FINAL REPORT

EVALUATION AND IMPLICATIONS OF THE THERMAL ACTIVITY OF MT. BAKER, WASHINGTON FROM AERIAL PHOTOGRAPHS AND INFRARED IMAGES

by

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Submitted to

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May 31, 1979
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SUMMARY

Mt. Baker is a Pleistocene stratovolcano in the North Cascades of Washington. In March 1975, it was observed that there had been a large increase in thermal activity at Sherman Crater. This study is a qualitative assessment of the current activity and associated geological hazards from the study of aerial photos and infrared (IR) images. The current activity is also compared to that in 1975.

Two IR detectors with different temperature sensitivities were used so that both fumarole clusters and thermal anomalies could be detected. The thermal features on images taken 13 October 1978 and 21 March 1979 were traced onto topographic maps using a Zoom Transfer Scope (ZTS). The ZTS was also used to map snow-free areas from photos taken 13 October 1978. The images and photos were supplied by Dr. C. L. Rosenfeld of the Oregon State University: Geography Department.

In 1975, thermal activity was most intense in the east breach and central pit. Activity also occurred along the southwest, west, and north rims of the crater. The central pit was formed in April 1975 by ice and snow collapsing around fumaroles to form a shallow lake. Geological hazards included avalanches of hydrothermally altered rock, especially from Lahar Lookout, Sherman Peak, and the east breach; mudflows, drainage of acidified water, and hydrogen sulfide gas levels. By March 1976 only one small earthquake was identified beneath the mountain. Small tilt and gravity changes were recorded but their cause and significance were not completely understood.
Currently, thermal activity is most intense along the west and northwest rims. Activity has decreased in the east breach and the southwest pits, and the 21 March 1979 image documents no activity in the central pit. There is new activity between the northwest rim and the north pits, and north of the 1975 activity along the northwest rim. The potential for dangerous mudflows and avalanches has decreased since activity has declined near Sherman Peak and Lahar Lookout. Steep slopes off these sites could transport material down the mountain-side toward Baker Lake Reservoir.

The study concludes that there is a preferred path of convective heat flow through permeable breccia layers along the west to north rims and the fumarole locations may be controlled by concentric fractures, possibly associated with the initial formation of Sherman Crater. Sub-surface alteration of breccia and lava contacts may be opening new convective heat paths. Avalanches and mudflows can still occur because all the rock rimming the crater shows some alteration and because Lahar Lookout and Sherman Peak will progressively alter even with less activity near them. Avalanches have occurred from Sherman Peak in the last two decades.

It is recommended that geophysical, geochemical, and aerial surveillance continue to develop more baseline data, and studies be made concerning the structure of Sherman Crater and the effects of heated water draining under Boulder Glacier. The public closure area initiated in April 1975 for Sherman Crater, Boulder Creek and Valley should be continued, and geological hazards from the thermal activity and future eruptions should be considered in making land-use decisions for river valleys near Mt. Baker.
INTRODUCTION

Mt. Baker is the northern-most of the large Quaternary strato-volcanoes of the Cascade Range, which extends from Mt. Lassen in Northern California to British Columbia (Coombs 1939, p. 1495). The summit of Mt. Baker is 3,285 m high and is located 48 km east of Bellingham, Washington. Because of its high latitude and precipitation, Mt. Baker is almost completely covered by glaciers.

Figure 1: Mt. Baker and Vicinity
(adapted from Hyde and Crandell, 1977, p. 1)
Mt. Baker has been watched closely since March 1975 when there was a two-fold increase in the thermal activity of Sherman Crater, located 350 m below the summit. The increase in thermal activity was manifested by increases in the number and intensity of fumaroles and thermal anomalies. From March 1975 to March 1976, Mt. Baker was extensively monitored for changes which might prophesy an eruption. Participating in the monitoring were scientists from the U.S. Geological Survey (USGS), the U.S. Forest Service (USFS), Los Alamos Scientific Laboratory, the University of Washington, Western Washington State College, Central Oregon Community College, and Oregon State University (OSU). From June 1976 to the present, a lower level of monitoring has been carried out. Research has been, or is being, done concerning thermal activity, seismicity and gravity, gas chemistry, tilt, petrology, geological hazards, and water quality.

This paper provides a qualitative evaluation of the current thermal activity of Sherman Crater from infrared (IR) images and aerial photos taken in October 1978 and March 1979. The photos and images were supplied by Dr. Charles L. Rosenfeld of the OSU Geography Department. The present activity is compared to the 1975 activity, and the significant results and implications are discussed. Also included is a summary of other studies done at Mt. Baker from March 1975 to March 1976 to put the thermal activity in perspective.

The present thermal activity offers an excellent opportunity for scientists to learn more about the structure and behavior of Cascade volcanoes. The practical value is the monitoring of existing geological
hazards. Currently, there is a possibility of mudflows and avalanches beginning from Sherman Crater. They could travel down Boulder Creek and reach Baker Lake to cause flooding, and damage to campgrounds and the hydroelectric dam (Fig. 1). A small pyroclastic eruption could spew ash on roads in the area; lava flows could start forest fires; a small nuee ardente could destroy towns such as Concrete (Fig. 1). Though these situations are hypothetical, they illustrate that cities, transportation networks, and natural resources could be disrupted or harmed by an eruption.

More positively, thermal activity suggests Mt. Baker may be a source of geothermal energy in the future.
TECHNIQUES AND METHODOLOGY

Aerial Surveillance

Purpose. The purpose of the IR images taken at Mt. Baker are threefold:

1. to spatially depict the relationship between thermal emissions and geological structure and landforms,

2. to monitor changes in thermal activity, and

3. to document new activity.

Air photos are used to recognize anomalously steep snow and ice margins, and to decide whether they are the result of thermal activity or atmospheric conditions. In addition, photos are used to identify potential geological hazards and, with IR images, are used by ground crews to locate specific features (Rosenfeld and Schlicker, 1976, p. 27-28).

Techniques and Equipment. The IR images were taken by HRB Singer AN/ASS-14A IF line-scanners aboard an OV-1C Mohawk aircraft. Two IR detector heads with selected band-pass and temperature-range filters were used (Rosenfeld and Schlicker, 1976, p. 28):

<table>
<thead>
<tr>
<th>Detector</th>
<th>Peak Spectral Range</th>
<th>Temperature Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mercury, Cadmium, Telluride (MCT)</td>
<td>10.0-13 μm</td>
<td>15°C</td>
</tr>
<tr>
<td>Indium Arsenide (InAs)</td>
<td>3-3.2 μm</td>
<td>80°C</td>
</tr>
</tbody>
</table>

μm = micrometer

Images from the MCT detector are designed to indicate heat anomalies and important terrain features; the InAs images indicate the location of
specific fumarole vents, and reduce the atmospheric attenuation by steam. The IR images were taken at night to minimize the documentation of anomalies caused by the diurnal changes in surface temperatures from solar radiation.

A KA-30 camera was used to take the photos (Rosenfeld and Schlicker, 1976, p. 28).

