Part

UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON 98195

Graduate Program in Geophysics

February 20, 1976

TECHNICAL REPORT #1 - February 21, 1976

Grant Number:	U.S.G.S. #14-08-0001-G-268
Name of Grantee:	University of Washington Seattle, Washington 98195
Principal Investigators:	Stephen D. Malone Stewart W. Smith Geophysics Program University of Washington
Government Technical Officer:	Jack F. Evernden U. S. Geological Survey
Short Title:	Mount Baker Volcano Studies
Effective Date of Grant:	July 21, 1975
Grant Expiration Date:	July 20, 1976
Amount of Grant:	$54,994

Sponsored by the
U. S. Geological Survey

Introduction

The research sponsored by this grant is a continuation and extension of the research begun by the University of Washington in the spring of 1975 on Mount Baker in northwestern Washington. In response to increased fumarolic activity at Mount Baker, first observed on March 10, 1975, we began an intensive research effort directed toward two main objective. The first objective was to document the observed changes by visiting the crater area and providing logistical support for others with certain expertise to do likewise. The second objective was to establish improved seismic stations and monitor seismic changes in the Mount Baker area as they might occur.

The funds provided by the current U. S. Geological Survey grant have allowed us to continue our logistical support of other people's investigations, and to increase our seismic coverage from two to six permanent stations. We have also been able to engage in additional lines of research; such as, gravity monitoring, temperature measurements, and a small-scale, portable seismic array. Our monitoring activity is continuing through the winter months with minor problems due to the extreme environmental conditions.

Included in the appendix of this report are reprints of papers on subjects of interest to this grant. Some of the research reported in these papers was supported by other grants.

Mount Baker Seismic Monitoring

In the summer of 1972 the U. S. Geological Survey installed single component, short period telemetered seismic stations on each volcano--Mounts St. Helens, Rainier and Baker as part of the volcano surveillance network. The operation of these stations was taken over by the University of Washington, Geophysics Program, in 1973 and has been made a part of our Western Washington regional seismic network since then. This network has been capable of locating earthquakes of magnitude 2-1/2 and greater over most of Western Washington. Epicenters for all located earthquakes during 1972-1974 are shown in Figure 1. While most of the seismic activity is centered in the Puget Sound lowlands, there are obvious clusters of events around the three southern volcanoes--Mounts St. Helens, Rainier, and Glacier Peak. Mount Baker is conspicuous due to its apparent lack of seismic activity.

The above observation is confirmed by examining the individual records from the three volcano monitoring stations. Seismic events readily identifiable as local earthquakes appear on the records for the stations at Mounts St. Helens and Rainier, while no earthquakes local to the Mount Baker station can be identified on its records. This peculiar absence of even small earthquakes at Mount Baker has been additionally confirmed by the installation of a more comprehensive network of stations in the immediate area and additional investigations are under way to determine if there are other fundamental seismic differences between Mount Baker and the other Cascade volcanoes.

Installation of the Baker Seismic Network. On March 30, 1975, three weeks after increased fumarolic activity at Mount Baker was first observed, a short-period, telemetered seismic station was installed on the rim of Sherman Crater, less than 500 meters from the center of the fumarolic activity. This station has been kept in almost continuous operation since then. In late summer 1975 an additional five stations were installed on and near the mountain to increase the coverage. Table 1 lists the stations forming the Mount Baker network and Figure 2 shows the locations of the stations on the mountain along with other points of interest.

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

The extreme environmental conditions found high on Mount Baker have placed a number of limitations on our research there. 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 formations. The ice is the worst problem since it can produce very high loads on antenna structures and cannot be avoided. We are pleased that the crucial stations MBW, SCW, AAB, and BBB have kept operating through the middle of the winter, and feel that at least some of these should last until spring. We have one complete station in reserve for repair or to install rapidly if we detect seismic activity that warrants additional coverage.

<u>Seismic Data and Interpretation</u>. The data from the Mount Baker array have been disappointing because of the lack of interesting seismic events. As was mentioned before, there have been no events local to Mount Baker that could definitely be identified as earthquakes. The few events that we do record seem to be of the type that are produced by ice movement. The preprint by Weaver and Malone, included in the appendix, on glacier noises explains our reasons for

continued at a high rate. Because of difficulties obtaining stable reference points, the short time span of the survey was not sufficient to define ice velocities to the accuracy needed. The survey will be repeated next summer to see what the net change in ice level over a year will be.

Future Operations

Our primary responsibility is to maintain our seismic monitoring activities and make observations of the thermal activity when we are at the crater. We feel confident of keeping the four critical stations (SCB, MBW, AAB, BBB) going through the winter and spring. With these stations it would be possible to detect upper crustal earthquakes under Mount Baker down to magnitude 0. or less and to locate most earthquakes in the range M_L = 0. to 1. and all earthquakes over M_L = 1. In late spring the other three stations will be repaired and perhaps moved to increase our coverage.

We are planning one mid-spring trip to the crater for observations, sample collection and gravity stations. In the summer additional trips will be made for repair and maintenance of the seismic stations, and a complete survey of all gravity stations. We feel it is extremely important to complete a year's gravity data because of the possibly large effect of the yearly snow cycle.

There are two additional experiments we are planning for the summer. Several explosions will be set off around the base of the volcano and recorded on stations both permanent and portable distributed in various configurations. Preliminary results from such experiments on St. Augustine in Alaska indicate that it may be quite easy to detect anamolous zones in the core of a volcano by such means (J. Kienle, University of Alaska, personal communication). We also are planning to do a magnetic survey at the same locations as our gravity stations. This will be used as base line data in case Mount Baker undergoes additional obvious changes in its thermal emission.

We will also continue giving whatever assistance we can to other investigators who are interested in doing experiments on Mount Baker.

TABLE I

MOUNT BAKER ARRAY

Name	Location	Elevation	Description	Start Date	Reliability
MBW	48.7847N 121.9008W		Grouse Ridge 7 km west of Crater	Summer, 1972	Currently operating; 25% useless data due to wind
SCB	48.7677N 121.8155W		South rim of Sherman Crater	March 30, 1975	Currently operating; 5% useless data due to radio interference
BBB	48.8035N 121.7837		Lander Cleaver 4 km NNW of crater tile site B (USGS)	September 20, 1975	Currently operating; almost no down time
AAB	48.7367N 121.8112W		Craig view 3 km south of crater tile site A (USGS)	September 30, 1975	Currently operating; 5% useless data, unknown cause
WRB	48.7685N 121.8187W		West rim of Sherman Crater	September 19, 1975	Failed January 5, 1976, due to ice destroying antenna
LLB	48.7718N 121.8115W		Top of Lahar Lookout; NE corner of crater	September 19, 1975	Never worked; could not repair because of weather and snow conditions
MLB	48.6889N 121.6867W		Near Martin Lake	September 30, 1975	Intermittent until January, 1976; 25% no data
LYW	48.5353N 122.1017W	192M	34 km SW of crater part of Western Washington original net	April, 1975	Currently operating; 5% useless data

