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Potential geologic hazards in  
Lassen Volcanic National Park, California

By

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Administrative Report  
for National Park Service

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**LASSEN VOLCANIC NATIONAL PARK**  
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INTRODUCTION

An investigation of the potential geologic hazards in Lassen Volcanic National Park, California, was started by the writers in August 1968, and completed in September 1969. In this study, we attempted to assess the geologic hazards in the areas of greatest use rather than in the entire park. Our first objective was to appraise the potential hazards in the Manzanita Lake area, where there is the greatest concentration of visitor and park-operation facilities, and where facilities may be expanded in the future. Later, we assessed the potential hazards along the Lassen Park Road, near Cinder Cone, and at two of the park's hydrothermal areas, Bumpass Hell and Devils Kitchen. During August 1969, the Geological Survey monitored seismic activity in the park for a period of about 2 weeks; only microearthquakes were noted and most of these occurred in areas other than the zone in which explosive volcanism has been concentrated within recent geologic time. The results of the seismic work, prepared by John Unger and John Coakley who interpreted the seismograph records, are described in Appendix B.

The report is divided into four main sections; in addition there are six appendices. The first section is a brief summary of the principal conclusions of our study, which are more fully developed in the subsequent three sections. The appendices include definitions of specialized geologic terms used in the report as well as other detailed information.

This report contains information that adds to, and in places differs from, findings and conclusions in our 1969 Administrative Report to the National Park Service entitled "Preliminary appraisal of potential geologic hazards near Manzanita Lake, Lassen Volcanic National Park,

California." This report therefore supersedes the earlier one. Where findings or conclusions differ significantly from those in the 1969 report, they are specifically noted.

Reference is made in this report to data and conclusions reached by other scientists and published in several articles. The articles and their authors are listed at the end of the report.

#### Brief summary

The principal geologic events of the last 12,000<sup>✓</sup> years were studied because we believe that the best clue to the effects of future catastrophic events is knowledge of the effects of such phenomena over a significant period of the past, especially the kind, scale, and frequency of volcanic activity during this period. The last 12,000 years approximately encompasses the time that has elapsed since the last major glaciation of the park.

Geologic events that may present major hazards in the future are chiefly explosive volcanic activity and landslides. Volcanism that could be of a hazardous nature includes the rise of new lava domes, renewal of activity at old domes such as Lassen Peak, eruptions of lava flows or volcanic ash, eruptions of hot avalanches of gas and pumice (nuées ardentes), lateral blasts, and volcanic mudflows. Floods also could be expected to accompany volcanic activity. Dangers from future landslides include those from small rockfalls at Diamond Peak and, more importantly, vastly larger rockfalls such as those that formed the Chaos Jumbles. Our description of the sequence of past geologic events in this report is basically the same as that presented in the 1969 report. However, we have now concluded that nuées ardentes have been erupted<sup>✓</sup> during only one relatively short episode since Lassen Peak was formed, rather than during several episodes as we previously thought. We also have concluded that only one<sup>✓</sup> episode of rockfalls and avalanches produced the Chaos Jumbles, and that the avalanches were not widely spaced in time.

The third main part of the report describes the kinds and relative severity of hazards posed by the variety of potentially dangerous

geologic events. We believe that the direct hazard presented by the eruption of lava flows and domes is minor; however, hot lava flowing onto snow could start destructive secondary mudflows and floods like or even larger than those of the 1915 eruptions. Rock fragments thrown into the air by violent eruptions, as well as accompanying gases, could cause injuries, fatalities, or fires close to the volcano and for some distance downwind. Beyond a few miles, however, their effects are more likely to be troublesome than dangerous. Hot and cold rock avalanches and mudflows are especially dangerous for several reasons: (1) they can be large enough to bury or submerge valley floors and to destroy everything in their paths, (2) some are hot enough to inflict fatal burns on persons, (3) they can travel at speeds as high as a hundred miles per hour, and (4) some can occur without warning. An important conclusion is that the greatest hazards are presented by avalanches and mudflows that could move down the floors of valleys heading on the various volcanoes, and that these valley floors should be avoided as much as possible.

These hazards are rated in a relative sense only. We believe that certain kinds of geologic events are more dangerous than others and that some localities will be affected more frequently, and by more dangerous hazards, than other localities. We have not estimated the probability or frequency of hazardous geologic events in the future because there have been too few of these in the recent geologic past to form a basis for such predictions. For example, within the last 12,000 years, there may have been only a single episode of major rockfall avalanches, and only four episodes of highly explosive volcanic activity (including the Lassen Peak eruptions of 1914-17). Thus, the overall low frequency of the most hazardous geologic events in the past suggests that these events will also be infrequent in the future. However, we believe that the hazards are significant enough that they should be reduced by placing park facilities in areas of relatively low risk.

Conclusions and recommendations constitute the fourth main part of this report. In brief, we have rated (in terms of relative degree of

risk from potential geologic hazards) several sites of present and possible future facilities, and have recommended that some facilities be relocated. In our 1969 report we recommended that certain facilities now present on the Chaos Jumbles be relocated. Although we now believe that the risk there probably is less than we first thought, we still believe that the risk is relatively high and that the Chaos Jumbles is the least suitable place in the Manzanita Lake area for visitor facilities or park residences. In the 1969 report we also recommended that no additional development be undertaken in the Manzanita Lake area until a more detailed study was made, because of the apparent history of that area having been repeatedly covered by hot volcanic avalanches. We now believe that the hot avalanches of the last 12,000 years occurred during only one episode rather than many, and that there will be sufficient warning to prevent loss of life before any similar episode in the future. The principal hazard from this type of eruption, therefore, is one directed toward park facilities rather than lives, and the probable future frequency is low. We now suggest that the hazard from this type of eruption need not necessarily prohibit continued use of the Manzanita Lake area, provided a system to detect warning signs of eruption is maintained. If expansion of facilities is considered, care should be used to select the least hazardous sites available.

We also recommend that the volcanoes be monitored, both instrumentally and visually, to permit early recognition of warning signs of an impending eruption, and we suggest procedures to be followed if certain warning phenomena occur. Instrumental monitoring for earthquakes, other than very small ones, is now being conducted by scientists at the University of California by means of a seismograph station at Mineral. Visual observations, especially during the visitor season, could be made a regular and purposeful activity rather than an incidental one for park personnel whose duty stations provide views of the several volcanoes in the park.

We further recommend that large, separated rock masses on Diamond Peak that threaten sections of the Lassen Park Road be anchored or removed, and that dangerous zones and walkways in hydrothermal areas,

particularly in Bumpass Hell, be more clearly marked, and in places provided with wooden walks.

#### GEOLOGIC EVENTS OF THE LAST 12,000 YEARS

This study encompasses events of only the last 12,000 years because earlier geologic events are less well known. Events of this time interval are subdivided according to age into four groups in the following discussion: (1) older nuées ardentes and rise of the Lassen Peak dome and one or more domes east of Sunflower Flat, (2) younger nuées ardentes and formation of the Chaos Crags domes, (3) pyroclastic eruptions and lava flows from Cinder Cone, and (4) historic eruptions at Lassen Peak.

#### Volcanic eruptions

##### Older nuées ardentes and formation of volcanic domes

A group of at least eight volcanic domes lies east of Sunflower Flat between the Chaos Crags and Lost Creek Camp. Although the southern five domes seem to be quite old and probably date from a period before the last major glaciation of the park, the northern three, which lie directly east of Sunflower Flat, seem to be relatively young. Older than at least one of these young domes, and possibly older than all three, are loose gravelly deposits that form the broad, nearly flat area at Lost Creek Camp. These gravelly deposits were formed by nuées ardentes, which were erupted from one or more vents in the area east of Sunflower Flat and moved northward beyond the north boundary of the park. The weathering characteristics of the nuée ardente deposits indicate that they are no older than the last major glaciation; we believe that they were probably formed during a late phase of that glaciation but before Lassen Peak appeared. The vent (or vents) from which the nuées were erupted was subsequently covered by one or more of the young domes east of Sunflower Flat.

A nuée ardente deposit that was erupted from a different source can be seen along the Lassen Park Road at the Upper Meadow along Kings Creek (fig. 1, in pocket). The deposit overlies a glacial moraine that was formed as the former Kings Creek glacier melted back toward the

head of the valley, and is interbedded with the sand deposits of a temporary glacial lake. The lack of a soil on the moraine suggests that only a short time elapsed between the disappearance of the glacier and the eruption of the nuée ardente. In fact, the presence of the nuée ardente deposit on the tops and flanks of hills at the south side of the meadow, but not elsewhere, suggests that the area was still partly buried by glacier ice at the time of the eruption. We believe that much of the nuée ardente came to rest on snow and ice but that the resulting deposit was partly removed when the snow and ice melted.

The source vent of the nuée ardente has not been identified. However, the only known late glacial or early postglacial volcanic vent in the upper Kings Creek valley is at Lassen Peak. We surmise, therefore, that the nuée ardente was erupted from a vent at the site of the Lassen Peak dome.

The Lassen Peak dome probably formed soon after the nuée ardente was erupted, perhaps a little more than 11,000 years ago. The dome rose as a large mass of stiff, pasty lava was extruded from a vent, and it may have reached its full height within a year or two. We have found no evidence that the dome's formation produced large landslides. However, a thick deposit of dozens of mudflows is exposed in the sides of deep gullies in the Devastated Area northeast of Lassen Peak. The mudflows may have been formed during or shortly after the eruption of the dome.

Small glaciers that developed after the dome lava had cooled formed moraines at altitudes of 8,000-9,000 feet on Lassen's south and west sides, at altitudes of 8,100-8,200 feet on the southeast side at the head of the West Fork of Hat Creek, and at lower altitudes on the north side. The weathering characteristics of these moraines are similar to those elsewhere on deposits of the last major glaciation; thus, the moraines seem to date from a late phase of that glaciation. In western Washington a similar late phase of glacier growth occurred between about 11,000 and 10,000 years ago.

Our 1969 report describes pyroclastic deposits north of Lassen Peak that were thought to have been erupted from a vent at the site of Lassen.

We now believe that these pyroclastic deposits are older than 20,000 years. Their source vent has not been identified, but it probably was somewhere north of Lassen Peak, perhaps a short distance southeast of Sunflower Flat.

Williams described Crescent Crater (fig. 1), a short distance north of Lassen, as a lava cone with a deep, cylindrical vent, and suggested that it is of about the same age as Lassen Peak. However, Crescent Crater seems to predate the last glaciation, and thus volcanism probably had ceased there by 20,000 years ago.

No evidence has been found of any volcanic activity in the western part of the park after Lassen Peak was formed (probably about 11,000 years ago) until about 1,200 years ago. Pyroclastic debris began to be erupted from vents at the site of the Chaos Crags about 1,200 years ago; this debris typically directly overlies soils developed on moraines formed during the last glaciation.

Pyroclastic eruptions, nuées ardentes, and dome formation at Chaos Crags

The Chaos Crags did not exist before about 1,200 years ago. In their place, shortly before they were formed, was a group of low volcanic cones from which hot pyroclastic debris was intermittently erupted. This debris is distributed on all sides of the Crags. It is particularly thick and coarse on the south side, in and near the remaining part of one cone, where blocks as much as several feet across are common. Pumice that fell 2 miles east of Chaos Crags was still hot enough to convert wood to charcoal. The pyroclastic material extends as a thin layer eastward beyond the Butte Lake area of the park, and northward beyond the park boundary. It thins and becomes fine grained within a short distance to the west; it is too thin to be recognized beyond the park's west boundary.