**Mons of the Thermal Activity**

**Preparation.** A Baush and Lomb Zoom Transfer Scope (ZTS) was used to transfer the IR image and photo features onto paper to be traced. The distortions of the images were lessened, and the features magnified to the same scale using the ZTS. The distortions are caused by an increased ground resolution of the scanner at greater flight heights without spatial change on the film. It causes the ground distance to be slightly compressed (Boxham, 1972, p. 113).

Overhead light was passed through the IR images, and features were traced with pencil onto white paper mounted over a topographic map. For the aerial photos, light was reflected off the print and onto the ZTS mirror. Snow perforations were traced so they could be compared with the thermal anomalies.

**Sources of Error.** In dark regions of the image or photo, it was sometimes difficult to see the lines being drawn on the map. Also, the distortions cannot be entirely eliminated. In addition, on the MCT images it was difficult to recognize steam blowing against the west walls of the crater from thermal activity.
Formation of the Mt. Baker Landscape

Mt. Baker is a young stratovolcano formed during the Pleistocene, but is underlain by Paleozoic and Mesozoic sedimentary and metamorphic rocks. These basement rocks are older than those below Mt. Rainier and Mt. St. Helens, Washington. The basement rocks consist of Paleozoic greenstones and phyllites, Mesozoic shales and sandstones, and early Tertiary shales, arkose sandstones, and coal seams. The Chilliwack granodiorite (late Jurassic to early Miocene) intrudes the area (Coombs, 1939).

When Mt. Baker first erupted, the underlying rocks already formed a rugged terrain similar to that of today. Thus, many of the early lava flows were intracanyon. The first eruption occurred from Black Buttes, two miles northwest of the present crater (Fig. 1). Two flows which originated from Black Buttes have been dated by potassium-argon as 400,000 ± 100,000 years old (Mastebrook and Rahm, 1970, p. 20).

Mt. Baker erupted mostly lava flows; pyroclastic material such as volcanic ash and cinders constitute only five percent of the mountain's volume. This is in contrast to most other Cascade volcanoes which erupted more pyroclastics (Coombs, 1939, p. 1499). The early flows were relatively fluid and formed an 80 sq. mile base (Harris, 1976, p. 235). Later flows were more viscous but show little change in composition. The flows are mainly pyroxene andesites (Coombs, 1939, p. 1502).
Mt. Baker is much less modified by glacial erosion than are Mt. Rainier, or Mt. Hood in Northern Oregon. This suggests Mt. Baker was formed in the late Pleistocene and was active in recent time (Harris, 1976, p. 237).

The north and west rims of Sherman Crater consists of alternating units of breccia and basalt lava. The dips of the units suggests that part of the material was erupted from an older vent to the north which is now buried by snow and ice (Frank and others, 1977, p. 17).

Post-Glacial Volcanic Activity of Mt. Baker

Mt. Baker has exhibited a variety of volcanic activity from Sherman Crater during the last 10,000 years. Jack Hyde of Tacoma Community College and Dwight Crandell of the USGS concluded from a recent study that during this period, Mt. Baker has erupted airborne pyroclastics at least four times, lava flows twice, numerous mudflows and a pyroclastic avalanche (Hyde and Crandell, 1975, p. 7). The Sulfur Creek lava flow, the longest (19.2 km) discovered on Mt. Baker, is post-glacial (Harris, 1976, p. 237).

In the 19th century, many eruptions were reported. Eruptions definitely occurred in 1843 and 1854; the 1843 eruption coincided with an eruption on Mt. St. Helens, Washington. Other probable eruptive activity occurred in 1858, 1859, 1870, and March 1850. Many accounts of Baker eruptions were probably just sightings of intensified vapor emissions (Harris, 1976, p. 241). Thermal activity was high in the
second half of the 19th century. However a significant decline was noticed in August 1906 (Harris, 1976, p. 249); lower levels remained until 1975. The thermal activity during this century was most intense in the east breach (Fig. 2). At least six times from 1958 to 1973, avalanches of snow, ice, and hydrothermally altered rock have fallen from Sherman Peak by the crater (Frank and others, 1975, p. 77-78).
Visual Observations of Thermal Activity

New Areas of Heat Emission. During March 1975, three new clusters of thermal activity were identified: the north pit, Boulder Glacier pits, and the new main fumarole at the base of Lahar Lockout (Fig 2). The north pit formed in a previously smooth ice slope and enlarged throughout the summer due to ice caving. The new main fumarole was the largest fumarole during 1975. This fumarole emitted particulate matter in March 1975, and periodically throughout the summer.

The Boulder Glacier pits formed through the upper part of the glacier at the northeast base of Sherman Peak. The original two pits coalesced during the summer, and another trough developed nearby in a crevasse. The Boulder Glacier pits were probably formed from warm, subglacial water which drained the crater (Frank and others, 1977, p. 81).

Old areas of Heat Emission. Two large fumarole clusters located near the east breach in the central part of the crater coalesced into a single fumarole cluster which contained the new main fumarole (Fig. 2). Many of these fumaroles were superheated to temperatures as high as 131°C when measured in September 1975 (Frank and others, 1977, p. 9).

A depression in the center of the crater deepened quickly in March 1975 as crevasses formed around it. In April, the ice collapsed and melted to form a shallow lake, 50x70 m across. Fumaroles occurred on the shore of the lake and within it during 1975; however, only one upwelling re-
mained through March 1976. The lake fluctuated in depth throughout the year by drainage under the ice on its east margin.

The southwest pit enlarged in 1975. Ice collapsed around it and vapor was issued from crevasses in the area. By December 1975, a large new pit had developed between the southwest pit and the west rim.

The linear west rim fumarole cluster enlarged by downslope formation of new fumaroles. The northwest thermal area, located in the same breccia zone as the west rim fumaroles, expanded too. However, its activity declined during the winter 1975-1976 (Frank and others, 1977, p. 3).

Summary of Other Studies

During the period from March 1975 to March 1976, there was little geophysical or geochemical evidence of a forthcoming eruption.

Seismicity. Nearly all eruptions or increases in volcanic activity are preceded by and commonly accompanied by earthquake swarms or tremors. However, the relation of the seismic and volcanic activity is peculiar to each volcano (Minakami, 1971, p. 17). Six seismic stations were installed during 1975 on and around Mt. Baker. There was only one earthquake recorded, that a small quake \( M_L = 1 \) on 27 February 1976, with its epicenter located 1 km southeast of the crater at a depth of 3-6 km. Most other seismic events recorded were probably caused by glacial ice movement (Malone, 1977, p. 20).

\[ M_L \]: Local earthquake magnitude approximated by coda length
Gravity and Tilt. Gravity anomalies on volcanoes are probably caused by a mass redistribution from magma entering the reservoir system, and subsidence and inflation of the ground (Civetta and others, 1974, p. 331). Gravity stations were established on the south and west rims of Sherman Crater, as well as other locales. There was an average net 0.40 mGal increase in gravity at the crater rim stations from May 1975 to February 1976 (Malone, 1977, p. 22). Because there is little statistical information on this phenomena from other studies, this gravity flux was not well understood.

Inflation of volcanoes prior to an eruption, and deflation after, is well documented on Hawaiian volcanoes and is probably caused by filling and emptying of the magma chamber (Minakami, 1971, p. 17). Tiltmeters installed on Mt. Baker recorded a 7.5 urad (=7.5 mm/km) inflation toward the southwest, and a 7 urad inflation to the west from 8 July 1975 to 30 September 1975. This is not considered significant, suggesting little if any intrusion of magma during this time (Frank and others, 1977, p. 25).

