds at altitudes between 3000 and 16 000 m blow into a sector between north-northeast and south-southeast about 82 percent of the time, while winds blow toward the west into a sector between northwest and southwest only about 5 percent of the time.

Prevailing westerly winds above Medford, Oreg., are similar in speeds and directions to westerly winds at similar altitudes near Mount St. Helens in Washington (Crandell and Mullineaux, 1976, p. 16-17). More than 90 percent of the known tephra deposits from Mount St. Helens lie east of the volcano, and only 1 of more than 10 relatively large tephra deposits lies west of that volcano (D. R. Mullineaux, oral commun., 1978). These data suggest that risk from tephra is considerably less west of Mount Shasta than toward the east and that ash from about 90 percent of the future tephra eruptions will fall east of the mountain.

It is possible, however, 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. As a result ash could be deposited on the communities that lie generally west, southwest, and south of Mount Shasta (fig. 2). In fact, an eruption of rhyolitic tephra at Little Glass Mountain, about 50 km east-northeast of Mount Shasta, occurred about 1100 ^{14}C years ago, while prevailing winds were blowing toward the west, and deposited tephra on the northeast flank of Mount Shasta. While such an event is probably infrequent, it does

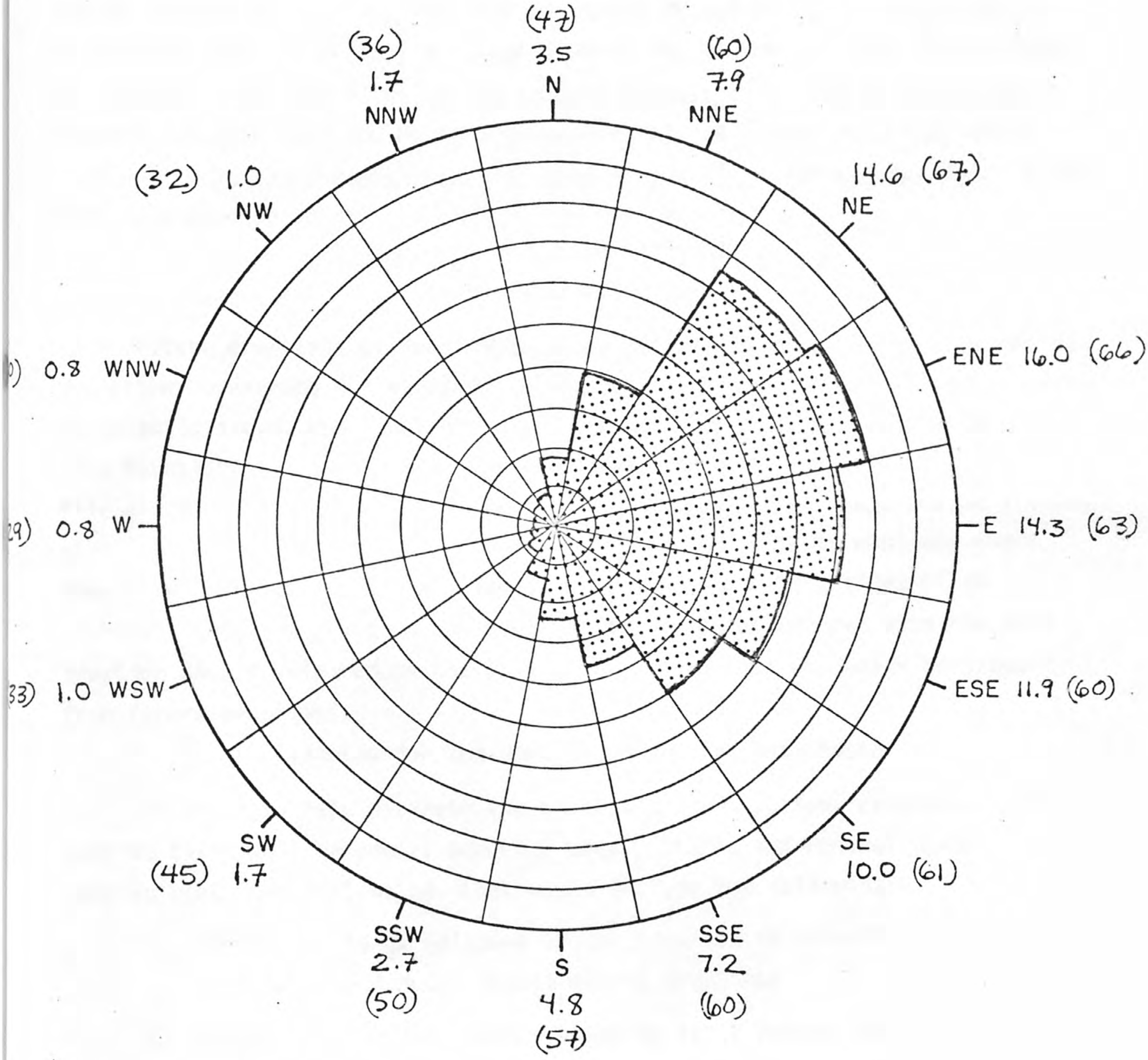

Figure 6.--Percentage of time annually that the winds at elevations between 3000 and 16 000 m blow toward pie-shaped sectors along principal compass directions over Medford in southern Oregon (indicated by stippled pattern). Average wind speeds in kilometers per hour (rounded off to the nearest whole 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.)

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 with the volume of layer T from Mount St. Helens or the Red Banks eruption could deposit more than 50 cm of ash on communities like Weed and Mount Shasta (fig. 5). 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.

Future Eruptions and Mitigation of Their Effects

Future eruptions of Mount Shasta are certain to occur eventually 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 where 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 well before it occurs. Local, State, and Federal agencies could develop contingency plans now that would include the following:

1. Procedures to be followed by the populace in potentially hazardous zones around Mount Shasta during eruptions.
2. Preparation of contingency plans to limit access to and use of potentially hazardous areas and possibly to evacuate such areas.
3. Evaluation of the possible effects of tephra and other eruptive products on local transportation routes, communication systems, water supplies, and other necessary 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 volcanic

eruptions. Such a pamphlet could be distributed to the populace around Mount Shasta if an eruption seems imminent and could include information on the kinds of events that might occur, their probable range 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 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 could be modified as necessary as 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 it is possible that 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 detection and interpretation of such events in time to evacuate people from threatened areas and to initiate other measures to mitigate the effects of an eruption.

