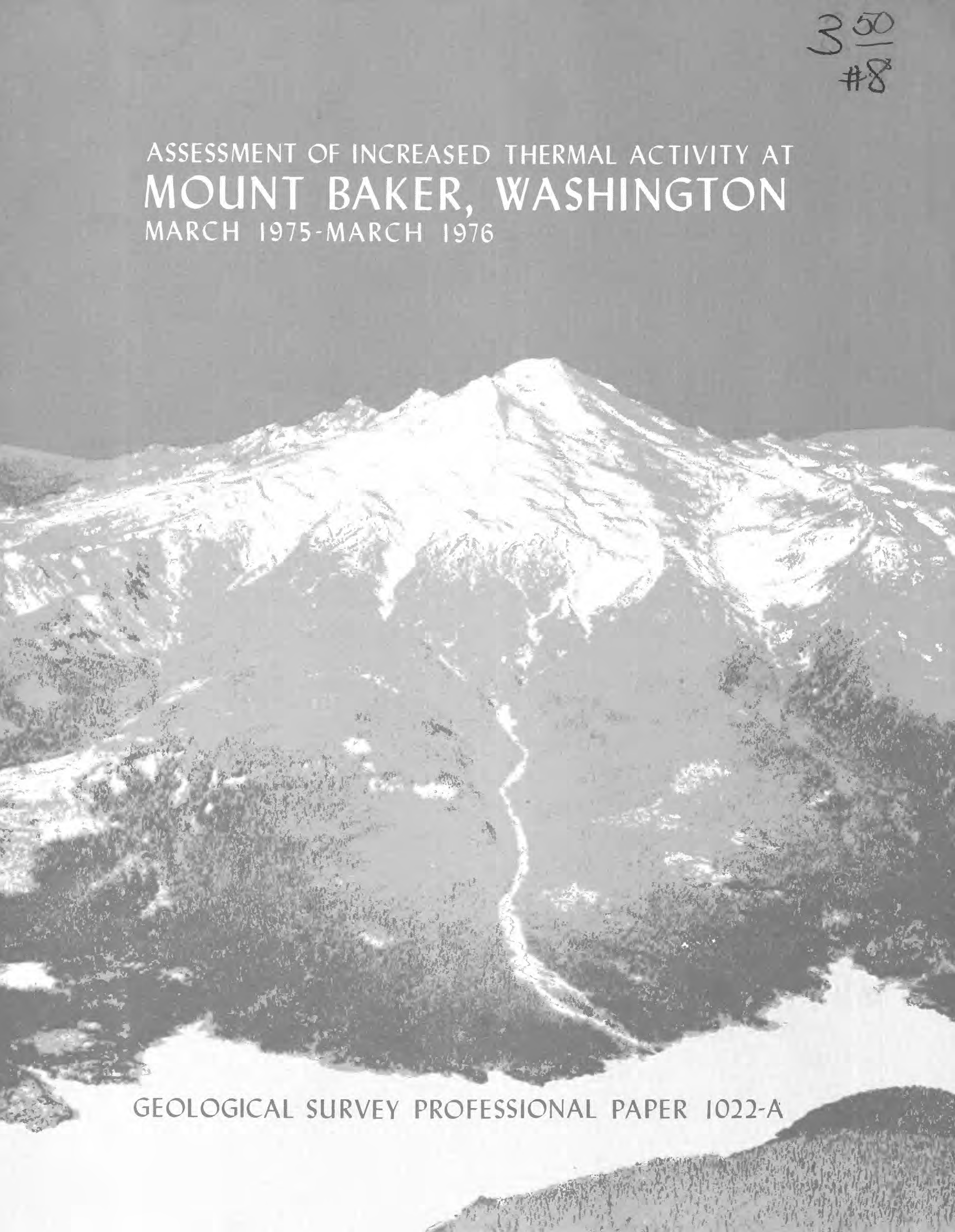
ASSESSMENT OF INCREASED THERMAL ACTIVITY AT MOUNT BAKER, WASHINGTON MARCH 1975-MARCH 1976



GEOLOGICAL SURVEY PROFESSIONAL PAPER 1022-A

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Frontispiece. — Mount Baker Volcano. Mount Baker stands more than 3 km above Baker Lake. Acidic water drains through the breach in the east rim of Sherman Crater (top center), flows beneath Boulder Glacier and into Boulder Creek, and eventually empties into Baker Lake (foreground), 12 km east of the crater. Aerial photograph taken March 4, 1976.

Assessment of Increased Thermal Activity at Mount Baker, Washington, March 1975–March 1976

By DAVID FRANK, MARK F. MEIER, *and* DONALD A. SWANSON

with contributions by JAMES W. BABCOCK, MARVIN O. FRETWELL,
STEPHEN D. MALONE, CHARLES L. ROSENFELD, RONALD L. SHREVE, *and* RAY E. WILCOX

VOLCANIC ACTIVITY AT MOUNT BAKER, WASHINGTON

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A summary of geothermally induced changes, progress report on geophysical and geochemical monitoring, and analysis of hazards at Mount Baker

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1977

UNITED STATES DEPARTMENT OF THE INTERIOR

CECIL D. ANDRUS, *Secretary*

GEOLOGICAL SURVEY

V. E. McKelvey, *Director*

Library of Congress Cataloging in Publication Data
Frank, David.
Assessment of increased thermal activity at Mount Baker, Washington, March 1975-March 1976.
(Volcanic activity at Mount Baker, Washington)
(Geological Survey Professional Paper 1022-A)
Bibliography: p.
Supt. of Docs. no.: I 16:1022-A.
1. Baker, Mount, Wash. 2. Earth temperature—Washington (State)—Baker, Mount.
I. Meier, Mark F., joint author. II. Swanson, Donald A., joint author. III. Title. IV. Series. V. Series: United States Geological Survey Professional Paper 1022-A.
QE523.B18F7 551.2'1'0979773 76-608347

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402
Stock Number 024-001-02981-2

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ABBREVIATIONS

A ..... area
BM ..... bench mark
cm ..... centimeter
ft^3 ..... cubic foot
m^3 ..... cubic meter
°C ..... degree Celsius
db ..... decibel
d ..... day
D ..... average snow and ice thickness
FM ..... frequency modulation
ft ..... foot
H ..... heat flux
h ..... water equivalent thickness
hr ..... hour
Hz ..... hertz
J ..... joule
kg ..... kilogram
km ..... kilometer
L ..... latent heat of melting
l ..... liter
m ..... meter
mGal ..... milligal
M_L ..... local earthquake magnitude approximated by coda length
mm ..... millimeter
mo ..... month
MW ..... megawatt
μm ..... micrometer
μrad ..... microradian
ppb ..... parts per billion
ppm ..... parts per million
ρ ..... density
s ..... second
ft^2 ..... square foot
m^2 ..... square meter
t ..... time
W ..... watt
yr ..... year
10^3 ..... thousand
10^5 ..... hundred thousand
10^6 ..... million
10^7 ..... ten million
10^9 ..... billion

TERMINOLOGY

Air-cushioned avalanche. An avalanche of debris that moves at high speed on a cushion of trapped air.

Avalanche. A large mass of snow, ice, soil, or rock, or mixtures of these materials, that falls or slides at high speed under the force of gravity.

Debris flow. A mudflow; also used as a rapid mass flowage of coarse rock debris.

Ejecta. In this report, fragmental airfall debris produced by fumarolic activity.

Eruption. The ejection of volcanic material by a process triggered by a magmatic source.

Firn. Snow that remains after at least one melting season.

Friction coefficient. A characteristic of mass movements, such as avalanches or mudflows; the vertical drop divided by the horizontal distance of travel.

Fumarole. A vent having a diameter of a few centimeters to several meters at the ground surface, from which volcanic gases and water vapor or steam are exhaled, often at high temperatures.

Fumarole field. A cluster of fumaroles and associated warm ground.

Fumarolic activity. The surficial expression of noneruptive heat emission from a subsurface source, which may be a recent lava flow, a cooling body of magma or hot rock (either rising or already in place), or a hydrothermal system of hot water or steam.

Geothermal. Pertaining to heat from beneath the earth's surface.

Heat flux. The flow of heat per unit time.

Heat flux density. The heat flux per unit area.

Hydrothermal activity. The action of heated water within the earth.

Hydrothermal alteration. The chemical and physical transformation of rock by reaction with heated water.

Lahar. A mudflow which originates on a volcano.

Lava. Molten rock near or on the ground surface, relatively poor in gas content; also the same material after it has cooled and solidified.

Magma. Molten rock at some depth. Differs from lava in that it contains more gases, which are lost as magma nears the surface and changes to lava.

Mudflow. A mass of water-saturated rock debris that moves downslope under the force of gravity.

Pyroclastic flow. A hot, dry mass of volcanic rock debris that moves away from an active volcanic vent.

Radiant flux. The flow of radiated heat per unit time.

Stratigraphic. Pertaining to layered deposits of rock.

Tephra. General term for airfall debris produced by a volcanic eruption. Includes but is not limited to ash, pumice, and bombs.

Thermal area. Spatial area of thermal ground.

Thermal ground. In this report, ground heated by a volcanic source.

Water equivalent. The amount of water that would result from the complete melting of a body of deposited snow, firn, or ice, expressed as thickness (depth) or volume.

ASSESSMENT OF INCREASED THERMAL ACTIVITY AT MOUNT BAKER, WASHINGTON, MARCH 1975–MARCH 1976

By DAVID FRANK, MARK F. MEIER, and DONALD A. SWANSON

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ABSTRACT

In March 1975 Mount Baker showed a large increase in thermal emission, which has persisted for more than 1 year. Fumarole ejecta accompanied the thermal activity from March to September, but the ejecta had no constituents that suggest a magmatic source. Estimates of that part of the total heat flux that would account for the observed snow and ice loss show that the heat-flow increase was roughly one order of magnitude, from about 2 megawatts at 10 watts per square meter, averaged over Sherman Crater before 1975, to about 30 megawatts at 180 watts per square meter, during 1975. Almost half of the glacier that occupied the basin of Sherman Crater was melted in 1975.

The new activity generated great concern among the public and the government agencies responsible for geological evaluation of potential hazards and for protection of life and property. The past geologic history, current topography, rock alteration, and location of major fumarolic activity indicate that large rock avalanches and mudflows on the east slope in Boulder Creek valley are the potential hazards of most significance related to present conditions. The most probable types of large mass movements would be mudflows, having speeds of as much as 50 kilometers per hour, that would originate from mixtures of snow, ice, and melt water and avalanches of structurally weak clay-rich rocks that make up the rim of Sherman Crater. Similar mudflows from the volcano have traveled at least 12 kilometers 8 times during the past 10,000 years. A possible worst case event, however, might be a larger, air-cushioned avalanche of as much as 20 to 30 million cubic meters that could hit Baker Lake at speeds of more than 300 kilometers per hour and generate a wave of water large enough to overtop Upper Baker Dam.

At least 30 million cubic meters of potentially unstable material occurs as hydrothermally altered remnants of the rim of Sherman Crater and could provide the required volume for the estimated worst case event or for smaller avalanches and mudflows. An earthquake, steam explosion, or eruption could provide a suitable trigger to initiate movement. Although such triggering events were possible before 1975, the probability might have been as much as 10 times greater in 1975 because of the increased thermal activity. The threat of avalanches and mudflows on Boulder Creek valley and Baker Lake prompted the closure by management agencies of the Boulder Creek drainage and of Baker Lake and its shoreline in the summer of 1975. Additionally, Baker Lake was kept below full pool at a level calculated to prevent overtopping of Upper Baker Dam by waves which could result from a worst-case avalanche.

In 1975 an interdisciplinary program of seismic, tilt, gravity, gas, hydrologic, petrologic, thermal infrared, and photographic studies by Federal and university scientists was initiated to evaluate the impact of the current thermal activity and to monitor changes that might indicate an impending eruption. By March 1976 only one small earthquake had been identified beneath Mount Baker. Tilt and gravity changes have been observed but cannot be attributed solely to volcanic causes. The data available thus far provide no evidence of an impending eruption, but they cannot be fully interpreted without many additional geophysical and geochemical measurements, as it is not yet possible to clearly distinguish volcanic effects from nonvolcanic background effects.

Inasmuch as current activity continues unchanged — without steam explosions, eruptions, or frequent or large earthquakes — the probability of a suitable trigger for large avalanches and mudflows should decrease and should approach that of a more average year. Such an average year would have a hazard probability at least as great as that which existed before 1975, although that level of hazard was not recognized at the time by the public or by administrative agencies. The potential hazard and the uncertainties of future activity at Mount Baker necessitate continued observation and instrumental monitoring.

INTRODUCTION

Thermal activity at Mount Baker, Wash., increased drastically in March 1975 and led to speculation that a volcanic eruption might be imminent. Through the next 12 months, Mount Baker was the site of the most intensive monitoring ever applied to a volcano in the Cascade

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Range. By spring of 1976 the thermal activity had remained strong, but no further evidence of an impending eruption had surfaced; however, the collected data provide valuable insights into potentially hazardous processes that might be expected in the future at any quiescent volcano.

Mount Baker (48°47′ N., 121°49′ W.) is the northernmost of the Quaternary stratovolcanoes of the Cascade Range of northern California, Oregon, and Washington (Coombs, 1939). The summit is 3,285 m above mean sea level and 48 km east of Bellingham Bay. The volcano is drained on the east and south by tributaries of the Skagit River and on the west and north by headwaters of the Nooksack River (fig. 1). Owing to high precipitation and to the high latitude of the volcano, it is almost completely covered by glaciers.

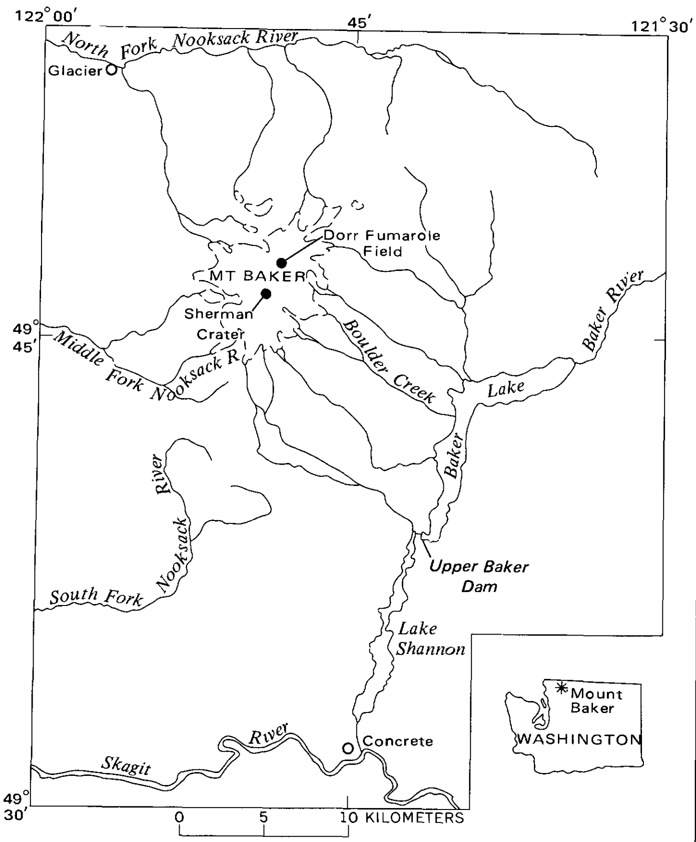


FIGURE 1. — Index map of the Mount Baker, Wash., area. Glaciers are outlined by dashed lines.

This report provides a compilation and discussion of thermal changes that occurred on Mount Baker between March 1975 and March 1976. Because many of the changes were detected primarily by visual observation, the historic record of the past 75 years is first reviewed to place current activity into perspective with older thermal features. Geochemical and geophysical monitoring activities during the past year are then summarized, and significant results are discussed. Finally, existing and potential hazards are evaluated, and the resultant administrative and public responses are described.

ACKNOWLEDGMENTS

Data concerning pre-1975 activity were derived from photographs and reports from various mountaineering sources; from aerial photographs, primarily by Austin Post, taken from glacier research and kept at the U.S. Geological Survey Project Office, Tacoma; from recent field and infrared remote sensing studies by the U.S. Geological Survey; and from the University of Washington investigations of volcanic seismicity. Special appreciation is extended to Alex Horstman, S. M. Lea, Peter Shreve, M. A. Spiers, and I. J. Virsnieks, who, without any foreknowledge that we are aware of, provided assistance in acquiring valuable field data during 1972–74 that established much of the basis on which to judge the extent of recent changes.

Data on 1975–76 activity were drawn from interdisciplinary studies by researchers of the U.S. Geological Survey, U.S. Forest Service, Los Alamos Scientific Laboratory, University of Washington, Eastern Washington State College, Western Washington State College, Oregon State University, and Central Oregon Community College. Some of those most involved in the present monitoring programs at Mount Baker include S. D. Malone, seismicity and gravity; R. M. Krimmel and Austin Post, aerial photography; Motoaki Sato, gas chemistry; J. E. McLane, J. W. Babcock, and R. E. Wilcox, petrography; D. A. Swanson and W. T. Kinoshita, spirit-level tilt; Rex Allen, Anselmo Rodriquez, J. D. Unger, and D. H. Harlow, borehole tiltmeters; Bruce Nolf, tilt-bar stations; C. L. Rosenfeld, infrared studies; and G. C. Bortleson, M. O. Fretwell, and A. D. Zander, water quality. The sections on monitoring in this report were compiled from summaries prepared by many of these individuals.

PRE-1975 THERMAL ACTIVITY

The history of volcanic activity during the past 10,000 years has been reviewed by Hyde and Crandell (1975, 1977), who found stratigraphic evidence of a major eruptive episode of pyroclastic flows, lava flows, and tephra during the early part of this time period. These eruptions were followed by at least two small eruptions of tephra, the most recent of which was within the past few hundred years. Historic reports of eruptive activity were reviewed by Malone and Frank (1975), who found references to eruptions of tephra and, possibly, lava flows during the mid 1800's. However, no definite correlation has been made between the most recent

FIGURE 2. — Dorr Fumarole Field, on the northeast slope of Mount Baker. A vapor plume (arrow) can be seen in this August 2, 1969, view of the field, which lies in a small cirque at the head of Mazama Glacier. Sherman Crater lies to the south, behind and to the left of the summit. Aerial photograph K692–16, by Austin Post.

deposits found by Hyde and Crandell (1975, 1977) and the 19th-century eruptions.

Reports by observers show that fumarolic activity has been common since the mid-1800's. Coleman (1869) reported fumarolic activity in 1868 in Sherman Crater about 1 km south of the volcano's summit, and William Henry Dorr[4] reported vapor emission on the north slope of the volcano in 1884 in an area now called the Dorr Fumarole Field (fig. 1).

Although no large changes have occurred recently at the Dorr Fumarole Field, it is described here because it has been overlooked in most of the literature concerning Mount Baker. In 1884 W. H. Dorr viewed what he thought was "a steaming crater on the northeast slope" of the volcano (fig. 2).

In 1906 a more extensive examination was made by Landes (1907, p. 6–7), State Geologist, who wrote:

> The steam vents occur over about 2 acres and this area is now wholly bare and free from ice. There are hundreds of vents from which steam is constantly escaping and in the summer air the vapor rises forty or fifty feet before it becomes invisible * * *. Along with the steam much sulphur is escaping, and for several miles away the odor of it may be detected. The sulphur in a variety of colors is being deposited upon the rocks about the vents. From many of the vents small streams of boiling water flow, and these unite in a brook that soon plunges beneath ice.

Landes' (1907) description could equally apply to present conditions. Aerial photographs taken since 1940, as

[4] Reported in C. F. Easton's "Mt. Baker, Its Trails and Legends," an unpublished 262-page compilation of photographs, newspaper articles, and manuscript commissioned in 1911 by the Mount Baker Club and kept in archives at the Whatcom County Museum of Natural History, Bellingham, Wash.

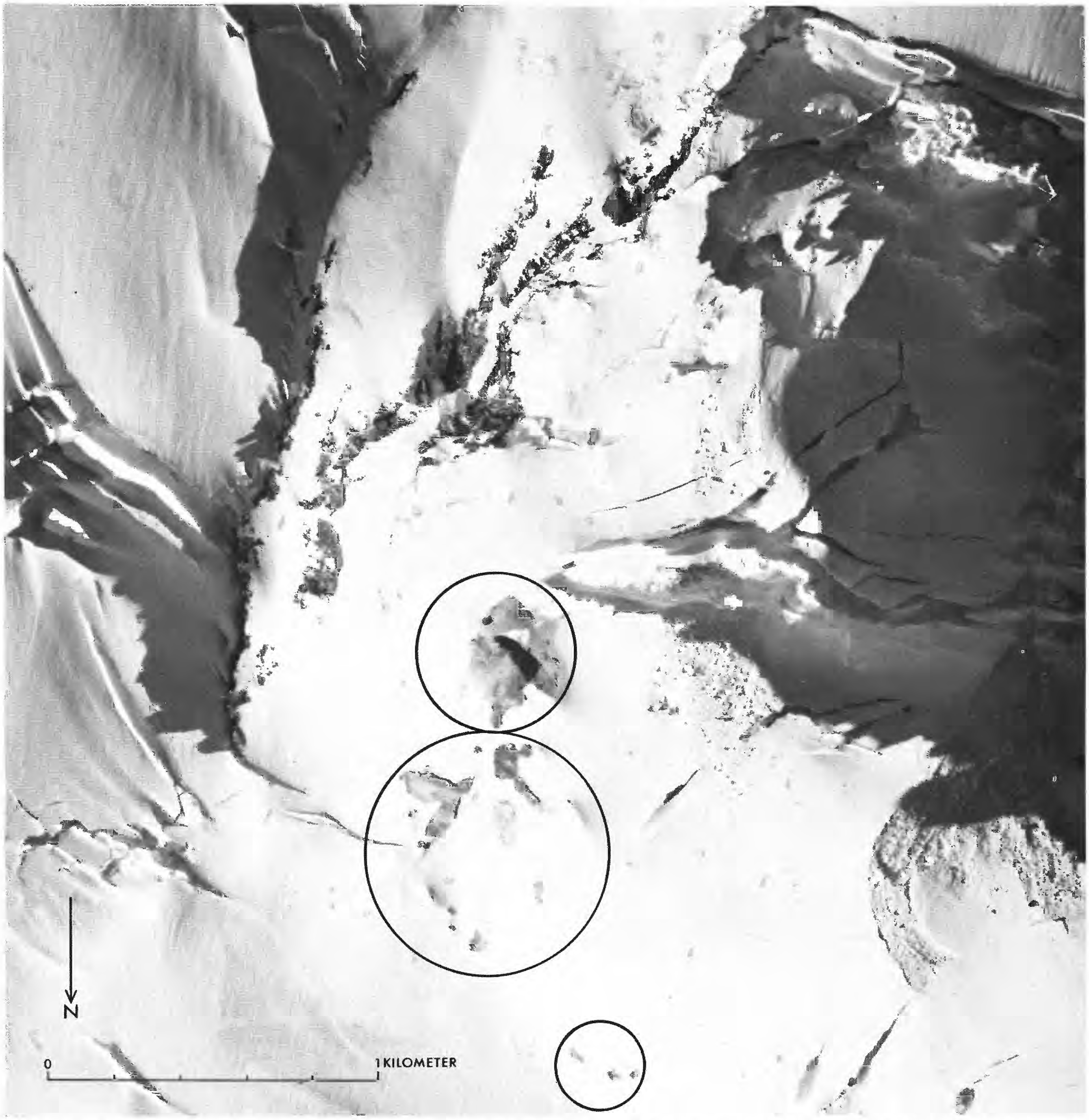


FIGURE 3.—Vertical view of Dorr Fumarole Field. About 4,900 m² of heated, snow-free ground (circled) is visible. Aerial photograph 75MB1–25, by R. M. Krimmel, June 10, 1975.

well as infrared thermographs made from 1970 to 1975, show little change in the area of snow-free thermal ground at the Dorr Field.[5] The midsummer size of the area, as measured from a 1975 photograph (fig. 3), is 4,900 m². Typically, the Dorr Field contains small fumaroles, generally a few centimeters across but in places as much as 20 cm, that have temperatures of about 90°–91°C, the approximate boiling point of water at that altitude. Vapor plumes from the area are usually visible from the air, and sometimes they may be seen from north of the volcano at Austin Pass.