Geochemistry. Theoretically, concentrations of reducing gases should increase prior to an eruption. A sensor was installed and operated from mid-July to mid-October 1975, at a west rim fumarole. Though changes in the composition of the gas were detected, they did not suggest an impending eruption. Gases emitted were hydrogen, hydrogen sulfide, and sulfur dioxide (Frank and others, 1977, p. 26).
A small amount of volcanic ash was ejected from fumaroles during 1975. However, it was not attributed to fresh magma, but was probably material torn off the walls of the fumarole vents by melt water and ejected by the gases (Babcock and Wilcox, 1977, p. 25).
CURRENT THERMAL ACTIVITY

The current thermal activity is most prevalent along the west and northwest rims of Sherman Crater (Appendices 1-3). This is in contrast to 1975, when the most prominent activity was located in the central pit and the east breach area. From the images used in this study, it is difficult to assess whether thermal activity has increased since 1975, but there is a definite shift in the location of activity.

Old Areas of Heat Emission

The southwest pits, west rim, northwest pits, north pit, and east breach continue to have fumarole activity. The activity of the northwest pits has moved slightly to the south (Appendices 1-3). The east breach has declined noticeably in activity, though fumaroles are still located near the site of the main fumarole and superheated fumaroles of 1975. The activity along the northwest and west rims has expanded along the permeable breccia layers at the edge of Sherman Crater.

Two areas are no longer active:

1. the two westerly of the southwest pits which were active beginning in September 1975, and

2. The central pit. The image of 21 March 1979 shows no activity (Appendix 3). The image of 13 October 1978 still indicates a thermal anomaly, while the photo of that day shows a sizable ablated area (Appendix 4). Oblique photos taken 12 December 1979 display a few small holes through the snow.

An ablated area delineating the location of the westerly southwest pits (Appendix 4) suggests thermal activity may have occurred there earlier in the year. A thermal anomaly at the easterly of the Boulder Glacier pits
is probably the result of heated, subglacial waters draining from the east breach (Appendix 1).

New Areas of Heat Emission

The most striking development is the formation of fumaroles and thermal anomalies to the north of the activity in 1975 along the north rim. Also a new fumarole area has developed between the northwest rim and the north pits. The thermal anomaly in this area was larger on 21 March 1979 than on 13 October 1978 (Appendices 1, 2). In general, thermal activity along the northwest and west rims has expanded slightly toward the center of the crater.

Geological Hazards Associated with the Activity

Avalanches. Associated with the hydrothermal activity are hot fluids, including sulfuric acid, which rise to the ground surface and penetrate interstices of rock. Resulting reactions lead to the formation of clay-rich alteration products such as kaolinite and montmorillonite (Bockheim and Ballard, 1975, p. 1000). Steam and gases released from fumaroles also alter rock. The altered rock leaves the rock masses unstable and prone to failure, leading to avalanches. These avalanches could be triggered by earthquakes, steam explosions, formation of new gas vents, changes in pore-water pressure, or entirely by gravity (Hyde and Grindell, 1978, p. 12). Virtually all the rock rimming Sherman Crater shows some degree of alteration (Bockheim and Ballard, 1975, p. 1001).
During 1975 to June 1976, a chief concern was avalanches and mudflows originating at the crater and travelling down Boulder Creek into Baker Lake. This would cause damage to the shoreline and possibly a breaching of the Baker Lake dam, causing flooding. This hazard still exists today but is less because the main thermal activity has shifted away from Sherman Peak and Lahar Lookout. The steep slopes leading off these peaks would provide rapid downslope transport of rock down Boulder Creek (Frank and others, 1975, p. 36). Lahar Lookout and Sherman Peak have been sources of small rock avalanches in the last three decades, and the east breach was formed by a mass wasting event in post-glacial times. With less activity near these sites thermal alteration will not occur as fast. However, the activity will still progressively weaken the rock, and ice splitting could erode already altered rock. Ice splitting is the breaking of rock by water freezing in cracks.

The north and west rims of Sherman Crater are less likely to be sources of serious rock and ice avalanches in the future, because the topography is not favorable to allow the transport of the material outside the crater confines. However, the potential rock mass, should one occur, is great (Hyde and Crandell, 1977, p. 12).

Mudflows. Heat from the fumaroles melts snow and ice. If this melt water mixed with pyroclastic material or altered rock debris, small mudflows could form. Rock and ice avalanches could also begin from the rims of the crater and progress into a mudflow as it descended Boulder Creek (Frank and others, 1977, p. 36).
Pollution. Hydrogen sulfide (H$_2$S) gas emissions have caused physiological damage to forest trees in some areas. The effects of H$_2$S being emitted at Sherman Crater on the trees on the slopes of Mt. Baker probably should be studied. In addition, H$_2$S poses serious health hazards in the vicinity of Sherman Crater since the human sense of smell can be destroyed by it (Frank and others, 1977, p. 31).

The acidity of Boulder Creek will probably continue to be periodically high as surface and ground water drains the crater. The acidic water slightly affects the water quality of Baker Lake. The acidic water can be toxic to aquatic life (Frank and others, 1977, p. 32).
CONCLUSIONS AND RECOMMENDATIONS

The significance of fumarole activity varies for each volcano.

Fumaroles in craters can represent heat released during a dormant period of a volcano, from a cooling magma chamber which erupted in the past, or from a magma body at shallow depths (Wilcoxson, 1966, p. 154-158).

Changes in thermal activity do not necessarily prophesy an eruption, though it was the only pre-eruption sign at Taal in 1965 (Foxham, 1971, p. 104), and thermal anomalies increased in temperature prior to the eruption of Aso in Japan in 1958 (Givetta and Others, 1974, p. 329).

There is a lack of baseline data on Mt. Baker to help interpret the thermal activity; however, some conclusions and observations can be made,

1. The activity is no longer concentrated in the east breach area, where thermal activity had been most intense during this century.

2. Increasingly, the preferred path of convective heat flow is through permeable breccia layers along the west and northwest rims of the crater. The breccia alternates with units of basalt.

3. The potential for rock avalanches and mudflows emanating from the crater and travelling down Boulder Creek toward Baker Lake has decreased since activity has declined near Lahar Lookout and Sherman Crater. However, hazards still exist.

4. There is a semicircle of fumarole clusters and anomalies along the inside rims of the crater. The pattern may be from heat rising through a concentric set of fractures which formed during the initial development of the crater (Friedman and Williams, 1968, p. 782). This was noted in the assessment of the activity during 1975 (Frank and others, 1977, p. 17).

5. New convective paths could be forming by sub-surface alteration of contacts between breccia and lavas along the west and northwest sides of the crater.
The recommendations arise from a need to better understand the current thermal activity and the changes which have occurred, and to identify and deal with its ramifications.

1. Aerial, geophysical, and geochemical monitoring should continue on a regular basis to add to the body of knowledge on the behavior of Mt. Baker and other volcanoes. The geophysical and geochemical monitoring should be done both at the crater and at other points on the mountain since if eruptive activity were to begin, it would not necessarily occur at Sherman Crater, but possibly on the flanks of the volcano.