TABLE II

TEMPERATURE AND SAMPLE SITES IN SHERMAN CRATER

esignator	Type	Date	Result
SCB	Seismometer and Gravity	March 30, 1975	
WRB	Seismometer and Gravity and gas box electronics	May 13, 1975	
CLP	Lake samples and temperature	June 11, 1975	34°C, 2 qt. water
		August 8, 1975	26.5°C, sampler
		September 5, 1975	31°C (river)
MOTF	Gas monitoring fumarole and gas sampling	Several times by Sato prior to August 6, 1975	
		August 6, 1975	88.7 - 88.9°C
		August 8, 1975	87.9 - 88.8°C
		September 5, 1975	89.6°C - 3 samples
		September 19, 1975	89.5°C - 3 samples
		September 30, 1975	89.5°C - 2 samples
		February 6, 1976	89.6°C - 2 samples
LAS	Temperature in largest fumarole north of MOT	August 8, 1975	88.8°C
UPS	Water sample from creek as it comes out of ice	September 5, 1975	1 qt. sample Bw -13 -2
		September 30, 1975	14.7°C
LLB	Seismic station	September 18	Never worked
BBF	Temperature	September 19, 1975	85.7°C (loudest)
		September 30, 1975	83.9°C
LWS	Stream temperature	September 30, 1975	21.2°C
FOMF	Old main fumarole temperature	September 30, 1975	101.5°C
WOMF	West of old main 20 m	September 30, 1975	90.0°C
COMF	Center of cluster 5 m west of main ridge 10 m above creek	September 30, 1975	116.2°C
ANTF	2 m west of DCP antenna	September 30, 1975	90.4°C
		February 6, 1976	89.6°C
NWSF	Farthest northwest cluster wall	September 30, 1975	122.4°C - 3 samples
		February 6, 1976	122.8°C
NWB	Biggest in northwest cluster	September 30, 1975	131.0°C
NPS	Stream from north pit	September 30, 1975	5.4°C
SBF	Stream bank near UPS	September 30, 1975	125.4°C

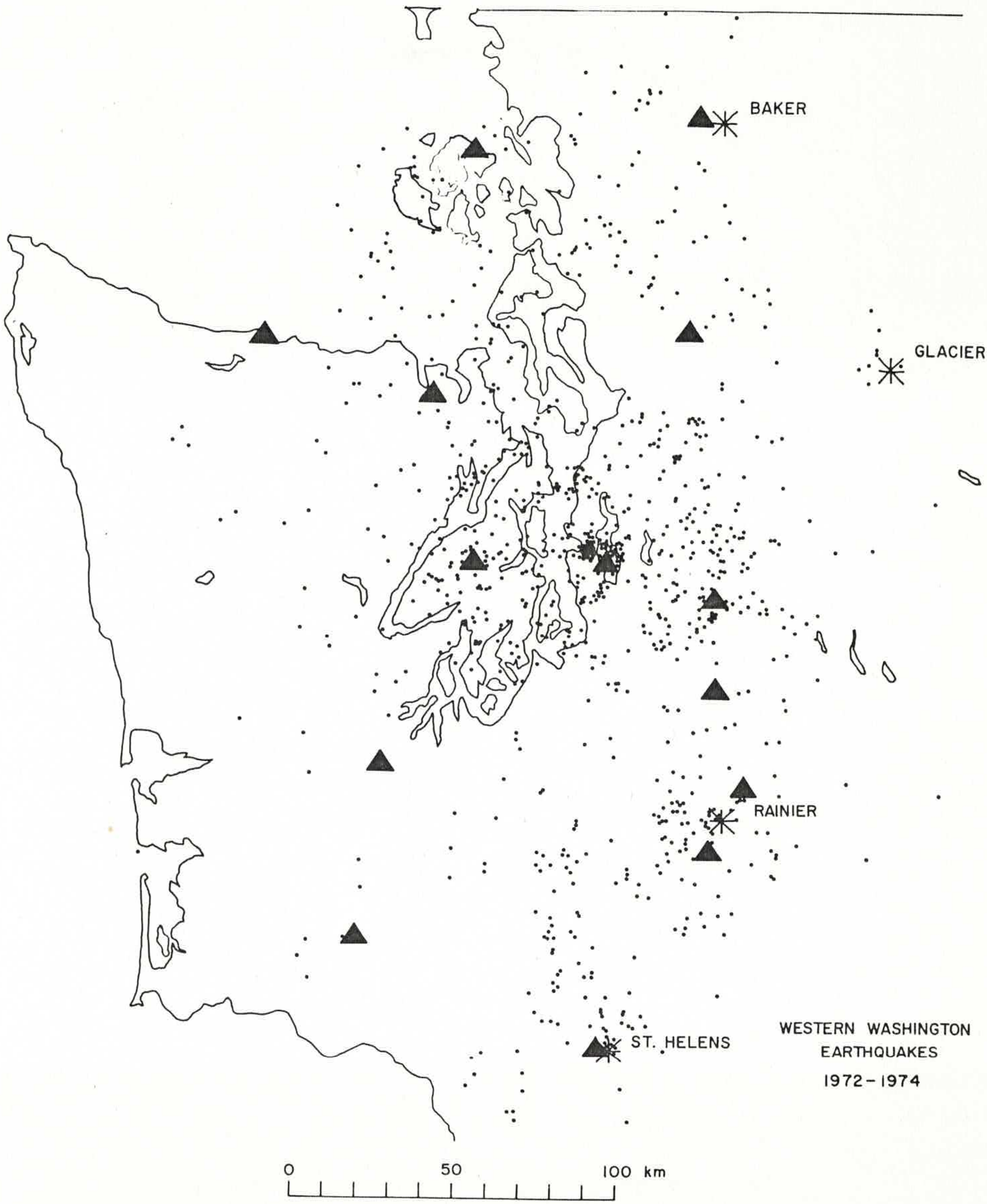


FIGURE 1. Western Washington Seismicity for last three years. All earthquakes over magnitude $M_L = 2\frac{1}{2}$.