[5] A report containing the results of an experiment to monitor temperature by satellite-transmitted data during 1973–74 at the Dorr Fumarole Field and an analysis of aerial infrared surveys of Mount Baker during 1970–73 is now being prepared by J. D. Friedman.

FIGURE 4. — Sherman Crater, viewed to the south from near the summit of Mount Baker, July 20, 1908. Reports of mountaineers as early as the 1890's mention sulfurous vapors which issue from an ice pit within Sherman Crater. The same prominent ice pit (arrow) as that of late 19th-century reports lies between Sherman Peak to the south and Lahar Lookout in the left foreground. Asahel Curtis photographed this early view.

Newspaper accounts record several climbers' reports of steam emission at Sherman Crater in the 1890's. A photograph taken in 1900, viewed southward from the top of Lahar Lookout, shows vapor issuing from a large ice pit near the east breach of the crater rim (Rusk, 1924, p. 130). The surface of the snow in the crater is otherwise very smooth; only a few crevasses are on the upper slopes of Sherman Peak, the highest part of the south rim of the crater. Figure 4 is one of a series of photographs with a similar view that were taken in late summer, in the early part of this century. These photographs all show a large ice pit near the east breach. By the time of our first field investigations, in 1972, the general ice cover in the crater was markedly lower than it was in 1900, either because of increased subglacial melting from volcanic heat or because of a decrease in glacier thickness generated by climatic conditions; however, the large ice pit was still present. Elsewhere in Sherman Crater, photographs taken during the early part of the century show small clusters of fumaroles (figs. 5, 6). Rough estimates of the amount of heated snow-free ground, as represented by the features visible in early photographs, indicate at least several hundred square meters of thermal area prior to 1940. These are minimum estimates because not all of the crater can be seen in early photographs.

The earliest available photographs that show the whole crater were taken in 1940 (Frank and others, 1975, fig. 3), a time that coincides approximately with a 20th-century minimum in glacial extent in the North Cascades (Hubley, 1956). If volcanic heat had been constant and in equilibrium with ice thickness in Sherman Crater since 1940, the extent of the snow-free thermal

FIGURE 5. — Fumarole cluster on the west rim of Sherman Crater, 1909. Photograph by Henry Engberg.

FIGURE 6. — Part of the west-rim thermal area, 1914. Photograph by Clyde Banks.

FIGURE 7. — Northward view of the old main fumarole near the east breach of Sherman Crater, August 16, 1974. This fumarole lies at the south base of Lahar Lookout.

area would have decreased after 1940 as the glacial cover increased at high altitudes. Instead, aerial photographs taken during late-summer snow conditions in 1940 and almost every year since 1956 show that the snow-free thermal ground in Sherman Crater has increased from about 5,500 m^2 in 1940 to almost 10,000 m^2 during the past decade. A thermal-infrared survey in November 1972 found 8,800 m^2 of infrared anomalies warmer than 0°C in Sherman Crater (Frank and others, 1975, p. 84). This value is in good agreement with our estimates of the thermal area made from the more recent aerial photographs (1966 and later).

Field investigations in 1972–74 showed that thermal features consisted of warm ground and small fumaroles. The fumaroles were generally a few centimeters across, although some were as large as 50 cm, and all had temperatures at or below 90°C. Fumaroles occurred in clusters along the southwest, west, and northwest rims and near the east breach area of the crater rim. One particularly loud, pressurized fumarole (fig. 7) near the east breach bordered a stream that drained surface water from Sherman Crater. This fumarole, referred to as the old main fumarole, appeared to produce the largest vapor plume in Sherman Crater—not only during pre-1975 field investigations but also in most aerial photographs of the crater taken before 1975. A temperature of 84°C measured at the old main fumarole in August 1974 was distinctly lower

FIGURE 8. — Prominent depression (arrow) in ice surface in middle of Sherman Crater. In this late afternoon view, shadow accentuates the depression. Other pre-1975 thermal features mentioned in text are as follows: EB, two clusters of fumaroles near the east breach; WR, west-rim fumaroles; NWR, northwest-rim fumaroles; and NWP, northwest pits. The prominent plume in the lower right originates from the old main fumarole. Aerial photograph FR6025–135, by Austin Post, September 27, 1960.

than temperatures in nearby, less pressurized fumaroles. The lower temperature at the time may have reflected a large input of cooler creek water. Other fumaroles near the east breach occurred in two main clusters, in the area of the old main fumarole and upstream near a small water fountain (perforations d and e, respectively, of Frank and others, 1975).

The drainage creek from Sherman Crater was investigated in 1973 with tracer dye (Frank, 1975). It was found to travel beneath Boulder Glacier and to affect the pH and sulfate content of Boulder Creek. As described later in this report under "Hydrology," the monitoring of Boulder Creek during 1975 showed degradation of water quality to be a major environmental result of increased fumarolic activity.

Photographs taken after 1956 show a prominent depression in the surface of the ice in the central part of the crater (fig. 8). Frank, Post, and Friedman (1975, p. 86) interpreted this depression to be a surficial expression of some subglacial source of heat, possibly a warm lake. Subglacial exploration in ice caves by Kiver (1975, p. 87) revealed that in 1974 a pond only 10 m long was evident beneath the depression.

Thermal activity in the southwestern part of the crater was first noted in photographs taken in 1956. One pit, and sometimes two, persisted in this area throughout the 1960's. Photographs show that these pits were often completely covered by snow during the winter but that they always melted open in the summer.

Fumaroles have been present along the west rim of the crater since the early 1900's. Although photographs taken intermittently from 1909 through the 1930's show some of the fumaroles, the total extent of activity was first revealed by 1940 aerial photographs, which show a linear zone of fumarole clusters about 100 m long midway across the inner slope of the west rim. The fumaroles along the west rim are the most accessible and have been the most closely observed in the crater.

Early 20th-century photographs show little of the northwest area of the crater. However, by 1940 thermal ground occurred at two locations along the rock-ice margin at the base of the steep northwest rim and in a shallow ice pit about 50 m downslope from the rim. These features changed little in subsequent years, although at times two adjacent shallow ice pits formed instead of one. Since 1956 the northwest ice pits have at times been completely covered by winter snow, as have the southwest pits, but they, also, have always melted open during the summer.

1975–76 THERMAL ACTIVITY

VISUAL OBSERVATIONS

An important feature of all pre-1975 photographs of Sherman Crater is the small number of crevasses and the general smoothness of the crater glacier (fig. 9*A*). The change in thermal activity in 1975 was accompanied by a tremendous increase in the area of heated, snow-free ground and by an increase in the number and size of crevasses as ice in the crater began to accelerate downslope toward the east breach and the new thermal areas (fig. 9*B*).

The first observations of abnormal activity were made on March 10, 1975, when personnel at Upper Baker Dam (fig. 1) and residents of towns south and west of Mount Baker noted unusually high, dark vapor plumes. During subsequent overflights of the crater, two major changes were most evident — the appearance of new, larger fumaroles, and the emission of fine-grained ejecta. Later effects of increased thermal activity were the massive breakup of snow and ice and the development of a crater lake. New thermal features developed in areas which had not previously shown thermal activity. In addition, virtually all the preexisting thermal features had enlarged (figs. 10*A*, *B*,*C*).

NEW AREAS OF HEAT EMISSION

Photographs and infrared images taken during the few weeks following March 10 showed the initial development of three new clusters of thermal activity — the north pit, the new main fumarole, and the Boulder Glacier pits (fig. 11). The north pit formed in a previously smooth ice slope that descended the north rim of the crater from the mountain's summit (fig. 10A). The pit enlarged through the spring, mostly as a result of ice calving, and has consistently been the source of a large vapor plume. Because of the pit's inaccessibility, little is known of the areal extent or the temperatures of fumaroles that feed this prominent plume. From the location of ice-cave entrances, it is judged that water drains subglacially from the north pit downslope to the east breach.

A new main fumarole had developed by March 10 on a ridge near the base of Lahar Lookout (fig. 12). The plume from this fumarole has consistently been the largest single fumarole plume during the past year, although the combined vapor from clusters of other fumaroles has at times produced more prominent plumes. The orifice of the new main fumarole was about 1 m in diameter when first observed in March; it developed into a 1- ×5-m fissure by summer and has remained about the same size through March 1976 (fig. 12C). Attempts at temperature measurement were never completely successful, giving only a minimum value of 86°C along the inside margin of the fumarole in September.

Most of the particulate matter ejected from Sherman Crater during 1975 apparently came from this single fumarole, although during at least one period, July 10–11, many of the other fumaroles also emitted ejecta. Ejecta in the main fumarole plume was noted in many field investigations and overflights between March 27 and September 30 and probably was emitted continuously through the spring and summer of 1975. Mud streams from the lower lip of the main fumarole were noted in August and September and indicated that part of the fumarole consisted of a mudpot during this period. Analyses of ejecta and mud are summarized under "Petrography" later in this report.

After heavy snowfall began in October, no more ejecta from the new main fumarole were observed on the snow surface. The first winter field investigations, in

February 1976, revealed two additional changes that had occurred after late September. Mud extrusion had stopped, and the inside lip of the fumarole had been lightly coated with yellow sublimates — probably sulfur. These changes suggest that vapor in the new main fumarole became considerably drier after September 1975.

Photographs and infrared images made in March 1975 showed the presence of two small ice pits in the upper part of Boulder Glacier at the northeast base of Sherman Peak (fig. 11). By summer, the two pits coalesced into a single trough between ice in the east breach and a rock outcrop on Sherman Peak, and a second trough developed nearby within a crevasse in Boulder Glacier. Both troughs persisted through the winter of 1975–76 (fig. 13), and infrared images show that they have been warmer at times than other nearby crevasses. Small amounts of vapor have occasionally been observed within the troughs. Possible sources of subglacial heat responsible for the troughs are either local fumarolic activity or warm water (perhaps ponded) from the subglacial stream that drains the crater.

EXPANSION OF OLD AREAS OF HEAT EMISSION

In addition to activity in new areas, all pre-1975 sites of thermal activity have changed to some extent. The most prominent changes occurred near the east breach in the central part of the crater, and along the southwest, west, and northwest rims.

In 1975 the two large clusters of fumaroles near the east breach expanded into a single cluster of activity that included the new main fumarole. Many other fumaroles were superheated, reaching temperatures of as much as 131°C when measured in September 1975 and February 1976. The hotter fumaroles were typically associated with greater amounts of sulfur deposits and higher vapor pressures (fig. 14). A water fountain, which had been in a pool about 2 m across and 30 cm deep in 1973 and 1974, had dried up by September 1975. The greatest density of superheated fumaroles occurred in the area of this old water fountain, which corresponds to the site of the large ice pit in early 20th-century photographs (fig. 4). This location has consistently been the site of the hottest and largest cluster of heat emission in Sherman Crater in this century.

During the summer of 1975, as the ice margin receded upstream from the superheated area toward the north pit, a flat alluvial deposit of sand and silt was revealed that appeared to be sediment washed down from the area of the north pit. A pond was observed to be temporarily dammed here on July 3, but it had drained by September. Streams from this area merged with a stream from the central part of the crater. Drainage then skirted the superheated area, cut through the bank on which the old main fumarole was located, and cascaded about 20 m down into the narrow ice-covered gorge of the east breach, between Sherman Peak and Lahar Lookout. Stream discharge was not measured in 1975, but it appeared to be similar to that observed in September 1973 and August 1974. The apparently similar discharge, despite obviously increased ice melt, suggests that a significant amount of water is lost from the crater either underground or, more probably, by evaporation. Stream temperatures near the old main fumarole in September 1975 were 18°–21°C, in comparison to 7°–8°C in August 1974.

The depression in the central part of the crater quickly deepened in March 1975 as crevasses formed around it. In April ice collapsed and melted into a shallow oval lake about 50×70 m across at the bottom of a 40-m-deep ice pit. Fumaroles occurred both on the shore and within the lake. As many as 5 patches of upwelling developed in the north-central part of the lake from May through August, but only one major area persisted through March 1976 (fig. 15). The lake depth was less than 50 cm at 2 points about 10 m from shore, and the maximum depth was probably not much greater. If an average depth of 1 m is assumed for the lake, about 2,600 m^3 of water was impounded on the floor of the central pit. The lake has drained continuously since April 1975 beneath ice at its eastern margin, where it presumably feeds the main creek in the east breach. Lake temperatures varied between 26° and 34° C in the summer of 1975 and were probably strongly affected by the amount of ice which fell intermittently from the walls of the central pit. The lake level and shape has fluctuated somewhat since that time, but ice has failed to dam the lake outlet during the past year.

The southwest pit enlarged greatly in 1975, and investigation revealed an area of hot ground surrounding a small fumarole that was highly pressurized (fig. 16). This fumarole has consistently produced the highest pitched sound of any in the crater. By September, ice collapse was noted nearby, next to a prominent rim remnant (fig. 10*B*). Vapor issued, at times, from enlarging crevasses in this area, and by December 1975 a large new pit had developed between the southwest pit and the west rim (fig. 10*C*, NSWP). This new pit is one of the few major changes since the summer of 1975 and represents further expansion of fumarolic activity in the southwestern part of the crater.

A major expansion of the preexisting linear zone of thermal activity along the west rim occurred in 1975 as new fumarole clusters formed downslope from it. Because of accessibility, the west rim has been the site

FIGURE 9. — Southwestward view of Sherman Crater, from Lahar Lookout. *A*, August 1974, signs of thermal activity are the west-rim fumaroles and southwest pit have expanded, the central pit has

of repeated temperature measurements and gas sampling. Temperatures in 1975 were 89°–91°C. During at least one period — June 10–11, 1975 — many of the west-rim fumaroles emitted clayey ejecta similar to that from the new main fumarole.

The northwest thermal area also expanded in 1975. Two adjacent but distinct clusters of activity developed within the ice pits; however, much — but not all — of the hot ground was covered by snow during the winter of 1975–76. Fumarolic activity along the northwest rim occurs in a breccia layer which is a continuation of the same layer that contains much of the west-rim activity.

THERMAL INFRARED OBSERVATIONS

Infrared studies made during 1975 were conducted by several groups. A cooperative University of

fumaroles (right middle) and the southwest pit (behind snowdrift). A tent and standing man provide scale. *B* August 1975, the west-rim appeared, and the glacier has broken up considerably.

Washington–U.S. Forest Service infrared survey was made March 26, 1975, shortly after the onset of increased activity. These initial infrared images confirmed that the major areas of new thermal activity were near the east breach and in the north pit. The survey also detected anomalous heat in the two small ice pits at the northeast base of Sherman Peak (fig. 13).

In April, Los Alamos Scientific Laboratory also began to acquire infrared data (Eichelberger and others, 1976), and in May the Oregon Army National Guard and the Geography Department at Oregon State University (OSU) undertook a cooperative remote sensing program. The OSU program was headed by Charles L. Rosenfeld, who prepared the following summary.

FIGURE 10. — Vertical views of Sherman Crater. *A*, Thermal features on September 3, 1963. Snow-free areas which resulted from thermal activity are near the east breach (EB), southwest pit (SWP), west rim (WR), northwest rim (NWR), and northwest pit (NWP), all visible in this photograph. These features remained virtually unchanged until 1975. *B*, By September 24, 1975, all the old thermal features had expanded. A single dense plume issued from the new main fumarole at the south base of Lahar Lookout (arrow),

SUMMARY OF THERMAL INFRARED OBSERVATIONS

By CHARLES L. ROSENFELD

Beginning in mid-May, thermographic images were obtained at 10-day intervals by use of an infrared line scanner aboard OV−1C Mohawk aircraft. These aircraft (part of the 1042d Military Intelligence Company (Aerial Surveillance)), based at the Army Aviation Facility at Salem, Oreg., were also used to obtain aerial photographs at 20-day intervals. Special flights were also flown in response to signals from the ground-based monitors operated by other groups.

This infrared monitoring program was designed to provide high-resolution images for interpretation of thermal activity and to aid in evaluation of thermal changes and potential hazards associated with them. Flights were designed to provide both day and night coverage. A series of experimental flights was initially conducted to determine the best spectral response regions for the observation of thermal activity. Two infrared detector heads were used for the AN/AAS−14A line scanner employed in this project:

Detector	*Spectral range*
Mercury, Cadmium Telluride (MCT).	8−14 μm (10−13 peak response).
Indium Arsenide (InAs)	1−3.4 μm (3−3.2 peak response).

In addition, a selection of band-pass and cutoff filters were used. Images acquired by use of the MCT detector and the appropriate cutoff filter show a large anomalous area that is hotter than 15°C but obscured in some places by rising steam plumes. Figure 17 shows an image obtained on September 26, 1975, with the InAs detector, which was also used to pinpoint the loca-

and a thin cover of ejecta blanketed the snow surface. Other new features included the Boulder Glacier pits (BGP), the north pit (NP), and the crater lake in the central pit (CP). *C*, On April 3, 1976, the newly developed thermal features were still present despite peak accumulation of seasonal snowpack. In addition, a new pit, full of steam, developed in the southwestern part of the crater (NSWP). Aerial photography by Austin Post (*A*, V635–8; *B*, 75V5–262) and R. M. Krimmel (*C*, 76NC2–13).

tion of major "hotspots" and reduce the level of atmospheric attentuation by steam. The differences in image resolution make simultaneous acquisition desirable, in that the MCT detector shows pertinent terrain features that facilitate easy location of major anomalies, whereas the InAs detector (sometimes used with a cutoff at 80°C) resolves the exact location of fumarole vents but subdues locational information. Good fumarole locations can be identified by optically superimposing the InAs on the MCT imagery. Dual sensors were operated in a simultaneous mode throughout the monitoring program.

A log of all anomalies was maintained and updated at 10-day intervals. Daytime stereographic photographs (fig. 18) were then related to the thermal images, which were acquired at night to minimize anomalies due to solar heating. In figure 18, 7 major fumarole clusters can be identified. Each infrared "hotspot" has been assigned to a cluster, and its position and its initial observation date have been recorded.

Early attention was focused on the growth of thermal activity near the east-breach and north-pit areas, but the dramatic formation of the central pit between April 12 and April 20 demonstrated that sudden changes could also occur elsewhere within the crater. The total surface area of the crater was calculated to be 185,700 m^2, of which 35,200 m^2 (19 percent of the crater area) was free of snow and ice in August 1975. Infrared thermographs indicated that 12,600 m^2 (or more than one-third of the snow-free area) was heated to more than 15°C on August 24, 1975. Few changes were observed between August 1975 and March 1976. The 1975-76 winter snowfall has outlined a heated area of nearly 12,000 m^2 of persisting snow-free ground which approx-

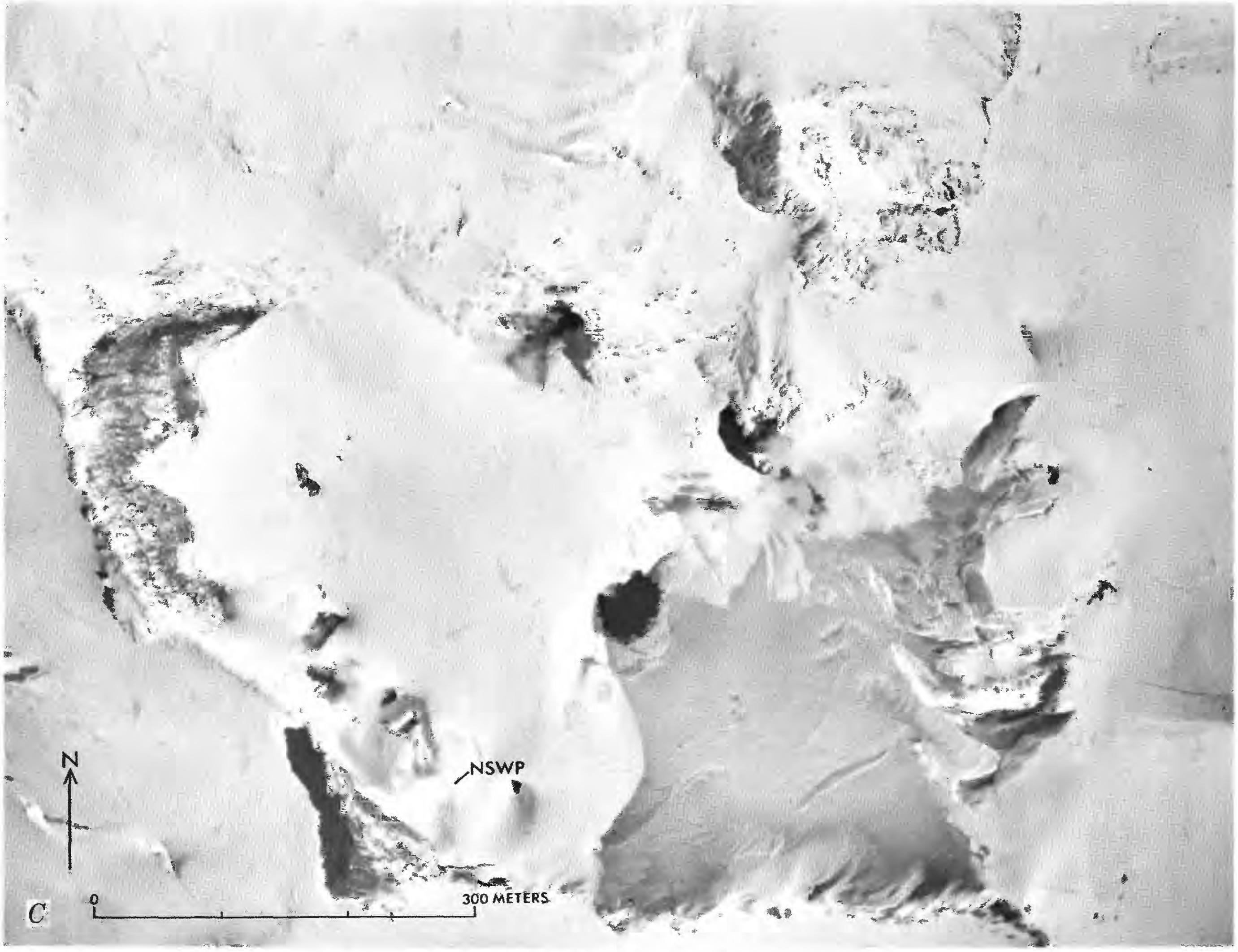


FIGURE 10. — Continued.

imately coincides with the summer surface that is hotter than 15°C. Some new ice perforations have appeared since summer, most notably along the southwest rim.

ESTIMATES OF HEAT FLOW

The change in area of heated snow-free ground (thermal area) was mapped (fig. 19) by discrimination of anomalously steep snow margins in aerial photographs and by field observations (Frank and Post, 1976). This method estimates the area of geothermally heated ground during late summer snow conditions. The major source of error is lack of differentiation between geothermal areas and solar-heated ground where snow is absent. Such error can be minimized by nighttime thermal infrared surveys. Nevertheless, photographs and several temperature measurements below the ground surface permit rough estimates of the thermal area to within a few hundred square meters.