2. A study of the structure of Sherman Crater should be made to identify the factors which are controlling the locations of fumaroles and thermal anomalies.

3. A study should be made of the effects on the Boulder Glacier of heated water draining under it from the crater.

4. The public closure area for Sherman Crater, Boulder Glacier, and Boulder Creek and Valley should continue. This closure was initiated in April 1975 to protect the public from direct geological hazards. (Mt. Baker Information Comm., 1976, p. 3-4).

5. The potential for avalanches and mudflows as well as future eruptions should be addressed in land use planning decisions for the Baker River Valley, and for the valleys of the South, Middle, and North Forks of the Noosea River (Fig. 1). Mudflows and avalanches arising on Mt. Baker would be largely confined to stream valleys, the very area where human activity is usually concentrated.

The increased thermal activity should augment public awareness that an eruption will probably occur in the future at Mt. Baker or other Cascade volcanoes. An eruption one-hundred years ago was probably little more than a curiosity to the few people in the region. However, as more persons move into the region and structures are built and land utilized closer to these volcanoes, the potential loss of lives and damage to
property and natural resources from an eruption becomes significant.
The increased thermal activity at Mt. Baker should be a reminder to
the people of the Pacific Northwest that the Cascade volcanoes are
probably only "slumbering giants".
ACKNOWLEDGMENTS

Thanks are extended to Dr. Charles L. Rosenfeld for providing the idea for the project, the photos and images, and background information; Jim Bell for instruction in the use of the ZTS, and the OSU Geography Department for use of their equipment.
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APPENDICES 1-5
April 20, 1979

David S. Shafer
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Dear Mr. Shafer:

Your inquiry to the Forest Service concerning Mt. Baker was forwarded to our office. I am sending a list of selected references of published material on Mt. Baker. Most of these you might already be familiar with as they should be available at the OSU library.

The Mt. Baker Information Committee has not released any recent reports; the last was Report #22 (enclosed) on March 2, 1978, when an area of about 1,000 m$^2$ of new fumaroles was first observed on the northwest rim of Sherman Crater. This area of new activity constituted one of the largest local changes in heat emission since 1975.

We are making aerial photographic surveys every few months, the last of which was March 2, 1979. Also, a field trip to the crater was made last October. Based on these and previous observations, the total level of heat emission as of last month seems to be similar to that of the last 4 years (since 1975). Unfortunately, no quantitative estimates of heat flow have been made since 1975 to confirm this conclusion. Although the total amount of heat emission may be unchanged, there have been significant changes in the locations of fumaroles since 1975. The March 1978 observations documented one of these occurrences. The general pattern of changes seems to be a lessening of thermal activity in the east part of the crater and an increase in activity in the west part, or in other words a shift from east to west of the major clusters of fumaroles and warm ground. Because of these local changes the thermal activity cannot yet be considered to have completely stabilized.

Dr. Charles L. Rosenfeld of the Geography Department at OSU has also conducted aerial observations at Mt. Baker and should have additional insights into the changes in thermal activity and their significance.

Best Regards,

[Signature]

David Frank
Hydrologist
SELECTED REFERENCES FOR MOUNT BAKER


Harris, S. L., 1976, Fire and ice, the Cascade volcanoes: Seattle, The Mountaineers, 320 p.


of the Cascade range. The lavas of Mt. Baker poured out on an erosion surface of Paleozoic and Mesozoic rocks which had a relief of approximately 5000 feet.

The first flows formed a cone known as the Blake Buttes, then the vent shifted 2 miles to the east and formed Mt. Baker. These lavas are noteworthy because of their lack of variation; all are porosone andesites. Almost all the lavas contain a type of hypersthene with in-lined extinction.

The lavas from Mt. Baker and the subsidiary vents probably began to form in the Pliocene, and activity continued until historic time.

INTRODUCTION

Surmounting the Cascade Range a series of volcanoes extends from northern California to Canada. The volcanoes in this chain, although differing slightly in form, have many characteristics in common. In petrographic and mineralogic details each is exceedingly similar. All were formed during the same general period of volcanism. Because of such similarities these volcanoes are commonly regarded as part of a system extending the length of the Cascades and possibly encircling the Pacific Ocean.

In northern California and Oregon, studies of the larger volcanoes have been made intermittently for the past 50 years, and an increased interest in volcanism during the past decade has resulted in the publication of many excellent papers.

In Washington, however, prior to 1937, the accounts of the Cascade volcanoes were limited to a few brief notes written from 30 to 60 years ago, recording the results of reconnaissance trips. It is the purpose of this paper to give more complete information on the general geology and petrography of Mt. Baker.

The closest approach to Mt. Baker is by a highway which follows the Nooksack River from Bellingham, Washington, to within 6 miles of the mountain. Another road comes within 7 miles of the volcano on the southeast side. These are the only approaches, but they are remarkable for they penetrate a comparatively wild area with a maximum relief of over 9000 feet.

The conditions for geological investigation are not ideal at Mt. Baker. Approximately half of the volcano is covered by glaciers. Most of the remaining portions are covered by dense growths of timber and brush so characteristic of western Washington. The mountains are extremely rugged, and the summer season when the snow is at a minimum is very short. The writer spent 2 months in the field during the summers of 1937 and 1938.

ACKNOWLEDGMENTS

It is a pleasure to acknowledge the many courtesies given by the rangers of Mt. Baker National Forest. The writer has profited immeasurably from discussions with his colleagues at the University of

![Sketch map of the Cascade Range](image)
Washington and from their criticisms of the manuscript. The writer wishes to express a debt of gratitude to Dr. Howel Williams for his work on many of the Cascade volcanoes and for his criticism of the manuscript. The chemical analyses and completion of the field work have been made possible by a grant from the Peacock Bequest of the Geological Society of America.

LOCATION

The Cascade Range forms a topographic unit almost continuous from northern California to the Canadian boundary. The type of rock, however, are not coextensive. One of the most decided breaks in lithology occurs in the vicinity of Snoqualmie Pass, 75 miles south of Mt. Baker. To the south of this break the Cascade are composed of Tertiary volcanic rocks. To the north, and extending under Mt. Baker, the greater portion of the exposed rocks are pre-Tertiary. The structural trend of the rocks on both sides of the break varies from N. 70° W. to E.-W. This structural trend is almost at right angles to the north-south alignment of the entire Cascade Range.

In the immediate vicinity of Mt. Baker Palæozoic to lower Tertiary sediments and metamorphic rocks are the chief basement rocks. The Palæozoic portion is represented by two principal groups—greenstones and associated sedimentary rocks, and carbonaceous phyllites. Sedimentary rocks of probable Mesozoic age range from fine, thinly laminated shales to coarse conglomerates, intermediate-sized clastic predominating. The lower Tertiary is represented by a thick series of shales and arkosic sandstones containing thin coal seams. A granodiorite-batholith invades some of these rocks, but its exact age is unknown.

Little is known of these formations, since all northward reports dealing with them are of a reconnaissance nature. It is not in the scope of this paper to deal extensively with these older formations, but the main types of rock underlying Mt. Baker will be briefly noted.