During the pyroclastic eruptions, hot rock debris occasionally swept downslope as nuées ardentes of gas, ash, and "breadcrusted" blocks of pumiceous rock, which probably destroyed all living things in their paths. Nuées repeatedly flowed down the Manzanita Creek valley to the vicinity of Manzanita Lake. Only one reached beyond the lake, and it terminated

at a point about 2.5 miles west of the park boundary. After each nuée came to rest, retained heat converted all the included wood to charcoal. One nuée deposit, which contains abundant charcoal logs, can be seen in cuts along State Highway 44 just beyond the west boundary of the park, and others can be seen along the road to the water tank in the Manzanita Creek valley. Radiocarbon dates on charcoal from two deposits of this eruptive episode in the Manzanita Creek valley are about 1,100 and 1,200 years, respectively. Each radiocarbon date, however, has a range of analytical error of plus or minus 300 years, so the deposits possibly are of nearly the same age. Other nuées ardentes moved eastward into the valley of Lost Creek, some reaching at least as far east as the northwestern part of the Devastated Area. The largest nuées flowed eastward, then northward down the Lost Creek valley to beyond the boundary of the park. Charcoal from a nuée deposit in the Lost Creek valley near the Lassen Park Road bridge has been dated as about 1,000 years old; this date has a range of analytical error of plus or minus 250 years.

Eruption of pyroclastic material continued even after the last nuées moved down the Manzanita and Lost Creek valleys. But later, masses of molten lava reached the surface at several places. Too stiff to move laterally outward and form lava flows, the hot lava gradually rose higher and higher under a mantle of cooled, hardened, and broken blocks. The group of domes that resulted when this lava solidified constitute the Chaos Crags. They are made up of several, perhaps as many as five, masses of rock that rose to different heights, but they all originated from the same general body of molten rock and may be nearly contemporaneous.

Parts of the Chaos Crags may have cooled to normal temperatures only within the last century. The central, highest dome was reported to have been issuing large volumes of steam and other gases as recently as 1857.

#### Pyroclastic eruptions and lava flows from Cinder Cone

A series of eruptions in the northeastern part of the park between the middle of the 16th century and 1851 centered at Cinder Cone, which

apparently was built during several periods of explosive activity. During some of these eruptions, lava flowed from vents at the base of the cone toward the south, east, and northeast. The most recent flow extended into Butte Lake in 1851. This eruption and earlier ones were described and dated by Finch, who documented the following succession of events:

| Type of activity            | Date         |
|-----------------------------|--------------|
| Lava flow                   | 1851         |
| Lava flow                   | 1785 (about) |
| Lava flow                   | 1720 (about) |
| Eruption of<br>volcanic ash | 1666         |
| Lava flow                   | 1666         |
| Eruption of<br>volcanic ash | 1567         |
| Lava flow                   | 1567         |

According to Williams, the volcanic ash from Cinder Cone covers an area of not less than 30 square miles around the cone; the thickest and most extensive deposits are to the north.

#### Historic eruptions at Lassen Peak

Eruptive activity at Lassen Peak since the dome was formed, but prior to 1914, has not been proven. According to a note by R. H. Finch, which was published in "The Volcano Letter" in 1930, La Perouse witnessed an eruption in northern California while at sea in 1786. Finch pointed out, however, that the eruption could have been either at Lassen Peak or Mount Shasta.

Day and Allen stated that a crater about 1,000 feet across was present at Lassen's summit before the 1914 eruptions and that it was a smooth bowl floored by volcanic sand and lapilli. It seems likely that the crater was a product of prehistoric eruptions that were similar in kind and scale to those of 1914-17. However, we have found no independent evidence of such eruptions in the form of pyroclastic deposits.

The most recent eruptive episode of Lassen Peak began on May 30, 1914,

when, with no known preliminary phenomena, rising clouds of ash and water vapor were observed above the volcano for about 10 minutes. Many similar pyroclastic eruptions, on various scales, occurred during the following year. Some of the eruption columns rose to heights of as much as 10,000 feet. Williams pointed out that

"During the first year, there were more than 150 explosions, most of them mild \* \* \*. Some of the ejecta were blown to the southward as much as 15 miles, but the majority was scattered in a northeasterly direction, most of it in the form of dust."

The character of the activity changed during the night of May 14-15, 1915, when a reddish glow was noted at the summit of the peak. By May 18 a mass of lava had appeared in the summit crater, and on the 19th it spilled over the west crater rim and probably also over the northeast rim. Shortly before midnight on the 19th, a large mudflow buried the valley floors of Hat and Lost Creeks northeast of the volcano, and short mudflows also extended down the north and west sides into the valley of Manzanita Creek. The mudflows apparently were caused by rapid melting of snow by tongues of lava that spilled down the flanks of the volcano.

The most violent eruptions of the entire eruptive episode occurred on May 22, 1915. A lateral blast knocked down virtually all the trees in the "Devastated Area," which is a sector 1 mile wide and 3 miles long northeast of the volcano's summit (fig. 1). The blast scorched the vegetation and started one small fire. It also melted snow and caused a flood in Lost Creek that did not subside until the following day. During this same eruption, and perhaps simultaneously with the lateral blast, a vertical eruption cloud rose to a height of more than 5 miles. Ash from this cloud drifted eastward and extended at least as far as Elko, Nevada, which is about 300 miles east of Lassen.

Strong eruptions continued intermittently at Lassen Peak until the end of June 1917, and minor clouds, which were interpreted by some as being of eruptive origin, were reported on a few occasions in 1919, 1920, and 1921.

Several small thermal areas still exist at the summit area of Lassen, although activity is much less than in the middle 1930's, when 30 or more fumaroles were reported to be constantly active. The highest temperature we found in the summit area on August 27, 1969, was about 176°F at a depth of about 8 inches in a small fumarole high on the outer part of the northeast crater rim.

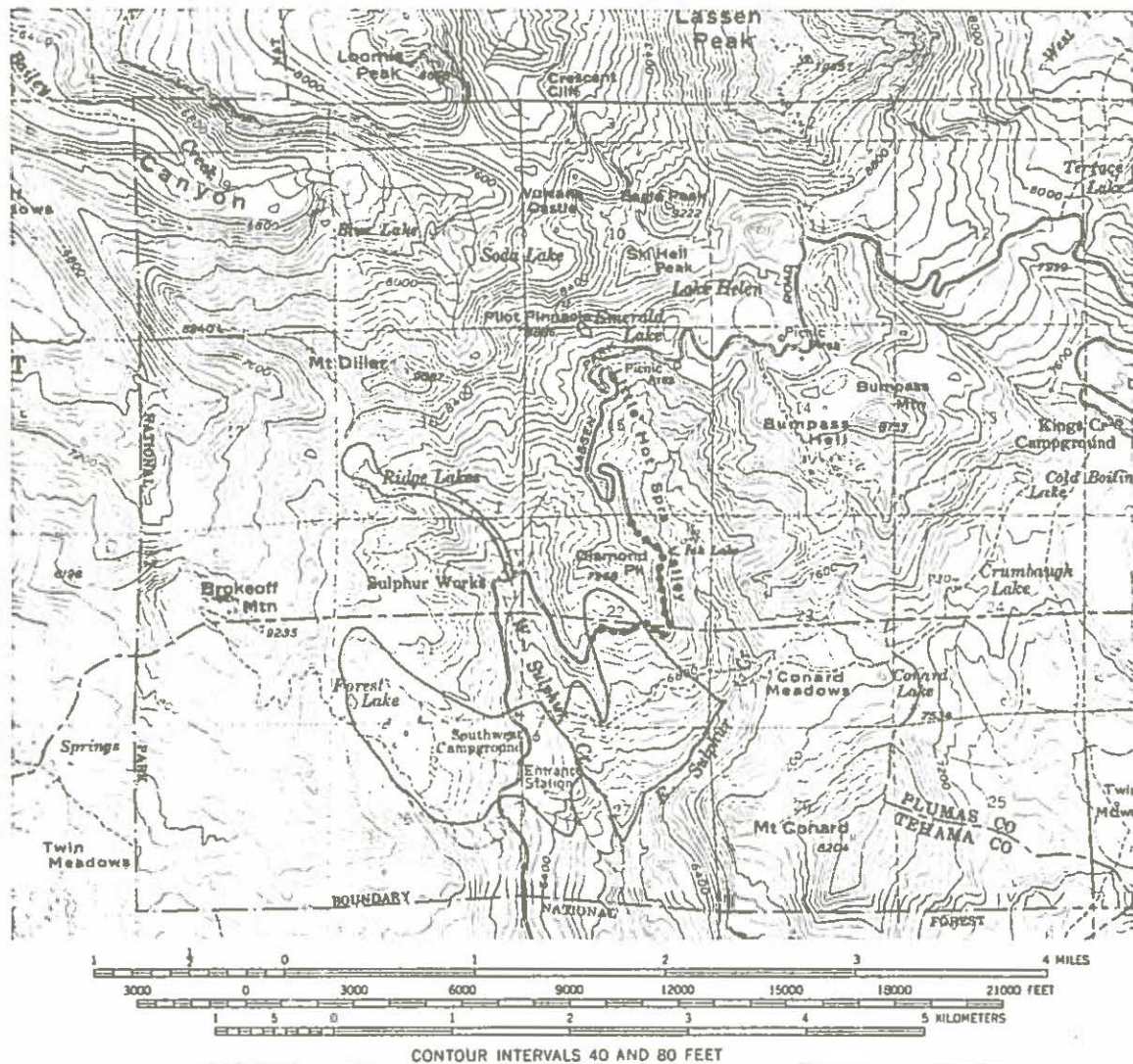
There is a more extensive thermal area on the north side of Lassen Peak at an altitude of about 8,600 feet. Here, at the north edge of sec. 34, there are many small fumaroles and extensive areas of hot ground. The highest temperature recorded on August 25, 1969, was 194°F at a depth of about 15 inches in an area of hot, moist ground. A smaller thermal area lies downslope a short distance to the northwest, in the southeast corner of sec. 28. The highest temperature found there on September 2, 1969, was about 168°F at a depth of 12 inches in an area of warm, moist ground. Both thermal areas are near the margin of the Lassen Peak dome.

#### Landslides

##### Landslides along the Lassen Park Road

Several landslides were identified along the Lassen Park Road south of Lassen Peak (fig. 2). Old slides, which do not seem to be moving now, are present on the south side of Diamond Peak and in the area from the east side of Brokeoff Mountain downslope to West Sulphur Creek. The Lassen Chalet, Sulphur Works campground, Lassen Park Road, and park entrance station are situated on the slide east of Brokeoff Mountain. Another old slide extends down a valley from Ridge Lakes to the Sulphur Works. Although no evidence was noted that indicates this slide to be moving now, reports in various issues of "The Volcano Letter" indicate that the lower part of the slide was moving at the Sulphur Works in the late 1920's. A small slide was recognized on the southeast side of Pilot Pinnacle but it does not extend downslope to the Lassen Park Road.

Each of these landslides is of the type called "earthflow," which forms when a mass of earth material breaks away from a cliff or slope and moves downhill in a pasty or semi-fluid condition. Observed



.....  
 Parts of the Lassen Park Road  
 which may be affected by  
 rockfalls from Diamond Peak

Figure 2.--Landslide areas south of Lassen Peak.

velocities of earthflows elsewhere generally have been in the range of a few feet to a few hundreds of feet per year. None of the earthflows along the Lassen Park Road shows any evidence of more rapid movement.

Large blocks of rock that have fallen from Diamond Peak in the past can be seen along the Lassen Park Road and on the slope between the road and the base of the peak. Diamond Peak itself is made up of several very large blocks of rock which have become detached from the bedrock and which now seem to be in an unstable condition.

#### Rockfall-avalanches from Chaos Crags

The Chaos Jumbles consist of coarse angular rock debris that covers a broad, low-relief area of a little more than 3 square miles north and east of Manzanita Lake. Williams suggested that the Jumbles is an avalanche or mudflow deposit caused by a volcanic explosion and by an ensuing landslide at the Chaos Crags about 200 years ago. More recently, Heath proposed that there were at least three separate avalanches, which he designated "oldest," "middle," and "youngest," and that each was separated from the others by an interval of several hundred years. The ✓Chaos Jumbles clearly do include three or more avalanche deposits, but ✓we think they all may have been formed during one short episode. The avalanche deposits underlie a considerable area occupied by some dwellings and visitor facilities near Manzanita Lake, and extend as far west as a point just a few hundred feet short of the west boundary of the park. We agree with Williams' estimate that the combined volume of avalanche deposits is at least 150 million cubic yards, and suggest that it may be as much as 200 million cubic yards. The latter volume is roughly the equivalent of a square mile piled to a depth of 200 feet.