Table 1 lists the amount of thermal area as mapped from vertical photographs taken after 1940 and as estimated from ground photographs taken prior to 1940. The chronological change in thermal area is displayed in figure 20. Generally, a small but consistent increase in thermal area occurred prior to 1975. In 1975 the thermal area expanded by a factor of 3 from conditions of the previous year. By late summer 1975, about 28,000 m^2 of thermal ground was apparent in photographs. At the same time, about 12,600 m^2 of infrared anomaly above 15°C occurred within this area, as previously described by Rosenfeld. The 1975 increase was by far the greatest change during the last 75 years. This threefold increase in thermal area, however, represents only part of the total heat increase. A lower limit for total heat flux from Sherman Crater can be calculated from the volume of newly melted snow and ice.[6] This method produces a minimum value because it neglects heat flux involved in evaporation and radiation from snow-free areas, as well as advection in water and vapor discharge.

[6] As used in this report, "snow and ice" includes firn.

FIGURE 11. — Early westward view of increased thermal activity, March 27, 1975. Initial signs of new activity were the north pit (not shown), main fumarole (arrow), increased crevassing, and Boulder Glacier pits (BGP). For scale, the distance across the east breach from the top of Sherman Peak (upper left) to the top of Lahar Lookout (middle right) is about 500 m. Aerial photograph by Austin Post.

Figure 21 illustrates the method by which heat-flow estimates can be made. Core areas of intense heat flow are free of snow even in winter (fig. 21*A*); areas of moderate heat flow become snow free during the summer (fig. 21*B*); and the remaining snow, firn, and ice mass of Sherman Crater thins from year to year (fig. 21*C*), presumably owing to melting at the base or to extension toward thermal areas. The development of new thermal areas in 1975 caused intense local extension and crevassing toward these areas (fig. 21*D*) because additional heat went into melting of nearby snow and ice.

Heat flux from the core thermal areas (fig. 21*A*) is difficult to estimate. Two approaches are used in this estimation: First, these areas remain free of snow and probably are hot enough to melt snow as fast as it falls or drifts in. White (1969) estimated that 419 W/m^2 of heat flux was necessary for such rapid snowmelt. This flux density is sufficient to melt snow at a rate of 11 cm of water (equivalent thickness) per day, which is not an unreasonable limit at Mount Baker, considering the high precipitation and rapid wind-drifting environment. The actual heat-flux density could be slightly lower or considerably higher. Second, some areas, such as the central pit, had flux densities as high as 2,400 W/m^2, as judged by snowmelt and icemelt in the spring of 1975. If one assumes that the heat flux does not vary seasonally, such maximum values of observed flux densities can be used to estimate heat flux in adjacent areas that are free of snow during times of peak snowpack, as these areas cannot have had lower flux densities. These various estimates of core-area heat flux are given in table 2. Pre-1975 values are less than 1 MW; 1975–76 values are considerably greater than 1 MW.

Heat flow marginal to the core geothermal areas (figs. 21*B*, *C*, *D*) can be estimated somewhat more precisely from the anomalous loss of snow and ice in summer. The heat flux is given by

$$H = \rho DAL/t$$

where ρ is average density (600 kg/m^3 for snow; 700 kg/m^3 for snow and ice undifferentiated), D is average

TABLE 1. — *Snow-free thermal area, in square meters, at Sherman Crater*

[Areas not completely shown in photographs are indicated by a query (?). Zero indicates area was snow covered at the time photograph was made]

Date of photograph	East breach	Old south-west pits	New south-west pit	Central pit	West rim	North-west rim	North-west pits	North pit	Boulder Glacier	Total
1900....	300?	0	0	0	?	?	?	0	?	300?
1908–14....	300?	0	0	0	800?	?	?	0	?	1,100?
Sept. 1933..	2,000?	?	?	?	2,400	500	0	0	?	4,900?
Sept. 1940..	2,000	0	0	0	2,800	500	200	0	0	5,500
Aug. 22, 1956..	2,300	200	0	0	3,100	500	300	0	0	6,400
Sept. 27, 1960..	2,800	400	0	0	3,800	500	100	0	0	7,600
Sept. 3, 1963..	2,200	500	0	0	4,300	900	200	0	0	8,100
Aug. 1965..	3,000	1,000	0	0	4,900	900	400	0	0	10,200
Sept. 22, 1966..	2,300	700	0	0	4,800	900	100	0	0	8,800
Aug. 22, 1969..	3,000	600	0	0	4,500	900	400	0	0	9,400
Mar. 1, 1971....	800	0	0	0	1,000	200	0	0	100	2,100
Apr. 22, 1972.	[1] 1,100	0	0	0	800	200	0	0	0	2,100
Aug. 27, 1972..	3,400	900	0	0	4,400	900	200	0	100	9,900
Aug. 16, 1974..	3,100	1,000	0	0	4,200	900	300	0	100	9,600
Mar. 24, 1975..	3,800	200	0	0	1,400	300	100	800	100	6,700
June 10, 1975..	7,100	300	0	2,600	6,600	900	600	4,000	100	22,200
July 20, 1975..	8,100	500	0	2,700	9,800	900	700	2,900	100	25,700
Sept. 7, 1975..	8,900	500	100	2,800	9,900	900	1,700	3,900	200	28,900
Sept. 24, 1975..	9,000	500	400	2,900	9,900	900	2,000	3,900	200	29,700
Dec. 5, 1975..	1,100	100	100	1,500	1,200	500	100	400	200	5,200
Mar. 4, 1976..	2,600	100	200	1,500	2,200	900	200	2,700	200	10,600
Apr. 3, 1976..	3,300	100	200	1,600	2,500	900	200	2,700	200	11,700

[1] Area measured from infrared image.

TABLE 2. — *Estimates of heat flux from core areas of thermal ground*

[Data are in megawatts]

Date	Flux estiamted by assuming a flux density of 419 W/m²	Flux estimated from highest observed flux density
Mar. 1, 1971	0.9	([1])
Apr. 22, 1972	.9	0.2
Mar. 24, 1975	2.5	5.8
Mar. 4, 1976	4.3	10.0
Apr. 3, 1976	4.7	11.2

[1] No estimate made.

snow and ice thickness, A is area, L is latent heat of melting (336×10^3 J/kg), and t is time required for thickness, D, to melt. This simple equation, however, underestimates the heat flow from areas shown as B in figure 21 because near the core geothermal regions the snow and ice melt more rapidly than in outlying areas, whereas t in the above equation is the total time required to completely clear an appreciable area of ice and snow. Furthermore, this method neglects heat lost by advection in steam plumes or through warm streams in subglacial tunnels.

Table 3 lists the heat-flux values estimated from loss of snow and ice between spring and summer in geothermal areas that are marginal to the core areas used in table 2. Areas and times are derived from data in table 1, and the water equivalent thickness of melted snow and ice is estimated from field observations (where water equivalent thickness, h, is equal to ρD divided by the density of water). Heat flux during 1975 in these areas is more than 10 times greater than before 1975.

Table 4 summarizes estimates of heat flow from snow and ice melt in the various regions (A, B, C, D) represented in figure 21. Before 1975 an estimated minimum of about 2 MW of heat was released from Sherman Crater at an average heat-flux density of about 10 W/m^2. In 1975 a minimum of about 30 MW of heat was released at an average flux density of about 180 W/m^2. Thus, the heat flow required to melt snow and ice increased roughly by one order of magnitude in 1975.

Implicit in this discussion of heat flow is that, except for the spring of 1975, H did not change significantly with time over periods of about 1 year. Such an assumption presently seems reasonable for 1975–76 because visual observations have not indicated any marked change in the overall level of fumarolic activity since the spring of 1975. Although activity increased slightly before 1975, as reflected by retreating snowlines, the yearly change from 1971 to 1972, for which pre-1975 heat-flow estimates were made, and in 1974 is probably not significant.

STRUCTURAL IMPLICATIONS OF HEAT PATTERN

Surficial thermal features represent locations of conduits from the deeper thermal system of the volcano. Four possible controls on heat flow can be inferred from the fumarole pattern:

1. At the west and northwest rims, much of the activity is confined to breccia that is interlayered with lava flows. As rising heat nears the ground surface, a preferred path of convective flow is evidently through the more permeable breccia.

TABLE 3. — *Heat flux estimated by loss of snow and ice*

[Zero indicates area was snow covered at the time observation was made. Leaders (. . .) indicate no estimate was made.]

Location	Area, A (m²)	Water equivalent thickness, h (m)	Heat flux, H (MW)	Area, A (m²)	Water equivalent thickness, h (m)	Heat flux, H (MW)	Area, A (m²)	Water equivalent thickness, h (m)	Heat flux, H (MW)
	Apr. 22 to Aug. 27, 1972			**Mar. 10 to June 10, 1975**			**June 10 to Sept. 24, 1975**		
East breach	2,300	4	0.28	3,300	28	3.9	1,900	28	2.0
Old southwest pits	900	4	.11	100	4	.02	200	4	.03
New southwest pit	0	0	0	0	0	0	400	28	.41
West rim	3,600	3	.33	5,200	4	.88	3,300	4	.49
Northwest rim	700	1	.022	600	1	.03	. . .	. . .	. . .
Northwest pits	200	1	.006	500	2	.04	1,400	2	.10
North pit	0	0	0	3,200	14	1.9	. . .	. . .	. . .
Local crevasse extension	0	0	0	8,200	10	3.4	. . .	. . .	. . .
				Mar. 10 to Apr. 21, 1975			**Apr. 21 to Sept. 24, 1975**		
Central pit	0	0	0	2,600	25	6.3	300	28	0.21
	1925 to July 27, 1974			**July 27, 1974, to July 4, 1975**					
Remainder of crater	156,000	[1]13	0.44	137,000	[1]4	6.2	. . .	. . .	. . .

[1] These values for h were derived from summer photographs of the crater center, taken from the same position on the west rim in 1925, 1974, and 1975. The 1974-75 figure was increased by 2 m to account for observed thinning of 7–15 m near the west and south rims.

TABLE 4. — *Summary of snow and ice loss and heat-flow estimates for Sherman Crater*

	Pre-1975	1975
Water equivalent volume of total snow and ice in crater (millions of m³)	[1]2.2–2.7	1.2–1.7
Water equivalent volume of snow and ice lost from crater (millions of m³):		
By expansion of thermal ground	(2)	0.47
By thinning of remaining snow and ice	(2)	.55
Percentage of snow and ice loss	(2)	37–46
Heat flux, H (MW):		
A.[3] Core thermal area free of snow in winter	0.3–0.9	2.5–11.2
B.[3] Thermal ground where snowcover melted in summer	0.8	16.3
C.[3] Thinning of remaining snow and ice	.4	6.2
D.[3] Localized extension of crevasses into central and north pits	(2)	3.4
Total	1.5–2.1	28–37
Average of minimum heat-flux density[4] for Sherman Crater (W/m²)	8–11	150–200

[1] Calculated for a paraboloid of revolution with a maximum water-equivalent depth of 28 to 35 m.
[2] Not estimated.
[3] Letters refer to areas illustrated in figure 21.
[4] Average worldwide heat flow in nonvolcanic areas is 0.06 W/m².

2. Fumarole clusters form a discontinuous semicircle of activity along the inside rim of Sherman Crater, except where hydrothermal activity seems to be absent along the south rim. (See fig. 19*C*.) Such a pattern suggests that most of the hydrothermal emission is controlled by concentric fractures that might be associated with the initial formation of the crater. Surface displacements related to such structural features, however, have not been identified.
3. The location of some of the new activity suggests an east-west structural control across the center of Sherman Crater. For example, two long east-trending lobes of activity extend downslope from the west rim, and an east-west line of fumaroles occurs along the north shore of the lake and the north bank of the outlet stream.
4. The east breach apparently overlies the most direct permeable path from the volcanic heat source because this area has the hottest and largest fumaroles. Furthermore, heat activity has historically been concentrated in this area since at least 1900. The presence of the breach itself indicates that at some time in the past either local hydrothermal or volcanic activity or erosion facilitated by hydrothermal alteration removed a section of the crater rim.

Thus, the fumarole pattern provides a hint of underlying structures. The distribution of hydrothermal activity can be summarized as a central core of heat emission, 60–80 m in diameter, near the east breach, on which is superimposed a semicircular zone of activity, about 400 m in diameter, along the inside crater rim and possibly an east-west crosscutting zone through the center of the crater. In some areas, zones of heat convection come to the ground surface along relatively permeable layers of breccia rather than along lava flows.

All these thermal features are apparently related to structures associated with Sherman Crater, although the dips of many of the units that form the north half of the crater rim suggest that much of the material there was erupted from an older vent to the north, now buried by snow and ice. The extent and composition of deposits in Boulder Creek valley (Hyde and Crandell, 1977) indicate that eruptions occurred during the past 10,000 years at Sherman Crater, but no products known to be from other vents in the summit area have been dated.

GEOPHYSICAL AND GEOCHEMICAL MONITORING

Visual monitoring of thermal activity provides important information on changes that have taken place or are currently in progress but supplies little evidence of where or when future changes will occur. Because the timing, as well as location, of future eruptive activity should be known for proper protection of life and prop-

FIGURE 12. — View from Sherman Peak of the site of the new main fumarole at the south base of Lahar Lookout. *A*, August 17, 1974, the two clusters of activity are evident near the east breach, including a prominent plume from the old main fumarole. *B*, July 6, 1975, a dense particle-laden plume extends from the 1- × 5-m opening of the new main fumarole, which occurs on a rock rib that had no sign of vapor

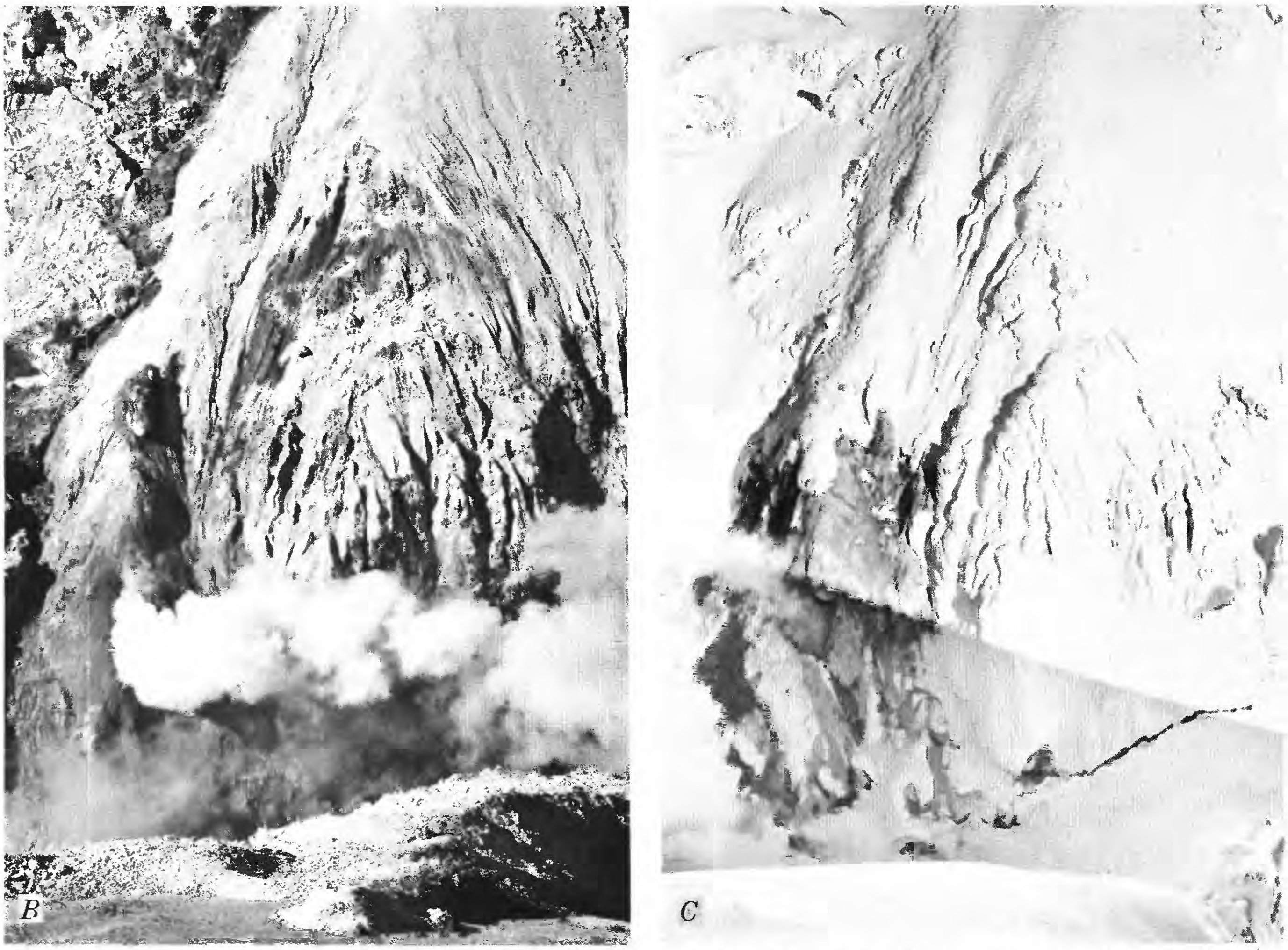
erty, other types of monitoring are necessary — in particular, geophysical and geochemical investigation of the volcanic processes. Such investigation provides many clues to the basic cause of volcanic processes, which should be understood for eventual eruption prediction.

No one method of volcano monitoring has yet proved to have sure predictive capability for eruptions. However, many different monitoring methods in other volcanic areas have at times successfully anticipated eruptions in a general way and may eventually lead to more precise predictions. Prediction of Cascade volcanism is complicated, in part because past monitoring in the Cascade Range has generally been of a reconnaissance nature and in part because no recent eruptions have occurred to provide data on precursory patterns.

Personnel of the U.S. Geological Survey, other government agencies, and several colleges and universities have initiated various types of monitoring programs. Most of the programs were designed to evaluate the potential for a future eruption. The programs involved six broad types of study: seismicity, gravity, tilt, petrography, gas, and hydrology. All these programs provided useful information on the state of the volcano.

Most eruptions are preceded by increased seismicity at the volcano. Consequently, monitoring of seismicity is probably the single most effective means of evaluating the potential for an eruption in the near future. A seismometer was installed near Mount Baker by the U.S. Geological Survey in the summer of 1972 (fig. 22, MBW) and is currently operated by the Geophysics Program of the University of Washington.

Grants from the U.S. Geological Survey and National Science Foundation enabled the Geophysics Program to increase its seismic coverage of Mount Baker in the spring and summer of 1975. This work was done under the supervision of Stephen D. Malone, who supplied the following summary.



emission in 1974. *C*, February 6, 1976, vapor still issues from this fumarole, but without ejecta. The snowmelt pattern delineates the area of thermal ground around the fumarole.

SUMMARY OF SEISMICITY AND GRAVITY

By Stephen D. Malone

SEISMICITY

On March 30, 1975, 3 weeks after increased fumarolic activity at Mount Baker was first observed, a short-period telemetered seismic station was installed on the south rim of Sherman Crater, less than 500 m from the center of the fumarolic activity. This station has been in almost continuous operation since then. In late summer 1975, 5 additional stations were installed on and near the mountain to increase the coverage. Table 5 and figure 22 specify the stations that form the expanded Mount Baker network.

The characteristics of the Mount Baker seismic stations are similar to those of the standard short-period station used by the U.S. Geological Survey: 1 Hz seismometer, nominal magnification of 100,000 to 500,000 at 20 Hz, and conversion to FM subcarriers for telemetry over radio and (or) telephone communication links. Data are recorded on Geotech develocorders with a single channel being monitored on a helicorder. The records thus produced are reviewed daily for changes in seismic activity. Photographic copies of selected events are made for additional analyses.

The severe environmental conditions found high on Mount Baker have placed a number of limitations on seismic research. Special effort was made when installing the seismic stations to prepare the site to withstand very cold temperatures, high snow accumulation, and heavy rime-ice formation. Ice presents the worst problem, as it can produce very high loads on antenna structures and cannot be avoided. Despite these difficulties, the crucial stations MBW, SCW, AAB, and LLB kept operating through the winter.

Data from the Mount Baker array have been very interesting because they show an almost complete lack of earthquakes local to the volcano both before and after March 1975. The seismic events recorded seem to be of the type produced by ice movement (Weaver and

TABLE 5. — *Seismometers at Mount Baker*

NOTE: — All data are telemetered to the University of Washington for recording and analysis.

Symbol	Location (lat and long)	Description	Start date	Reliability as of March 1976
MBW	48.7847° N., 121.9008° W.	Grouse Ridge, 7 km W. of Sherman Crater.	Summer 1972	Currently operating; 25 percent useless data due to wind.
SCW	48.7677° N., 121.8155° W.	South rim of Sherman Crater.	March 30, 1975	Currently operating; 5 percent useless data due to radio interference.
BBB	48.8035° N., 121.7837° W.	Landes Cleaver, 4 km N.-NE. of Sherman Crater. Site of tilt station B.	Sept. 20, 1975	Never worked; could not repair because of weather and snow conditions.
AAB	48.7367° N., 121.8112° W.	Crag View, 3 km S. of Sherman Crater. Site of tilt station A.	Sept. 30, 1975	Currently operating; 5 percent useless data, unknown cause.
WRB	48.7685° N., 121.8187° W.	West rim of Sherman Crater.	Sept. 19, 1975	Failed Jan. 5, 1976, due to ice destroying the antenna.
LLB	48.7718° N., 121.8115° W.	Top of Lahar Lookout, NE. corner of crater.	do.	Currently operating; almost no down time.
MLB	48.6889° N., 121.6867° W.	Near Marten Lake, 8 km E. of Sherman Crater.	Sept. 30, 1975	Intermittent until January 1976; 25 percent no data.
LYW	48.5353° N., 122.1017° W.	34 km SW. of crater. Part of western Washington regional net.	April 1975	Currently operating; 5 percent useless data.

Malone, 1976). The main reasons for this interpretation are the rapid dispersive characteristic of a very shallow source in a highly stratified medium, the low phase velocity, and the similarity to events on Mount St. Helens, where additional evidence for a glacier source is available. A possibility remains that some or even many of these events on Mount Baker are very shallow earthquakes, although the evidence is against it. Even if they were earthquakes, their rate of occurrence is not high and seems to have decreased during the fall and winter months. The level of earthquake activity at Mount Baker contrasts sharply with the moderate seismicity at three other Cascade volcanoes to the south, Glacier Peak, Mount Rainier, and Mount St. Helens.

In addition to the glacier-source events observed on the seismic records, there have been periods of high seismic noise that last from tens of minutes to half a day. These noise periods are characterized by rather monochromatic bursts of about 5 Hz from 5 to 10 seconds apart that vary from 6 to 24 db above the background level for quiet times. They do not appear to be caused by wind, for there seems to be no correlation between weather activity and their presence. The noise bursts appeared mostly during the spring and early summer of 1975 and have not occurred since July 1975. These periods of increased noise may have been fumarolic venting which occurred only when the new fumaroles were young, or perhaps this is a different form of glacier noise, being produced by short continuous ice motion rather than discrete slips.

On February 27, 1976, a small earthquake ($M_L \simeq 1$) occurred at Mount Baker, the only definitely identifiable earthquake to occur locally since seismic coverage extended to the region in 1972. The earthquake was about 1 km east-southeast of Sherman Crater at a depth of 3–6 km. Inasmuch as this has been the only local earthquake of record since March 1975, there is no compelling seismic evidence to suggest an increase in stress within the volcano, such as might occur prior to an eruption.

GRAVITY

Both a change in mass near a point and a change in elevation of a point can cause changes in the acceleration of gravity as measured at the point. Such changes measured on an active volcano could signify, among several possibilities, the influx of magma into the volcano's reservoir system. The University of Washington has been testing this concept since May 12, 1975, when two gravity stations were established on the south and west rims of Sherman Crater and another was located 29 km to the south at the Concrete Airfield.