The most effective monitoring techniques are instrumental and include a variety of geophysical and geochemical methods. Seismometers are widely used to detect earthquakes associated with the rise of magma into a volcano. Such movement of hot magma generally results in swelling of the volcano and produces tilting on the flanks. Swelling can be measured with tiltmeters or other precision instruments that are capable of measuring minute changes in slope or distance at the ground surface.

Other techniques involve measurement of changes in heatflow 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. Changes in the composition or relative abundances of fumarolic gases and their temperatures often precede eruptions. These changes can be monitored by repeated exminations of gas samples. Many other types of instrumental monitoring techniques may be useful in detecting warning signs of an impending eruption (Frank and others, 1977).

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

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

The first visible signs of an eruption, if it began on a small scale, might include one or more of the following (Crandell and Mullineaux, 1976; Crandell, written commun., 1978):

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

Predicting future eruptions and eruptive events

Mount Shasta has erupted on at least 13 separate occasions during the last 10 000 years and at least 8 times during the last 4500 years (table 1). Although data in table 1 indicate that additional eruptions occurred, several of the events listed there may have been part 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 10 000 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 that were separated by quiet intervals of variable length, but lasting as long as about 2000 years (table 1). The duration of the present dormant interval cannot be predicted at this time.

Mount Shasta erupted last about 200 radiocarbon years ago (table 1). The eruption may have been observed from the Pacific Ocean by La Perouse in 1786 (Finch, 1930). Such recent eruptions, along with the thermal and hot spring activity that has continued near the summit, suggest the possibility that molten 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 could conceivably erupt 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 may include many kinds of events, and various types and scales of activity may extend over many weeks or months. Future eruptive episodes will probably begin with small tephra eruptions, as has been described by Harris (1976) in his fictional account of an eruption of Mount Shasta. Later events may 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 might 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 and plans for possible evacuation of such areas.

4. Put into effect an emergency communication system which could be used to warn people in potentially hazardous areas of the likelihood of an eruption and what to do.

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 geochemical techniques.

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