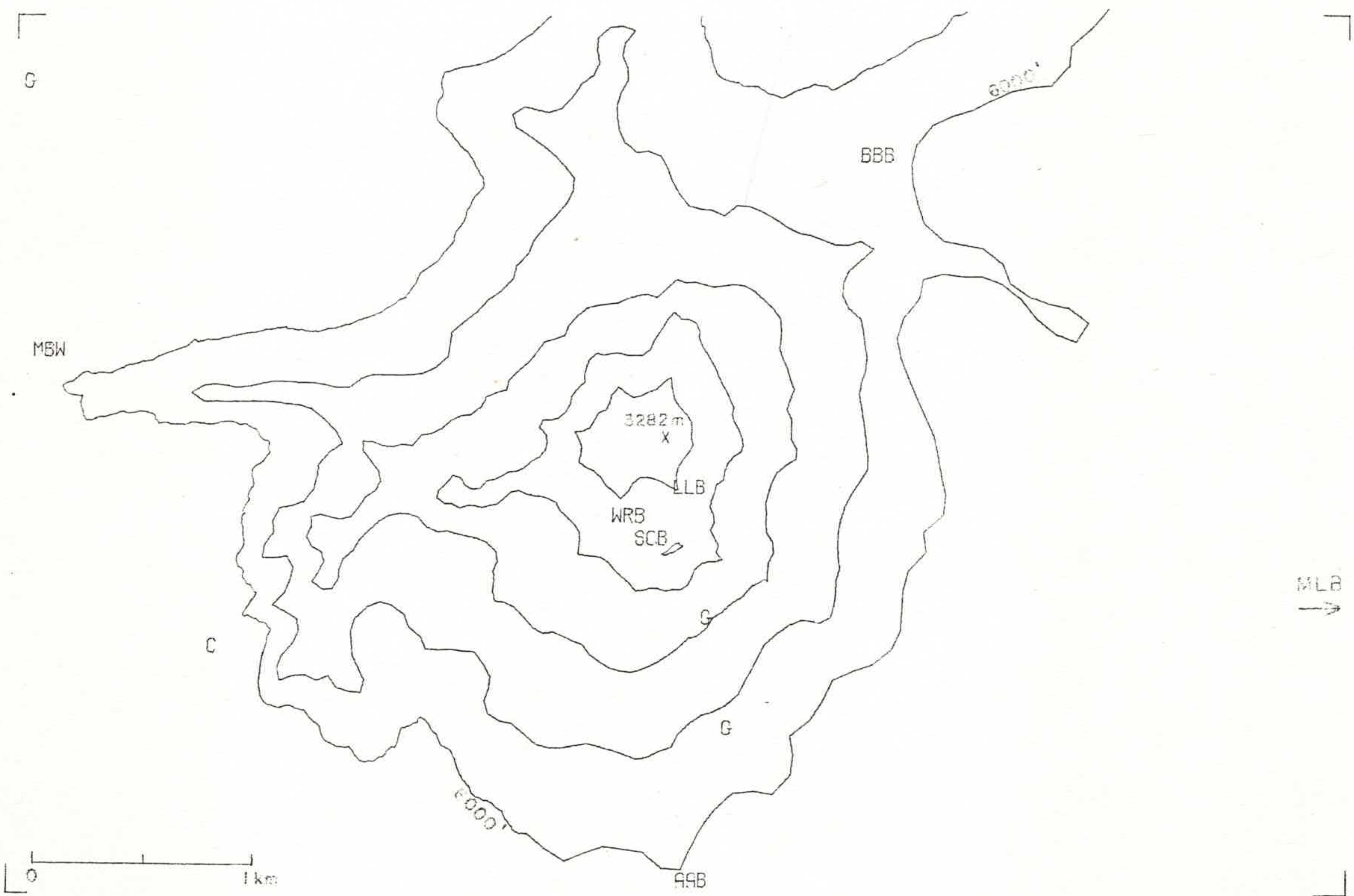


FIGURE 2. Map of upper point of Mount Baker with 1,000 ft. contours. U.S.G.S tilt stations are located at AAB, BBB, AND C. Gravity stations are located at WRB, SCB, BBB, AAB and all G's. Seismic stations are three letter designators and are listed in Table I.

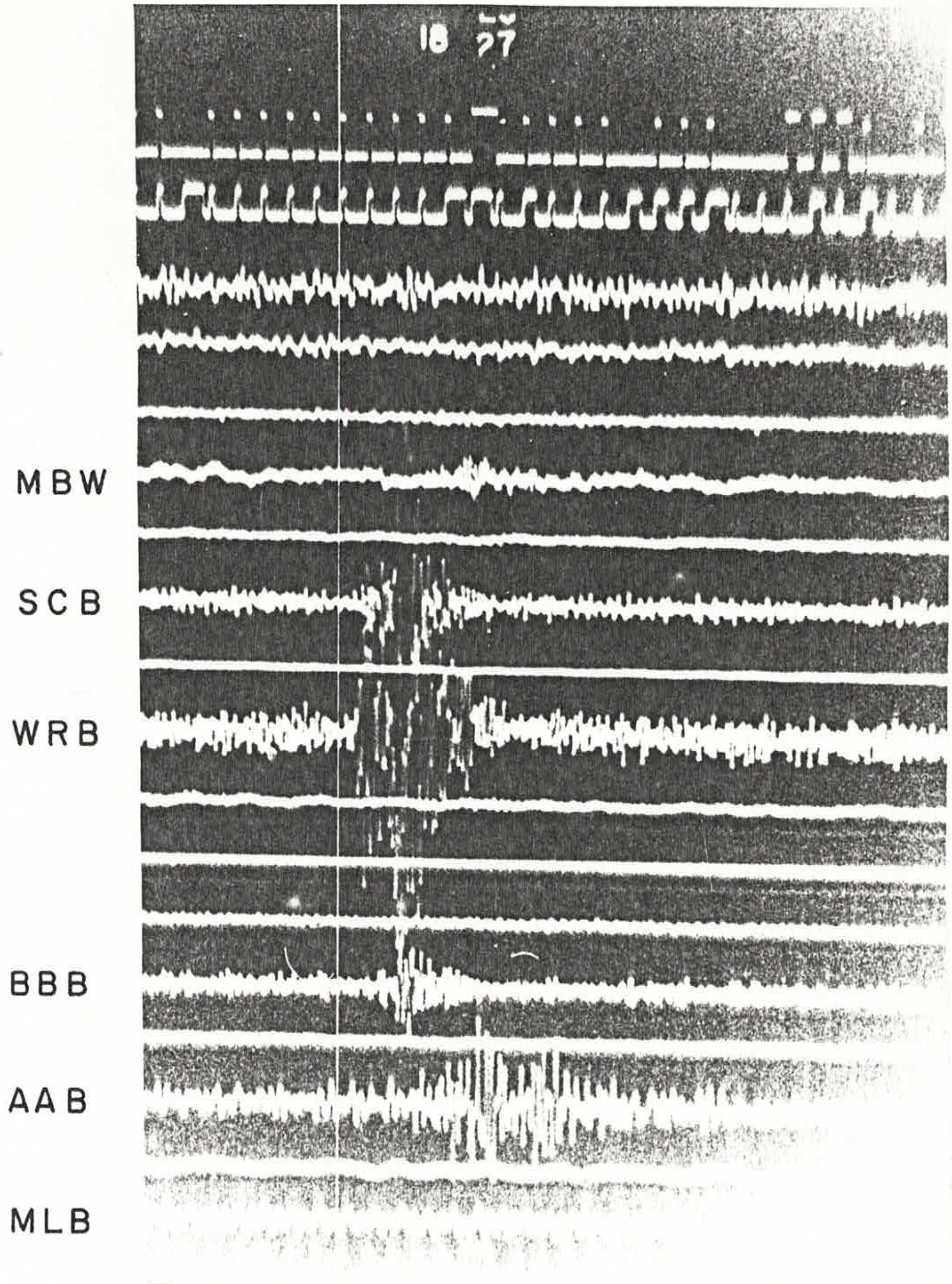


FIGURE 3a. Sample of low frequency glacier event on Mount Baker seismic array.