FIGURE 13. — Two ice pits (arrows) in upper Boulder Glacier just outside Sherman Crater, March 4, 1976.

Data from these stations are shown in figure 23. A Lacoste and Romberg G gravity meter was used. A set of gravity readings was repeatable within 0.05 mGal, and instrument drift relative to an assumed stable base at the University of Washington was linear and less than 0.1 mGal/mo.

Gravity was remeasured at these stations several times throughout the summer, and again at the south-rim station on February 6, 1976 (fig. 23). The readings were corrected for Earth tides and show that the gravity decreased at the two Sherman Crater stations during the summer, about 0.46 mGal on the west rim and 0.61 mGal on the south rim. This trend reversed at the south-rim station during the fall and winter, with an increase in gravity of about 0.13 mGal between late September 1975 and February 6, 1976. Gravity fluctuations at Concrete remained within experimental error. At the end of the summer of 1975, seven additional gra-

FIGURE 14. — Superheated fumarole in the eastern part of Sherman Crater. Large deposits of sulfur have formed around the hottest fumaroles. Photograph by S. D. Malone, September 5, 1975.

vity stations were established at various elevations, but they were not resurveyed prior to spring 1976.

Interpretation of the gravity data is presently ambiguous and must await the acquisition of measurements for at least 1 more year. Correcting for snowmelt is a difficult problem because little is known about the amount of water lost to evaporation and runoff over the upper reaches of the mountain. In the immediate area of the two gravity stations on the crater rim, estimates of the amount of lost mass have been made from the observed decrease in the snow level and measured snow density. Corrections for these local effects reduce the gravity change over the summer to about 0.4 mGal at both stations.

The gravity decrease can be explained several ways. The most obvious is an elevation increase. A change of 0.4 mGal represents a free-air change of 1.3 m. Uplift of this amount, if present, must be local to the crater or purely pluglike in form, as tilt data show too little defor-

FIGURE 15. — Main area of upwelling within the crater lake. The lake was about 50 m across at this time, and the upwelling was about 2 m in diameter. Aerial photograph taken from the south, April 3, 1976.

FIGURE 16. — Highly pressurized high-pitched fumarole in the southwest pit (SWP), July 16, 1975. The fumarole opening is about 15 cm wide, and the ice pit is about 20 m wide, from left to right.

mation to be consistent with large elastic inflation of the volcano.

Mass withdrawal from within the volcano is another possible cause of gravity change. Two calculations which assume a point mass distribution 100 m below

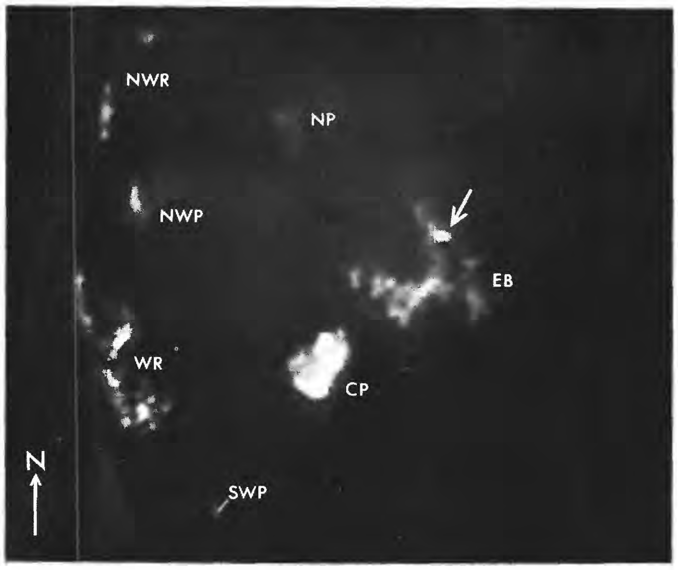


FIGURE 17.—Infrared image of Sherman Crater, September 26, 1975, acquired by Oregon Army National Guard. The brightest spot (arrow) in the east breach (EB) corresponds to the new main fumarole. Bright spots along the north margin of the central pit (CP) correspond to fumaroles grouped on a mound above waterline along the north shore of the lake. Two particularly strong groups of fumaroles are evident on the west rim (WR). The north pit (NP) and southwest pit (SWP) are not very bright because of vapor and partly overhanging ice which shield the fumaroles from the infrared sensor. Other fumarole clusters are the northwest pits (NWP) and northwest rim (NWR).

each gravity station or 100 m below the center of the crater require masses of 6×10^8 or 4×10^9 kg, respectively. Withdrawal of magma of these amounts would reasonably be accompanied by seismicity. Mass discharge of sulfur, other gases, and dust into the air is thought to be less than 10^8 kg.

The observed increase in gravity in midwinter 1976 suggests that changes in mass due to snowmelt and accumulation over the entire mountain may be more important than the very local effects near the crater. A 0.4-mGal gravity decrease over the summer due to snow lost over the entire mountain requires loss of 4.4 m of water equivalent thickness (about 7.3 m of snow and ice) distributed evenly on the surface of a cone at an angle of 28° to the horizontal (the average slope of Mount Baker). The snow accumulation and summer melt rates on Mount Baker are unknown but probably are about half this figure. Furthermore, the mountain as a whole should have gained during the winter at least as much snow as it lost during the summer. The gravity results do not show this relation although the only winter measurement (fig. 23) was made about 2 months before the peak in snow accumulation. Snow effects still do not seem to account for all the gravity change, but it will take at least 1 complete year of data to resolve this question.

TILT

Many volcanoes are known to have inflated before eruptions and to have deflated after eruptions, presumably in response to filling and emptying of a magma reservoir system. Probably the best way to detect such deformation is by determining the changes in inclination (tilt) of the ground surface at several points on the cone. Three different systems for measuring tilt, one of which is still experimental, have been installed at Mount Baker. Results to date have been somewhat conflicting but probably indicate no significant inflation of the volcano.

Three spirit-level tilt stations were installed and measured on July 8–9, 1975, and were subsequently reoccupied on August 2–5 and on September 30, 1975; locations are given in figure 22. This type of tilt station involves precise leveling between fixed points that are 20–40 m apart. Comparison of elevation for leveling surveys made at different times indicates whether the ground has tilted. Tilts of about 5 μrad (5 ppm, or 5 mm/km) or more are resolvable by this method. Under favorable conditions of site stability, such tilt can be interpreted in terms of volcano deformation. However, site conditions at Mount Baker are not considered to be favorable, owing to freeze-thaw problems and the highly fractured nature of the lava flows and breccia in which the stations are located.

The net tilt from July 8–9 to September 30 was: Site A, 7.5 μrad toward the south-southeast; site B, no change; site C, 7 μrad toward the west (fig. 23). The tilts at sites A and C are directed away from the summit area and are marginally greater than the expected error. The tilts are not considered to be significant, however, in view of their small magnitude, the 3-month period over which they accumulated, and the problems of site stability. Furthermore, small tilts directed away from the cone would be expected to develop during the summer, owing to unloading of the cone by loss of snow and ice. The spirit-level tilt data are, in all probability, in accord with the seismic data in suggesting little if any intrusive activity during July through September 1975.

Two continuously recording borehold tiltmeters were installed near sites A and B in early August 1975. These electronic instruments, each placed about 1.5 m underground in a 9-cm-diameter hole drilled in an andesite flow, are capable of continuously recording tilts of a fraction of a microradian. Data from the battery-operated meters are relayed via satellite telemetry and are eventually recorded at an office of the U.S. Geological Survey in Menlo Park, Calif. The two instruments operated successfully through the winter.

Data from the two borehole tiltmeters from August 10, 1975, to March 10, 1976, are plotted in figure 24.

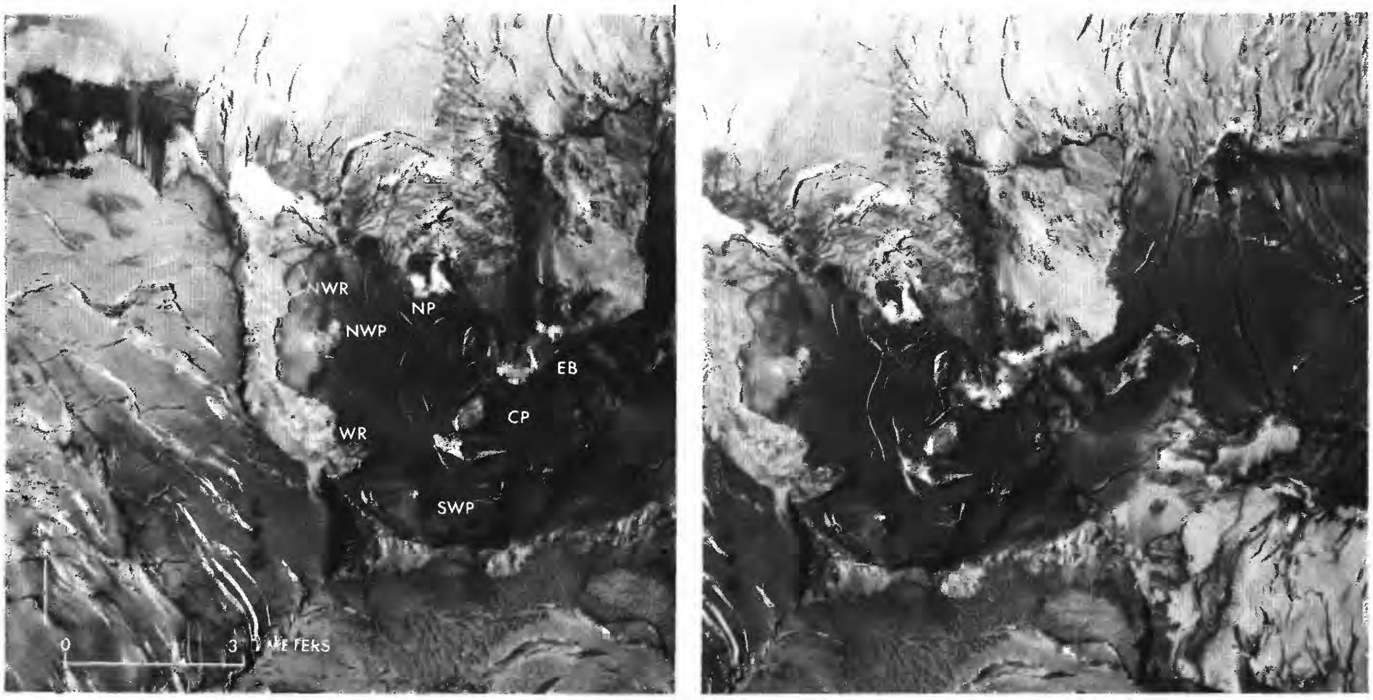


FIGURE 18.—Stereophotographs of Sherman Crater, August 20, 1975, acquired by Oregon Army National Guard. Seven major clusters of fumaroles can be correlated with those listed in figure 17. The initial breakup of ice which eventually resulted in the formation of an eighth cluster—the new southwest pit—is evident against the crater rim between SWP and WR. Ice in Sherman Crater and upper Boulder Glacier appears to be almost black in these photographs because of the thin but dark blanket of fumarole ejecta.

Breaks in the curves represent missing data, owing to equipment malfunction or telemetry loss. Tiltmeter A was rezeroed in early September following a period of equipment failure; this accounts for the prominent offset in the curves.

Data from the two tiltmeters show a consistent pattern of subsidence north of site A from August to early December, west of Site B from October to December, and only slight change at both sites thereafter. The cumulative tilt before December is approximately 100 μrad on a bearing of about S. 84° W. at site B and at least 50 μrad on a bearing of about N. 7° E. at site A. Projections of the two tilt vectors intersect in the region of the upper Mazama Glacier, north of the Dorr Fumarole Field. The data are far "noisier" before December than after, particularly those from site B. Some of this noise occurred at both sites simultaneously, whereas other noise affected only one site. From August to October the data at site B are less consistent and might reflect a settling period in the instrument site or a combination of different processes.

The data can be interpreted in two quite different ways, and it is not known which is preferable. One possibility is that the data indicate deformation of the volcano during the August–December period and lack of deformation during the December–March period. Under this interpretation, the pre-December deformation could have been related to withdrawal of magma from a high-level storage system centered beneath upper Mazama Glacier. Such an explanation would account for the synchronous changes in tilt at both sites between October and December, but the evidence is less conclusive for the period from August to October.

Two other sets of data appear to be inconsistent with the subsidence shown by tiltmeter data at site A from August to October: (1) the gravity readings, which suggest the possibility of uplift of the summit region extending until at least late September, when the last 1975 field measurement was made; and (2) the spirit-level tilt data, which suggest little, if any, outward tilt until at least late September.

A nonmagmatic process that could explain subsidence between October and December is loading by winter snow accumulation, which began in the first week of October. This explanation, however, would also conflict with tiltmeter data at site A between August and October, a period when summer snow ablation was still in progress.

An alternative interpretation of the tiltmeter data involves the more localized effects of weather and snow accumulation superimposed on slightly unstable sites. In this interpretation, the tilt before December would result from local differential movement of either the tiltmeter relative to the wallrock or a small block in which the meter is emplaced relative to the mountain as a whole. The azimuth of tilt could be largely fortuitous, although the azimuth at site B is nearly perpendicular to a high cliff overlooking Mazama Glacier and could be strongly influenced by rotation toward the free face. The decrease in noise in early December could record the accumulation of a heavy snow blanket that damps out thermal and storm effects. This alternative interpretation may be somewhat limited in application, but it does not conflict with any other observations, nor does it require explanation of inconsistencies in August–October data. Whatever the interpretation, the data provide no evidence of significantly large inflation of the volcano, as might be expected prior to an eruption.

A third type of tilt-measuring system, using a 1.2-m base Sylvester model tilt bar, was installed at several locations by Bruce Nolf (Central Oregon Community College). It is experimental and, so far, has given data that conflict with both the spirit-level and the borehole data (Nolf, 1976). This method is promising, however, and may eventually become an inexpensive and reliable means of monitoring ground tilt.

PETROGRAPHY

The nature of the material ejected from the fumaroles within Sherman Crater was of utmost importance, for, if it contained juvenile volcanic ash, the presence of an eruptible molten body of magma would be implied. With this in mind, the coarse fractions of samples of ejecta collected at intervals from March 31, 1975, to February 6, 1976, were examined petrographically by James W. Babcock and Ray E. Wilcox, who provided the following summary.

RESULTS OF PETROGRAPHIC EXAMINATION OF SAMPLES

By James W. Babcock and Ray E. Wilcox

For petrographic examination, a fraction coarser than about 10 μm was obtained from each sample by repeated settling in water and decanting of fines. The constituents were identified in immersion mounts under the polarizing microscope; some constituent identifications were also supplemented by spindle-stage and X-ray methods of analysis.

Results of the petrographic examination are summarized in table 6 for 24 samples of the 1975 ejecta, 5 samples of pre-1975 surficial debris, and 1 sample of suspended sediment in the crater lake. Collection sites are shown in figure 25. Samples of 1975 ejecta are arranged in order of probable time of ejection. For many samples this could be narrowed to periods of a few days or less because of the known times of snowfall with which the samples were mixed (fig. 26) or because of collection directly from the plume. Other samples represent undifferentiated mixtures of ejecta expelled from March 10 to the time of collection. The pre-1975 deposits include a 10-cm-thick white tephra layer (Bd–30–1) from the top of Lahar Lookout, a black sand deposit (Bd–15–1) from near the summit, and other mixed surficial debris that contains no 1975 ejecta. The sample of lake sediment probably contains 1975 fumarole ejecta as well as older material.

In every sample of the 1975 ejecta, opaline silica minerals (including tridymite and cristobalite) are present as major constituents — greater than 10 percent by volume. Large amounts of opaque sulfides (designated as pyrite in table 6) and lithic and scoriaceous fragments are also present in many of these samples. Minor constituents (less than 10 percent by volume) include old glass shards, sulfur, alunite, anhydrite, gypsum, opaque oxides (mainly magnetite), plagioclase, orthorhombic and monoclinic pyroxene, chalcedony, and, rarely, quartz. Four samples in which the clay fraction was analyzed contained more than 10 percent by weight of clay minerals.

Spheroids of pyrite, opal, and sulfur, ranging in diameter from 0.07 to 0.5 mm, are common among the predominantly irregularly shaped particles. The pyrite spheres average about 0.2 mm in diameter; those of opal and sulfur are generally smaller and less abundant. Some spheroids are composite and consist of a thin rind of pyrite crystals that coats a core of opal or sulfur. Other spheroids are mainly opal with included pyrite crystals, or mainly sulfur with a filamentous meshwork of opal. One apparent change in ejecta composition through time is a decrease in pyrite from a major to a minor constitutent in early July.

None of the constituents of the 1975 ejecta is attributed to the eruption of fresh magma during the current activity. Rather, all are logically to be expected in this setting and represent debris that was torn off the walls of the fumaroles or that slid into the fumaroles as small mudflows triggered by snowmelt. Although Radke, Hobbs, and Stith (1976) found fibers which they suggested were fresh volcanic glass (Pele's hair) in ejecta collected by aerial methods, their analyses of the fibers did not include elemental or mineralogical composition. U.S. Geological Survey studies found no evidence of Pele's hair in 1975 ejecta from Mount Baker. Scoria fragments and glass shards, which have refractive indices implying compositions of andesite to dacite, are encrusted with opaline silica and, therefore, predate at least the most recent fumarolic activity. The sulfur-bearing minerals are typical of the suite found at various levels in the throats of fumaroles.

The results of this petrographic examination are in general accord with those of others (Eichelberger and others, 1976; McLane and others, 1976a, b), although the proportions of some constituents differ. This, no doubt, reflects the complicated mixed nature of the

TABLE 6. — *Summary of > 10 μ m constituents in debris samples from Sherman Crater area; collected March 31, 1975, to February 6, 1976*

[M, major constituent (greater than 10 percent); ×, minor constituent; ?, trace amount suspected but not established]

	1975 ejecta														
	Snow surface														
Collection date in 1975	Mar. 31	Mar. 31	Mar. 31	Mar. 31	May 14	May 14	June 11	June 11	June 11	June 30	June 30	June 30	June 30	July 4	July 4
Probable time of ejection in 1975	Mar 10–11	Mar. 10–11	Mar. 12–31	Mar. 12–31	Mar. 10–May 14	Mar. 10–May 14	Mar. 10–June 11	Mar. 10–June 11	Mar. 10–June 11	June 14–30	June 14–30	June 14–30	June 14–30	Mar. 10–July 4	Mar. 10–July 4
Sample	[2]Bd–1–3	Bd–3–1	Bd–1–2	Bd–2–1	Bd–2–2	Bd–5–1	Bd–2–3	Bd–7–1	Bd–8–1	Bd–9–1	Bd–10–1	Bd–11–1	Bd–12–1	Bd–6–2	Bd–10–2
Opal, tridymite, and (or) cristobalite	M	M	M	M	M	M	M	M	M	M	M	M	M	M	M
Quartz and (or) chalcedony	×	×	...	...	...	×	...	...	...	×	×	...	×	×	×
Pyrite	M	...	M	×	M	×	M	M	M	M	×	×	M	×	M
Sulfur	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Pyroxene	...	...	...	×	...	...	...	...	...	×	?	×	?	...	...
Magnetite	×	×	×	×	×	×	×	×	...	...	×	×	×	×	×
Scoria and (or) lithics	M	×	M	×	M	×	×	M	M	×	×	×	M	M	×
Plagioclase	×	×	×	×	×	×	×	×	×	×	×	×	×	×	×
Gypsum	...	?	...	...	...	...	...	...	...	×	...	...	...	×	...
Alunite	...	...	×	...	×	×	×	×	×	×	×	×	×	×	×
Anhydrite	...	...	...	...	...	×	×	×	...	...	?	×	×	×	...
Glass	×	...	...	...	×	...	×	×	×	×	×	×	×	×	×
Refractive Index 1.550															
1.525															
1.500	■						■	■						■	

	1975 ejecta										Pre-1975 surficial debris				
	Snow surface									Lake	West rim		Lahar Lookout		Summit
Collection date in 1975	July 9	July 10–11	July 10–11	July 11–25	Aug. 8	Sept. 19	Sept. 19	Sept. 30	[1]Feb. 6	Aug. 6	June 30	June 30	Aug. 8	Aug. 8	Aug. 8
Probable time of ejection in 1975	July 9	July 10–11	July 10–11	July 11–25	Mar. 10–Aug. 8	Sept. 19	Sept. 19	Sept. 19–30	Mar. 10–Dec. 5						
Sample	Ba–1–1	Ba–2–1	Ba–11–1	Ba–3–1	Bd–14–1	Ba–1–2	Bm–1–1	Ba–1–3	Bd–26–1	Bf–1–1	Bd–11–2	Bd–13–1	Bd–14–2	[3]Bd–30–1	Bd–15–1
Opal, tridymite, and (or) cristobalite	M	M	M	M	M	M	M	M	M	M	M	M	M	×	×
Quartz and (or) chalcedony	?	...	...	...	×	×	...	×	...	...	...	...	...	M	...
Pyrite	×	×	...	×	M	×	×	×	×	×	...	...	×	×	...
Sulfur	...	×	...	...	×	×	×	×	×	...	×	...	×	×	...
Pyroxene	...	...	...	...	×	...	×	...	...	...	?	...	...	...	×
Magnetite	...	×	×	...	×	×	×	×	×	...	×	×	×	×	×
Scoria and (or) lithics	×	×	M	×	M	M	M	M	M	×	×	×	M	×	M
Plagioclase	?	×	×	?	×	×	×	×	×	?	×	×	M	×	M
Gypsum	...	...	...	...	×	...	×	...	×	...	×	×	×	×	...
Alunite	×	×	×	...	×	...	×	×	×	×	×	×	...	×	×
Anhydrite	×	...	×	...	×	×	×	×	...	×	×	...	...	...	...
Glass	...	×	×	...	×	...	×	...	...	...	M	M	M	×	M
Refractive Index 1.550															
1.525															■
1.500		■	■		■		■				■	■	■		

[1] Collected in 1976.
[2] Contains a trace of microcline feldspar.
[3] Tephra layer (10 cm thick).

ejecta. Electron microprobe analyses by McLane, Finkelman, and Larson (1976b) of 7 glass samples from the ejecta showed an average composition, in weight percent, of SiO_2, 65.4; Al_2O_3, 14.1; Fe_2O_3, 3.5; K_2O, 4.0; Na_2O, 4.4; CaO, 1.5; MgO, 0.9; and TiO_2, 0.6.

Samples of pre-1975 material contain a suite of minerals similar to that in 1975 ejcta, although some differences in proportion are distinguishable. In particular, major amounts of glass are present in four of the pre-1975 samples, and major amounts of quartz are present in the fifth sample. Glass and quartz are either absent or present in only minor amounts in samples of 1975 ejecta.

GAS

There is a theoretical basis for believing that the concentration of reducing gases, such as hydrogen, hydrogen sulfide, and sulfur dioxide, emitted from fumaroles increases before a magmatic eruption. As an experiment designed to test such theory, Sato, Malone, Moxham, and McLane (1976) designed a continuously recording sensor and installed it in one of the fumaroles on the west rim of Sherman Crater (figs. 25, 27) in May 1975. The sensor, which monitors temperature as well as reducing capacity of the fumarole gas, was connected via radio to the University of Washington, where data were compiled. Various instrument problems hampered operation of the device, but data were obtained successfully from mid-July to mid-October. Changes in gas composition were observed; however, at no time did the data suggest an impending eruption.

Aerial surveys of gases and aerosols were made by Radke, Hobbs, and Stith (1976), who measured 0.35 and 1.3 kg/s of gaseous sulfur in the fumarole plume on March 27 and June 30, 1975, respectively. They further found that the 10-ppb contour of gaseous sulfur could extend as far as 90 km downwind, as it did on March 27, when the plume was traced southward above Everett, Wash. A later flight, on November 18, recorded a rate of sulfur emission similar to that recorded during the June flight (L. F. Radke, oral commun., 1975).