The distance that the Jumbles avalanches traveled over relatively gentle slopes and up the flanks of Table Mountain suggests that they ✓moved as high-speed, air-cushioned avalanches. Each avalanche originated from a massive fall of rock on the northwest side of Chaos Crags. It is of interest that the rockfalls did not originate on the side of the highest dome of the Chaos Crags, which is the part of the Crags that was reported to have been steaming from 1854 to 1857, but from one or

two domes adjacent to it on the north. The tremendous kinetic energy developed by each rockfall through a vertical distance of more than a thousand feet caused the rock masses to avalanche downslope to the north and west at high speeds. By the time the "oldest" avalanche reached the foot of Table Mountain, 1.5 miles from its source, it still had enough energy to carry it upslope through a vertical distance of 400 feet, as it was being deflected to the southwest. If it is assumed that as the avalanche reached its highest point its kinetic energy was wholly converted into potential energy, and none was utilized in overcoming frictional resistance, it must have had a speed at the foot of Table Mountain of not less than 100 miles per hour. It seems certain that the actual speed was substantially greater because frictional resistance would have developed within the avalanche as it struck the toe of Table Mountain and moved upslope. The high speed of the avalanche at Table Mountain and some of its present surface features provide the main evidence that the avalanche debris moved on a cushion of compressed air. ✓ The marked transverse ridges and furrows in each avalanche deposit closely resemble features described by Shreve in the surface of the Blackhawk landslide in southern California. Shreve concluded that the Blackhawk slide could only have moved to its present position, more than 5 miles beyond its source area, if it had moved at a high velocity on a layer of compressed air. He explained the transverse ridges and furrows as structural features produced when the slide came to rest. The low gradient on which the Chaos Jumbles avalanches moved also suggests that there was low frictional resistance. The slope of the lower 1.5 miles of the "oldest" and "middle" avalanche deposits is only about 200 feet per mile.

Williams suggested that the cause of the initial rockfall and avalanche was a steam explosion at the northwest base of the Craggs, and he thought the presence of Chaos Crater at the base of the Craggs substantiated his suggestion. The crater seems to coincide with the position of the margin of one of the Chaos Craggs domes. Williams postulated that the crater resulted from a steam explosion like the one which he

believed triggered the initial rockfall.

Heath, however, believed that if steam explosions were the cause of the rockfalls they would have had to be repeated at widely separated times, and to be followed by a concluding explosion which formed Chaos Crater after the last rockfall. He also noted the absence of an air-laid deposit of rock fragments near Chaos Crater, which, if present, would support the hypothesis of a steam explosion.

We believe that any one of several events conceivably could have caused the rockfalls. If, as we suggest, the rockfalls followed one another in quick succession, the first one might have been triggered by a steam explosion as suggested by Williams, and the subsequent falls could have resulted from the collapse of steep, unstable cliffs left by the initial rockfall. Chaos Crater could have been formed by a later steam explosion, or it could be merely a depression--similar to two smaller ones nearby--left between the Craggs and the mass of the youngest avalanche that moved outward from the base of the Craggs.

An alternative cause of the rockfalls could have been the intrusion of a dome into the central part of the Chaos Craggs about 300 years ago, or renewed movement of one of the existing domes. Although we have no direct evidence of either of these events, the fact that the highest dome of the Craggs was reported to be emitting steam and other gases constantly during the period 1854-1857 suggests that this dome is younger than the others. It adjoins the domes in which the rockfalls originated. If a new dome had been intruded into the central part of an older group of domes, it could have caused oversteepened slopes by pushing and tilting the surrounding rocks. If these rocks were already highly fractured and unstable, the oversteepening could have resulted in one or more massive rockfalls.

Still another possibility is that the rockfalls were caused by the collapse of unstable cliffs during an earthquake, especially if a quake had been accompanied by a strong ground acceleration toward the northwest.

There is little evidence that favors one of these hypotheses over the others, and any one of the processes described could cause another

large rockfall from the Chaos Crags in the future. Because some of these causes might not be preceded by any warning, we regard the areas immediately downslope from the Chaos Crags as hazardous. If there had been three or more avalanches at widely separated times in the past, as suggested by Heath, the potential hazard would be even greater because of the implication that the event or events that caused the rockfalls were repeated at widely spaced intervals during the 1,000 years since the Crags were formed. For this reason, we have critically reexamined the geological and botanical evidence cited by Heath to support his suggestion that the rockfalls and avalanches were separated by significant periods of time (Appendix C). Our study suggests that the rockfalls and avalanches probably occurred in quick succession about 300 years ago, and we believe that they were triggered by an event, or by a combination of events, which has not been repeated.

#### GEOLOGIC HAZARDS

The three principal kinds of geologic hazards that have been identified in the park are (1) those that could accompany a future volcanic eruption, (2) those that are associated with various kinds of landslides and which might or might not accompany an eruption, and (3) those that are associated with visitor use of the park's hydrothermal areas.

##### Volcanic activity

The most dangerous kinds of volcanic eruptions that should be anticipated are those that produce nuées ardentes, lateral blasts, and the fall of pyroclastic debris; eruptions that produce volcanic domes and flows are generally less dangerous. Floods and mudflows are also hazards that could result from these or other kinds of eruptions.

The principal dangers from nuées ardentes result from (1) the basal flow of incandescent rock debris, which can bury and incinerate all living things in its path; (2) the cloud of hot ash and gases which may accompany the basal flow or occur alone--such a cloud may cause asphyxiation, burning of the lungs by hot dust or steam and other gases, and burning of the skin, and large rock fragments and other debris carried

in the cloud may cause severe injury by impact; and (3) fires that may be started by the hot rock debris.

The especially great hazard represented by a *nuée ardente* is partly caused by its high speed of movement and by its high temperature. *Nuées* have been reported to move at speeds ranging from 35 to at least 75 miles per hour; their velocity probably depends mostly on their size, on gas emission by the included rock particles, and on the slope of the surface over which they move. The great *nuée ardente* from Mont Pelée in 1902 killed 28,000 persons in St. Pierre, Martinique, because it overwhelmed the entire town so rapidly that no one could give warning or escape. The cloud that swept across the town carried rock fragments having an estimated temperature of 800°C, which started many fires. Catastrophic *nuées* formed during the 1951 eruption of Mount Lamington, Papua, which killed 3,000 persons, were hot enough to char wood, and the cloud of one *nuée* was estimated to have maintained a temperature of 200°C for a period of 1 1/2 minutes as it passed one site about 6 miles from its point of origin.

The chief dangers from a lateral blast are those of being struck by flying debris, asphyxiation, and burns or scalds caused by hot rock debris or steam. The hot blast of May 22, 1915 at Lassen Peak, scorched and charred leaves and branches of trees within and at the margins of the Devastated Area and started a small fire.

Pyroclastic eruptions that do not produce a *nuée ardente* may be dangerous because of falling bombs and blocks of pumice or dense rock. The thickest and coarsest material would probably fall within 5 miles of the vent if the eruption was directed vertically, and if the wind was light during the eruption. A laterally directed eruption, or one accompanied by a strong wind, might result in a significant hazard from falling debris to a somewhat greater distance. Within areas of pyroclastic fallout, breathing of hot dust and gases constitutes another hazard, but this danger exists chiefly downwind and would diminish rapidly with increasing distance (See Appendix D).

There is little direct danger from the eruption of a volcanic dome.

The process is relatively slow, and even if parts of the dome should be fluid enough to flow laterally, it is unlikely that the flow of lava would move rapidly or extend more than a mile or two. The greatest potential danger associated with a dome eruption is from the gas pressure that could build up. Resulting explosions could cause large rock-falls from the dome, and these, in turn, might become swiftly moving avalanches.

Similarly, there probably would be little direct danger from a lava flow from the Chaos Crags or Lassen Peak, or from some other vent in the same general area. The lavas that have been erupted from these areas in the past have been of a type that flows slowly. However, if even a short lava flow extended into an area of deep snow, the melting that would result could cause destructive floods and mudflows along the slopes and valley floors below.

The chief dangers of mudflows and floods to human life are those of burial or drowning, and those carrying hot rock debris might also cause scalds or severe burns. Dangers to buildings include burial and removal. Mudflows may have a wide range in depth. The thickest deposit left by a mudflow in the Manzanita Lake area is only about 12 feet thick, but the mudflow itself probably was deeper when it was moving. Mudflows can move at high speed and considerable distances--some have been reported to travel at speeds of as much as 55 miles per hour. Velocity depends mostly on the gradient and fluidity of the flow. A mudflow caused by the eruption of a lava flow onto snow at Lassen Peak in 1915 traveled more than 15 miles from its place of origin, and an even greater distance might have been reached if there had been a larger volume of material. Mudflows tend to move down valley floors, but those of very large volume may overtop streambanks and spread widely onto adjacent surfaces of low relief. Where a mudflow encounters constrictions in a valley that impede flowage, such as bridges and culverts, the mudflow temporarily ponds and increases in depth. Because of their high viscosity and vast carrying power, however, mudflows commonly sweep away even massive and heavy bridges in their paths. Swiftly moving mudflows rise along the outsides of bends in their courses, and slop up onto obstacles in their paths.

## Landslides

The hazard presented by a rockfall or rapidly moving rockfall-avalanche is obvious. Such an event can precede or accompany a volcanic eruption, or can occur without any associated volcanic activity. The likelihood of a rockfall-avalanche would increase during an eruption, however, because of the probability, then, of earthquakes and volcanic explosions that might trigger the collapse of a potentially unstable cliff. Very large rockfall-avalanches are particularly hazardous because of their possible high speed; velocities of 65 to 210 miles per hour have been determined or inferred for large slides of this kind elsewhere in the world. Such a speed would make almost any kind of an alarm system ineffective. For example, an avalanche traveling 100 miles per hour could move from the base of the Chaos Crags to Summertown or Loomis Museum in 1 1/2 minutes.

A rockfall might or might not be preceded by any warning. If one were caused by the formation of a new dome in the Chaos Crags area there probably would be some advance warning, though not necessarily a specific warning of an impending rockfall-avalanche. A rockfall triggered by an earthquake or steam explosion could occur without warning.

Collapse of part of a cliff might result in the creation of a second unstable slope, with the result that one avalanche might be quickly followed by others. For example, at Mount Rainier in 1963, at least seven successive large rockfall-avalanches occurred within a short time, possibly within minutes or hours of each other. Such a quick repetition could make rescue attempts particularly hazardous after a rockfall-avalanche.