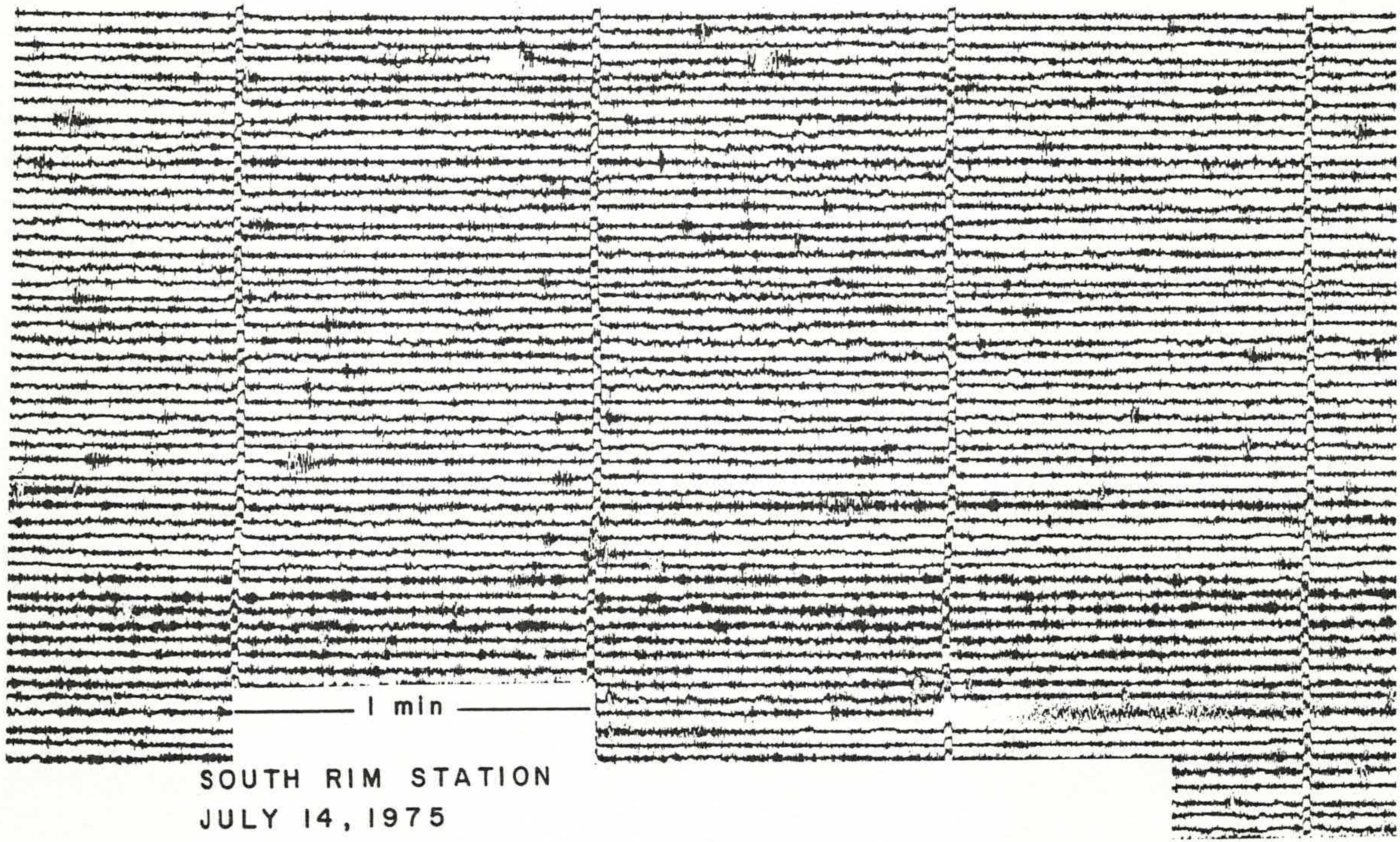


FIGURE 3b. Section of helicorder record from SCB showing typical background activity.

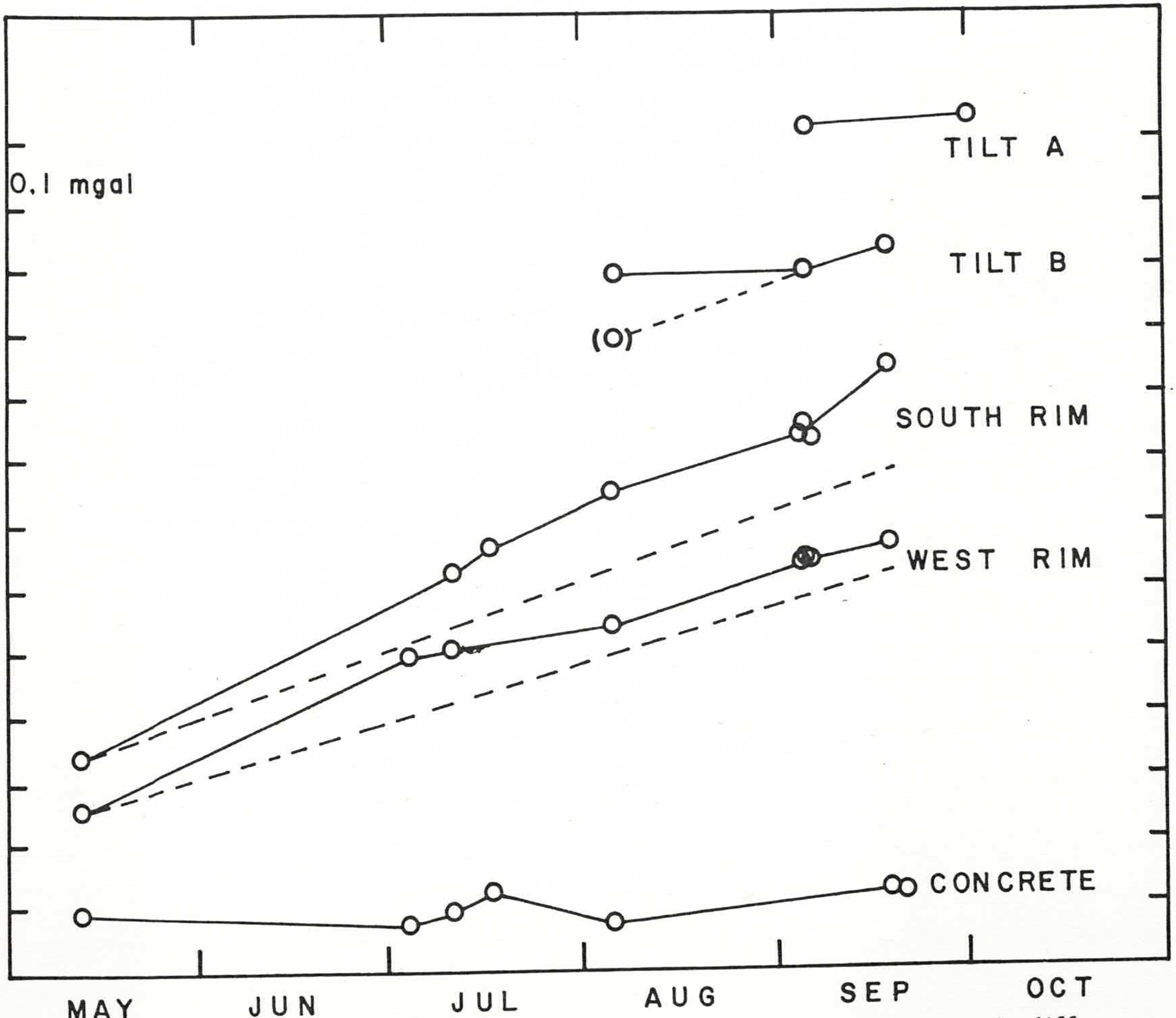


FIGURE 4. Relative gravity changes over five-month period in 1975. Points plotted are the differences between the University Base Station and stations on Mount Baker and near its base (Concrete). The data from tilt site A and B are not complete enough to interpret.