BEDROCK BENEATH THE VOLCANO

GREENSTONE

Early reports (Smith and Calkins, 1904, p. 35) mentioned the projection of older rocks above the surface of the Mt. Baker lavas in the vicinity of Herman Mountain, due north of Mt. Baker. This older rock is part of a series containing greenstone, sandstone, and graywacke. The thickness of the series is unknown but it may be several thousand feet. The greenstones and associated sedimentary rocks vary from light gray to dark green. Sheared portions are noticeably lighter in color. Numerous veins of quartz, calcite, and epidote traverse the mass in a most irregular fashion.

BEDROCK BENEATH THE VOLCANO 1497

Under the microscope the rock is seen to be decidedly altered. The plagioclase has been sericitized. Relics of former mafic minerals are surrounded or completely replaced by chlorite and actinolite. Diabasic textures and amygdaloidal structures suggest that the rock was of intermediate or basic igneous composition.

It is possible that the greenstone may correspond to Daly's (1912, p. 521) Chilliwack Volcanic formation of Upper Carboniferous age. The andesite in the Chilliwack Volcanic formation has been altered into typical greenstones, or, where the shearing has been particularly intense, into green schists. The type locality is only 6 miles north of Herman Mountain, and the total thickness was estimated by Daly to be 2000 feet. It is also possible that the greenstone may correspond to Daly's (1912) Vedder greenstone located 18 miles to the northwest. Recently Crickmay (1930, p. 487) assigned the Vedder greenstone to the Triassic.

CARBONACEOUS PHYLLITES

Carbonaceous phyllites outcrop at many widely scattered localities. The typical phyllites are black to slate gray. Alternating with these more carbonaceous phases are medium-gray, gritty graywackes. Less abundant are thin laminae of almost pure quartzitic sandstone. The phyllites are invariably wrinkled and often badly contorted. Slicken-sided surfaces are marked by innumerable quartz veins.

Phyllites have been mentioned by Bauerman (1882, p. 32; Daly, 1912; Smith and Calkins 1904) who made an exploratory trip through the district to the north of Mt. Baker. Daly's (1912) Chilliwack series (not to be confused with the Chilliwack Volcanic formation), only 5 miles north of the phyllites under Mt. Baker, is composed of slates, phyllites, and limestone, whose total thickness has been estimated to be from 10,000 to 24,000 feet. On the basis of fossils found in the limestone members of the Chilliwack series, the age has been determined as Carboniferous. It is highly probable that the phyllites surrounding Mt. Baker belong in this same general sequence.

MESOZOIC SEDIMENTARY ROCKS

It is exceedingly difficult to distinguish Palæozoic from Mesozoic sedimentary rocks unless they contain fossils, for the stratigraphy has not been studied. Fossils have been found, however, in the Canyon Creek area, 10 miles northwest of Mt. Baker, and the age of these rocks has been established as Mesozoic (Crickmay 1930)—probably Upper Jurassic.

Smith and Calkins (1904) provisionally assigned a Mesozoic age to some of the rocks along the Nooksack River near Mt. Shuksan because they were distinctly less metamorphosed than the Palæozoic rocks.
The writer has found probable Mesozoic rocks below the east side of Mt. Baker along the headwaters of Rainbow Creek. The rocks vary from thinly laminated, buff to dark-gray shales, graywackes, and impure sandstones to gray and white lithic tuffs and ash. Little can be said of their age, but they appear to overlie and are far less altered than the greenstones and phyllites.

TERTIARY ROCKS

A sedimentary sequence several thousand feet thick borders the western margin of Mt. Baker. The various sandstones, shales, arkoses, and thin coal seams are known collectively as the Chuckanut formation. The stratigraphy has been worked out by Weaver (1937, p. 90) who states

"The Chuckanut formation may represent the time interval beginning in late Cretaceous and continuing into the middle or possibly late Eocene."

Daly (1932) gives the name Huntingdon formation to similar strata to the north, but this is only a provisional name to be used until a definite correlation can be made with the Chuckanut.

GRANODIORITE

Much of the area contiguous to Mt. Baker and for some distance to the northeast is underlain by granodiorite. Daly (1912) encountered this same batholith on his boundary survey and gave it the name of Chilliwack granodiorite. He thought it might have been intruded as late as the Miocene Snoqualmie granodiorite of the Mt. Rainier-Snoqualmie district. Equally probable is a Jurassic age which corresponds with numerous other batholiths in the Cascade Range. Daly has described the rock petrographically and has given chemical analyses of it.

PRE-MT. BAKER TOPOGRAPHY

Although the rocks underlying Mt. Baker are much older than those below Mt. Rainier and Mt. St. Helens, it is thought that the erosional history of these areas had much in common during the latter part of the Tertiary. The writer has dealt with the pre-Pleistocene valley cutting in the Mt. Rainier district at quite some length in a previous paper (Coombs, 1936). It will suffice to say here that even a brief visit to Mt. Baker would convince one that a rugged topography prevailed prior to and during the growth of Mt. Baker.

Smith and Calkins (1904) report: "The relations of the lava to the older terrain are interesting because they show that the lavas were poured out on a topography as rugged as at present, and that the main drainage features of the region, the Nooksack, had at the time of their eruption, the same position and even practically the same level, that it now has."

Creekley (1930) came to the same conclusion when working in the Harrison Lake and Fraser River districts to the north. The writer has
encountered no evidence about Mt. Baker to establish more definitely the time of uplift of the northern Cascades, but during the early Pleistocene the topography of these older rocks was very rugged. This conception is not compatible with many statements in the literature that the entire Cascades were peneplained during the Pliocene and that their present height is due to a major uplift at the close of the Pliocene.

**MT. BAKER AND ASSOCIATED LAVAS**

**FORM OF THE VOLCANO**

The volcanic rocks associated with Mt. Baker may be divided into three groups, from youngest to oldest: Mt. Baker, the Black Buttes, and the scattered flow remnants and subsidiary vents.

Mt. Baker is a relatively smooth, andesitic cone, little dissected by erosion. Approximately one-fourth of its 50 square miles (including the Black Buttes) is covered by glaciers. Ice has modified and accentuated the concave profile of the cone, but such dissection as exists can be measured in hundreds instead of thousands of feet as at Mt. Rainier. The base of the volcano averages 5000 feet in elevation, and the summit is 10,750 feet above sea level. Thus the actual cone is approximately a mile in height.

Most of the material that issued from the central vent was in the form of flows. These range in thickness from 15 to 50 feet. The pre-dominating colors are medium to dark gray, black, and red. Columnar jointing is pronounced, and columns from 4 to 8 inches in diameter are most abundant. A peculiar modification of some of the columns is an offset every few inches giving the appearance of an irregular stack of books. A remarkable parallel streaking or flow structure, with alternating red and gray, or light- and dark-gray bands a fraction of an inch in thickness, is common in the Mt. Baker rocks. The thinness of the bands and their perfectly straight alignment are features worthy of more study.