Very large poised blocks of rock at the summit of Diamond Peak (fig. 3) seem to present a direct and immediate hazard to motorists on the Lassen Park Road. These blocks are no longer attached to the bed-rock and are sitting in precarious positions. One tilted block (labeled "A" in fig. 3) at the northwest end of Diamond Peak has maximum dimensions of about 15x25x35 feet; its weight is estimated to be at least a thousand tons. If disturbed, block "A" could topple and roll either

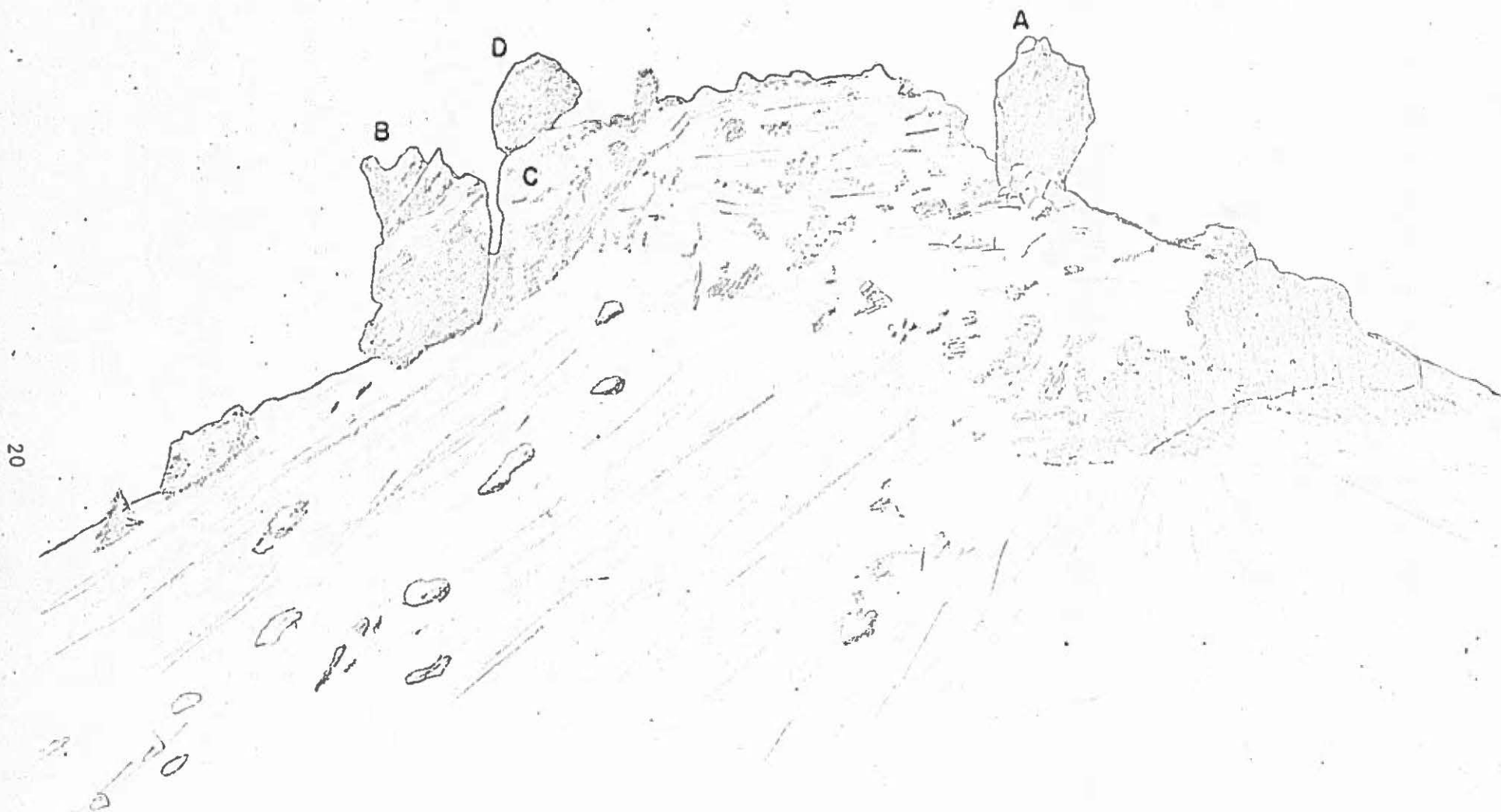


Figure 3.--View of Diamond Peak from the northeast; Lassen Park Road is out of view to the bottom left. Letters indicate detached blocks that are described in the report. The height of block A is about 35 feet, that of block B, about 45 feet. Sketched from a photograph.

to the northeast or southwest. The Lassen Park Road lies about 1,300 feet downslope to the northeast from the base of the block, and the intervening slope averages about 30°.

Another large tilted block (labeled "B" in fig. 3) is detached from the southeastern end of Diamond Peak. The block overhangs on the east side, and, if it should topple, it would roll downslope to the east toward the Lassen Park Road. The block has maximum dimensions of about 20x40x45 feet and probably weighs more than 2,000 tons. Block "B" adjoins another, much larger, block (labeled "C") on the west, from which it is separated by a fissure 1-2 feet wide. Although block "C" is nearly in its original position and appears in the sketch to be a solid rock ledge, it is separated by large cracks from the underlying and adjacent bedrock. A conspicuous feature of Diamond Peak is the large rock (labeled "D") that appears to be a "balanced rock" but which is an integral part of block "C".

Future rockfalls at Diamond Peak could endanger motorists or hikers on the Lassen Park Road below. Such rockfalls probably would occur without warning. They could be triggered by the freeze or thaw of moisture in cracks, or by ground motion caused by an earthquake or a volcanic explosion. It is conceivable that a sonic boom caused by aircraft could trigger a rockfall if the mass were already in a highly unstable condition.

We believe that an earthquake or volcanic explosion strong enough to cause a rockfall at either Diamond Peak or Chaos Crags could occur in the park. However, we now have no way to predict the probability of such an earthquake or explosion in the near future, or to determine how strong an explosion or earthquake would be required to cause a rockfall.

Movement on the earthflows along the Lassen Park Road south of Lassen Peak might be renewed by a severe earthquake, particularly if a quake occurred at a time when the ground is saturated. Renewed movement possibly could be initiated solely by saturation. Such movements probably would proceed at a slow rate and would not directly endanger park visitors. They might, however, damage parts of the Lassen Park Road and other facilities that have been built on the earthflows.

### Hydrothermal activity

Several hydrothermal areas in Lassen Volcanic National Park were examined during the summer of 1969 in order to identify possible hazards to visitors. The hazards in these areas appear to be very localized, and to result from the fact that visitors wander, with too few restrictions, through areas adjacent to boiling water and mud and through areas of unstable hot ground. The potential hazards appear to be limited chiefly to burns that could result from a person slipping into a pool of hot water or mud, or falling through unstable ground into such a pool.

### CONCLUSIONS AND RECOMMENDATIONS

Several courses of action are recommended in order to reduce the risk from future geologic events in Lassen Volcanic National Park: (1) locate facilities so as to avoid areas of greatest potential hazard, relocate certain facilities that are now at points of relatively high hazard, and select localities of relatively low hazard for any future expansion of facilities; (2) monitor Lassen Peak, Chaos Crags, and closely adjacent areas so as to detect preliminary signs of an impending eruption, and follow certain procedures to remove people from endangered areas if certain warning signs appear; (3) reduce the hazard from landslides at Diamond Peak by restricting parking along the road and by removing or anchoring loose blocks; and (4) improve visitor-guidance facilities at hydrothermal areas. Our specific recommendations are presented and discussed below.

#### Location of facilities

All explosive dacitic volcanism within the park in postglacial time has been concentrated in a zone of only about 7 square miles--an area that is also the focus of visitor interest. This zone extends from Lassen Peak northward to the domes east of Sunflower Flat (fig. 4). The repetition of volcanism here suggests that future eruptions of a similar and hazardous character will recur at one of the existing vents or at some new vent within or close to this area. We now regard the

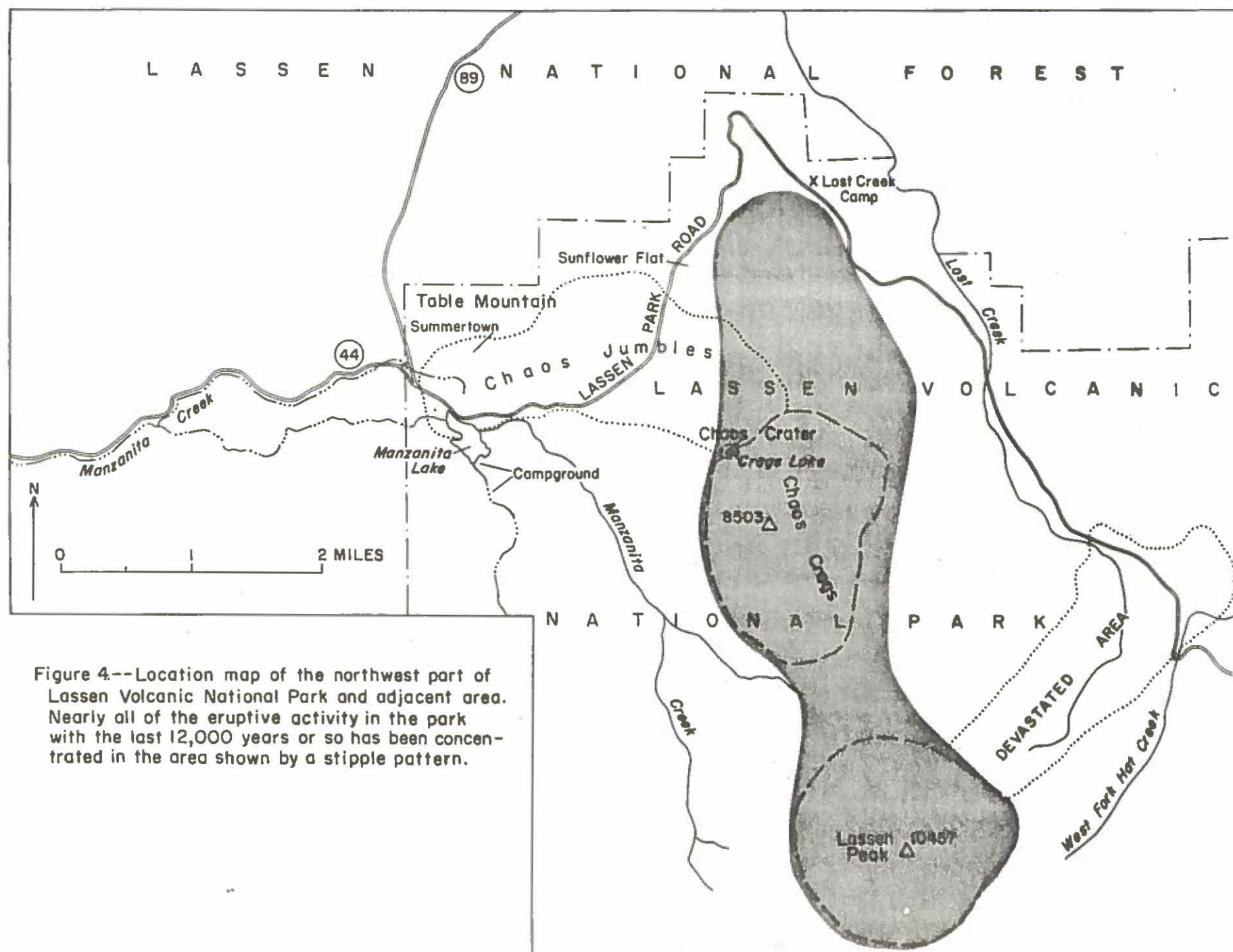


Figure 4.--Location map of the northwest part of Lassen Volcanic National Park and adjacent area. Nearly all of the eruptive activity in the park with the last 12,000 years or so has been concentrated in the area shown by a stipple pattern.

risk in this area to be somewhat lower than we stated in our previous report. Nevertheless, the risk is higher in this zone than in other places, and the risk from catastrophic events increases as this zone is approached. We believe that future development in the park should avoid this zone as well as areas immediately adjacent to it for facilities that can be placed elsewhere. If, however, further development of facilities within or near the zone becomes essential, the relative hazard at various possible sites should be carefully judged so as to use, insofar as possible, the sites of least risk.

Areas outside the zone shown in figure 4 are regarded as being significantly less threatened by future volcanism. No catastrophically explosive volcanism in postglacial time is known elsewhere in the park. The type of volcanism that produced Cinder Cone and many other similar volcanoes in and near the park would produce mild pyroclastic eruptions and lava flows, and would be preceded by adequate warning.

Within the park, the Manzanita Lake area has repeatedly been affected by catastrophic phenomena of at least two kinds in recent geologic time. Continued use of that area, therefore, expectably will be accompanied by a risk that is higher than most other sites in the park. One advantage of the Manzanita Lake area with respect to future eruptions, however, is that evacuation by State Highways 44 and 89, as well as by forest roads west and northwest of the park, should be comparatively easy if there is an adequate warning of an eruption and if the Lassen Park Road is not blocked at Manzanita Lake.

Table 1 shows the kinds of geologic hazards that should be considered, and the relative degree of risk at various places within the Manzanita Lake area. This appraisal is based on the frequency, scale, and extent of destructive effects of catastrophic events in the past, and special importance has been given to the expectability of some kind of warning before similar events occur in the future.