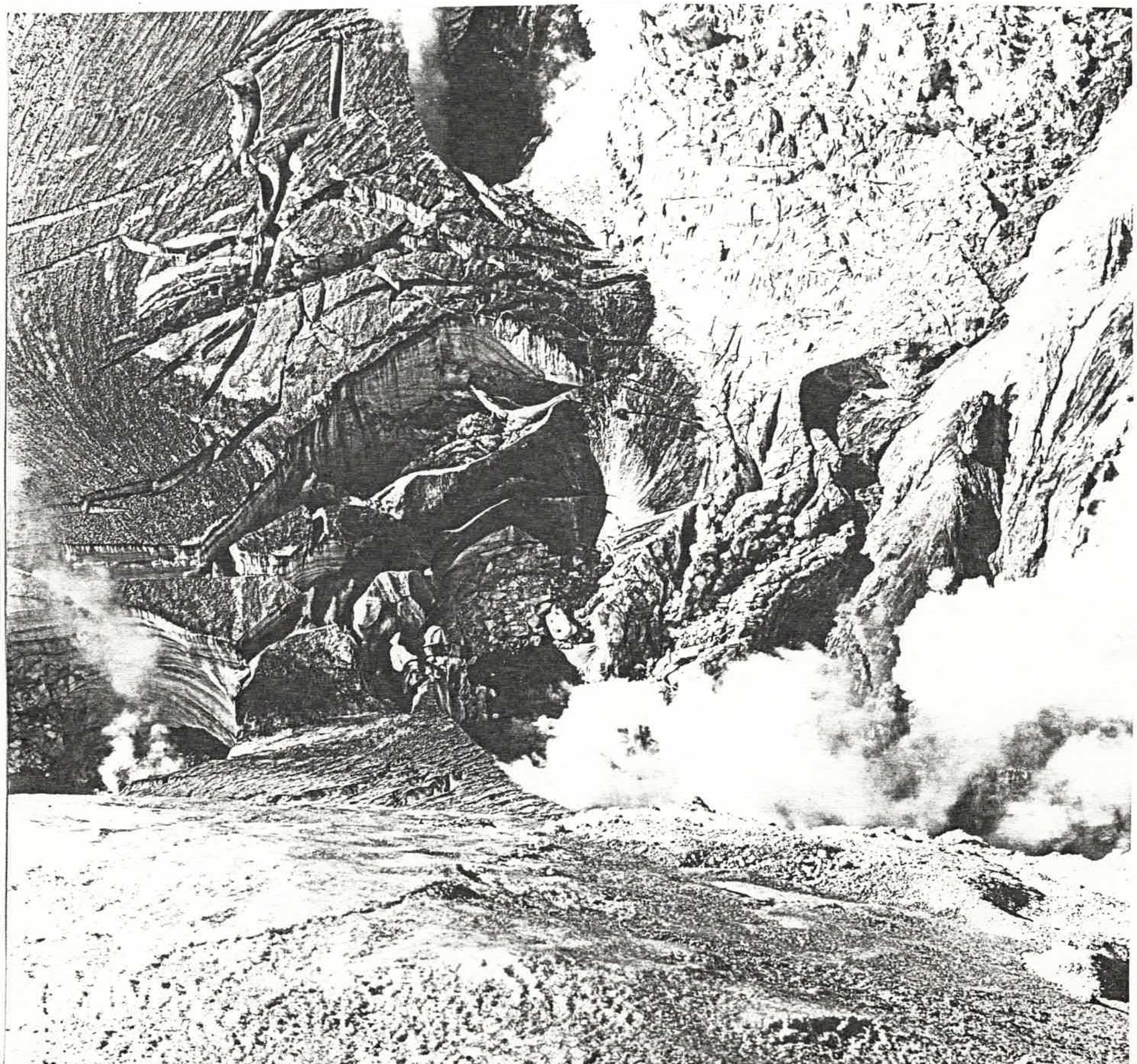
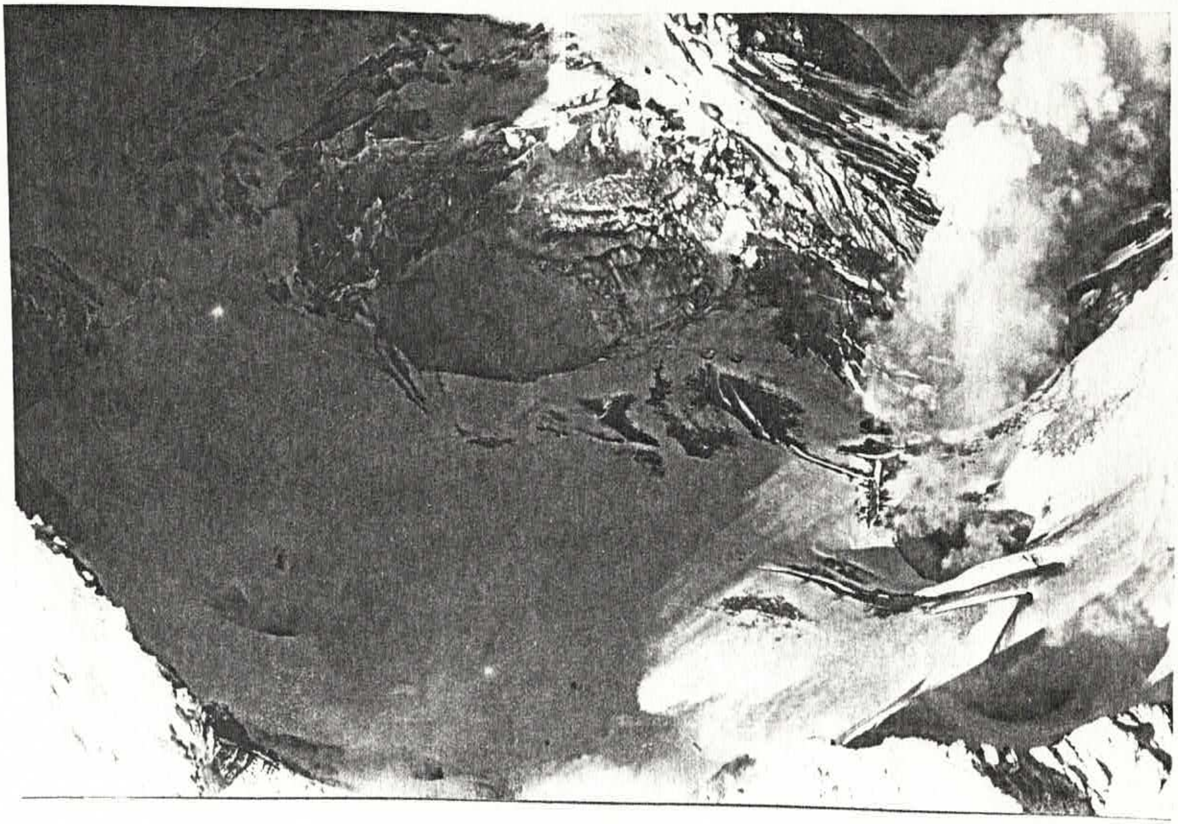


FIGURE 5. Photograph taken from Sherman Peak looking down into active part of Sherman Crater. The east breach is to the right, lake pit to the left and north pit at the top.