Some of the flows from Mt. Baker were quite fluid especially when compared to those of most of the other large volcanoes in Washington. The largest flow, and one of the latest, follows the course of Sulphur Creek for 12 miles down to its confluence with the Baker River. An older flow reached the banks of the Nooksack River 9 miles north of Mt. Baker. This older flow may have originated in a fissure on the north side of Mt. Baker, as did the flows to the west of Austin Pass and those which poured down Bagley Creek.

Pyroclastic rocks constitute probably less than 5 per cent of the total volume of Mt. Baker, in distinct contrast to the volcanoes to the south which include abundant pyroclastic material. Tuff and pumice occur radically, but dark crystal ash is the most abundant pyroclastic.
At the summit are two peaks originally part of a continuous rim, now separated from each other by a crater several hundred feet deep. The north peak is a flat-topped area covered by snow and ice. Just below the ice on the west side, a narrow ledge of flat-lying red andesite can be seen in late summer. The present crater is an east-west breach in which the rocks are noticeably lighter in color than elsewhere on the mountain. The predominant colors are buff, gray, white, and red. Sulphur is extremely abundant and sublimates in cavities filling most of the porous rocks in the crater. Solfataric activity has been extremely effective in transforming much of the vent material to a mass of brilliant white opal and kaolin or in coating many of the rocks with a pellucidous cover of opal. The south peak is composed of yellow, red, and buff tuff and flow material capped by ice and snow. The flows emerging from under the ice have an initial dip to the southward of approximately 20 degrees.

The summit of the Black Buttes (8000 feet) is overtopped by the crater of Mt. Baker approximately 2 miles to the east. The flows from the two cones meet in a saddle at an elevation of approximately 7800 feet. The Black Buttes have been greatly dissected by the Coleman and Thunder glacial on the north and by the Deming Glacier on the south. The result is a series of sheer walls several thousand feet high, clearly exhibiting the successive flows from a central vent. These crags are so steep that little snow and ice remain on them during the summer. On account of their dark color, these crags stand out in marked contrast to the smooth ice-covered slopes of Mt. Baker.

Because the Black Buttes are so thoroughly dissected by erosion as compared with Mt. Baker, it is assumed that the Black Buttes are the older, rather than a later parasitic cone. Flows from the Black Buttes must have been very viscous as the tongues of lava moved but a few miles from the central vent and show dip slopes as high as 30 degrees.

Scattered flow remnants occur at several places to the north of Mt. Baker. Many of these were undoubtedly derived from local vents several miles from Mt. Baker. The most accessible localities are at Table Mountain, Shuksan Arm, and Mt. Baker Lodge. These flow remnants are identical with the lavas of Mt. Baker and the Black Buttes and are at least in part contemporaneous with the larger volcanoes.

**AGE OF THE VOLCANO**

It is thought that the greater portion of Mt. Baker was formed contemporaneously with the other volcanoes to the south during the Pleistocene. The latest eruptions from Mt. Baker have been recorded within historic time. Gibbs (1870, p. 140) stated,

"I am informed both on the authority of the Hudson's Bay Co., and also the Indians, that the eruption of 1813 was the last known. It broke out somewhere on the north side of the mountain, which was still covered with snow..."
The Black Buttes probably had a much earlier beginning than Mt. Baker. The Black Buttes also seem to be older than most of the other Cascade volcanoes (Mt. Thielsen excepted) if the amount of erosion is a criterion.

The small remnants of flows to the north of Mt. Baker present evidence of both early and late origin. On Shuksan Arm, overlooking Mt. Baker Lodge, andesitic remnants cling to the side of a severely glaciated valley several hundred feet above the valley floor. This would represent one of the earliest flows, either of preglacial or interglacial age. In contrast, the bottom of the valley in which Mt. Baker Lodge is situated is covered by an extremely fresh flow of andesite which definitely did not pour out until after the valley was glaciated. It is impossible to correlate these flow remnants with either Mt. Baker or the Black Buttes, but undoubtedly they are all phases of the same general period of volcanism.

**Petrography**

*General considerations.*—Petrographically the lavas from Mt. Baker are so similar to those of Mt. Rainier that little need be given here regarding their mineral content and texture. A more complete account of the petrographic details has been published (Coombs, 1936). In this discussion only the salient points of the Mt. Baker lavas will be discussed, and an attempt will be made to correlate, as much as possible, the petrographic character of the rocks with their relative positions in the volcano.

Hague and Iddings (1883) were the first to appreciate the variety of lavas encountered in the southern Cascade volcanoes as compared to the lack of variation in the lavas in the northern Cascades. Although they were not acquainted with Mt. Baker, this volcano fits well into their general impression of the Cascade volcanoes. Mt. Baker is composed exclusively of andesite, and of this amount 90 percent is pyroxene andesite.

Rather than describe a few specimens in detail, the writer will describe each mineral in order of its importance, and mention any unusual features.

**Plagioclase.**—Smith and Calkins (1904, p. 58) described a specimen of andesite from Austin Pass and were impressed by the size relationships of the plagioclase crystals. They state

"At the first preliminary examination of the thin section through the low pow-..."
in the crystals. In those heavily charged with magnetite, the 2V drops as low as 60°, but in the more common clear crystals, 2V averages 70°.

Occasionally augite has crystallized in jackets around the partially resorbed hypersthene so that both pyroxenes have their c axes and their prismatic cleavages parallel. A similar structure was observed by Williams (1933) at Mt. Thielsen, by Coombs (1936) at Mt. Rainier, and by Thayer (1937, p. 1524) in the lavas of the Sardine series in the Oregon Cascades.

**Augite and pigeonite.**—The pyroxenes are far less abundant than hypersthene. Pigeonite with a 2V = 40° was seen in only five specimens. Augite is common to almost all the lavas. After the abundance of augite in 20 sections picked at random was plotted it was evident that augite is far more plentiful and forms definitely larger phenocrysts in the earlier more fluid flows. The average length of the augite crystals in all the lavas is .5 mm. The diopside nature of the augite is indicated by the following optical properties: \( \alpha = 1.690, \beta = 1.700 \) and \( \gamma = 1.720; \) the optic angle varies little from 60°; \( Z \alpha c = 40°-60°. \)

The peculiar association of pigeonite and olivine (now partially altered to antigorite) and hypersthene was noted in a specimen from the southern slope of Table Mountain. The only other reference to such an association of minerals is by Verhoogen (1937, p. 65).

**Olivine and hornblende.**—One of the most striking characteristics of the Mt. Baker lavas is the presence of olivine in most of the early flows. It is not to be inferred, however, that olivine is abundant in the Mt. Baker rocks for seldom does it make up over 10 per cent of the rock. In occurrence in the long tongues of early valley-filling flows is rather to be expected as these flows were far more fluid and probably hotter than the later viscous flows of Mt. Baker. Most often associated with the olivine are hypersthene and augite. A few slides show both hornblende and olivine as well as the pyroxenes, but in these the hornblende is resorbed almost entirely replaced by magnetite. The perfectly euhedral outlines of the replaced hornblende leave little doubt as to its identity.

Both basaltic hornblende and ordinary hornblende are present. The ordinary type is more abundant and shows the following pleochroism: \( X = \) golden yellow, \( Y = \) olive brown, and \( Z = \) deep golden brown; \( Z \alpha c = 20°. \) The hornblende always presents euhedral outlines. Occasional hornblende crystals were perfectly fresh, others were rimmed by magnetite, and some were completely replaced by magnetite.