In the area of the Chaos Jumbles, rockfall avalanches from Chaos Crags on a scale similar to those of the past clearly should be of the greatest concern. These might start with no warning and might travel

Table 1.--Evaluation of kinds of potential geologic hazards and estimated degrees of relative risk at several locations in the Manzanita Lake area, based on the kind, magnitude, and frequency of the events that have affected these or similar locations within the last 12,000 years

| Areas                                                             | Present facilities                                            | Rockfall-avalanche | Nuée ardente                     | Mudflow and<br>(or) flood | Fall of ash<br>and lapilli |
|-------------------------------------------------------------------|---------------------------------------------------------------|--------------------|----------------------------------|---------------------------|----------------------------|
| Chaos Jumbles                                                     | Museum, administrative<br>and public buildings,<br>Summertown | Very high          | Very high                        | Low                       | Low                        |
| Area between<br>Manzanita<br>Creek and<br>campground              | Cabins                                                        | Moderate           | Very high                        | High                      | Low                        |
| Valley south of<br>Manzanita Lake                                 | Campground                                                    | Moderate           | Moderate                         | Moderate                  | Low                        |
| Bench west of<br>campground                                       | None                                                          | Moderate           | High (cloud)<br>Low (basal flow) | Low                       | Low                        |
| Area at west park<br>boundary, north-<br>west of Chaos<br>Jumbles | None                                                          | Low                | Moderate                         | Low                       | Low                        |
| SE part of<br>sec. 19                                             | None                                                          | Low                | Moderate                         | Moderate                  | Moderate                   |

at a very high speed--the short time required for one to reach Manzanita Lake would surely preclude evacuation in time to prevent loss of life. There seems to be no way to warn or protect persons in the path of such an avalanche, and the safest course in planning would be to avoid use of the areas that might be so affected. In particular, we recommend that no new facilities be developed anywhere on the rockfall-avalanche deposits of the Chaos Jumbles, and that existing facilities, including Summertown, be relocated as soon as practicable.

Other sites in the Manzanita Lake area that are now in use seem to be in areas that are distinctly less risky than the Jumbles, even though they could be affected by future eruptions in the zone of explosive dacitic volcanism shown on figure 4. The area between Manzanita Lake and the campground, which is occupied in part by cabins, could be endangered by nuées ardentes, mudflows, or floods originating either at Lassen Peak or the Chaos Crags. The area might also be within reach of a large rockfall-avalanche from the west side of the Chaos Crags, but the risk seemingly is appreciably less than in the area of the Chaos Jumbles. The campground seems to be somewhat better situated because it is in a small valley that does not extend to Lassen Peak or to the Crags and so would not be along a likely route of nuées ardentes or volcanic mudflows.

A ground reconnaissance of the area surrounding Manzanita Lake, supplemented by inspection of aerial photographs, failed to reveal any site that seems wholly suitable from the standpoint of size, accessibility, topography, vegetation, and absence of potential geologic hazards for the relocation or expansion of major visitor-use facilities. There are, however, a few small sites that seem to be appreciably less hazardous than some of the areas currently being used.

A small area that might be suitable for a visitor-use facility such as a museum is on a low bench directly west of Manzanita Lake campground and south of the lake. The bench is high enough above the adjacent valley floor to prevent damage from the basal flow of a nuée ardente, or from a mudflow on a scale similar to those of the past. The site might be subject to the dangers caused by the fall of lapilli and ash from

pyroclastic eruptions at the Chaos Crags or Lassen Peak, to possible heat and blast effects of hot clouds of a nuée ardente, and to burial if a very large rockfall-avalanche occurred on the west side of the Chaos Crags. Nevertheless, we believe that the site is significantly less hazardous than that of the present museum.

Another site is bounded by the west boundary of the Park, the southwest base of Table Mountain, and the northwest margin of the Chaos Jumbles. The site is flat, much of it is forested, and it is directly underlain by a compact but uncemented deposit of an old nuée ardente. Charcoal from this deposit at another locality was determined to have a radiocarbon age of more than 32,000 years. Thus we conclude that the site has not been affected appreciably by any recent catastrophic geologic event.

Still another small area that might be suitable for limited expansion, perhaps of the Manzanita Lake campground, is in a valley in the southeast part of sec. 19, south of the existing campground. The small valley in which it lies heads on Loomis Peak, and it is separated from the drainage heading on Chaos Crags and Lassen Peak by a low divide. It is therefore less subject to the effects of a relatively small nuée ardente or mudflow than much of the area near Manzanita Lake. However, it might be buried by a very large nuée or mudflow, or by a large rockfall-avalanche originating on the west side of the Chaos Crags.

Sites in the park not far from Manzanita Lake that might seem to be suitable for future visitor-facilities, but which actually are in areas of some risk, include one near Sunflower Flat and another near Lost Creek Camp. The first site extends north along the Lassen Park Road from the north edge of the Chaos Jumbles to Sunflower Flat. Sunflower Flat is underlain by thick pumice that may be the deposit of a nuée ardente erupted from a vent not more than a mile to the southeast. The pumice is older than the last major glaciation of the park. The Sunflower Flat area would not be affected by nuées ardentes or mudflows from the Chaos Crags or Lassen Peak, and probably would be little affected by a lateral blast or by pumice erupted from those volcanoes.

The other site is the broad flat area at Lost Creek Camp; it is underlain by one or more nuée ardente deposits that are younger than the last major glaciation. Both sites have been affected by volcanism in the past, and both are close to the zone in which explosive volcanism has repeatedly occurred in postglacial time. Furthermore, both sites would be endangered by renewed volcanism in the area of the domes east of Sunflower Flat. We believe that the relative degree of potential hazard increases markedly as the zone of dacitic volcanism is approached, and thus we recommend that neither the Sunflower Flat nor the Lost Creek Camp area be developed for permanent visitor or park-maintenance facilities in the future.

Several other sites now in use are near the zone of dacitic volcanism. The campground at Summit Lake seems to be at a locality of relatively low geologic hazard because it does not lie within a valley that heads on Lassen Peak. In the event of an eruption the chief hazard at this campground probably would be that of falling pyroclastic material and accompanying volcanic gases. The same is true of the Kings Creek campground, although a very large nuée ardente, flood, or mudflow might descend the southeast flank of Lassen Peak and conceivably could move down the Kings Creek valley and affect the campground area. An adverse factor at both campgrounds is the difficulty of evacuating campers if an eruption rendered the Lassen Park Road impassable. Both campgrounds should be evacuated at once if there are warning signs of an impending eruption.

If permanent visitor facilities are planned for other parts of Lassen Volcanic National Park in the future, we recommend that an evaluation of potential geologic hazards be made in advance at the site of each proposed facility in order to minimize risk to park visitors.

#### Monitoring

We believe that the concentration of public and administrative facilities in the Manzanita Lake area, and the heavy visitor use of that area in the summer, warrants a monitoring program directed toward the detection of signs of an impending eruption. Even though some volcanoes

have erupted violently without any apparent warning, most eruptions are preceded by preliminary warning signs and by days, weeks, or even months of volcanic activity on a small, relatively harmless scale. Probably the most significant pre-eruption phenomena are the following:

1. A large, continuing increase in the frequency and magnitude of local earthquakes.
2. The appearance of steam jets and clouds of water vapor, possibly accompanied by explosions and rockfalls.
3. Subterranean rumbling noises.
4. A substantial increase in the temperatures and activity of hot springs and fumaroles, and the appearance of these features in new areas.
5. An increase in the amount of sulfur and chlorine or fluorine in fumarolic gases.
6. Repeated landslides on the flanks of a volcano.

One of the best ways in which both the time and location of a volcanic eruption might be anticipated is by seismic monitoring within or very close to the park. Seismologists at the University of California at Berkley now monitor the seismographs located at Mineral (park headquarters) on a day to day basis. In addition, the Geological Survey in 1969 monitored the western part of the park with portable seismographs, designed to record even very small earthquakes, in an attempt to locate epicenters of seismic events in the park and to evaluate the present seismic state of the park. A brief report of that investigation by John D. Unger and John Coakley (Appendix B) shows that 29 seismic events were recorded in 13 days, many of which were so small that they may not have been recorded on the Mineral seismographs. No concentration of quakes was noted near Lassen Peak, Chaos Crags, or in any other part of the zone that has been volcanically the most active in the recent past. Although six seismic events were concentrated in a relatively small area near Brokeoff Mountain (fig. 1), none could be definitely attributed to a volcanic, rather than a tectonic, cause.

Unger and Coakley noted that within the past few decades swarms of earthquakes have originated within the Lassen Park region, although their epicenters have not been accurately determined. Many of these

earthquakes have been strong enough to register on the Mineral seismographs and other instruments in the area, and many were felt within Lassen Park. A similar earthquake swarm did not occur during the 2-week study in August, 1969, so we cannot tell where these swarms originate and what they might mean in terms of potential volcanism.

There is clearly a need for additional permanent seismograph stations whose primary function is to monitor seismic activity within the park. Until such stations are established and the records continuously interpreted, there can be no guarantee that seismic activity preliminary to an eruption will be recognized.

Seismic monitoring probably would provide warning of an eruption by detecting earthquakes generated by molten rock moving upward toward the ground surface, but quakes are also caused by tectonic activity--that is, by shifting of the earth's crust that is not related to volcanism. Thus, if earthquake activity increased at some time in the future--and the past record of earthquake swarms in this region suggests that it will--the location and the probable cause of the quakes should be determined as quickly as possible. If the quakes are of tectonic origin, the resulting hazard would be chiefly from landslides, rather than from volcanic phenomena.

In our 1969 report we recommended that periodic aerial infrared surveys be made in order to monitor the thermal state of Lassen Peak and adjacent areas. However, in order to anticipate an eruption during the time of maximum park attendance, infrared imagery would be required in very early summer, at a time when normally there is an extensive snow cover at the higher elevations. The identification of abnormally warm areas under such conditions would be difficult because of the thermal contrast between areas of snow and bare rock. The best season for infrared imagery probably is early fall, when the snow cover is at a minimum. This is a time when park attendance normally is low, and the absence of thermal activity then would be of little significance concerning the likelihood of an eruption the following summer.

For the reasons just described, we do not recommend that reliance be placed on periodic examination of the Lassen Peak area with an

airborne infrared sensing device as a means of anticipating an eruption during the summer visitor season. The high cost of making such an examination often enough to be of tangible benefit does not seem to be warranted at present. It is possible, however, that future infrared monitoring of Lassen Peak, as well as of other volcanoes, can be accomplished at frequent intervals by a remote-sensing satellite. If an eruption were to begin, or if other signs were to suggest an impending eruption, infrared imagery from aircraft would be desirable in order to outline the area of thermal activity.

We believe that repeated determinations of the temperatures and gases of hot springs and fumaroles probably would be of little value in forecasting an eruption unless carried out on a comprehensive scale. However, we do recommend that an inventory be made as soon as possible of the thermal features in the park. This inventory should include a map, or maps, showing the location and extent of all known thermal areas, as well as photographs and descriptions of the areas. Existing infrared images of the park made in previous years would be invaluable in preparing this inventory. Not only would the inventory serve as a base for evaluating future changes in the thermal state of the park, but it might also contribute toward a better understanding of the park's present thermal activity.

We suggest that the Lassen Peak-Chaos Crags area be visually monitored by Park Service personnel in the course of their other duties. Those engaged in this activity should be aware of the importance of detecting the initial sign or signs of an impending eruption (described on p. 29). Such signs might be seen first by a Ranger on highway patrol along the Lassen Park Road, or by a Ranger-Naturalist leading a group to the summit of Lassen or Brokeoff Mountain, or possibly by a fire lookout at Mount Harkness. We suggest, for example, that the eastern side of the Chaos Crags and the northern side of Lassen Peak be deliberately examined with binoculars each morning, when light is good, from the Devastated Area.

Suggested procedures to be followed if unusual geologic phenomena occur

We regard the area from Lassen Peak northward to Lost Creek Camp as being the most hazardous with respect to future volcanism. This area is readily visible from highways, campgrounds, and trails at relatively close range (1-4 miles) throughout the time of principal visitor use. We believe an eruption would be preceded by visible thermal activity, especially if it were to occur early in the summer when the ground is saturated by snowmelt. The movement of molten rock or steam toward the ground surface at such a time would produce clouds of water vapor. Thus, it seems likely that the appearance of a new eruptive center, or the renewal of activity at an existing one, would be detected within a few hours, even if the initial activity were to be on a small scale. Furthermore, the relatively easy accessibility of Lassen Peak, the Chaos Crags, and the domes north of the Crags would permit a quick examination on the ground if phenomena of a suspicious nature were reported.