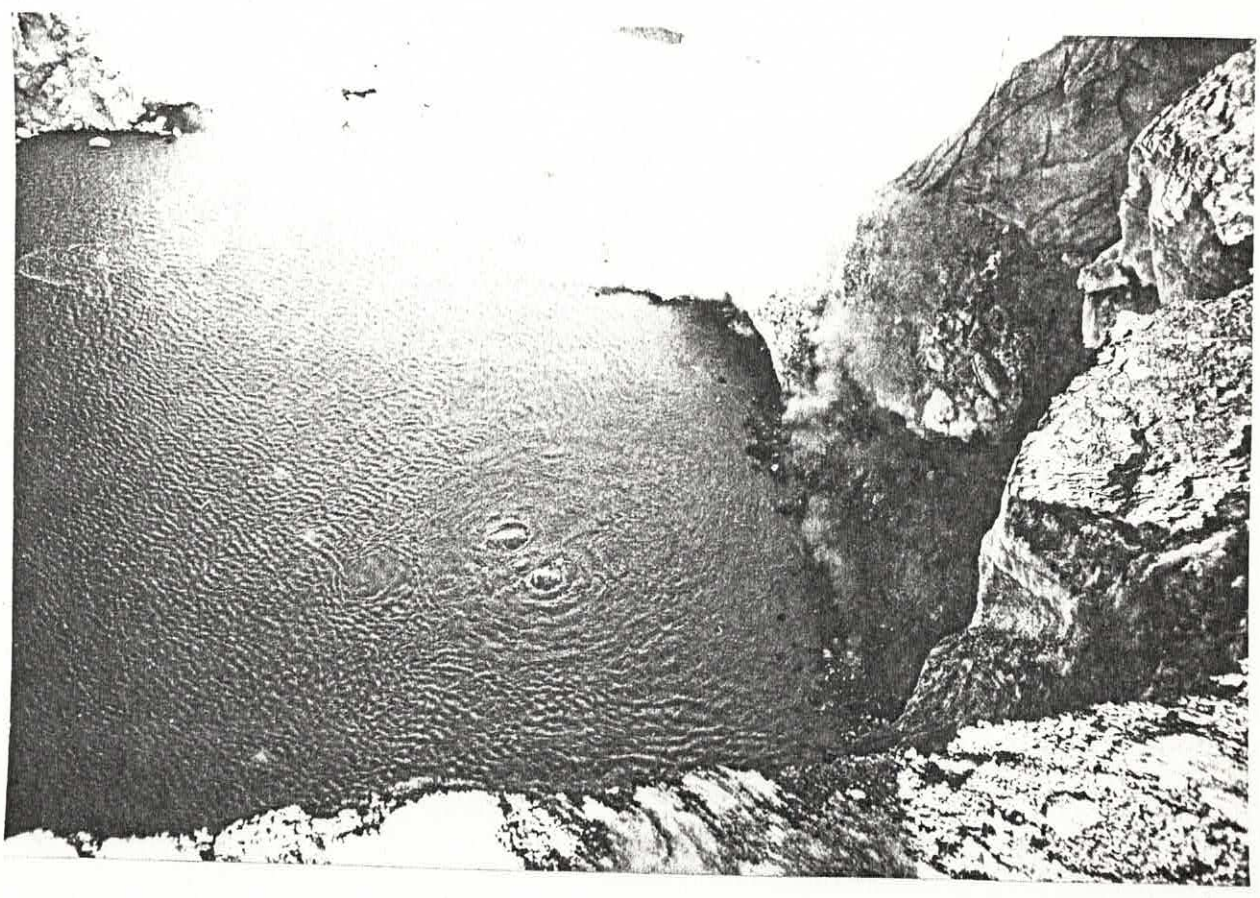


FIGURE 6. (Top) Areal view of Sherman Crater from the west looking east. Large pit in upper center is the north pit.

(Bottom) Looking from the edge of the central lake pit down to the lake. Note up-welling in lake indicating submerged fumaroles.

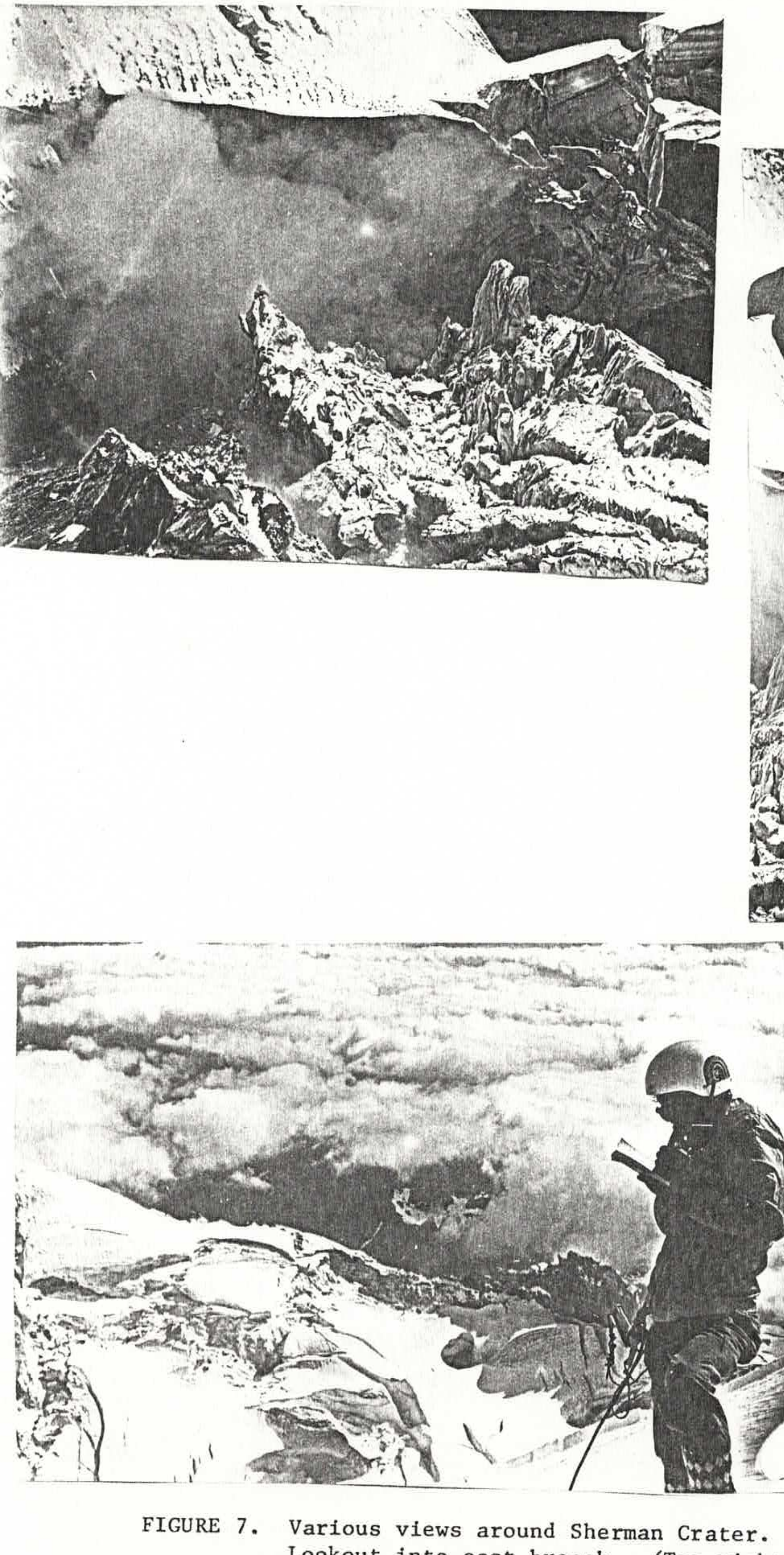


FIGURE 7. Various views around Sherman Crater. (Top left) From lower Lahar Lookout into east breach. (Top right) From upper Lahar Lookout toward central pit and broken ice to the west of the each breach. (Bottom) From Mount Baker Summit with Sherman Crater below in the background.