HYDROLOGY

Much of the concern about Mount Baker's increased thermal activity after March 1975 has focused on the possible occurrence of lava eruptions, pyroclastic flows, and mudflows and associated flooding. However, to date (March 1976), the greatest undesirable effects of the increased activity have been an increase in atmospheric pollution and a decrease in the quality of some local waters (Wilson and Fretwell, 1976). The water-quality monitoring relative to Mount Baker's increased activity is summarized by Marvin O. Fretwell.

MONITORING OF WATER QUALITY

By Marvin O. Fretwell

Water-quality data from the Mount Baker area were very meager before heat emission increased in March 1975. Since then, however, a considerable amount of water-quality data has been collected by several agencies, including the U.S. Forest Service, U.S. Geological Survey, Washington State Department of Game, Washington State Department of Ecology, and the University of Washington. The need for a background data base and a compilation of all pertinent water-quality data prompted Wilson and Fretwell (1976) to prepare a table of data listing all the historic and current water-quality data available through December 31, 1975, for Sherman Crater, Boulder Creek, Park Creek, Sandy Creek, Sulphur Creek, Rocky Creek, and Baker River (below Baker Lake). Bortleson and Wilson (1976) tabulated the data for the detailed survey of Baker Lake made in September 1975. These two reports were later expanded and updated by Bortleson, Wilson, and Foxworthy (1976).

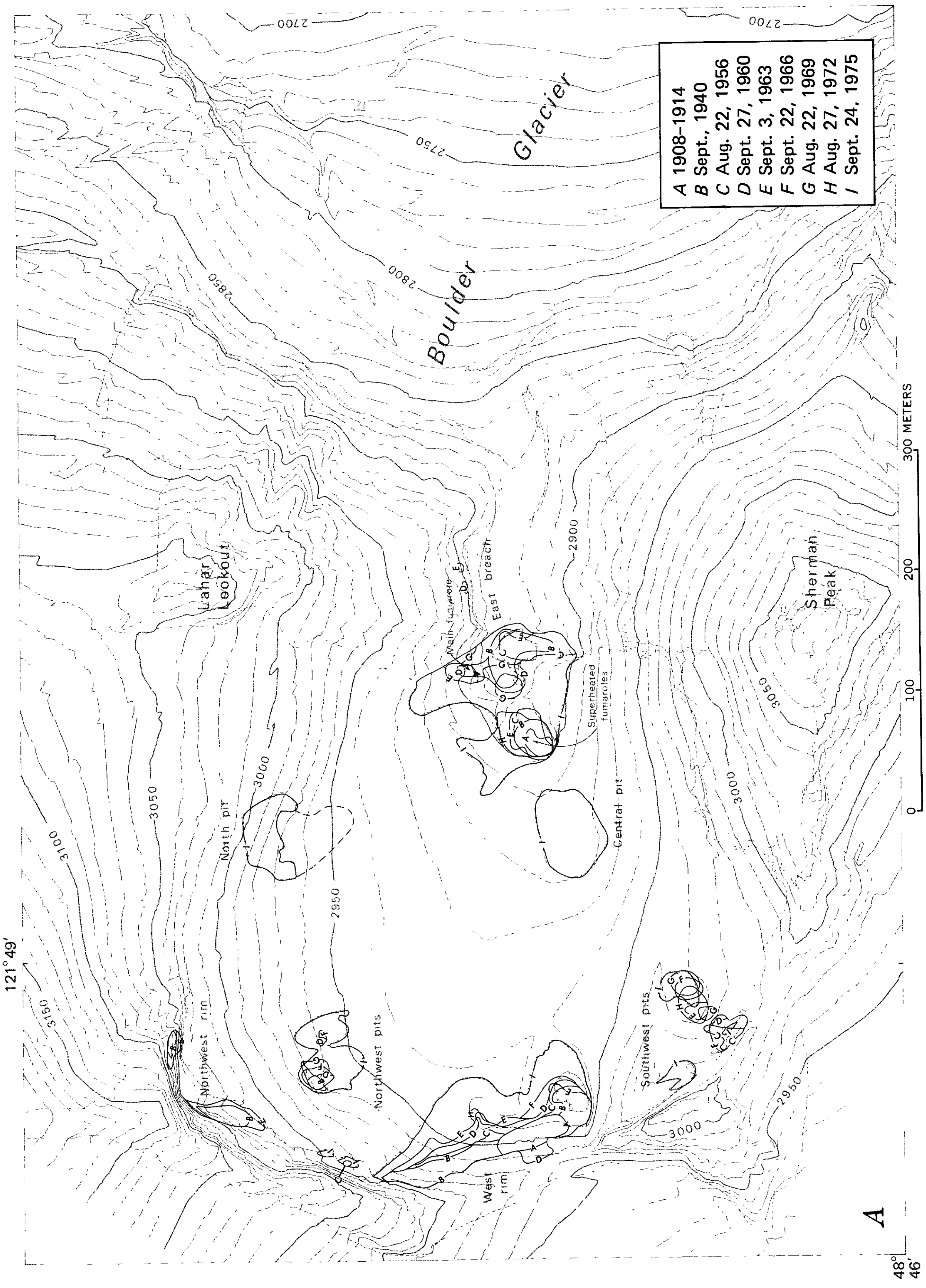
The increased thermal activity has apparently produced additional flow of acidic water into Boulder Creek (fig. 1), which drains Sherman Crater. The discovery of acidic water in Boulder Creek raised questions about possible detrimental effects on Baker Lake, into which Boulder Creek discharges, and on the Skagit River, farther downstream. Therefore, a preliminary reconnaissance was made by personnel of the U.S. Geological Survey in March 1975 to measure various water-quality parameters in Boulder Creek, Baker Lake, Baker River, Skagit River, and several unaffected streams near Boulder Creek that flow into Baker Lake. The reconnaissance indicated that the acidity problem was confined to Boulder Creek and Baker Lake and was not detectable below the lake. Also, in this and later surveys, the toxic-metal content in the outflow of Baker Lake was found to be no higher than that in the unaffected streams flowing into Baker Lake.

A more detailed survey of Baker Lake's water quality was conducted in September 1975. Measurements were made of specific conductance, pH, temperature, and dissolved oxygen. Data from this survey, tabulated by Bortleson and Wilson (1976), indicate that the acidic water at that time was moving downstream close to the lake bottom in the shallower part of the lake until it reached deeper waters of the same density, at which depth it fingered out into the lake as an acidic wedge. Although the exact areal extent of the acidic wedge is not known, it did not extend beyond a sampling transect 1.8 km downlake. The acidic water at this time was established as neither being pooled in large quantities on the bottom nor corroding the concrete in the dam. Concentration and movement of acidic water in Baker Lake is expected to vary according to the Boulder Creek discharge and according to the seasons of the year. Additional surveys are planned in 1976 to maintain observation of the lake conditions.

A joint-agency monitoring program was initiated to maintain surveillance of the Boulder Creek–Baker Lake–Baker River system. U.S. Forest Service personnel measured pH, specific conductance, temperature, and water stage approximately every 3 to 5 days during the summer of 1975 at the bridge crossings of Boulder and Park Creeks. Also, about every 2 weeks Forest Service personnel collected samples for chemical analysis of common constituents and toxic metals at these two sites and at Baker River, below Baker Dam. Chemists of the U.S. Geological Survey analyzed these samples. Sampling frequency was sharply reduced during the winter, owing to access problems.

Data from this program show that average concentrations of sulfate, iron, manganese, aluminum, arsenic, and fluoride in Boulder Creek are 10 to 100 times higher than in nearby streams. Average summertime pH in 1975 in Boulder Creek was about 3.9, and in nearby streams, about 7.2. Immediately downstream from Baker Lake, the pH averaged about 7.0. After fall and winter freezeup at higher elevations, the average pH of Boulder Creek rose to about 5. Acid loads from Boulder Creek in the summertime ranged from a few thousand to several thousand kilograms of H_2SO_4 per day. To date (March 1976), no significant acidity has been detected downstream from Baker Lake.

In an attempt to maintain surveillance of this potential problem, a radiotelemetering monitor was installed in early 1976 on Boulder Creek to warn of sudden changes in streamflow or in pH, either of which may be early indicators of undercutting or damming of the breach or of a mudflow. The monitor, which was not yet fully operational by March, measures water stage, pH, temperature, specific conductance, and dissolved oxygen. These data are relayed hourly by radiotelemetry to the Tacoma office of the U.S. Geological Survey.


A 1908–1914
B Sept., 1940
C Aug. 22, 1956
D Sept. 27, 1960
E Sept. 3, 1963
F Sept. 22, 1966
G Aug. 22, 1969
H Aug. 27, 1972
I Sept. 24, 1975
Boulder Glacier
Lahar Lookout
Main fumarole
East breach
Superheated fumaroles
Central pit
North pit
Northwest rim
Northwest pits
West rim
Southwest pits
Sherman Peak
121°49′
48°46′
2700
2750
2800
2850
2900
2950
3000
3050
3100
3150
0 100 200 300 METERS
CONTOUR INTERVAL 10 METERS
A

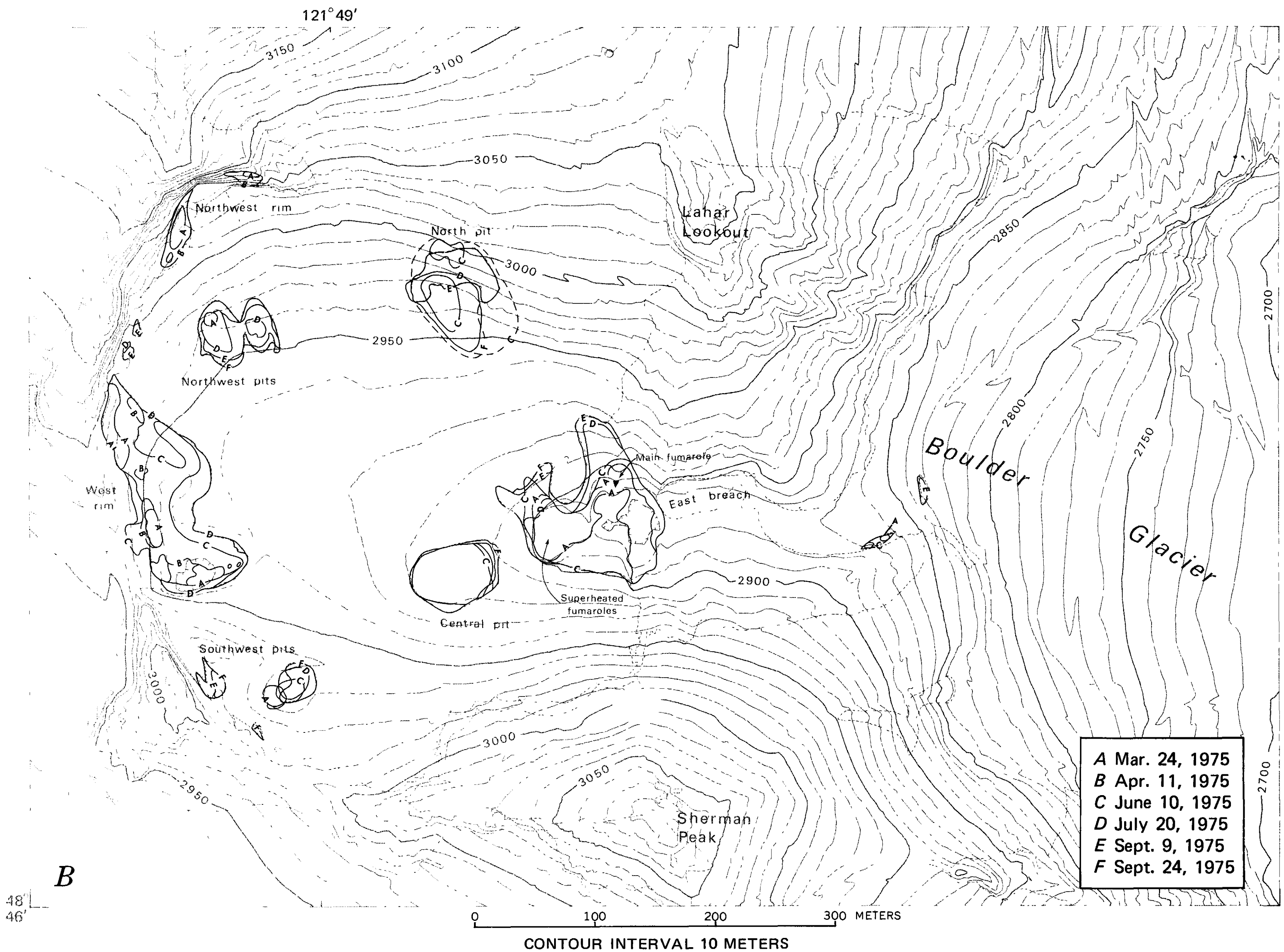


FIGURE 19. — Thermal area as mapped from photographs. *A*, Thermal area during late summer snow conditions from 1900 to 1975 was mapped by interpretation of anomalous snowline margins in conjunction with 1972–75 field data. Thermal areas for 1908–14 represent minimum areas because only part of the crater was visible in available photographs. *B*, Thermal area from March to September 1975. Letters refer to photograph dates. Dashed areas around the north pit are locations of anomalously high heat flow, where ice did not melt completely because of almost continual replenishment by ice calving into the north pit. Base from U.S. Forest Service, 1:24,000, 1975.

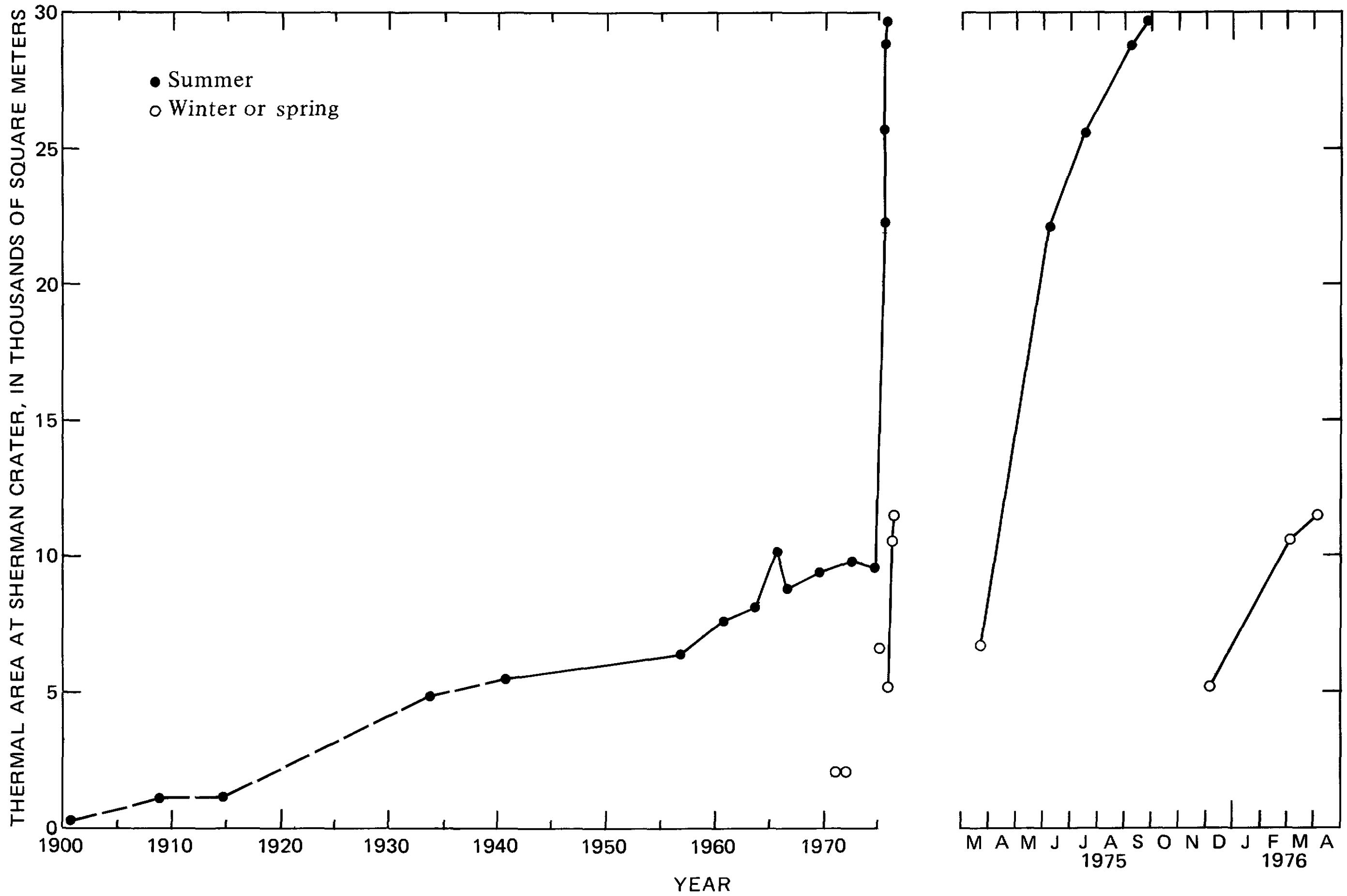


FIGURE 20. — Change in snow-free thermal area through the 20th century. Values of thermal area prior to 1940 (dashed) may be somewhat low because not all of Sherman Crater was visible in the earlier photographs. A small general increase in area is apparent from 1900 to 1974; a threefold increase occurred in 1975. The 1976 winter thermal area remains almost 3 times greater than the late winter areas of 2 previous years.

HAZARD ANALYSIS

Quiescent volcanoes often create interest only as scenic wonders or opportune watersheds, and not as having potentially destructive capabilities. Active volcanoes, on the other hand, draw more serious considerations. Because many of the Cascade Range volcanoes erupted at various times during the last few thousand years, the verbal record of Native Americans is permeated with legends of volcanic catastrophies. Indeed, the most explosive postglacial eruption of the North American Continent, which culminated in the collapse of Mount Mazama about 6,600 years ago to form Crater Lake, Oreg., was probably witnessed by local residents.

Twentieth-century civilization in the Pacific Northwest, however, has not had the opportunity to fully appreciate the hazards associated with volcanic eruptions. Explorers of the 1800's recorded accounts of eruptions as seen from great distances, and, to be sure, the explosive eruptions of Lassen Peak in 1914–17 generated some excitement, but the low density of nearby civilization resulted in recognition of these events mostly as curiosities.

For many decades society has been building its structures ever closer to the Cascade volcanoes. Only in the past 15 years, however, have stratigraphic studies of postglacial volcanic deposits prompted serious consideration of the risk presented by the volcanoes. So, not only do we face the volcanic threat to future land use, but also we must confront the unforseen dilemma of the already established, economically important structures — such as hydroelectric power reservoirs — that lie in the path of potential danger. In such circumstances, it is not enough to make a simple scientific estimate of risk; it is also necessary to weigh the risk to life and property against the socioeconomic advantages of taking some, part, or all of the risk. The latter problem certainly should not be dealt with solely by scientists but should be addressed by all people threatened by volcanic hazards.

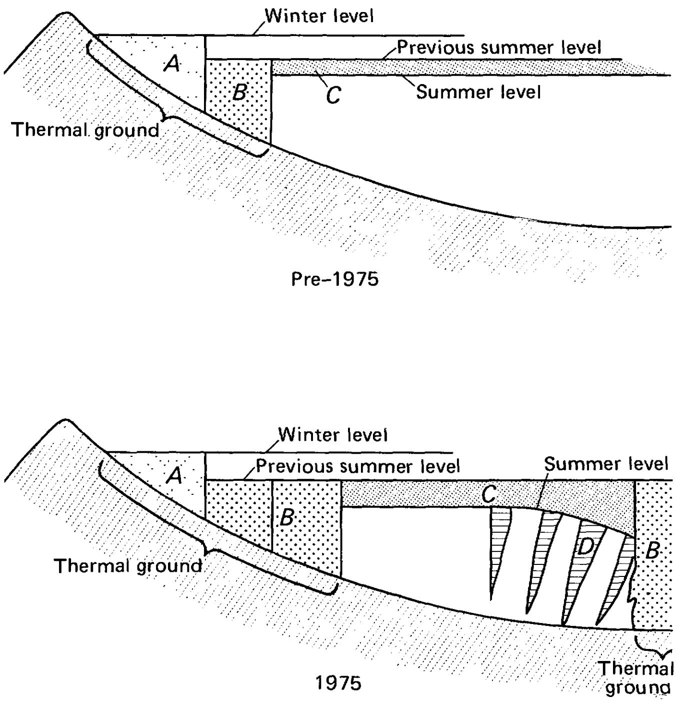


FIGURE 21. — Diagrammatic cross section of part of Sherman Crater, showing how heat flow can be estimated from snow and ice loss. *A* represents the volume of snow melted to keep the area snow free in winter. Heat-flux estimates for *A* were derived in two ways: (1) Heat-flux density was assumed to be 419 W/m^2, or (2) the maximum heat-flux density measured elsewhere in the crater was used. *B* represents the volume of snow (pre-1975) or of snow, ice, and firn (1975) melted as thermal ground becomes snow free in summer. *C* shows the volume lost from thinning of remaining snow and ice from year to year because of either local melting or gradual extension toward the thermal areas. *D* is crevasse volume due to local extension toward new thermal areas and was measured only west of the central pit and north and east of the north pit. For *B*, *C*, and *D*, densities were assumed to be 600 kg/m^3 for snow and 700 kg/m^3 for snow and ice undifferentiated, and heat flux was calculated on the basis of the rate of removal of snow and ice.

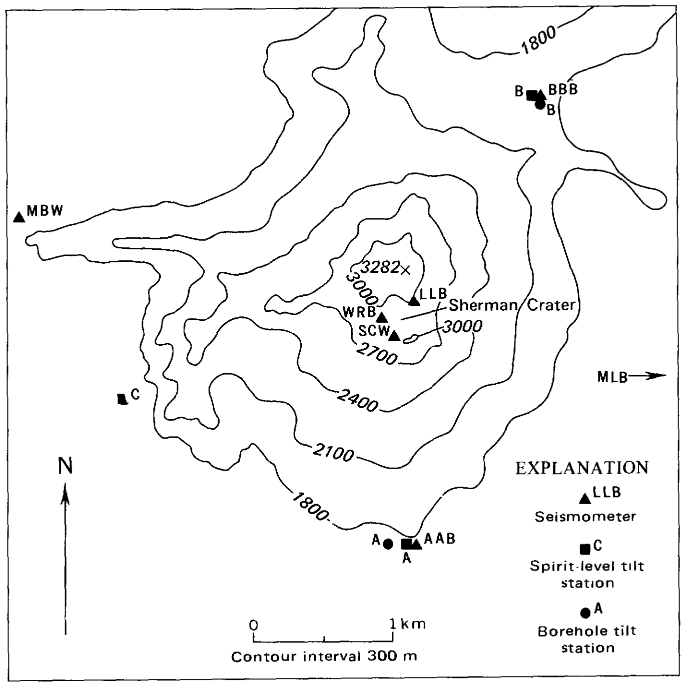


FIGURE 22. — Locations of seismic, tilt, and gravity stations on Mount Baker.

Should Mount Baker erupt in the future, certain areas would be threatened by a variety of volcanic phenomena (Hyde and Crandell, 1977). Even though Mount Baker is now dormant, the current hydrothermal activity presents some hazards, which include pollution by gaseous and liquid effluents and possible avalanches of rock debris and mudflows. The following section discusses present hazards and responses to them by administrative agencies.