We recommend that certain procedures be followed if any of the following events occur in the future in the area from Lassen Peak northward to Lost Creek Camp.

1. Extensive clouds of water vapor ("steam") appear.

Recommended action. Investigate source area on the ground, determine if a new thermal area is developing, or if the steam is issuing from an old hydrothermal area, note if there are extensive areas of hot ground, approach steam vent very cautiously and determine whether there are odors of volcanic gases (See Appendix D). Report results of these investigations to the Chief, Pacific Environmental Geology Branch, U.S. Geological Survey, Menlo Park, California (telephone 415-325-6761 or 415-324-1661) for further action.

2. Earthquakes are felt repeatedly by people in the Manzanita Lake area.

Recommended action. Ask seismologist at the University of California, Berkeley, (telephone 415-642-3976) for the epicentral location of the earthquakes. If the earthquakes cannot be precisely located by the Berkeley seismologist, request U.S. Geological Survey to monitor with portable seismographs. If the quakes are originating in the area

from Lassen Peak northward to Lost Creek Camp, close northwest part of park to entry and evacuate the Manzanita Lake area.

3. Extensive clouds of water vapor ("steam") appear and are accompanied by repeated earthquakes felt in the Manzanita Lake area.

Recommended action. Evacuate park visitors from the Manzanita Lake area and Summit Lake and Kings Creek campgrounds. Close park to entry. Follow other recommendations under paragraphs 1 and 2, and request an immediate investigation by the U.S. Geological Survey (Menlo Park office).

4. One or more large rockfalls occur on the northwest side of the Chaos Crags (a large rockfall might be defined as one which results in the movement of rock debris outward at least as far as a point several hundred yards beyond the base of the Chaos Crag, or one that leaves a fresh scar on the side of the Crag that is at least hundreds of square yards in area).

Recommended action. Evacuate visitors from the Manzanita Lake area and park personnel from the area of the Chaos Jumbles. Close Lassen Park Road at Devastated Area and West Entrance. Request the U.S. Geological Survey to make immediate investigation of the Chaos Crag to determine the likelihood of additional rockfalls before reopening the Manzanita Lake area and Lassen Park Road.

5. Volcanic eruption begins.

Recommended action. Evacuate visitors from the western part of the park as rapidly as possible and close park to further entry. Request investigation by the U.S. Geological Survey. Notify State Civil Defense of the possible need for a warning to inhabitants of region east of Lassen Park.

It seems unlikely that a geologic investigation could begin before a full day had elapsed following the initial notification of the Geological Survey. Conclusions and recommendations resulting from such an investigation would take even longer. Thus, the National Park Service probably would have to take immediate action without the benefit of geologic advice under the conditions described in paragraphs 3, 4, and 5. We suggest that it would be better to overreact to an unusual geologic event

than to disregard it or misinterpret it, and thereby to allow possible loss of life from an unanticipated catastrophic event. We wish to emphasize that if a volcanic eruption begins, the western part of the park should be evacuated without delay. Although the eruption might be on a small scale initially and might not seem to present an immediate threat to people in the park, it could develop at any time into a disastrous eruption.

A future pyroclastic eruption at Cinder Cone, if of the same type and on the same scale as those of the past, would result in an ashfall that would endanger campers at Butte Lake campground. The campground should be evacuated even if the initial volcanic activity is on a small, seemingly harmless scale. It would be dangerous for anyone to remain within a distance of at least 5 miles downwind from Cinder Cone during such a period of activity. Because of the frequency of eruptions at Cinder Cone in the recent past, it seems inadvisable to construct extensive permanent visitor facilities nearby.

It is possible that the next eruption in the park will occur at a wholly new vent, but it is unlikely that the type of eruption would differ from those described in this report. The type of eruption and the location of the vent will determine the specific actions that should be taken, but any kind of eruption near or west of the Lassen Park Road would warrant evacuation of park visitors.

#### Reduction of landslide hazard at Diamond Peak

Two procedures are recommended to reduce the rockfall danger along the Lassen Park Road below Diamond Peak. First, parking should not be permitted along the road in the danger areas indicated on figure 2 until the unstable blocks are either stabilized or removed. There are several automobile turnouts along this segment of the Lassen Park Road, including viewpoints Nos. 8 through 11. Although viewpoint No. 8 is situated below Diamond Peak, it is at a location that seems to be safer from rockfalls than the others noted. Second, consideration should be given either to stabilizing the northwest and southeast blocks (blocks A and B, fig. 3) at Diamond Peak, or to removing them by blasting.

A series of measurements was made in 1969 by Crandell across cracks separating block A from the adjacent bedrock, block B from block C, and block C from firm bedrock (Appendix F). If similar measurements were to be repeated in the future by Park Service personnel, additional movement might be detected. However, we do not believe that this procedure is an effective way to prevent a possible accident; both the northwest and southeast blocks are now so precarious that they might fall without warning.

#### Reduction of hazards to visitors at hydrothermal areas

Of the several hydrothermal areas examined for possible hazards to visitors only the Sulphur Works seems to provide the visitor with adequate guidance, protection, and warning. At two others, Devils Kitchen and Bumpass Hell (fig. 1), paths should be more clearly marked, and at Bumpass Hell some bridging seems desirable across areas of potentially unstable hot ground.

A trail does not seem to exist now through Devils Kitchen except insofar as one can follow the footsteps of some previous visitor. Unfortunately, one can find footprints almost everywhere, and in some places they approach dangerously close to roaring fumaroles and hot mud pots. We suggest that if Devils Kitchen continues to be recommended to the public as a worthwhile place to visit, a single well-marked trail should be constructed through the hydrothermal area and adequately marked.

Our recommendations with respect to Bumpass Hell are rather extensive and are presented in detail in Appendix E; they are based on our observations of visitor behavior and on personal judgment concerning hazardous areas along the trail. The recommendations have little to do with geology; almost any person with good judgment could readily identify the areas of possible hazard. The techniques used in evaluating hazardous areas included feeling the ground with the hand to determine whether it was hot, striking the ground with a hammer and noting the amount of vibration, and measuring the temperatures of a few hot springs. Hot ground suggests the presence of steam at depth, and excessive vibration

of the ground when it is struck indicates that the area could collapse.

We recommend that wood duckboards be placed along hot and potentially unstable parts of trails in hydrothermal areas. Such structures would clearly delineate the trail and should have a beneficial psychological effect because their presence would imply that the area is dangerous and that the visitor should not leave the trail. Even more important, however, would be the bridging action of duckboards should a part of the trail collapse over a boiling spring or fumarole. For maximum benefit, duckboards should be unjointed from end to end.

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## Appendix A

### Some geologic terminology

Some geologic terms are explained here so that the reader will understand what is meant as they are used in this report.

The term pyroclastic refers to deposits of rock fragments that were thrown through the air by explosive eruptions of a volcano, or to the type of eruption that produces such deposits. The force of a pyroclastic eruption may hurl the rock debris many thousands--or even tens of thousands--of feet into the air. The size of the erupted debris commonly ranges from fine dust to blocks several feet in diameter. The dust may travel many miles downwind, but the large fragments generally fall close to the volcanic vent. If the erupted material is molten and rich in expanding gas, the rock that results will be full of bubbles and light in weight. This rock, called pumice (adjective: pumiceous) is more easily carried long distances by wind than erupted material that is denser and heavier.

Some names of products of pyroclastic eruptions, as differentiated by fragment size, are volcanic ash, lapilli, and blocks. Ash and lapilli refer to particles less than 4 mm in maximum dimension and between 4 and 32 mm, respectively. Ash and lapilli can consist of mineral fragments and whole crystals, pieces of dense rock, glass which may be pumiceous or dense, or two or more of these materials combined. Blocks are rock fragments larger than 32 mm. Some blocks of pumiceous rock have surfaces that resemble the crust of a loaf of bread; this feature is referred to as a breadcrusted surface.

Pyroclastic material may be thrown out of a volcano by gas pressure within the magma (molten rock beneath the ground surface) as it rises into the crater, or by steam explosions. Steam explosions commonly are caused by water moving downward into a volcano and encountering molten or very hot rock, and some are among the most violent of all volcanic phenomena. Explosions with a strong sideways component may knock down and sweep away forests in their paths, and may blast rock fragments outward at high speed.

If the magma is stiff and viscous, and gas pressure is low, a volcanic dome may be formed. A dome forms when a hot mass of stiff pasty lava pushes, like toothpaste, out of a volcanic vent and is so viscous that most of its movement is vertical. Some domes have rapidly grown to large size. One that formed in 1951 at Mount Lamington volcano in Papua reached a height of 1,500 feet in only 6 weeks, and it grew as much as 100 feet vertically in a single day. The sides of domes are typically unstable and domes may be partly destroyed by landslides during or soon after their formation.

Lassen Peak, Chaos Crags, and the domes north of Chaos Crags are composed of a volcanic rock known as dacite. Dacite is distinguished from other kinds of volcanic rocks by the minerals it contains and by its chemical composition.

Erupted material generally falls or slides onto the flanks of a volcano, and may move down to or beyond the base of the cone as a nuée ardente, a hot or cold mudflow, or a rockfall-avalanche.

The term nuée ardente (literally, glowing cloud) is used in this report to designate a hot dry avalanche of rock debris that slides or flows down the side of a volcano; it may extend miles beyond the base of the volcano. The downslope movement of a nuée ardente is due chiefly to gravity. If the nuée is initiated by an explosion with a strong lateral component, the flow might start down the volcano with a large initial velocity and have a higher speed than if motivated by gravity alone.

Nuées commonly have two components: a basal flow of hot rock debris of many sizes, and an airborne cloud of fine material that moves downslope over the basal flow and also rises above it to heights of hundreds or thousands of feet. The cloud commonly spreads over a broader area than the basal flow; it is commonly accompanied by temperatures of several hundred degrees centigrade which may last for several minutes at a given location. Nuées ardentes may contain gas-rich or gas-poor rock debris. The basal flow of both kinds of debris overrides, traps, and incorporates air as it moves down a slope. This air is heated, expands, and gives the flow great mobility, so that the rock debris moves as a

fluid. In addition, gas given off by rock debris in some flows during movement reduces friction between the rock fragments and further increases the flow's mobility.

Nuées ardentes can be formed in several ways. A gas-poor nuée ardente might be caused by the expulsion of hot--but solid--rock debris from a vent in such great quantity that the fragments begin to slide downslope. Such a nuée might also be formed by the collapse of all or part of a volcanic dome while the rock of the dome was still hot. A gas-rich nuée can originate when a mass of molten rock rises into a crater, and then boils over the sides as gas pressure shatters it into countless fragments of extremely hot, viscous, gas-emitting lava.

A mudflow is a mass of water-saturated rock debris that moves downslope as a fluid under the influence of gravity. Requirements for mudflow formation are a source of loose rock debris having a significant proportion of fine-grained material (say 30-50 percent of material sand-size or smaller), a slope, and enough water to mobilize the rock debris under existing conditions. The rock debris on the slopes of a volcano commonly includes abundant newly erupted, fine-grained pyroclastic material, and water may be provided by rainfall, snow, or the overflow of a crater lake. Mudflows are sometimes started by lava flowing over snow, as was the case at Lassen Peak on May 19, 1915. The resulting water rushed down the northeast side of the volcano, picked up great quantities of loose rock debris, and became a mudflow that moved down the Lost and Hat Creek valleys for many miles. A nuée ardente moving across snow-covered ground might also start a mudflow.

Mudflows can be either hot or cold. The presence of a large amount of hot rock debris can heat up the entire mudflow, and movement will stop if the lubricating water in the mudflow evaporates. The deposits of a hot mudflow may be nearly indistinguishable from those of some nuées ardentes.