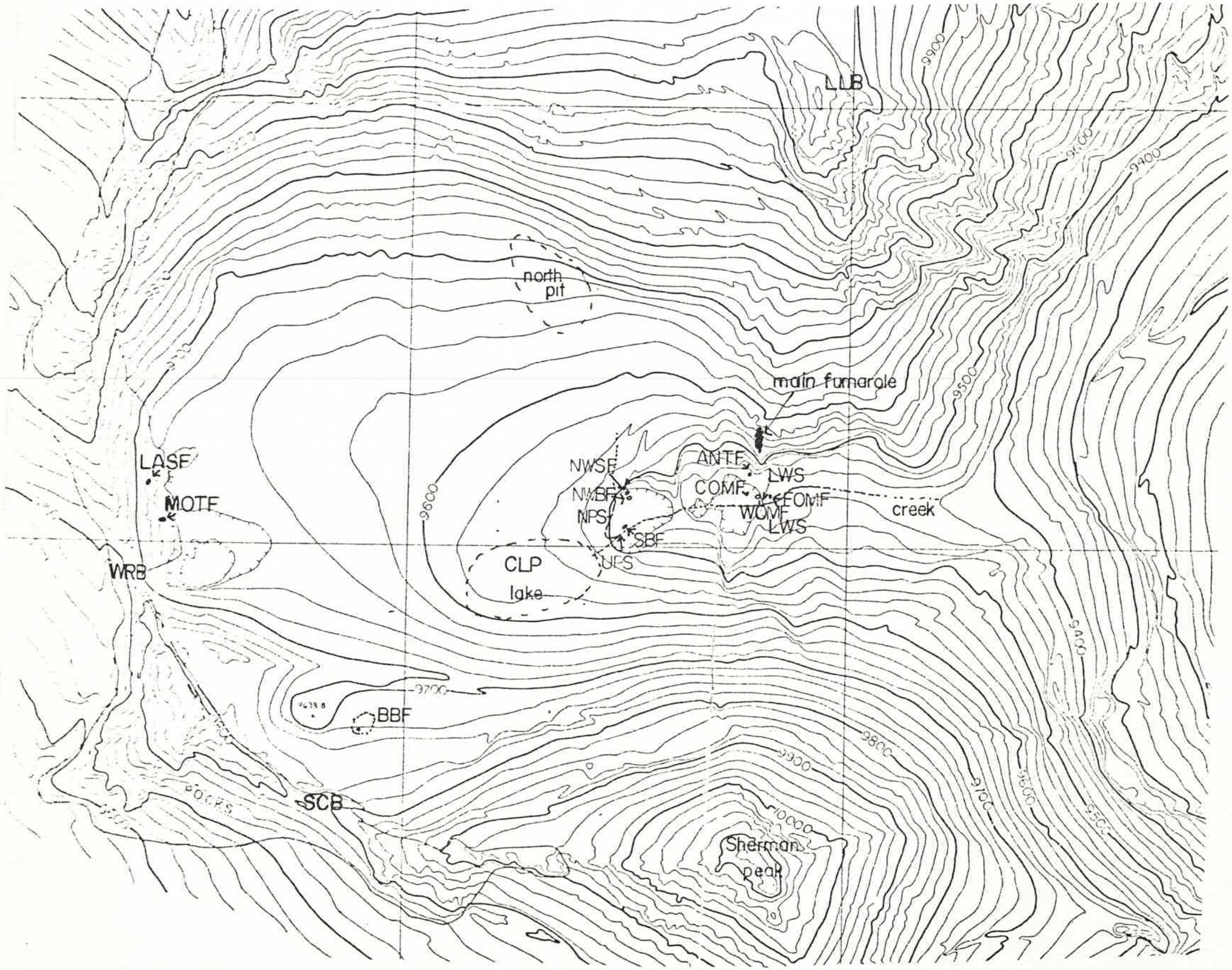


FIGURE 8. Detailed map of Sherman Crater showing approximate locations of significant features and sampling sites. Letter codes are keyed to Table II.

APPENDIX

Acknowledgements

It must be acknowledged at the outset that our work on Mount Baker has been dependent on a number of individuals and institutions cooperating to pool their experiences, data, expertise and just plain, manual labor. Working on a high mountain in the Cascade Range requires a degree of team work not usually necessary in field projects. The excellent cooperation of many individuals; too many to list here, has made our field work to date remarkably successful. In particular we acknowledge the efforts and assistance of David Frank who has been on almost every trip to the Sherman Crater and has spent countless hours assisting with our efforts. The following lsit includes the names and addresses of many of the individuals with whom we have had fairly close contact.

Categories of research on Mount Baker exclusive of the Geophysics Program of the University of Washington. Letters refer to the names On next page.

Aerial Photography	A E G I
Hazard Analysis and Mapping	A D H M
Stream flow and water quality	J M P
Airborne thermal infrared imagery	E G J
On-site gas analysis and samples	C E F
Tilt stations and tilt meters	B K
Time lapse photography	A E
Debris analysis	C E N O
Ice caves study	F
Airborne cloud physics and air quality studies	L

Names and addresses of individuals participating in some aspect of the Mount Baker research. This list is not necessarily complete.

A. Dr. Mark F. Meier
U. S. Geological Survey
1305 Tacoma Avenue S.
Tacoma, WA 98402

B. Dr. Don Swanson
U. S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025

C. Dr. Motoaki Sato
Mail Stop 959
National Center
U. S. Geological Survey
Reston, VA 22092

D. Dr. Dwight Crandell
U. S. Geological Survey
Federal Center
Denver, CO 80225

E. Dr. John Eichelberger
Mail Stop 978
Los Alamos Scientific Lab
P. O. Box 1663
Los Alamos, NM 87544

F. Dr. Gene Kiver
Department of Geology
Eastern Washington State College
Cheney, WA 99004

G. Dr. Charles Rosenfeld
Department of Geography
Oregon State University
Corvallis, OR

H. Dr. Jack Hyde
Department of Geology
Tacoma Community College
5900 South 12th Street
Tacoma, WA 98465

I. Dr. Don Easterbrook
Department of Geology
Western Washington State College
Bellingham, WA 98225

J. Don Campbell
Forest Supervisor, Baker-Snoqualmie National Forest
1601 Second Avenue
Seattle, WA 98101

K. Dr. Bruce Nolf
Science and Mathematics
Central Oregon Community College
College Way
Bend, OR 97701

L. Lawrence Radke
Atmospheric Sciences AK-40
University of Washington
Seattle, WA 98195

M. Duane Wegener
State Department of Ecology
4350 150th N.E.
Redmond, WA 98052

N. Dr. Fiorenzo Ugolini
Forest Resources AR-10
University of Washington
Seattle, WA 98195

O. Dr. Ray Wilcox
U. S. Geological Survey
Federal Center
Denver, CO 80225

P. Jack McCall
U. S. Geological Survey
1305 Tacoma Avenue S.
Tacoma, WA 98402

In Press
Geophysical Research Letters
March, 1976 V3 #3

MT. SAINT HELENS SEISMIC EVENTS:

VOLCANIC EARTHQUAKES OR GLACIAL NOISES?

by

Craig S. Weaver* and Stephen D. Malone
Geophysics Program, University of Washington
Seattle, Washington 98195

Abstract

Low frequency seismic events have been recorded on Mt. Saint Helens, an historically active stratovolcano in the Cascade Range of Washington State. While the character of the events is similar to volcanic seismic events recorded on active volcanoes in many parts of the world, the seismic evidence gathered during an experiment on Saint Helens indicates the glaciers on the mountain as the source of the low frequency activity. The experimental results illustrate the current problem of predicting volcanic behavior from seismic data in such geophysically complex areas as glacier clad volcanoes.