POLLUTION

To date, effluents of volcanic gases and acidic waters have been a major hazard at Mount Baker. An abundant gas from fumaroles in Sherman Crater is toxic hydrogen sulfide (H_2S). A concentration of only 1 ppm is detectable as a rotten-egg smell, but the human sense of smell can be quickly destroyed by H_2S. Thus, smell alone is not a suitable warning of overdose. The Occupational Safety and Health Administration recommends protective breathing apparatus for H_2S concentrations greater than 10 ppm. Analyses by J. E. McLane (oral commun., 1975) of several samples of vapor from fumaroles in Sherman Crater during 1975 indicated H_2S concentrations of several percent, enough to cause death in minutes. Monitoring of H_2S in the open air along the rim of Sherman Crater during the summer of 1975 showed that concentrations greater than 50 ppm are to be expected, even tens of meters downwind from fumarole openings. At times, H_2S has been smelled at lower altitudes, particularly in the Boulder Creek valley but also as far as 30 km to the west at the community of Deming. Although not yet studied in detail, current levels of H_2S concentration at such great distances are probably too low to cause much harm to people. However, the physiological effect of sulfur gases on plants — timber in particular — has been significant in other areas (Carlson, 1974) and bears further study at Mount Baker. From aerial surveys in June 1975, Radke, Hobbs, and Stith (1976, p. 96) concluded that Mount Baker at that time produced Washington's largest single plume of gaseous sulfur, natural or industrial.

Another abundant fumarole gas at Sherman Crater is carbon dioxide (CO_2). Although not toxic, CO_2 is heavier than air and has caused animal suffocation in enclosed basins near fumaroles in Iceland (Thorarinsson, 1970, p. 36–37). Other common toxic gases in fumaroles at other volcanoes (but which are not pre-

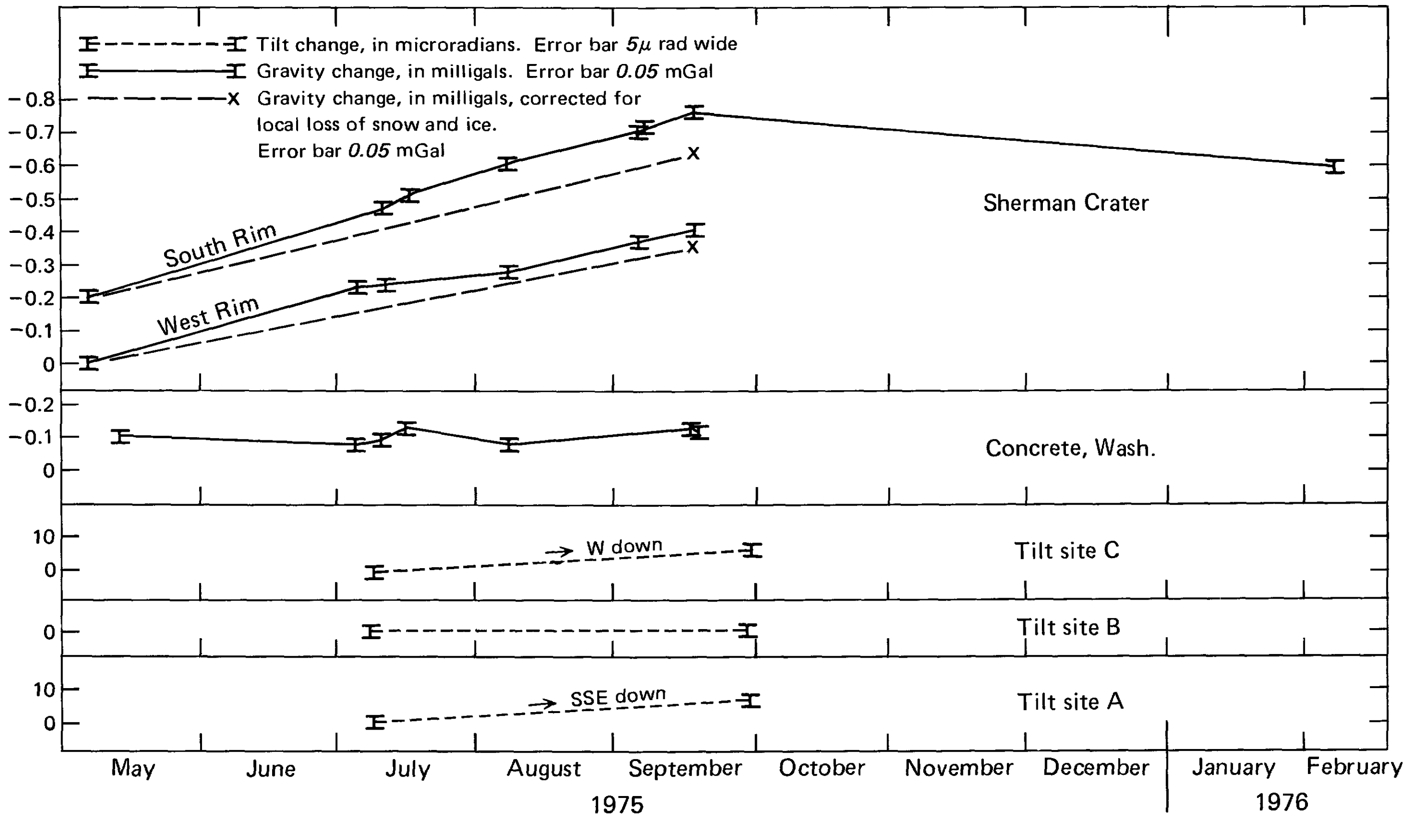


FIGURE 23. — Spirit-level tilt and gravity measurements.

dominant in the 1975 analyses of gas from Sherman Crater (J. E. McLane, oral commun., 1975)) are sulfur dioxide (SO_2), carbon monoxide (CO), ammonia (NH_3), flourine (F), and chlorine (Cl). The precautions taken during the recent field investigations at Mount Baker limited the observed effects of fumarole gas to occasional nausea, headache, and eye irritation. However, the hazardous potential of such gases was shown in 1934, when either toxicity or displacement of oxygen by fumarole gas in a hydrothermal area on Mount Hood, Oreg., resulted in one of the few known human deaths from a volcanic cause in the United States (McNeil, 1937, p. 178–191).

Acidification of surface water and ground water commonly occurs in fumarole fields by oxidation of fumarole gases (Schoen and others, 1974, p. 4). Fretwell previously described the flow path and chemistry of acid-charged water that drains from Sherman Crater. Acid can be toxic to aquatic life and can cause structural deterioration, particularly of concrete. The degree of hazard depends primarily on the initial concentration and dilution downvalley of toxic substances in water discharged from the crater. Because the present drainage from Sherman Crater flows into Boulder Creek, the major effect on water quality is limited to Boulder Creek and downvalley areas. High levels of acidic water in 1975 did not extend farther downstream than Baker Lake. Bortleson, Wilson, and Foxworthy (1976) provide a more detailed analysis of the water quality implications of present hydrothermal activity.

Tests of water samples from the drainage system of the Dorr Fumarole Field in 1974 indicated that the water did not flow freely through Mazama Glacier into Bar Creek at that time. Because there was no evidence of increased fumarolic activity at the Dorr Field in 1975, acid waters probably still do not appreciably affect Bar Creek. Future increases in activity, however, might be reflected in high acidity in Bar Creek, Wells Creek, and possibly the North Fork Nooksack River.

AVALANCHE AND MUDFLOW HAZARD

Hydrothermal activity in fumarole fields typically consists of hot fluids that rise to the ground surface and penetrate interstices of the surrounding rocks. Chemical equilibration of rocks with the hydrothermal environment produces various alteration products, depending on the temperature, pressure, and chemical composition of the fluids. Under the strongly reactive conditions that usually accompany hot fluids, rock alteration can first cause physical and chemical changes along fissures and cavities and eventually can affect the entire mass.

The mechanical stability of rock that has been altered depends largely on fluid pressure, on fracturing

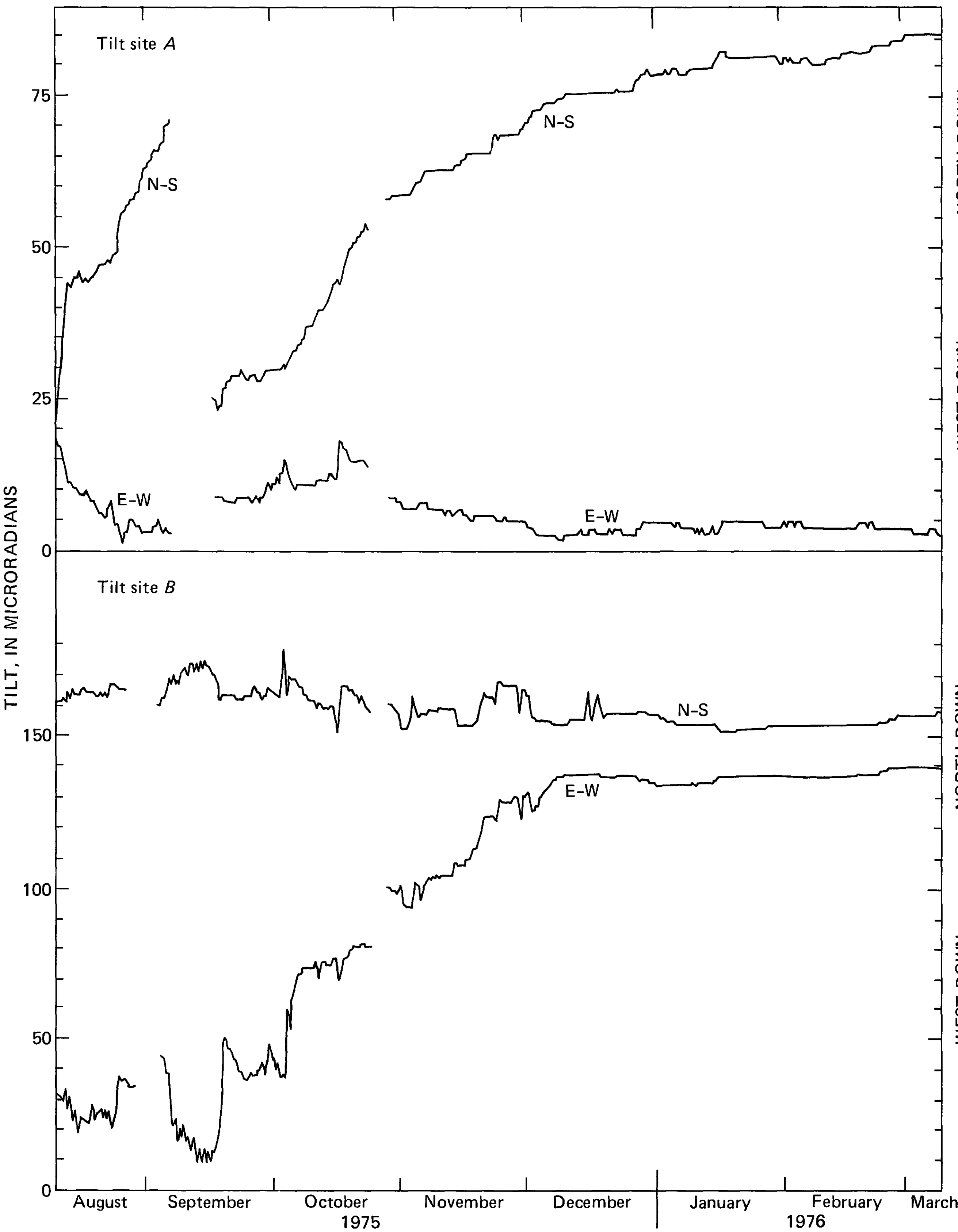


FIGURE 24. — Tiltmeter data at sites A and B.

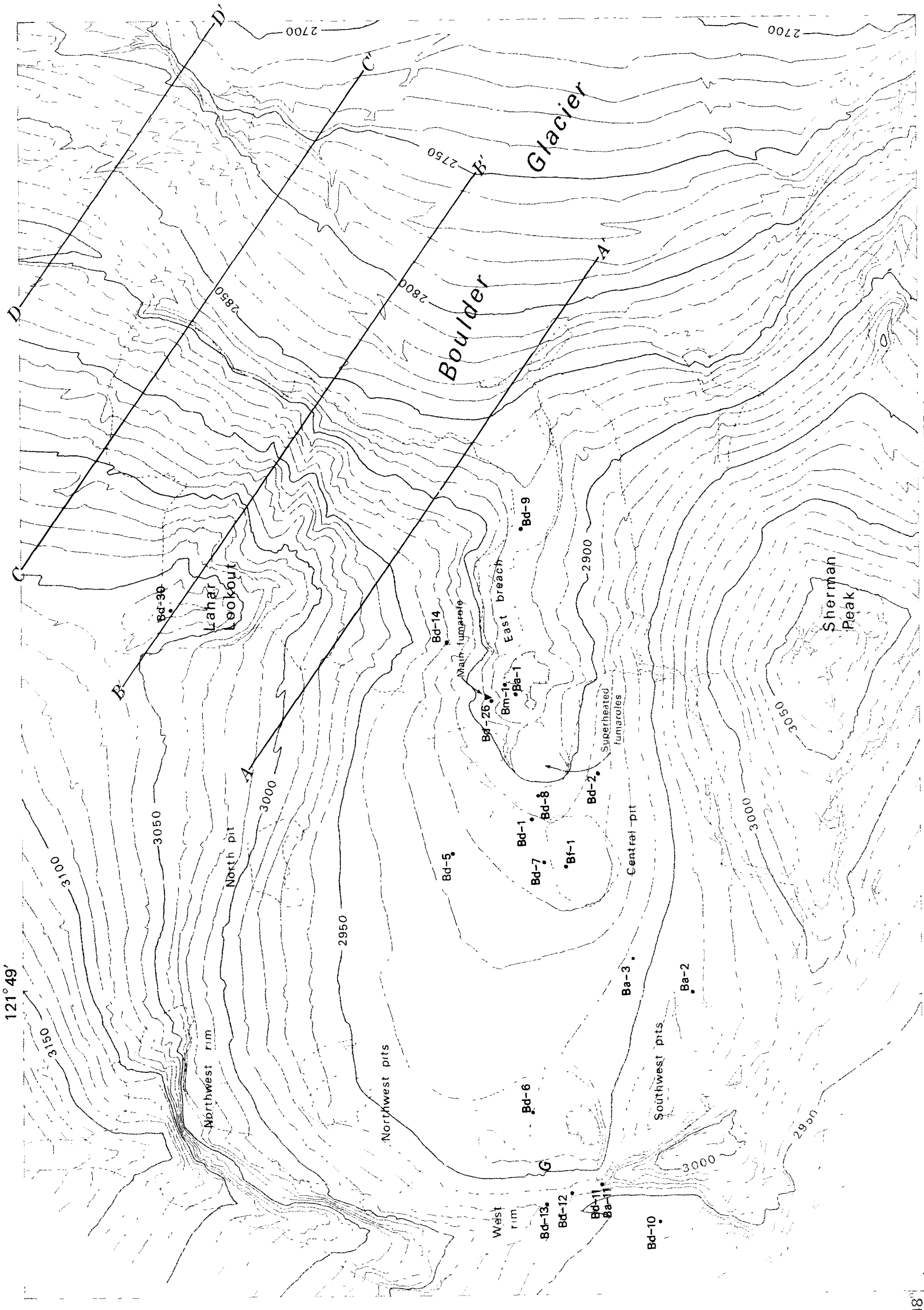


FIGURE 25. —Sampling sites (dots) of ejecta in the Sherman Crater area, and location of profiles across Lahar Lookout. Gas sensor was located at *G*.

FIGURE 26.—Two layers of ejecta (samples Bd–1–2 and Bd–1–3, table 6) in crevasse wall 100 m west of the new main fumarole. Ejecta was being deposited on the snow surface at the time this photograph was taken, March 31, 1975.

FIGURE 27.—Location of gas sensor on west rim, February 6, 1976.

generated by crystal growth and thermal and (or) tectonic stresses, and on the physical properties of the mineral products of alteration. Clay is a common alteration product at the ground surface, as well as at depth, in hydrothermal systems. In some geothermal areas, clay has been found to be a major rock component at depths of as much as 900 m. (For example, see Sumi, 1970.) Old volcanoes, such as Mount Baker, at which fumarolic activity has been going on for thousands of years, might be expected to contain large, structurally weak bodies of clay-rich material. Montmorillonite and kaolinite clay are abundant on the surface of Sherman Crater (Bockheim and Ballard, 1975) and reflect the alteration to various degrees of virtually all the rock rimming the crater. Although the extent of alteration beneath the surface is unknown, its presence at depth is indicated by major concentrations of clay minerals in the 1975 ejecta.

Hydrothermally altered material is a prime source of rock debris for avalanches and mudflows. Mass movements of such debris can be initiated by the opening of large new fumarole conduits, as well as by other volcanic-related events, such as earthquakes, eruptions, or steam explosions. In order to examine the potential hazard presented by large mass movements at Mount Baker, two approaches have been taken: investigation of the recent geological record and appraisal of current conditions.

HAZARD ANALYSIS BASED ON HISTORICAL RECORD

The time, place, or magnitude of a natural-hazard event usually cannot be predicted. However, the probability of its occurring at a specific place and having a specific magnitude can be estimated if a relatively complete history of occurrences is available. Probability estimates for future events, then, rest only on the assumption that the statistical characteristics which describe past events carry on into the future. This procedure is widely used in regard to certain other natural hazards, such as floods, droughts, and severe storms.

Data gathered by Hyde and Crandell (1977) were used to estimate probabilities in 1975 for two types of events: (1) a mudflow sufficiently large to reach Baker Lake, having an estimated probability of 1 in 100 in a given year, and (2) an air-cushioned avalanche into Baker Lake, having an estimated probability between 1 in 1,000 and 1 in 10,000 in a given year. (See app. 1.) These probability figures are only estimates because of the small sample of data; the uncertain conditional probability that a given mudflow would occur in the Baker Lake drainage, and not elsewhere; the quantitatively unknown influence of the 1975 thermal activity as a mudflow trigger; and the possibility (which was not considered) that the frequency of mudflows may have increased, as shown by the geologic record of the last 500–600 years (Hyde and Crandell, 1977).

HAZARD ANALYSIS BASED ON PRESENT CONDITIONS

Although the probability of occurrence of large mudflows can be estimated by analyzing the frequency of similar events in the past, this type of study yields little information on such important parameters as the shape and velocity of the mudflow. Good estimates of these parameters are necessary before any analysis can be made of the most important hazard from such a flow — its effect on Baker Lake. These estimates can be made by determining the present conditions at Mount Baker and by comparing these conditions with those where mudflows and avalanches have been observed elsewhere.

If a large mass from the rim of Sherman Crater were set in motion, it could begin as an avalanche of rock, snow, and ice. After descending the steep slopes of Mount Baker, its motion might continue downvalley as a wet slurry (mudflow), as an air-cushioned avalanche of broken rock, or, possibly, as a fluidized mass with intermediate characteristics. Air-cushioned avalanches are known to travel much faster than mudflows, but they cannot form unless a certain critical volume of debris is involved and other specific conditions are met. Thus, evaluation of this hazard includes ascertaining whether unstable rock masses exist which could be set in motion and whether the volume of rock would be sufficient and other conditions met so that an air cushion would form and be retained under the sliding rock debris.

SOURCES OF MUDFLOWS OR ROCK AVALANCHES

Large steep masses of altered and weakned rock currently exist high on Mount Baker. Almost all of the rim of Sherman Crater is composed of highly altered lava flows and breccias. Favorable topography outside Sherman Crater, which would allow rapid downslope movement of rock debris, exists at Sherman Peak and Lahar Lookout. At both places, the rock debris would probably descend the Boulder Creek valley and could reach Baker Lake (frontispiece).

Sherman Peak (altitude 3,089 m) stands about 220 m above the east breach and is mostly sheathed by snow and ice. The slope toward the notch is about 40°; toward Boulder Glacier, about 43°; and toward Talum Glacier (also tributary to Boulder Creek), about 39°. Small avalanches of about 35×10^3 m^3 of snow, firn, and altered rock from Sherman Peak have occurred at least 6 times since 1958 (Frank and others, 1975). Much larger avalanches seem possible. Frank, Post, and Friedman (1975) estimated that an avalanche of about 5×10^6 m^3 was conceivable if additional material undercut by the smaller avalanches also broke off. If all of Sherman Peak slid off to the east, possibly as a result of a massive steam explosion or earthquake, as much as 16×10^6 m^3 of material could be set in motion. Such a volume is represented by the material above a hypothetical surface dipping 24.5° E., originating on the south rim of Sherman Crater about 170 m west of Sherman Peak and emerging east of the peak at an altitude of 2,590 m. The slope of this possible shear surface is somewhat less than the average angle of repose of disaggregated dry rock, so an additional mobilizing agent — steam, water, or explosion — probably would be required to move a mass this large. The present distribution of fumaroles does not appear to coincide with the hypothetical fracture surface.

Lahar Lookout is a more likely source for a huge avalanche or mudflow because (1) a larger mass of altered rock is present above a possible shear surface; (2) rock exposed there is thoroughly altered and cut by several structures which might expedite failure; and (3) existing steam conduits pass close to or through the possible shear surface. Profiles through Lahar Lookout (fig. 28) suggest that, for a width of 490 m, the volume above a possible curved shear surface beneath Lahar Lookout is about 33×10^6 m^3, and the volume above a planar shear surface that slopes 34° (angle of repose of dry rock fragments) is about 16×10^6 m^3. An additional amount should be added to these figures because of snow and ice beside or below the outcrop of the hypothetical shear surface, perhaps equal to 30 percent of the rock volume. Although extremely unlikely, it is possible that an even larger mass could break up.

MOTION OF POSSIBLE AVALANCHE OR MUDFLOW

Air-cushioned rock avalanches are known to travel very fast, so the possibility of one of these reaching Baker Lake and delivering a large impulse to the lake is clearly the worst possible hazard to consider. Table 7 lists dimensions and other parameters of large debris slides elsewhere which are believed to have traveled, at least in part, on an air cushion, together with relevant information on a previous avalanche and mudflow at Mount Baker. A possible 20 to 30×10^6 m^3 avalanche down the Boulder Creek valley would drop 2,800 m within a distance of 12,500 m, and would have a "friction coefficient" of 0.22. It would therefore have parameters similar to those of the air-cushioned avalanches at Frank, Alberta; Sherman Glacier, Alaska; Little Tahoma Peak, Washington; and Huascarán, Peru. Thus, rapid motion is considered possible.

The following analysis of such an air-cushioned avalanche at Boulder Creek is a statement by Ronald L. Shreve; his complete statement is given as appendix 2.