A rockfall-avalanche is formed when a mass of rock falls from a high cliff, and shatters on impact into a mass of fragmental material that moves swiftly downslope. Large rockfall-avalanches are sometimes launched into the air as they hurtle over a cliff or hill. Then, as

they settle back toward the ground, air can be trapped under them and compressed to such a high pressure that the moving sheet of debris is temporarily buoyed up by a cushion of air. Airborne avalanches move very swiftly--some at speeds exceeding 100 miles per hour. The temporary near-absence of basal friction has permitted some air-cushioned avalanches to move several miles beyond their place of origin. If the avalanche moves up onto a hill in its path, the approximate minimum velocity of the material can be calculated by assuming that there is no frictional loss of energy, and that the kinetic energy ( $\text{mass} \times \text{velocity}^2$ ) of the avalanche is wholly transformed into potential energy ( $\text{mass} \times \text{gravity} \times \text{height}$ ). The value of height in the potential energy formula is the height to which the avalanche rises on an obstacle in its path.

#### Appendix B

##### Microearthquakes near Lassen Peak, California

by John D. Unger and John Coakley

Eight portable seismographs were in operation around Lassen Peak volcano from August 13 to August 26, 1969. These instruments recorded only vertical ground motion. During the 13 days, 29 events were recorded at three or more seismographs, or an average of 2.2 events per day. This average is similar to the 1.2 events per day recorded by a single high-gain, portable, smoked-paper seismograph operated by the Geological Survey during an 89-hour interval at Manzanita Lake near the end of August 1969.

Epicenters of the seismic events recorded on the Lassen Peak network were determined by computer. The hypocenters showed no clustering around either Lassen Peak or the Chaos Crags. The only concentration of earthquake epicenters was near Brokeoff Mountain, which is on the western rim of a caldera formed by the collapse of ancient Mount Tehama. The floor and walls of the now-eroded caldera contain many normal faults, along which, according to Williams, are found hot springs and other hydrothermal features. Most of the microearthquakes of this cluster occurred in a small swarm on August 20. The remaining epicenters are in a wide, poorly defined NNW-SSE zone that passes through Lassen Peak.

This zone also contains normal faults and some areas of hot springs and steam vents.

The magnitudes of the microearthquakes determined in this study range from -0.9 to 1.9; these are too weak to be felt, and can be detected only by seismographs. This distribution is similar to the range of magnitude of the microearthquakes around Mount Rainer, -1.0 to 1.2, recorded during the summer months of 1968 and 1969.

Caution must be used in extrapolating the results of this study because the recording interval was so short. Since the early 1930's various semi-permanent seismographs at Manzanita Lake, Mount Harkness, and Mineral have recorded for rather long periods of time. Records from these seismographs show periods of several months when the seismicity of the Lassen region has increased markedly. This seismicity is in the form of local earthquake swarms during which the frequency of occurrence of local events is 2-3 orders of magnitude greater than normal. The instruments which recorded the different swarms have sensitivities at least a factor of 10 less than the portable seismographs used by us. These swarm-like periods of high seismicity have been reported to occur typically every 10-20 years. With this picture of local seismicity in mind, it seems that the portable instruments were recording in the Lassen region during one of the normal, more quiet intervals. Of course, the background of seismic activity reported here may not have any spatial relationship to the swarm-type activity. The Lassen Peak network should be reoccupied in the future when a new episode of earthquake swarms occurs.

#### Appendix C

##### Age of the Chaos Jumbles

The principal evidence that led Heath to conclude that the successive avalanches that formed Chaos Jumbles were widely separated in time was described by him in 1960 as follows:

"The most recent avalanche shows a paucity of trees and almost no shrubs at all. The dacite fragments are sharp and essentially unweathered and soil pockets of any kind are rare \* \* \*."

"The middle avalanche deposit is characterized by taller and more numerous trees, in some parts by a distinctive cover of bitterbrush (Purshia tridentata) and some other shrubs, and by dacite which is definitely grayer and exhibits many weathered fragments. In many parts of this avalanche deposit, soil has developed in the interstices so that in the areas of heaviest cover there is an actual mat of needles and soil \* \* \*."

"The first of the three avalanche deposits \* \* \* exhibits the greatest difference from the others; its cover is that of a nearly mature or sub-climax forest and most of the surface is mantled with soil. In addition, the hummocks on the surface are much more rounded and flatter than those elsewhere in the Jumbles, their slopes departing much farther from the angle of repose. Furthermore, scattered pieces of the Table Mountain lavas have drifted over the avalanche deposit in many places. Such transport must have required a long period of time."

These criteria mentioned by Heath, which differentiate the youngest and oldest avalanches, include the character of vegetation and several geological attributes: soil development, sharp edges of rock fragments, slopes on loose debris, and presence of large basalt fragments on the oldest avalanches. The geological conditions are examined first, because it is clear that they strongly influence the character of the vegetation.

In order to evaluate Heath's statement that there is progressively less "soil" and less weathering on the avalanche deposits from oldest to youngest, shallow pits were dug into material of similar texture, and corners and edges of rock fragments examined on the oldest and youngest deposits. No discernible difference was found in the degree of oxidation or of edge-rounding in the two deposits--both are typically gray even at the ground surface and contain similarly sharp fragments. At one locality, near the west entrance of the park, a very faint brownish discoloration was noted on rock fragments in the uppermost 1-2 inches of the oldest avalanche deposits. A comparable discoloration was also

seen in the youngest avalanche deposit at one place about half a mile east of Reflection Lake. In contrast, material of similar texture in the 1,000-year-old nuée ardente deposits along Manzanita Creek is lightly oxidized to a depth of as much as 10 inches.

A larger proportion of "soil" or fine material does seem to be present directly at the ground surface of the oldest avalanche deposit than of the youngest. This does not necessarily prove a substantially greater age for the oldest deposit, however, because the difference in texture could have resulted from a different character of the source rock of the two deposits or from the amount of disintegration during the movement of the rockfalls and avalanches. Similar differences of lithology, texture, and topography have been noted by Crandell in the deposits of seven separate avalanches that originated on the northeast side of Mount Rainier in December 1963. The avalanches at Mount Rainier all occurred within a short period of time--perhaps within minutes of each other, certainly all within a period of not more than 2 months. The more-rounded surface topography of the oldest avalanche deposit of the Chaos Jumbles, which Heath noted, probably is a function of its finer texture. Furthermore, this finer texture also may cause the oldest deposit to be more water-retentive than the coarser, more blocky youngest deposit.

Heath reported that basalt fragments are present on top of the oldest avalanche along its north margin, which came from rock outcrops on the south slope of Table Mountain. He inferred that a long time must have elapsed in order for these rocks to have moved downslope onto the surface of the avalanche. Our examination of the north margin of the oldest avalanche east of Summertown verified the presence of the basalt rock fragments. However, some of these must have been transported by the avalanche itself, because they are at the tops of knolls or ridges that are as much as 20 feet higher than the surrounding surface. Slow downslope transport from Table Mountain cannot explain the presence of these blocks, and thus they have no bearing on the age of the oldest avalanche deposits.

We believe, therefore, that the geologic evidence does not support the hypothesis that the youngest and oldest deposits are of significantly different age. The oldest avalanche does have a finer texture, however, which helps to explain the difference in tree sizes between the two deposits. Williams also recognized the difference in texture in different parts of the Jumbles and noted that the trees are larger where fine material is present.

Heath associated the striking differences in the vegetative cover with the ages of the three different avalanche deposits he described, and noted that the oldest deposit is covered by very large trees, whereas the youngest is sparsely vegetated by small trees. Robert S. Sigafos of the U.S. Geological Survey examined the forests of the Jumbles and surrounding areas on September 1-3, 1969, and pointed out that solely from the appearance of the forest, the distinction of the boundary between the Jumbles and the adjacent, older surface is difficult in most places.

From studies of trees growing on the surface of the youngest avalanche deposit, Heath concluded in 1959 that the avalanche occurred between 263 and 275 years ago. In an article written in 1967 he estimated the age of the youngest deposit to be about 300 years and the middle deposit to be between 2 and 3 times as old as the youngest; he referred to the middle one as the "750-year avalanche." He believed the oldest avalanche to be at least twice as old as the middle one, and referred to it as the "1,500-year avalanche." However, inasmuch as all of the avalanche deposits are younger than the Chaos Crag domes, which in turn are younger than the nuée ardente deposits exposed along Manzanita and Lost Creeks, we believe that none of the avalanche deposits can be more than about 1,100 years old.

It seems that the ages assigned by Heath to the "oldest" and "middle" avalanches were based on the geologic character of the deposits and size of trees rather than on ages of trees cored. Four trees examined by Heath on the intermediate deposit were all somewhat more than 200 years old, and one was 261 years old in the late 1950's. Of three trees Heath selected at random on the oldest deposits, the oldest was 284 years old.

During the course of our studies, Crandell counted the growth rings of about 20 stumps of trees in three different areas of the "oldest" avalanche deposits. These stumps had diameters of 30-50 inches, and had been cut at heights of less than an inch to 6 feet above the ground surface. The tree that seemed to be the oldest of those examined had about 280 growth rings at ground level. The innermost 30 growth rings were very wide and occupied the inner 16 inches of the tree's 50-inch diameter; thus the tree grew very rapidly in its early life. Two other trees had 260 growth rings at a stump height of about 1 foot; one of these had 37 growth rings in the first 16 inches of the tree's diameter. All but one of the 20 stumps examined had wide rings in the inner 16-22 inches of the diameter, and the years represented by the wide rings ranged from 30 to 50.

Neither Heath's tree-ring counts nor our study indicate that the oldest trees on the "oldest" avalanche deposit are appreciably older than those on the "youngest" deposit; thus, the trees on the "oldest" Jumbles are not bigger simply because they are older. Heath recognized this fact, and implied that the trees on the "intermediate" and "oldest" deposits do not represent first-generation forests. However, he also noted that old forests that exist beyond the limits of the "oldest" avalanche deposit include some trees that are well beyond the usual maximum age for the species; in addition, these areas contain "numerous scattered logs in various stages of decay \* \* \*." One recently cut stump of a Ponderosa or Jeffrey pine, in a nearby old forest like the one described by Heath, is about 4 feet in diameter at a height of 18 inches above the ground; about 530 growth rings were counted in this stump, 100 of which are in the first 8 inches of the diameter. In contrast, trees that are substantially older or larger than the average, or abundant decaying logs, were not described by Heath on the surface of the "oldest" avalanche deposit, nor were they observed by us.

The distribution and growth of the two kinds of forests that are typical of the "oldest" and "youngest" avalanches are believed by Sigafos to be related to their distance from the seed source and the effect of the fine material upon moisture available to the seedlings.

The "youngest" avalanche generally is more than a quarter of a mile from trees bordering the Jumbles, whereas the "oldest" avalanche forms much of the margins of the Jumbles. Yet, amounts of seed adequate to assure full restocking of a barren area can travel only 150 to 300 feet from the source forest, according to a 1965 report of the U.S. Forest Service. Thus, seed supplied to the "oldest" avalanche generally would be abundant, and seed reaching the youngest avalanche in the central part of the Jumbles would be sparse. Further, seed must have moisture to germinate and grow well. The center of the "youngest" Jumbles avalanche apparently is seasonally dry because of the climate and the coarse nature of the deposit there. Most precipitation falls as snow in winter and spring and only occasionally in summer as rain. When air temperatures become high enough for seed to germinate, the snow generally has disappeared, and the meltwater from it has moved into deeper parts of the coarse, blocky "younger" avalanche than into the finer-textured oldest deposit. The surface of the "younger" deposit dries rapidly and may remain dry throughout the summer and fall.

Dr. Sigafos suggested to the writers that the rapid early growth of the trees on the "oldest" avalanche could be explained if all the trees germinated in an open area where there was adequate moisture as well as abundant sunlight. A few of the largest trees on the "oldest" Jumbles have large dead branches nearly to their base; thus, they had a form early in life similar to trees that grow in the open. If this was indeed the cause, it would imply that all of the large trees on the oldest deposit started to grow as scattered individuals, a circumstance that could be explained if the trees were the first to grow on the deposit, or if they all started to grow after some event such as a forest fire destroyed previous vegetation. But those conditions would not have existed during seeding of a second generation forest.