**Types of groundmass.**—The general appearance of the Mt. Baker lavas is dependent mainly upon the groundmass. The more glassy varieties have a distinctive brilliance in color and luster; they are usually \( Al_2O_3 \) black, dark brown, or hematite red. In contrast, the less glassy rocks are usually intermediate shades of gray to light gray. All are charged with liberal quantities of magnetite or hematite dust, sometimes in sufficient quantities to render the thin sections opaque.

**Figure 3.**—Variation diagram of the Mt. Baker and Mt. Rainier andesites

(The analyses with double circles are from Mt. Baker.)

Approximately 90 per cent of the Mt. Baker rocks have a hypocrystalline groundmass. The amount of glass, however, varies within wide extremes. The remaining 10 per cent is mostly in the holocrystalline group. This is especially true of the dark pumice and ash. Holocrystalline rocks are rare.

**Chemical Composition and Interpretations**

**Variation diagram.**—As only two analyses are available from Mt. Baker, little can be said about the chemistry of the volcano. However, several analyses heretofore unpublished are now available from Mt. Rainier, and these will be included in the accompanying variation diagram.
The lack of variation is the most striking point in connection with these analyses. All specimens analysed were collected from widely separated localities and represent lavas extruded at different times. At Mt. Rainier it is probable that the lavas were extruded in rapid succession, allowing little time for differentiation. At Mt. Baker topographic evidence indicates that more time elapsed between the earliest and latest flows. Both analyses from Mt. Baker are from relatively late flows. Petrographically a small difference does exist between the earliest and latest flows as there is a definite dearth in the amount of olivine in the younger lavas.

The lavas from Mt. Baker and Mt. Rainier are slightly different from the andesites of the volcanoes to the south. The Mt. Shasta andesites, for example, are richer in alumina and magnesia and lower in potash and ferrous iron than the lavas from Mt. Baker and Mt. Rainier. At Lassen Volcanic National Park the andesites average 2 per cent lower in silica and approximately 1.5 per cent lower in potash and soda. Ferric iron, magnesia, and lime are over 1 per cent higher. The Mt. St. Helens andesites are approximately the same as the Mt. Baker andesites. It is noteworthy that the lavas must be extruded in coarser composition from rhyolite to basalt, and the intermediate types are especially abundant. In the lavas the north the the lavas are restricted to variations of andesitic.

**Interpretations.**—The problem of volcanism in the Cascade Range is a broad one and most writers believe that it is intimately associated with

<table>
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<th>Table 1. Chemical analyses of andesite</th>
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<tr>
<td>SiO</td>
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<tr>
<td>Al₂O₃</td>
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<td>TiO₂</td>
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<tr>
<td>Fe₂O₃</td>
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<td>MnO</td>
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7. Andesite from Mt. Rainier, a locality near the terminus of the Nezahaliu Glacier. One of the early flows resting unconformably on the andesite. H. B. Ellestad, analyst.

Several writers have discussed the relationships of the lavas in the High Cascades, as defined by Callaghan (1938, p. 243), with those of the west Columbia Plateau to the east. Williams (1938, p. 299) suggested two possibilities for the high calcic nature of the High Cascade lavas as compared to the calc-alkaline Columbia Plateau flows: (1) The High Cascade volcanoes tap lower levels in the primary basalt, and in these lower levels there is a concentration of early crystals; (2) the magmas beneath the High Cascades may have assimilated large amounts of shale, limestone, and dolomite, thus accounting for their rich lime content. In accordance with Williams' first point, there is little direct evidence. It is unknown whether the source magma for these volcanoes was a different magma caused by crystal settling of early, basic plagioclase feldspars and magnesian olivines and pyroxenes or whether it was due to some other cause. It is quite certain, however, that if differentiation was responsible for this source magma, this process was brought to a sudden halt when the lavas of Mt. Baker and Mt. Rainier poured forth on the surface. The conditions during the time of extrusion of these lavas must have been very stable, or the time between the earliest and latest flows was exceedingly short, for the lavas of these two volcanoes show practically no evidence of differentiation. In regard to the second point, the rocks beneath these volcanoes contain abundant lime and alumina in the form of calcareous shales, phyllites, and calcareous arkose. These underlying rocks may have had a decided influence in the ultimate character of the lavas. If these lavas represent contaminated fractions or differentiates of a regional primary magma (similar to the Columbia Plateau basalt), the volumetric proportions are also important. The andesites of both Mt. Baker and Mt. Rainier total less than 100 cubic miles. Compared to this, the Columbia basalt total over 100,000 cubic miles.

Van Bemmelen (1938) studied an area in the Seeadle Mountains of Oregon which is almost identical to the Mt. Rainier district. His theory as to the origin of these magmas involves the magmatization of pre-existing crystalline rocks by ascending emanations from the substratum (secondary or palingenic magmas) and hybridization or contamination of juvenile of palingenic magmas by assimilation of foreign material (synthetic or mixed magma). This theory might also apply to the northern Cascade volcanoes.

Callaghan (1938) and Thayer (1937) have pointed out many differences between the lavas of the High Cascades and those of the Western Cascades in Oregon. Wells and Waters (1935, p. 971) have demonstrated marked difference between the Eocene lavas and those of the Western Cascades.
Cascades in Oregon. More recently Waters has made a study of the Cascade Mountains and the Columbia Plateau and has drawn some striking relationships between the various magmatic groups within the general province.

It is the opinion of the writer that Mt. Baker is but a unit in a chain which may include all the major Cascade volcanoes. There seems to be a very definite relationship between the structural conditions prevailing in each unit of this chain and the chemical and petrographic character of the associated volcanic rocks.

It is possible that the lava and pyroclastic rocks of Mt. Baker may represent differentiates of a regional primary magma. Evidence for or against this theory can be obtained only by careful analysis of the petrographical, chemical, and structural data available. The evaluation of interpretations would remain a difficult problem even if these data were more abundant.

Evidence does indicate, however, that both Mt. Baker and Mt. Rainier were formed from magmas almost identical in composition, and during the growth of the cones there was little differentiation.

The condition and kinds of rock underlying these volcanoes may have a decided influence on the chemical composition of the lavas in these cones. The necessary petrologic and structural data on the underlying rocks are quite meager, and few chemical analyses are available.

WORKS TO WHICH REFERENCE IS MADE


Works to which reference is made


406 Snell Hall  
Corvallis, Oregon 97332  
April 24, 1979

Mr. Barry Lawler  
English Department  
Oregon State University  
Corvallis, Oregon 97330


Dr. Charles L. Rosenfeld, O.S.U. Geography Department, Wilkinson Hall

Dear Mr. Lawler:

Mt. Baker is a major volcanic peak of the Cascade Range in Washington. Scientists have been watching the mountain closely since March 1975, when there was a dramatic increase in the amount of steam and gas being discharged from the Sherman Crater. Dr. Charles Rosenfeld has been heading a study by the O.S.U. Geography Department of the thermal activity of the crater. The thermal activity is being monitored by aerial photographs and infrared images taken periodically. Using photographs and images taken in December 1978, I will describe the thermal activity at that time and discuss some of the changes which have occurred since 1975.