SUMMARY OF EVALUATION OF AIR-CUSHIONED AVALANCHE OR MUDFLOW AT BOULDER CREEK

By Ronald L. Shreve

Air-cushioned avalanches of the sort considered here do not occur frequently in nature and cannot be studied

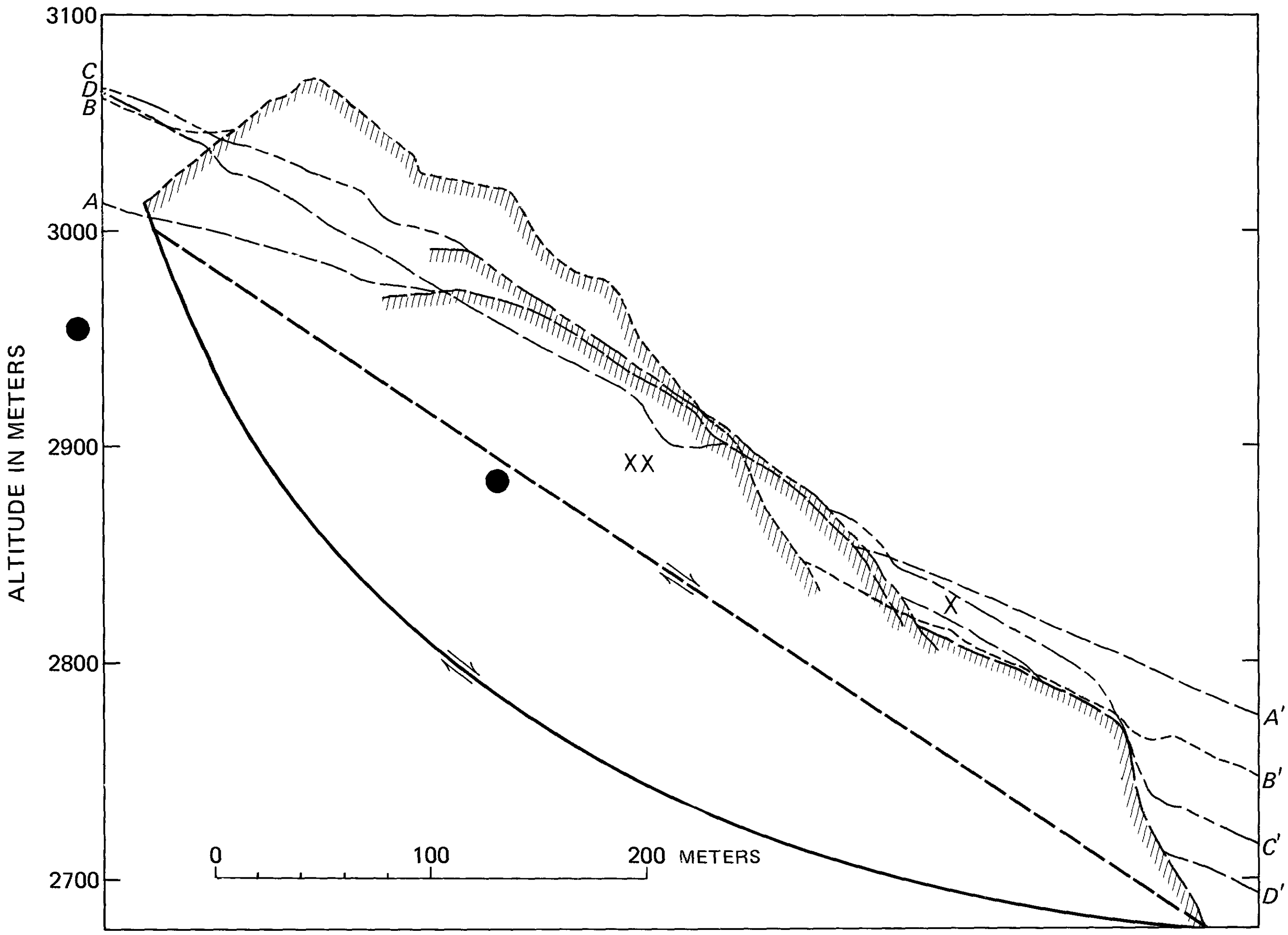


FIGURE 28.—Four parallel profiles across Lahar Lookout. Profiles are spaced approximately 120 m apart; their locations are shown in figure 25. Hachures indicate rock outcrops; dashed lines indicate snow. Heavy line is a possible curved shear surface; and heavy dashed line is a possible planar shear surface sloping 34°. Major new fumaroles in the Lahar Lookout mass emerge at dots; locations of heat emission which possibly are fumaroles emerge at ×.

in the laboratory. Therefore, relatively few comparable case histories exist, and even fewer established principles are available for use as a basis for prediction. The uncertainty is further compounded by the unpredictable effects of volcanic activity on a glacier-clad mountain. Thus, estimates given here must be viewed with caution.

Formation of an air-cushioned avalanche with long runout requires that the avalanche override and trap sufficient air to significantly reduce contact with the ground. This, in turn, requires a suitable break in slope to launch the avalanche into the air, high speed to enable it to override enough air, and sufficient thickness of the debris and smoothness of the ground to prevent excessive loss of air. An adequate slope break for launching is present at the 1,000-m level in the canyon of Boulder Creek. The speed of a hypothetical avalanche at this launch point would probably be at least 270 km/hr, which corresponds to conversion of one-eighth of the available potential energy to kinetic energy; observations at other areas suggest a somewhat higher fraction — possibly one-fifth — would be converted. Even at the speed of 270 km/hr, enough air could be trapped to form a layer about 2 m thick if compressed under 6 m of debris over the whole area of the avalanche down to the lakeshore.

The most important consideration is the probable thickness of the avalanching debris. On the basis of other observations it seems reasonable to assume that a minimum debris thickness of 5 m is necessary for long runout. In other avalanches, 75 to 85 percent of the debris was deposited beyond the launch point. At Mount Baker, the area of the probable avalanche path is 6.6×10^6 m^2 from the 1,000-m level to the lakeshore. If debris were to be spread over this area to a depth of 5 m, and if corrections were made for the amount left above the launch point and for the increase in volume of the rock as it disaggregates in the initial fall, the required

TABLE 7. — *Characteristics of observed and probable air-cushioned rock avalanches compared with a prehistoric mudflow and avalanche at Mount Baker*

[Leaders (. . . .) indicate no data available]

	Year	Volume ($m^3 \times 10^6$)	Vertical drop (m)	Horizontal distance (m)	Friction coefficient[1]	Observed speed (km/hr)	Calculated speed[2] (km/hr)	Air cushion
Blackhawk, California (Shreve, 1968)	([3])	300	1,200	9,000	0.13	...	120	Probable
Elm, Switzerland (Heim, 1882)	1881	11	600	2,000	.30	...	160	Observed
Frank, Alberta, Canada (McConnell and Brock, 1904)	1903	37	670	2,700	.26	...	175	Do.
Sherman Glacier, Alaska (Shreve, 1966)	1964	30	1,100	5,000	.22	...	185	Probable
Little Tahoma Peak, Washington (Crandell and Fahnestock, 1965)	1963	11	1,900	6,400	.30	...	100–150	Do.
Huascaran, Peru: (McDowell and Fletcher, 1962; Morales, 1966)	1962	13	3,500	14,500	.24	123	...	Do.
(Plafker and others, 1971)	1970	>50	3,500	14,500	.24	280–335	...	Observed
Mount Baker (Hyde and Crandell, 1977): Middle Fork Nooksack River mudflow	([3])	40	2,800	27,000	.10	...	...	Unknown.
Rainbow Creek avalanche	([3])	13	1,700	9,000	.19	...	...	Do.

[1] Vertical drop divided by horizontal distance; values given by original authors may not coincide exactly with values or ratios given in this table.
[2] Minimum speed computed on assumption of conservation of energy.
[3] Prehistoric.

(minimum) original volume of undisaggregated rock would be 25×10^6 m^3.

During runout, the trapped air must spread out more or less uniformly under the advancing debris. This process depends strongly on the variation with time of the thickness of the debris passing the launch point. Judging from other air-cushioned avalanches, long runout seems to require a thickness that tapers slightly toward the rear so as to partly compensate for the rapid removal of air from the launch region by shearing. At Mount Baker, the thickness could conceivably vary in such a way that the air layer would be unstable and break up rapidly, even though other factors, such as forward speed, air volume, and debris thickness, were favorable for development of an air cushion. A further requirement for a stable air cushion is that the product of permeability and bulk density of the debris at the base of the avalanche be less than about 0.7 times the product of harmonic mean permeability and arithmetic mean density for the whole thickness of the debris. In practical terms, a thin basal layer of finer, tighter material would suffice. At Mount Baker, this requirement would doubtless be satisfied by snow picked up from Boulder Glacier. An air-cushioned avalanche debouching from the narrow canyon of Boulder Creek onto the convex alluvial cone between the main road and Baker Lake very likely would tend to split into multiple lobes. This would lead to loss of air that, if great enough, might disrupt the air cushion short of the lake. Slowing of the avalanche and increased air loss would also occur if the surface of the alluvial cone had rough local relief greater than the thickness of the air cushion.

Thus, a rock mass having a volume of 20 to 30×10^6 m^3 that breaks off Lahar Lookout *might* travel down the Boulder Creek valley on an air cushion; if so, it *might* lose its air cushion before striking Baker Lake.

An air-cushioned avalanche large enough to reach Baker Lake would probably be about 350 to 450 m wide at the point where the main road crosses Boulder Creek. Also, it would spread laterally as it crossed the convex surface of the alluvial cone to the lakeshore, where it would most likely have a width of about 2,400 m. Speed of the avalanche on entering the lake would probably be in the range of 160 to 320 km/hr; its thickness on entering the lake would most likely be about 6 m.

If the avalanche did not capture and retain an air cushion, it could travel entirely as a mudflow, or it could travel part of the distance on an air cushion and the remainder of the way as a mudflow. A mudflow would tend to be narrower, thicker, and slower than an air-cushioned avalanche of the same volume. A mudflow down Boulder Creek that originated in a fall of 30×10^6 m^3 of rock from the vicinity of Lahar Lookout would probably have a width of about 800 m, a thickness of about 12 m, and a speed of about 50 km/hr as it entered Baker Lake.

Note that, unlike air-cushioned avalanches, there is no minimum thickness or minimum speed for a mudflow that could reach the lake. Hyde and Crandell (1977) found remnants of prehistoric mudflows that are less than 0.6 m thick along Boulder Creek between the main road and Baker Lake. Thinner flows will be slower, generally narrower, and occur more frequently than thicker ones. In addition, an air-cushioned avalanche too small to reach the lake could continue on as a high-speed mudflow, as did the Huascarán avalanche near Matacoto, Peru (Plafker and others, 1971). That mudflow traveled 150 km down the Rio Santa below Matacoto at an average speed of about 35 km/hr; its initial speed near Matacoto probably was several times higher. Thus, rock debris moving down Boulder Creek valley could enter Baker Lake at speeds ranging from almost zero to a few hundred kilometers per hour, depending on size of fall and mode of transport.

EFFECT OF POSSIBLE ROCK AVALANCHE OR MUDFLOW ON BAKER LAKE

As it is possible for a fast-moving avalanche to enter Baker Lake, the consequences should be assessed with respect to human life and property damage. Three possible effects of a large wave on the lake have to be considered: (1) safety of people on the lake, in public campgrounds, and in a private resort on the lakeshore; (2) safety of Upper Baker Dam (a concrete gravitational structure that impounds Baker Lake); and (3) safety of Lake Shannon (and Lower Baker Dam) and the populated Skagit River valley downstream from Baker Lake (fig. 29). An estimate of the possible wave height at the campgrounds and at Upper Baker Dam is an essential part of this analysis.

Puget Sound Power and Light Co. (Puget Power), managers of the Baker Lake hydroelectric power project, commissioned Tetra Tech, Inc., to estimate the effect of a possible avalanche or mudflow on the lake. The following analysis of possible wave heights is based on information contained in the report made to Puget Power.

The avalanche or mudflow is considered to be a rigid body, causing displacement of the lake surface. The energy dissipation due to impact of debris on the lake surface is neglected, and the lake margin is considered to be vertical. These two assumptions are conservative — that is, the real waves will be lower than those predicted. Wave propagation can then be described by the usual two-dimensional nonlinear long-wavelength wave equations. These equations can be solved by making finite-difference approximations and using any one of several solution techniques. As a result, time histories of water-surface elevation can be calculated at various points along Baker Lake and for any specified stage of the lake. Typical results are shown in table 8 for a wave arriving at Upper Baker Dam.

TABLE 8. — *Calculated height of waves at Upper Baker Dam in the event of an avalanche or mudflow*

[Overtopping of the dam was not considered in calculating wave height. Normal "full-pool" stage is 2.4 m below dam crest. Leaders (. . .) indicate no calculation was made. Information supplied by Puget Sound Power and Light Co. Data are in meters]

Assumed avalanche or mudflow speed	Lake stage below dam crest	Wave height above lake stage: For flow 2,400 m wide and 6.1 m thick	For flow 800 m wide and 12.2 m thick
Infinite	2.4	10.0	5.2
Do	5.5	8.3	4.1
Do	8.5	7.1	3.4
219 km/hr[1]	2.4	9.4	. . .
49.4 km/hr[1]	2.4	. . .	0.8

[1] Corrected avalanche and mudflow parameters; these figures were misplaced in the original table in the Tetra Tech report to Puget Power.

These results show that holding the reservoir stage about 7 m below the dam crest (4.6 m below normal full-pool elevation) is sufficient to prevent overtopping and any damage downstream resulting from an air-cushioned avalanche into the lake. Also, the difference in calculated wave heights between an instantaneous debris impact having infinite speed and a fast avalanche having a more realistic, finite speed is small (6 percent). For a slower mudflow, the actual speed must be used to calculate wave height.

Comparison of the present state of knowledge of avalanche or mudflow dynamics and that of water-wave dynamics is interesting. The propagation of a wave in water is described by known laws (the Navier-Stokes equations). Procedures for solving these equations numerically for specified conditions, such as a wave on Baker Lake, are well known. With the assignment of appropriate parameters and boundary conditions, solutions can be obtained in a straightforward manner and to almost any level of precision.

By way of contrast, very little is known about the dynamics of large mudflows or rock avalanches. Very few quantitative observational data have been obtained anywhere in the world. Even the appropriate flow law (rheology) is virtually unknown. Thus, simple questions, such as how fast would a specified debris mass move on a specified surface, cannot be answered. Certainly, this is a field ripe for research.

DISCUSSION OF HAZARD ANALYSES

The worst plausible geologic event at Mount Baker, assuming no volcanic or phreatic eruption, is a huge rock mass breaking from the rim of Sherman Crater, descending into Boulder Creek valley as a fast-moving avalanche, entering Baker Lake, and generating a large water wave. The geologic record of prehistoric events allows certain probabilities of occurrence to be estimated without reference to specific locations. On the other hand, study of present conditions and their relation to conditions of known avalanches in other areas allows estimates of likely parameters of an avalanche or mudflow moving down Boulder Creek valley to be made but does not allow the probability of occurrence of such an event to be calculated. The combination of these two methods adds somewhat to our knowledge. But a useful prediction cannot be made; probabilities of occurrence of specific avalanches or mudflows indicated by study of current conditions cannot be assigned with a high level of confidence, and no predictions of the time of occurrence can be made. Thus, only a generalized hazard probability can be stated, along with estimates of parameters of possible avalanches or mudflows.

RESPONSE TO MOUNT BAKER ACTIVITY

INITIAL RESPONSE

The dust-laden steam clouds at Mount Baker on March 10 and 11, 1975, caused considerable local apprehension and scientific interest. By midday, on March 11 (about 20 hours after the initial observa-

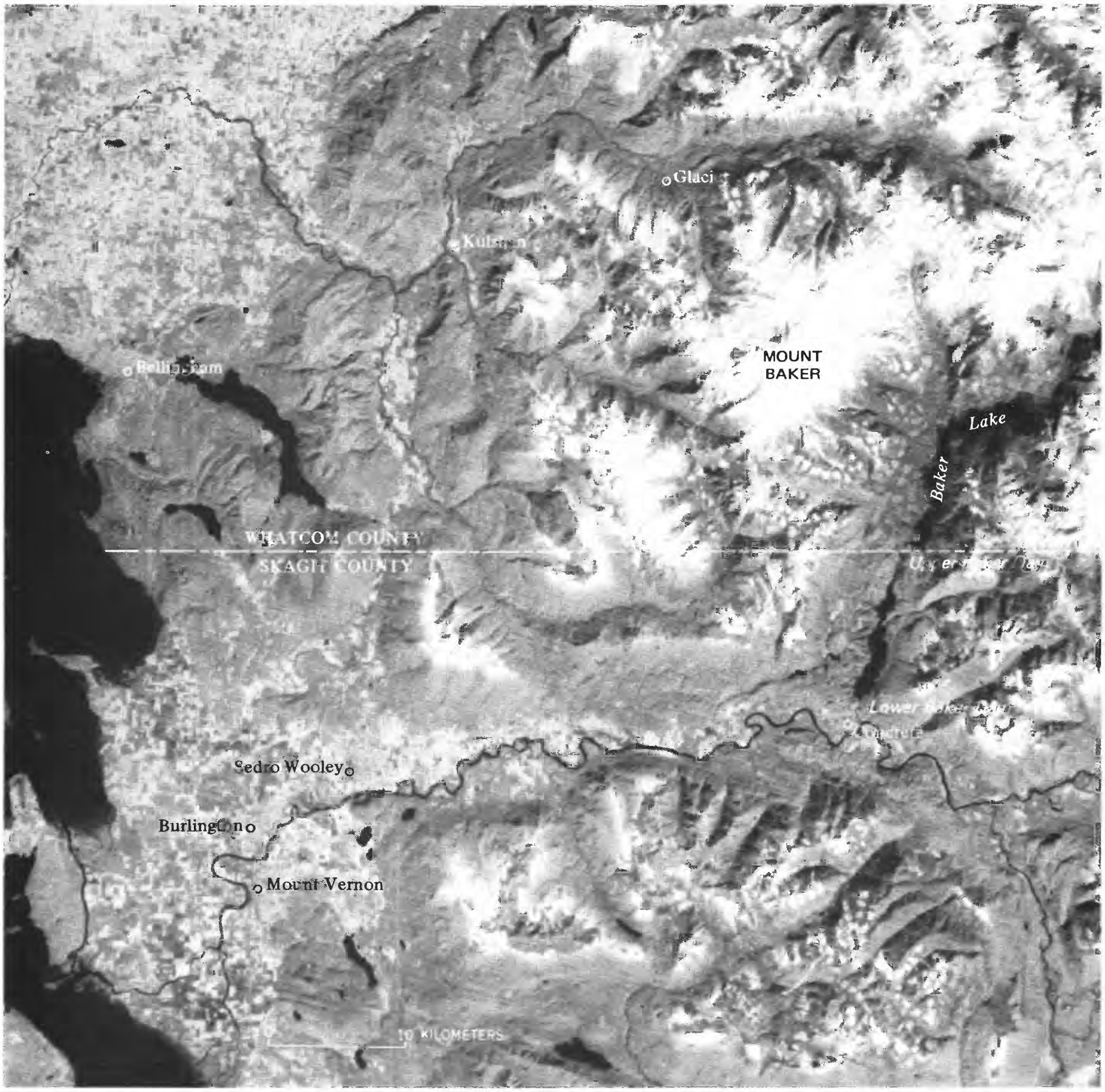


FIGURE 29. — This satellite view of northwestern Washington shows how drainage from Sherman Crater at the east slope of Mount Baker flows through two reservoirs and into the Skagit River. Cultvated areas in the region are illustrated by the checkerboard patterns of farms in the valleys and deforested clearcuts in the mountains. Except for seasonal resorts, Concrete, Glacier, and Kulshan are the nearest small communities in valleys which drain Mount Baker. Bellingham and Mount Vernon are major population centers, ERTS satellite image E–1258–18322, April 7, 1973.

tions), the University of Washington, Western Washington State College, Washington State Department of Emergency Services, Federal Disaster Assistance Administration, and the U.S. Geological Survey had been alerted, and several trips by aircraft had been made to observe and photograph the volcano. After a period of cloudy weather on March 12 and 13, continuing abnormal discharge of steam and ejecta was observed. Large steam plumes had been seen before, as on February 28, 1971, but they did not issue from new fumaroles nor did they contain ejecta, and the activity returned to normal within a day or so. In March 1975 it was obvious that there had been a major change in the steam activity of the mountain, and a number of scientists began to plan field investigations. At least initially, the various groups acted independently, depending on their resources and subjects of interest. By March 31 a seismometer and telemetry link has been installed on the rim of Sherman Crater.

On April 8 the first of many interagency meetings concerning Mount Baker's activity was held. This was arranged by the U.S. Forest Service to collect available scientific data, to prepare contingency plans, and to obtain advice on possible administrative actions needed to protect the public. An important result of this meeting was to bring together the various scientific investigators so that a more coherent picture of the steam activity was possible. Specialists were informally assigned for each critical monitoring activity, to keep track of developments in their fields of interest, and to communicate results to the U.S. Forest Service and to others. As a result of this meeting, the Forest Service closed Sherman Crater and the Boulder Creek drainage to public access. The U.S. Geological Survey assigned personnel to conduct and coordinate monitoring activities and to represent the agency at future meetings with public officials.

HISTORY OF BAKER LAKE CLOSURE ACTION

Briefings regarding potential hazards were presented by the U.S. Geological Survey to concerned governmental agencies during May 12–29. These included Federal, State, and local agencies: U.S. Forest Service, Federal Disaster Assistance Administration, U.S. Army Corps of Engineers, and National Park Service, the Washington Governor's Office and Washington State Departments of Ecology, Emergency Services, Community Relations, and Natural Resources, and the Skagit Regional Council, which included county commissioners, mayors, and city managers of the communities downstream from the Baker Lake area. The Department of Ecology, because of their concern with dam safety, requested information from the U.S. Geological Survey on the "maximum plausible" mudflow or avalanche that might be expected to enter Baker Lake. Consequently, data similar to those shown in table 7, together with estimates of speeds (20–50 km/hr for a mudflow, 150 km/hr for an air-cushioned avalanche) for a "maximum plausible" debris flow (volume 30×10^6 m^3), were furnished by the U.S. Geological Survey to the Washington State Department of Ecology and to Puget Power on May 30. This action triggered an important series of events.

Puget Power, recognizing that a fast-moving avalanche might cause a disastrous wave on the reservoir, met with U.S. Geological Survey personnel and shortly thereafter engaged a consulting firm, Tetra Tech, Inc., to analyze the possible wave. On June 16 the consultants' preliminary results were delivered to Puget Power and were divulged to the Federal Power Commission, the U.S. Forest Service, and the U.S. Geological Survey. The preliminary calculations were based on a greatly oversimplified model and suggested a wave higher than that indicated by a subsequent, more thorough analysis by the same firm. Drawing down the reservoir to prevent damage from such a large wave would mean an appreciable loss of hydroelectric power generation; such a potential wave could also cause loss of life to persons on the lake or shoreline. The U.S. Geological Survey was asked to evaluate the probability of hazard and to estimate the width, thickness, and speed of the "worst possible" avalanche as the basis for more refined analysis and action.

A statement by the U.S. Geological Survey as to the probability of the occurrence of mudflows or avalanches (app. 1) was presented at interagency meetings, which included representatives from Puget Power and Tetra Tech, on June 20 and 23. A task force was created on June 23, consisting of representatives of the agencies responsible for public safety in the area: U.S. Forest Service, Washington State Department of Ecology (representing the Governor's Office), County Commissioners of Skagit and Whatcom Counties, and Puget Power. The Federal Power Commission, the U.S. Army Corps of Engineers, and the U.S. Geological Survey were advisors to the task force.

On June 23 the task force recommended to the appropriate agencies that the Baker Lake area be closed to public access and that the reservoir be maintained at a safe level (initially 10 m below full pool) to accommodate the "worst possible" debris flow. The U.S. Forest Service and Puget Power announced these actions on June 25.

Subsequent task force recommendations included (1) upward adjustment of reservoir level, as more refined calculations by Tetra Tech indicated somewhat lower potential wave heights; (2) additional studies of a possible air-cushioned avalanche (performed by R. L. Shreve, app. 2) and the stability of Lahar Lookout; (3) studies by a consulting firm (Stone and Webster, Inc.), which concluded that Upper Baker Dam should not be allowed to be overtopped; (4) creation of an information committee (with representatives from the U.S. Forest Service, U.S. Geological Survey, University of Washington, and Puget Power), which issued weekly news bulletins about Mount Baker throughout the summer of 1975; and (5) development of contingency plans by the U.S. Forest Service, Puget Power, and the two counties.