In contrast, the slow rate of growth exhibited by trees on the "youngest" Jumbles very likely is related to the extremely coarse texture of the deposit and a low amount of moisture in the upper part of the deposit during the growing season. Heath noted that western white pines on the "youngest" avalanche deposit are dwarfed and distorted,

whereas those on the "middle" and "oldest" deposits are large and normally developed. He suggested the possibility that the roots of the large trees extend below the bottom of the avalanche deposits, but it seems more likely that the cause for the disparity lies in different water-retentive characteristics of the deposits.

We conclude that the differences in form and distribution of trees within the Chaos Jumbles can be best explained by differences in the geologic environment. No evidence was found to suggest that these two types of forests are different because the surfaces upon which they grow are of different age. The absence of features indicative of an old forest, and an apparent lack of a difference in weathering between the "oldest" and "youngest" avalanche deposits, suggest that all of the deposits are of about the same age, and the tree-ring data indicate that they all originated about 300 years ago.

#### Appendix D

##### The nature and relative dangers of volcanic gases

The following paragraphs are taken verbatim from a paper entitled "Some effects of recent volcanic ash falls with especial reference to Alaska" by Ray E. Wilcox (U.S. Geol. Survey Bull. 1028-N, p. 409-476, 1959). The reader interested in the effects of ash falls is encouraged to examine other sections of this informative report.

"Of immediate concern to the individual are his own personal health, safety, and continued efficiency. Many people at once associate the ash from volcanic eruptions with noxious gases and poisonous chemicals, and the terms "sulfurous fumes" and "toxic gases" are used more often than warranted in descriptions of eruptions. It is true that the odors of certain acid gases are frequently detectable in areas of falling ash, but at a distance from the vent the concentrations are usually only temporary and no more than met with in an adequately ventilated chemical laboratory, in which atmosphere the chemist works year after year with no ill effects.

"Some of the materials erupted as vapors, such as water, quickly condense in large part on liquids, while others such as carbon dioxide and sulfur dioxide may remain as gas for some time and gradually become diluted by mixing with the atmosphere. The odor characteristic of volcanic eruptions, frequently ascribed simply to "sulfur," may often be due to burned sulfur, that is, sulfur dioxide, less often sulfur trioxide, or to hydrogen sulfide, but it is rarely justifiable to presume that other gases are not present. In many cases where "sulfurous" fumes have been noted by sense of smell, it has been found by analyses that several other gases are in equal or greater quantities. These other frequently-present gases include hydrochloric acid, hydrofluoric acid, carbonic acid (carbon dioxide), and ammonia.

"All these gases may be harmful if inhaled in sufficient concentration for a sufficient length of time. The accompanying list gives the maximum concentration of industrial gases considered permissible for workers in steady contact (Sax, 1951), but somewhat greater concentrations of some of the gases can be tolerated for short periods of time. Thus, while 10 parts per million of sulfur dioxide is regarded as the maximum allowable concentration for continuous exposure, as much as 50 to 100 parts per million can be tolerated for exposures of half an hour to one hour duration. Ammonia, although perhaps common at the vents of some volcanoes, may be expected to quickly form less harmful compounds by reaction with one or more acid gases usually present in excess. Carbon dioxide is harmful only in very high concentrations, when it acts as a diluent of oxygen. Its density causes it sometimes to collect in low places where it may be a hazard, especially because of its lack of warning odor.

"Most of the other common volcanic gases are acidic, and have similar injurious effects, that is, irritational injuries to the eyes (conjunctivitis) and to the respiratory system (lung or bronchial edema). It is not possible to prescribe complete protective measures for all volcanic situations, and a properly fitted industrial gas-mask with acid-type filter is best. In the common case where such special equipment is lacking, it has been found a practical expedient to breathe through a dampened folded cloth, and if the eyes smart, to wear air-tight goggles. As the action of the damp cloth is to trap the acidic gas in the moisture of the cloth, it is advisable to renew the effectiveness of the cloth at intervals by rinsing.

"The sulfur-derivative gases deserve special attention because of the complexity of their relationships and the variety of effects under different conditions. In a strongly reducing environment the sulfur derivative may come forth as hydrogen sulfide, recognized by its well-known odor of rotten eggs. In a strongly oxidizing environment, the sulfur derivative may be sulfur dioxide, recognizable as the odor of a flaring match. It happens not infrequently that the conditions are neither strongly oxidizing nor reducing, and the product then may be a mixture of both gases. In the air their conversion to the stable sulfur trioxide or sulfuric acid goes on only slowly, in spite of the readily available oxygen, and in the absence of a catalyst the two original gases may persist for many miles downwind, with the concentration of the much-blamed "sulfuric acid" actually remaining quite low. This is not to say that sulfuric acid is rare or unimportant in volcanic products, for it no doubt comes out ready-formed in many eruptions. Its potency as a

# Effects of industrial gases on humans

[Generalized from Sax, 1951]

| Gas                              | Initially detectable odor (ppm) | Maximum allowable continuous exposure (ppm) | Effects of overdose                                                                           |
|----------------------------------|---------------------------------|---------------------------------------------|-----------------------------------------------------------------------------------------------|
| Ammonia. . . . .                 | 53. . . . .                     | 100. . . . .                                | Conjunctivitis, retention of urine, lung edema.                                               |
| Carbon dioxide . . . . .         | Odorless. . . . .               | 5,000. . . . .                              | Coma, asphyxiation.                                                                           |
| Carbon monoxide. . . . .         | . . . . .                       | 100. . . . .                                | Headache, dizziness, nausea, asphyxiation.                                                    |
| Chlorine . . . . .               | 3.5 . . . . .                   | 0.35 . . . . .                              | Conjunctivitis, lung edema.                                                                   |
| Fluorine . . . . .               | . . . . .                       | 1 mg/cu M. . . . .                          | Conjunctivitis, skin irritation, bone degeneration, lung inflammation.                        |
| Hydrochloric acid. . . . .       | . . . . .                       | 5. . . . .                                  | Conjunctivitis, edema or spasm of the larynx.                                                 |
| Hydrofluoric acid. . . . .       | . . . . .                       | 3. . . . .                                  | Eye irritation, blindness, skin burns, lung edema.                                            |
| Hydrogen sulfide . . . . .       | . . . . .                       | 20 . . . . .                                | Photophobia, inflammation of cornea and respiratory tract.                                    |
| Sulfur dioxide . . . . .         | 1 . . . . .                     | 10 . . . . .                                | Conjunctivitis, lung edema, lung paralysis.                                                   |
| Sulfur trioxide. . . . .         | 1 . . . . .                     | 2. . . . .                                  | Irritation of mucous surfaces, inflammation of lungs.                                         |
| Sulfuric acid (aerosol). . . . . | . . . . .                       | 1. . . . .                                  | Skin burns, lung damage (wide variation in individual susceptibility to respiratory effects). |

respiratory irritant is certainly decreased in this situation, however, by its existence not as a gas but as aerosol droplets which tend to take on moisture from the air to further dilute themselves and grow to sizes more likely to be filtered out of the inhaled air."

#### Appendix E

##### Suggested visitor guidance and protection measures at Bumpass Hell

The following comments with regard to improvements in visitor guidance and protection at Bumpass Hell are keyed to the numbered posts that are used for the interpretation program.

Post no. 18. Many visitors leave the trail here. Low railings between posts 18 and 19 should reduce cross cutting.

Post no. 19. There are several steam vents within 8 feet of the post. We recommend the construction of a bridge or a duckboard from the post to a point about 21 feet to the east. Visitors should not leave the post area here because of possible danger of breaking through into hot steaming ground. We recommend that a low platform with a railing be placed at post 19, and the addition of a sign warning the visitor to stay on the path.

Post no. 22. A warning sign DO NOT LEAVE TRAIL should be placed at a point about 40 feet east of post. The visitor is directed to note the white mound beside the trail at a point about 100 feet east of post 22. Observation revealed that many visitors walk onto the white mound, then proceed northward downslope into the basin instead of returning directly to the trail. A sign and railing should reduce cross cutting here.

The trail into Bumpass Hell should be identified at its junction with the trail to Cold Boiling Spring.

Post no. 24. The trail crosses hot ground from a point about 8 feet south of post 24 to the bridge across the outlet creek. A duckboard should be placed here on both sides of the creek, and should extend at least as far as a point 12 feet northeast of the creek.

Near this point, most people proceed northward to the pole that

bears the first aid box, even though they should head eastward in order to visit the points of interest in the sequence in which they are explained in the guidebook. During 30 minutes of observation on August 31, 57 out of a total of 72 visitors entering Bumpass Hell went the wrong way here. Some went as far as post 39 before retracing their steps. Many took short cuts in order to get back to the trail heading east. A sign should be placed at the outlet creek crossing to indicate the correct direction.

East of the outlet creek there is hot ground from a point 8 feet west of the DANGER STAY ON TRAIL sign, eastward for about 45 feet. Parts of this area vibrate markedly when struck. We recommend construction of a duckboard across this area. The trail east of the danger sign should be more clearly indicated.

Post no. 26. There is hot ground and much ground vibration from a point 25 feet west of post 26 to a point 25 feet southeast of post 27. A duckboard and railings should be placed along this part of the trail, as well as a sign warning visitors to stay out of the fumarole area south of the trail.

Post no. 28. The path needs to be more clearly marked from post 28 to post 30.

Post no. 30. A railing should be added along the south side of the trail from a point 18 feet west of post 30 to post 31.

Post no. 37. A railing should be placed along the north side of the trail from a point 35 feet east of post 37 westward to a point 10 feet west of post 38.

A duckboard should be placed from a point 25 feet west of post 37 westward to a point 30 feet east of post 38, and a bridge should be placed across the boiling spring 40 feet east of post 38.

Post no. 39. A duckboard and railings should be added to the trail from a point 30 feet north of post 39 to the spur trail that leads to post 40. Many visitors leave trail south of post 39 because of inadequate marking; this is especially dangerous at a point 15 feet south of the post because of a spouting hot spring.

Post no. 40. A duckboard and railings should be placed on the spur trail to post 40, and a warning sign DO NOT GO BEYOND THIS POINT should be placed at the post.

A duckboard should be placed on the trail across the area of previous collapse from the post 40 spur trail southward for 20 feet.

Post no. 43. There is little protection against a visitor slipping into the boiling spring here. A small boy nearly fell into this spring while Crandell was observing this area. A railing should be placed between the trail and the spring.

Many visitors were observed to cut across from post 45 to the area near post 41; these were mostly people who had proceeded into the area going the wrong direction. The cross-cutting route crosses an area of fumaroles and seems very dangerous. A sign should be placed near post 41 advising visitors not to leave the trail because of danger.

#### Appendix F

##### Measurements of rock dislocations at Diamond Peak

Measurements were made at several localities on Diamond Peak on July 26, 1969, to permit recognition of possible future movements of the three large detached blocks of rock. The localities were marked with white paint which may not survive from one year to the next. If the National Park Service wishes to conduct similar measurements in order to detect movements of the blocks in the future, a more permanent marker system should be devised, such as metal spikes cemented into holes made in the rock with a star drill. The blocks are identified below with the letters given them on figure 3.

##### Block A

All of the measurements were made along a crack that separates the south edge of block A from the adjacent bedrock. The measuring points are identified with white paint.

Locality

Distance (ft.) between  
points indicated on rock

N1

3.47

|    |      |
|----|------|
| N2 | 1.16 |
| N3 | 1.27 |
| N4 | 0.69 |

#### Block B

Locality S1 is on the north side of the block, S2 is at a crack at the southeast corner of the block, and S3 is high on the southwest corner of the block.

| <u>Locality</u> | <u>Distance (ft.) between<br/>points indicated on rock</u> |
|-----------------|------------------------------------------------------------|
| S1              | 1.16                                                       |
| S2              | 0.78                                                       |
| S3              | 2.60                                                       |

#### Block C

The measuring points are located on the opposite sides of a crack at the northwest corner of the block.

| <u>Locality</u> | <u>Distance (ft.) between<br/>points indicated on rock</u> |
|-----------------|------------------------------------------------------------|
| M1              | 3.02                                                       |