I will map the snow-free area in the crater and the location of gas vent clusters, review the 1975 volcanic activity, and try to suggest possible reasons and implications of the changes. The infrared images measure the heat patterns, while the aerial photographs document visual changes in the crater, aid in identification of landforms, and help ground crews locate specific features. The O.S.U. Geography Department study is part of a larger framework of investigation of the mountain, which includes seismic and gravity monitoring, measuring volcanic swelling, and recording the temperature and the composition of the gases in the crater.

The eruptive activity of volcanoes in the Cascades is difficult to predict; therefore, what is learned about Mt. Baker may help scientists predict future activity in the Cascades. This is important because as more people move into the Pacific Northwest, the potential damage to human habitation and natural resources from an eruption increases.

Sincerely,

David S. Shafer
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.
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).

A 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
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 piles 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.
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:

<table>
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<tr>
<th>Detector</th>
<th>Spectral range</th>
<th>Response</th>
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<tbody>
<tr>
<td>Mercury-Cadmium</td>
<td>8–14 μm (10–13 peak)</td>
<td></td>
</tr>
<tr>
<td>Telluride (MCT)</td>
<td></td>
<td>4.1 μm (4.2 peak)</td>
</tr>
<tr>
<td>Indium Arsenide (InAs)</td>
<td>1–5.4 μm (3–5.2 peak)</td>
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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-
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). 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, 76V5–262) and R. M. Krimmel (C, 76NC2–13).

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 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 m², of which 35,200 m² (19 percent of the crater area) was free of snow and ice in August 1975. Infrared thermographs indicated that 12,600 m² (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 m² of persisting snow-free ground which approx-
imately coincides with the summer surface that is hotter than 15°C. Some new ice perforations have appeared since summer, most notably along the south-west 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 m² of thermal ground was apparent in photographs. At the same time, about 12,600 m² 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. 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.

*As used in this report, “snow and ice” includes firn.
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-
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 measurements were 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 for-
MT. BAKER REPORT #11

Tilt stations anchored in the rocky slopes of Mt. Baker have detected no expansion or contraction of the steaming peak, scientists said today.

Tilt stations placed on the mountain early this summer were measured late last week and showed no change, said Dr. Don Swanson, U.S. Geological Survey geologist.

Last week scientists reported that there has been a slight decline in the pull of gravity atop the peak, corresponding to an uplifting of about four feet. However, such an uplift would be expected to be accompanied by a change in the tilt.

Swanson said today that it is possible that the uplifting is a local condition in the Sherman Crater area where unusual steam activity has been taking place since March. But he emphasized that it may be some time before scientists get a better idea of what is occurring within Mt. Baker.

While Dr. Swanson measured his tilt stations, other scientists checked and repaired automatic monitoring devices in and around Sherman Crater and did additional measurements of fumerole (steam vent) temperatures. The temperature measurements revealed the existence of several additional "superheated" fumeroles with temperatures hotter than the boiling point of water. One reading of 267 degrees F. is the hottest yet measured on Mt. Baker and, indeed, the hottest measured on any Cascade volcano this century. (More)
Since this is the first measurement of these temperatures, it will take future readings at the same spots to indicate whether the mountain is continuing to heat up.

A new set of instruments in the crater will measure the temperatures of gases coming from the largest fumerole as well as the temperature of water flowing from the crater. These readings will be transmitted to scientists via satellite.

The U.S.G.S. is continuing to seek old photographs of the steaming crater area on Mt. Baker. They are looking for any old photos taken of the summit and crater area prior to 1940, hoping to compare previous steam activity with current activity.

Persons with such pictures can call David Frank, U.S.G.S. geologist at Seattle, 543-5544, collect.

One full day of a two-day regional meeting of American Geophysical Union scientists in Seattle this week will be devoted to discussion of Mt. Baker. Friday, scientists of many disciplines who are studying the mountain will discuss their findings and plans for future study.

Thursday, session topics will be solid earth geophysics, space science, meteorology, hydrology and oceanography, said Dr. Steve Malone, University of Washington geophysicist, and program chairman.

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MT. BAKER REPORT #9

Scientists have taken Mt. Baker's temperature and have found surface readings hotter than on any other volcano in the Cascade mountain range.

Last weekend scientists from the U.S. Geological Survey and the University of Washington made their way to a steaming area in the east breach of Sherman Crater at the 9,500-foot level of Mt. Baker.

They found superheated fumeroles, with temperatures higher than the boiling point of water, said David Frank, U.S.G.S. geologist. They also saw tiny molten pools of sulphur and bright yellow sulphur cones that have built up around small fumeroles.

The temperature of the superheated fumeroles was 218 degrees Fahrenheit, though the boiling point of water at that altitude is only 193 degrees F. This doesn't necessarily mean that an eruption is in the works for Mt. Baker, Frank said. "But it may be significant because a superheated fumerole hasn't been measured in the Washington Cascades in this century."

Three more seismic stations have been installed on the mountain, said Dr. Steve Malone, University of Washington seismologist. It will take another week to establish the communications line that will automatically transmit data from the stations to the University.

(More)
Scientists hope that such seismic stations would detect a number of local earthquakes in advance of any actual eruption.

A trip also was made to the Dorr Fumerole Field, a steaming area on the North side of the peak that has been known since the 19th century. The area is only one-tenth the size of the steaming area in Sherman Crater, and its activity apparently has not increased in intensity this year.

Meanwhile, Eastern Washington State College scientists who visited the Sherman Crater area two weeks ago have announced some of their findings. They tested velocity and volume of gasses coming from some of the fumeroles and found gas speeds up to 166 miles per hour.

The gas speeds themselves probably are not highly significant, because the smaller the fumerole, the greater the pressure of escaping gas, said Gene Kiver, EWSC geologist. But it is hoped that readings to be taken at the same spots on later visits will give some indication of changes that may be taking place in the mountain.

Scientists report that snow and ice is continuing to melt in the crater area. Steam activity seems to be continuing at at least the same level as it has since March.

If the clear weather holds, additional trips probably will be made to the crater area before winter storms begin.

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March 2, 1978

MT. BAKER REPORT #22

Three, possibly four new sets of fumeroles (steam vents) were sighted yesterday in Mt. Baker's Sherman Crater by a University of Washington scientist who flew over the 10,778-foot mountain.

Experts with the U.S. Geological Survey, Mt. Baker-Snoqualmie National Forest, and Puget Sound Power and Light Company are waiting to meet next week with seismologist Dr. Stephen Malone and analyze pictures he took before determining the sitting's significance.

Yesterday's pictures will be compared with those taken in December by a U.S.G.S. geologist.

Dr. Malone said he saw no obvious new hazards because of the vents. He also reported that there were not any apparent snow and ice slides in the crater which in the past blocked some of the major vents.

Dr. Malone made yesterday's flight after reports of steam activity which was readily visible in yesterday's clear sky. He said it is not possible to pinpoint when the new fumeroles became active because the mountain has been mostly covered by clouds since December.

He added that a preliminary review of seismic records do not reveal any significant recent movement of the mountain, but will study them in detail to see if there is any indication of when the vents developed.