LIFTING OF BAKER LAKE CLOSURE

Closure of Baker Lake during the summer of 1975 caused loss of revenue at a private resort, diverted recreationists from the area (with attendant loss of business revenue in the nearby town of Concrete), and diminished production of electrical power. By the winter of 1975–76 the monitoring activities had shown no unequivocal evidence that an eruption was forthcoming, nor had any mudflows or large rock avalanches occurred. It was evident to the U.S. Forest Service and Puget Power that the closure needed reevaluation. A series of task force meetings, beginning on January 29, 1976, considered the effects of continued closure, monitoring evidence, possible changes in the mudflow or avalanche hazard, and how additional data on slope stability or avalanche parameters might be obtained.

Independently, the U.S. Geological Survey reconsidered the hazard probability. A new statement (app. 3) pointed out (1) that there was now no clear evidence of forthcoming eruption, whereas an eruption could have been imminent at the time of the earlier statement; (2) that the degree of mudflow or avalanche hazard now probably approached the level of that in an "average year" within the last 10,000 years; and (3) that the probability of the occurrence of a large fast avalanche had therefore somewhat diminished. Drafts of this statement were presented to the task force.

During a meeting on March 23, 1976, the task force accepted the Survey's draft statement and studied possible management alternatives. Public safety, generation of electrical power, preservation of the economic base of the local community, economy of the private resort, safety of structures, such as dams and highway bridges, public use, scientific research, and natural resources, such as fish and timber, were all considered. The group recommended opening Baker Lake to the public but keeping Sherman Crater and the Boulder Creek drainage closed — an action that recognized the apparent decrease in hazard by permitting public use of the lake, yet drew attention to a continuing hazard by keeping some areas closed. It was also recommended that Puget Power be allowed to operate the reservoir at a normal stage and that the various contingency plans (including possible reimposition of complete closure) be kept in readiness. The Survey's statement and a Forest Service–Puget Power–task force statement rescinding closure were announced at a press conference on April 6, 1976.

CONCLUSIONS

Fumarolic activity can have different meanings at different volcanoes. Fumaroles can represent the waning release of heat from a cooling magma chamber that last erupted hundreds or thousands of years ago. Alternatively, fumaroles can reflect the initial release of heat through new fractures that emanate from a rising body of magma. Any gradation between these two extremes is also possible, so that fumaroles might bear little relation to an increase or decrease in activity of a magma source but, instead, simply mark the background heat emission during a volcano's repose period between eruptions — a period that can last from days to centuries.

Increased thermal activity has been the first (and sometimes the only) observed sign of an oncoming eruption, as at Soufrière in 1971 (Aspinall and others, 1973) and at Taal in 1965 (Moxham, 1971, p. 104). Many, if not most, other volcanoes have been observed to have additional precursors, particularly seismic activity. Lack of a long period of baseline data, both visual and instrumental, during the repose period of a volcano greatly detracts from the ability to interpret new data. Under such limitations, eruption precursors can best be detected by conducting many different types of monitoring side by side over long periods of time.

The lack of a sufficient data base is clearly evident with respect to interpretation of present fumarolic activity at Mount Baker. A single year of intensive monitoring serves to show that a longer period of observation is necessary for rigorous examination and prediction of the future behavior of a volcano which obviously is in some state of change. Nevertheless, data acquired so far do support four conclusions:

1. The level of thermal activity has had a small upward trend for many decades.
2. In 1975, an increase in heat flux of roughly one order of magnitude occurred and represents the greatest change in thermal activity during the 20th century.
3. Despite the increased heat emission, other geophysical and geochemical data acquired during the past year have not provided evidence of an impending eruption.
4. Continuing hydrothermal activity provides some of the conditions necessary for the occurrence of avalanches of rock debris and potential mudflows, whether or not the volcano erupts. This hazard existed to some degree prior to 1975, although it was not fully recognized by the public or by agencies responsible for land management.

Less conclusive or presently uninterpretable results are much more numerous. What caused the gradual thermal increase prior to 1975 and the sudden jump in heat emission beginning in 1975? Exactly what does the past year's monitoring show? Are there signs of additional volcanic change hidden by the background noise that snow and weather imprint on seismic, tilt, and gravity data, or are virtually all of the instrumental changes due to nonvolcanic causes? Answers at this point are certainly premature, but presentation of the data acquired so far provides a useful base for future scientific work and administrative decisions.

As a quiescent volcano, Mount Baker will surely erupt at some time in the future. We cannot be certain that the time of that eruption will be predictable, regardless of the amount of monitoring, but we can anticipate the types of hazards which might accompany an eruption (Hyde and Crandell, 1977). We can also anticipate hazards that accompany thermal activity on Mount Baker, regardless of an eruption. These hazards range from localized volcanic gases around the fumarole fields to water pollution and potential mudflows and rock avalanches in the drainage system below Sherman Crater — primarily in Boulder Creek and Baker Lake. Perhaps the most significant result of increased activity at Mount Baker has been the increase in public awareness of these hazards.

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APPENDIXES 1 – 3

APPENDIX 1: U.S. GEOLOGICAL SURVEY STATEMENT ON MOUNT BAKER SITUATION, JUNE 19, 1975

Geologic hazard studies by the U.S. Geological Survey at Mount Baker indicate that there have been at least 2 major eruptive periods at the volcano during the last 10,000 years, as well as several additional minor eruptions which produced small amounts of volcanic ash and, probably, many others which left no recognizable deposits. The increased thermal activity that began March 10 at Mount Baker does not necessarily mean that an eruption is about to occur. However, this thermal activity does increase the likelihood of an avalanche of hydrothermally altered rock from the upper part of the volcano. During the last 10,000 years, such avalanches have caused at least 10 mudflows which probably were large enough to travel at least 13 km, the distance from the summit area to Baker Lake. One or more of these mudflows moved down each of five different valleys. The history suggests a probability of 1 in 1,000 that a mudflow of this type will occur in an average year. However, thermal activity on the scale of that since March 10 has not been observed for the previous 100 years, and, therefore, 1975 cannot be considered an average year. The probability of a mudflow traveling at least 13 km may now be as much as 10 times greater than during an average year, or 1 in 100. Such a mudflow could enter Baker Lake at a speed of 30–50 km/hr.

The 10 mudflows mentioned above range in volume from several million to 40 or 50×10^6 m^3. Flows as large as 25×10^6 m^3 occurred only twice during the past 10,000 years. Thus, the probability for a flow as large as this happening in any average year is only 2 in 10,000. In 1975, because of the increased thermal activity, it is perhaps 2 in 1,000. Mudflows are most likely to descend Boulder Creek but could go down Sulphur Creek, the Middle Fork Nooksack River, or other drainages.

The worst avalanche under existing conditions would be a very large one at the head of Boulder Creek which would trap a cushion of air and move rapidly downslope toward Baker Lake. The probability that such a high speed avalanche (more than 100 km/hr) would enter Baker Lake during 1975 would probably be less than 1 in 1,000, perhaps as low as 1 in 10,000.

It is not possible now to predict how long the thermal activity will continue at the present scale; it may subside, or it may progress into some kind of eruptive activity. If an eruption does occur, the chances of a mudflow or other hazardous event would be greatly increased.

APPENDIX 2: EVALUATION OF POSSIBILITY OF AIR-CUSHIONED ROCK AVALANCHE OR MUDFLOW FROM MOUNT BAKER

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[Report to Mark F. Meier, U.S. Geological Survey, July 21, 1975. All references cited in appendix 2 are listed in "References Cited" on p. A43–A44]

This is the report that you requested in our telephone conversation on 16 July. It summarizes my responses to the principal questions put to me as your consultant in connection with the possibility that a large rock avalanche or debris flow originating in the collapse of Lahar Lookout on Mount Baker might reach Baker Lake. I have responded to essentially four questions:

Question 1. — What is the likelihood that a large rockfall from Lahar Lookout might develop into an air-cushion avalanche that would reach Baker Lake?

Question 2. — In the event of such an avalanche, what would be its most likely width, thickness, and speed as it entered Baker Lake?

Question 3. — If, instead, a rockfall of comparable size developed into a debris flow, what would be its most likely width, thickness, and speed as it entered Baker Lake?

Question 4. — Could the estimates of probability of various possible debris flows and rock avalanches given in the "U.S. Geological Survey Statement on Mount Baker Situation" released on 23 June 1975 be improved?

I must emphasize at the outset that, in the present state of knowledge, none of these questions can be answered with much certainty. Large debris flows and rock avalanches of the sort contemplated in the questions do not occur frequently in Nature and cannot be studied in the laboratory. Therefore, there are relatively few comparable cases and even fewer established principles available as a basis for prediction. Moreover, the uncertainty is compounded at Mount Baker by the unpredictable effects of volcanic activity on a glacier-covered mountain. The estimates given in this report must accordingly be used with appropriate caution.

My previous report to you (letter dated 18 June 1975) dealing with questions 1 and 2, which was an emergency rush job that this report supersedes, was based on the 1:62,500-scale U.S. Geological Survey quadrangle maps of the Mount Baker area. I have since completely repeated all measurements and calculations using the much clearer 1:24,000-scale Interim Topographic Map of Mount Baker which you sent me a week ago. Although there are minor differences in some of the numbers, there are no significant changes in the conclusions.

Question 1. — Formation of an air-cushion avalanche with long runout requires that the avalanche override and trap sufficient air to reduce contact with the ground significantly. This, in turn, requires a suitable break in slope to launch the avalanche into the air, high speed to enable it to override enough air, and sufficient thickness of the debris and smoothness of the ground to prevent excessive loss of air.

In the case of the potential avalanche from Lahar Lookout, significant air launch is unlikely to occur anywhere along the likely path of the avalanche, except at the lip of the pronounced bench at the 3,000-foot level in the canyon of Boulder Creek. The speed of the avalanche at this point is likely to be at least 240 ft/s (75 m/s), which corresponds to conversion of one-eighth of the available potential energy (7,000 ft, or 2,100 m, of fall) to kinetic energy. The observations by Heim in the Alps (Shreve, 1968a, p. 41) and by myself of the Elm, Sherman, and Frank landslides (Shreve, 1966, p. 1639; 1968a, p. 4, 32, 35), which involved from 0.4 to 1.3×10^9 ft^3 (10 to 35×10^6 m^3) of debris, suggest a somewhat higher fraction, roughly one-fifth. Nevertheless, even at the lower speed, enough air could be trapped to form a layer about 6 feet (2 m) thick if compressed under 20 feet (6 m) of debris over the whole area of the avalanche from the 3,000-foot level down to the lake shore, assuming a water-surface elevation of 724 feet, the full-pool elevation. Even elevations as low as 700 feet, however, would not significantly change this figure. The thickness would be greater if the launch speed were higher. By way of comparison, I have computed an air-layer thickness of a couple of feet (0.6 m) for the Blackhawk landslide (Shreve, 1968a, p. 42). Thus, entrapment of sufficient air to provide an air cushion seems probable if a large avalanche travels down Boulder Creek.

The most important consideration is the probable thickness of the avalanching debris. The average thickness of the portion of the Little Tahoma Peak landslide that passed beyond the launch point at the terminus of the Emmons Glacier was about 15 feet (5 m; from figures given by Crandell and Fahnestock, 1965, p. A12–A13), of the Sherman was more than 10 to 20 feet (3 to 6 m; Shreve, 1966, p. 1639), and of the Huascarán was 15 feet (5 m) or more (Plafker and others, 1971, p. 556). The other probable air-cushion avalanches I have studied all had similar or greater thicknesses. Thus, it appears reasonable to assume that a minimum debris thickness of at least 15 feet (5 m) is necessary for long runout.

In the Little Tahoma Peak avalanche (or avalanches), 75 to 85 percent of the debris was deposited beyond the launch point (Crandell and Fahnestock, 1965, p. A12), and a similar figure would apply to all other probable air-cushion avalanches that I have studied. At Mount Baker the area of the probable avalanche path is 7.1×10^7 ft^2 (6.6×10^6 m^2) from the 3,000-foot level to the lake shore at 724 feet. If debris were spread over this area to a depth of 15 feet (5 m), it would have a volume of 1.1×10^9 ft^3 (30×10^6 m^3). Correcting for the approximately 20 percent left above the launch point and for the roughly 50-percent increase in volume of the initially solid rock as it disaggregates in the initial fall, gives a required volume of undisaggregated rock of 0.9×10^9 ft^3 (25×10^6 m^3).

Looking at the problem another way, the debris left above the launch point by the Little Tahoma Peak avalanche averaged about 3 feet (1 m) thick (Crandell and Fahnestock, 1965, p. A12), and, as before, a similar figure would apply to other probable air-cushion avalanches. At Mount Baker, the area of the probable avalanche path down to the 3,000-foot level is about 9×10^7 ft^2 (8.4×10^6 m^2). If covered to a depth of 3 feet (1 m), this would require 0.3×10^9 ft^3 (8×10^6 m^3) of debris. Adding this to the 1.1×10^9 ft^3 (30×10^6 m^3) required to cover the lower part of the path to a depth of 15 feet (5 m), and correcting for the 50-percent volume increase on disaggregation, gives 0.9×10^9 ft^3 (25×10^6 m^3) as the minimum volume of undisaggregated rock that would have to fall, in good agreement with the previous figure.

Thus, both lines of reasoning lead to 0.9×10^9 ft^3 (25×10^6 m^3) as the minimum volume of undisaggregated rock (and ice) that would have to fall at one time in order to produce an air-cushion avalanche that could reach Baker Lake. Water-surface elevations as low as 700 feet will not significantly change this result.

Assessing the likelihood of a single fall of this size from the vicinity of Lahar Lookout under present circumstances is, in my opinion, essentially impossible. According to the 1:24,000-scale map, which probably is not entirely accurate, roughly the required 0.9×10^9 ft^3 (25×10^6 m^3) of rock could be released from Lahar Lookout and Sherman Peak by failure along a curved surface of rupture sloping downward at an average angle of about 30 degrees and emerging at the 8,500-foot level at the head of Boulder Glacier. This may be compared with the angle of repose of loose, dry, disaggregated rock, which is 34° and with the average inclinations of the surfaces of rupture of the Sherman, the Frank, and, probably, the Little Tahoma Peak landslides, which were around 40° (Plafker, 1968, p. 377; Shreve, 1968a, p. 35; Crandell and Fahnestock, 1965, p. A18, A19). Thus, in ordinary circumstances a single fall of the required volume would not be very likely. For Mount Baker, however, account must also be taken of the potentially important and largely unpredictable effects of the weakening and undermining of Lahar Lookout and Sherman Peak and the possible steam explosions, or other disturbances, near or under them that might be caused by the current increased fumarolic emissions and glacial melting, not to mention possible future intensified volcanic activity.

During runout the trapped air must spread out more or less uniformly under the advancing debris. This process depends strongly on the variation with time of the thickness of the debris passing the launch point. Longitudinal and lateral variations in thickness cause pressure gradients in the air layer that, combined with the shearing due to the forward motion of the debris, redistribute the air. Judging from other air-cushion landslides, such as the Blackhawk (Shreve, 1968a, p. 27), long runout seems to require a thickness that tapers slightly toward the rear so as to compensate partially the rapid removal of air from the launch region by the shearing. For Mount Baker, I am unable even to guess the likely thickness variation, but it conceivably could be such that the air layer would be unstable and rapidly break up, even though other factors, such as forward speed, air volume, and debris thickness, were favorable for air-cushion avalanching.

A further requirement for a stable air-cushion is that the product of the permeability and the bulk density of the debris at the base of the avalanche be less than about 0.7 times the product of the harmonic mean permeability and the arithmetic mean density for the whole thickness of the debris (Shreve, 1968b, p. 655–656). In practical terms, a thin basal layer of finer, tighter material will suffice. In the Little Tahoma Peak, Sherman, and Huascarán landslides, the required basal layer was probably snow picked up from the glaciers onto which they fell (Crandell and Fahnestock, 1965, p. A1; Shreve 1966, p. 1639; 1968b, p. 656; Plafker and others, 1971, p. 550). At Mount Baker, this requirement would doubtless be satisfied by snow picked up from Boulder Glacier.

An air-cushion avalanche debouching from the narrow canyon of Boulder Creek onto the convex alluvial cone between the main road and Baker Lake very likely would tend to split into multiple lobes, like the Sherman landslide (Shreve, 1966, p. 1641). This would lead to loss of air that, if severe enough, might disrupt the air-cushion short of the lake. Slowing and increased air loss would also occur if the surface of the alluvial cone has rough local relief greater than the thickness of the air cushion — that is, greater than a few feet (a couple of meters).

Question 2. — An air-cushion avalanche big enough to reach Baker Lake from Lahar Lookout would be about 1,200 to 1,500 feet (350 to 450 m) wide at the point where the main road crosses Boulder Creek (at BM 1056) and would spread laterally as it crossed the convex surface of the alluvial cone to the lake shore. Judging from the behavior of the Sherman, Little Tahoma Peak, and Huascarán landslides (Shreve, 1966, p. 1640, fig 2; Crandell and Fahnestock, 1965, p. A2, fig. 1; Plafker and others, 1971, p. 551, fig. 3) and making allowances for inertia, it would most likely spread to a width of about 1.5 miles (2.4 km) at the lake shore, covering it from near the mouth of Little Sandy Creek on the southwest to a point about a third of a mile (0.5 km) north of the mouth of Boulder Creek on the north. Judging from the speeds computed from runup of the three previously mentioned landslides on adjacent slopes (Shreve, 1966, p. 1640; Crandell and Fahnestock, 1965, p. A19; Plafker and others, 1971, p. 558), its speed on entering the lake would probably be in the range from 150 to 300 ft/s (45 to 90 m/s), with 200 ft/s (60 m/s) the most likely. Judging again from the other three landslides and from the calculations given in the response to question 1, its thickness on entering the lake would probably be a minimum of 15 feet (5 m) and would most likely be about 20 feet (6 m).

These estimates assume that the volume of rock falling will be near the minimum required to reach Baker Lake, because the smallest falls are the most likely. Air-cushion avalanches from larger falls would have about the same width, greater thicknesses in direct proportion to volume, and somewhat greater speeds on entering the lake.

In summary, if a rockfall from the vicinity of Lahar Lookout were to develop into an air-cushion avalanche that reached Baker Lake, its width, thickness, and speed on entering the lake would most probably be about 1.5 miles (2.4 km), 20 feet (6 m), and 200 ft/s (60 m/s), respectively.

Question 3. — A debris flow would tend to be narrower, thicker, and slower than an air-cushion avalanche of the same volume. My opinion is that a debris flow down Boulder Creek that originated in a fall of 1×10^9 cubic feet (30×10^6 m^3) of rock from the vicinity of Lahar Lookout would have a width of roughly 0.5 mile (0.8 km), a thickness of about 40 feet (12 m), and a speed of about 50 ft/s (15 m/s) as it entered Baker Lake. This estimate of speed accords with that given in the "U.S. Geological Survey Statement on Mount Baker Situation," whereas I originally suggested a speed of 100 ft/s (30 m/s), based on the apparent speed of the debris-flowlike part of the Huascarán landslide which ran upslope near Matacoto (Plafker and others, 1971, p. 553, 556). After further discussion, however, I have concluded that the lower estimate is better. The estimated thickness is based on the thicknesses of prehistoric debris flows of comparable size from Mount Baker reported by Hyde and Crandell (1975, p. 8, 9, 11, 13), which would have approximately the same composition as one from Lahar Lookout and, hence, presumably similar properties.

An important point to note is that, unlike air-cushion avalanches, there is no minimum cutoff in the likely thickness and speed of a debris flow that could reach the lake. Hyde and Crandell (1975, p. 10) found remnants of prehistoric debris flows ranging down to less than 2 feet (0.6 m) thick along Boulder Creek between the main road and Baker Lake. Thinner flows will be slower, generally narrower, and more probable than thicker ones. In addition, an air-cushion avalanche too small to reach the lake could continue onward as a high-speed debris flow, as did the Huascarán landslide near Matacoto (Plafker and others, 1971, p. 553).

Question 4. — I can add little beyond concurrence to the estimates of probability given in the "U.S. Geological Survey Statement on Mount Baker Situation." The estimates appear to me to be derived by methods appropriate in the circumstances, to be based on the best available input data, and to be adequately qualified as to their limitations. Despite the considerable uncertainty that must be attached to them, they cannot, in my opinion, realistically be improved very much because of the uncertainties in the processes and materials involved, the highly incomplete geological record, and the present abnormal situation on Mount Baker.

APPENDIX 3: U.S. GEOLOGICAL SURVEY STATEMENT ON MOUNT BAKER SITUATION, APRIL 6, 1976

In early March 1975 increased thermal activity was reported at Mount Baker, Washington. This activity gave rise to concern that the volcano might pose an increased threat to life and property in the Mount Baker area. In June 1975 the U.S. Geological Survey issued a statement estimating that the chance of a destructive mudflow or avalanche was about 10 times greater than it had been prior to the onset of the increased thermal activity. The Survey, in collaboration with the University of Washington, intensified a program of geophysical, geological, geochemical, and hydrological monitoring of Mount Baker in an effort to document whether or not the volcano was building toward an eruption.

These monitoring activities have indicated that the thermal emissions, after increasing in intensity in March 1975, have remained at about the same level to the present time. Geophysical observations have not indicated abnormal local seismicity, and deformation measurements have not indicated inflation of the volcanic edifice, which commonly precedes volcanic eruptions. Thus, there have been no observed indications of an impending eruption at Mount Baker.

The Geological Survey statement of June 1975 pointed out that "It is not possible now to predict how long the thermal activity will continue at the present scale; it may subside, or it may progress into some kind of eruptive activity." A chief concern at that time was that the increased thermal activity was related to magma rising in the volcano and would be followed by an eruption. Mount Baker's present behavior, however, does not indicate that the chance of an eruption is appreciably greater now than it was prior to March 1975. Consequently, there now seems to be less need to maintain the intensified volcano monitoring activities that were implemented during the past year.

The situation with respect to possible avalanches and mudflows of rock debris from the volcano is more difficult to assess. In the June 1975 statement, it was noted that the geologic history of Mount Baker during the past 10,000 years suggested a probability of 1 in 1,000 that an avalanche or mudflow of sufficient size to reach Baker Lake would occur in an average year. It was further suggested that the increase in thermal activity, and the possibility that the volcano was building toward an eruption, may have multiplied by a factor of 10 the chance of such an event, so that the probability that a large avalanche or mudflow would take place in 1975 may have been as great as 1 in 100. However, thermal activity at the volcano has remained at about the same level for about 12 months, during which period neither avalanches nor mudflows have been recognized. Because of the lack of evidence that the volcano is building toward an eruption, the chance that a large avalanche or mudflow will be triggered by a steam explosion or some other volcanic event in the near future seems lessened. Even if the probability of a large avalanche or mudflow returned to pre-March 1975 levels, a certain degree of potential danger would remain, but it is one that existed prior to March 1975, even though its nature may not have been fully recognized by the public or by agencies responsible for land management.

The U.S. Geological Survey statement also suggested a probability of between 1 in 1,000 and 1 in 10,000 in 1 year that a very large rock mass would slide from Mount Baker and form an air-cushioned avalanche, which would enter Baker Lake at high speed. The probability of such an avalanche also may now be somewhat diminished. However, it is not possible to estimate the probability of such an event because of uncertainties concerning the likelihood that all conditions would be met for the formation of a very large air-cushioned avalanche.

If the present levels of thermal activity have not changed by June 1976, and if the volcano continues to show no signs of an impending eruption, the U.S. Geological Survey will reduce its monitoring program on June 30, 1976.

Other agencies and organizations may also elect to reduce their activities on Mount Baker, but it will be advisable to carry out periodic visual observations and to continue essential seismic and ground deformation measurements. This lower level "volcano watch" should be continued as long as the increased thermal activity persists.

☆U.S. GOVERNMENT PRINTING OFFICE: 1977-777-034/48