Introduction

For a number of years Japanese seismologists have been studying the occurrence of a variety of earthquakes recorded near active volcanoes in Japan. Prevalent on a large number of records are events which are characterized by emersio arrivals and predominant frequency content less than five hertz. These low frequency events, termed type B by Minakami,

---

* Now at N.C.E.R., U.S. Geological Survey, Menlo Park, California

apparently are associated with the eruptive process, since large increases in type B activity have been noted on several occasions prior to actual eruptions (Minakami *et al.*, 1969). While monitoring of the volcanic type B events has become a recognized technique for anticipating volcanic eruptions, the actual source of the type B events has remained unexplained. In recent years, the volcanic type B events have been recorded on a wide range of volcanoes around the world, including volcanoes in Alaska, Central America, and Indonesia (Matumoto and Ward, 1967; Shimozuru *et al.*, 1969; Shimozuru, 1971).

In the past ten years a number of seismicity studies have been made on or near some of the quiescent volcanoes of the Cascade Range in Washington State (Unger and Decker, 1970; Blank *et al.*, 1971; Unger and Coakley, 1971; Unger and Mills, 1973). Some of the investigations have noted the occurrence of low frequency events which seem to be similar in every respect to the volcanic type B earthquakes described by Japanese seismologists (Unger and Dicker, 1970). Monitoring the level of activity of these events as an eruption warning technique was obviously suggested by these studies.

In 1972 the U.S. Geological Survey installed a single seismic station on each of the Cascade volcanoes, Mt. Baker, Mt. Rainier, and Mt. Saint Helens, along with numerous volcanoes in other parts of the world (Endo *et al.*, 1973). At the same time, the University of Washington Geophysics Program began a study of Mt. Rainier and Mt. Saint Helens using an eight station portable seismic array. Mt. Rainier, a 4,389 meter stratovolcano in west central Washington, has numerous large glaciers, making operation high on the mountain logistically very difficult. Our brief operation around the flanks of the mountain, as well as the single U.S. Geological Survey station, confirmed the existence of the low frequency events but did not help to determine their causesor sources.

During the summers of 1973 and 1974 the University of Washington conducted seismic field programs on Mt. Saint Helens, about 100 kilometers south of Mt. Rainier. Mt. Saint Helens was chosen as the site for a detailed study since it is physically much smaller (2,950 meters) and had fewer and smaller glaciers but still had low frequency event activity levels similar to those on Mt. Rainier, as well as tectonic earthquakes. The choice of Saint Helens afforded better seismic coverage of the mountain with the available eight portable seismic stations and greatly reduced logistics problems. As a result of the work on Saint Helens, we are able to conclude that many, if not all, of the low frequency events recorded on Mt. Saint Helens are the result of surface glacial actions, rather than internal volcanic processes. In this report we will summarize the evidence used to draw this conclusion.

Analysis

Shown in Figure 1 is a map of the seismic arrays deployed during 1973 and 1974. The 1973 station sites were selected to provide examination of the overall seismicity patterns of the volcano, while those used in 1974 were picked explicitly to study the Nelson Glacier-Forsyth Glacier system. The permanent station, labelled SHW, was installed by the U.S. Geological Survey and is now a part of the western Washington regional network. All portable array stations were short period vertical instruments, with a nominal gain of a few million. In 1974 a pair of stations were operated near one another, one on loose volcanics over a crumbling dacite plug (DOG) and the other about 100 meters out on the glacier ice (CRV) to compare the signature of the events recorded on rock and ice. Data were telemetered to a field recording site 10 kilometers north of the mountain at Spirit Lake and were recorded on 14-track magnetic tape, with one channel being monitored on a helicorder. Selected events were played out on an eight-channel strip chart recorder or digitized for computer use. The time resolution for the array stations is about 0.01 seconds for well recorded events with a favorable signal to noise ratio.

Locations for the better recorded events, both tectonic and low frequency, were determined using a computer program which minimizes the differences between the calculated and observed arrival times in a least squares sense. Calculated times are determined using a velocity model described below and shown in Figure 2, which was tipped 28.5 degrees from the horizontal to approximate the slope of the north side of the mountain. All station positions fell within 50 meters of the surface of this model for the 1974 stations, and each arrival time was corrected for this difference.

In 1974, in addition to the six telemetered array stations a second small, high frequency array of 12 seismometers was deployed on the glacier ice in the vicinity of the stations CRV and DOG. The timing resolution of this array was on the order of 0.002 seconds, and this array was used for both exploration work with explosives and continuous recording for natural events. During the continuous recording, several low frequency events occurred within the 200 meter square area covered by the high frequency array, thus affording control on these event locations to within some tens of meters. This contrasts with the depth resolution of the telemetry array, which was limited to a few hundred meters by the station spacing and the velocity uncertainties.

Results

Results from the exploration shooting are summarized in Figure 2, which gives both the observed travel time curve and a graphical illustration of our interpretation. All closed circles are first arrivals; the two stars on the 1.5 km/sec branch are special cases and will be discussed below. The highest velocity observed occurs in the ice layer, where the P-wave velocity was found to be 3.18 km/sec. The solid curve labelled with P-wave velocity of 1.5 km/sec and the dashed curve labelled with 0.8 km/sec indicate structurally dependent propagation paths with different upper layer velocities. The 0.8 km/sec velocity is poorly determined because of a lack of data points. Local to DOG, an even lower velocity material, occurs with V_p being on the order of 0.6 km/sec. The makeup of the upper Dogshead is crumbling dacite and loose volcanic ejecta, and the low velocity seems in accordance with these materials (Minakami et al., 1970). The upper branch of the curve, with the determined P-wave velocity of 2.8 km/sec, likely represents the average velocity of the andesite-basalt composition of the mountain's outer core and is similar to the velocity found by other investigators on other composite volcanoes (Unger and Decker, 1970; Minakami et al., 1970). This higher velocity is observed over much of the cone. At an approximate depth of 700 meters an ill-defined higher velocity layer is observed. This is probably due to the presence of the ancestral Mt. Saint Helens (Verhoogan, 1937; Crandell and Mullineaux, 1960).

The two starred arrivals represent all rock paths between shots at the rock-ice interface and the recording station at NEL. The starred arrivals are sharp and impulsive and large. Preceding these arrivals, however, are small emergent arrivals that correspond to an ice-rock path. The initial wave in the ice is prevented from propagating to the station by large crevasses extending to the bottom of the glacier, the result being either refraction and scattering or simply scattering of seismic energy from the ice through the rock to the station. For a number of shots and events this precursor precedes the main arrival by fractions of a second and illustrates just one of the many sources of complexity on the seismograms.

A low velocity zone is created by the ice overlying a lower velocity, lower density, volcanic rubble and ejecta layer. This results in a low velocity shadowing phenomena for low frequency events recorded at CRV on the ice. Numerous comparisons among signals recorded at CRV and at DOG and NEL show this shadowing for low frequency events generated outside of the immediate, contiguous glacier area. Impulsive arrivals are seen at CRV for events located within the immediate glacier area. These same events have typical low frequency characteristics at stations several hundred meters away.

More important to the actual shape of the coda of the low frequency events is the highly dispersive structure, which is a result of the large velocity contrasts. Examination of the seismograms confirms the dispersive character of the medium. Figure 3 presents a comparison of a recorded low frequency event, an explosion, and a local tectonic microearthquake. The shot was five pounds of dynamite equivalent placed within the Forsyth

Glacier. Direct examination of the shot and the low frequency event reveals a number of similarities. First, as suggested by the velocity model, both events are rapidly dispersed, since in both cases all stations are within one kilometer of the epicenters. Second, the moveout observed with distance is almost the same. And third, as the signals propagate to outlying stations, the initial arrival loses its impulsiveness and becomes progressively more emersive. In both cases, relative enhancement of the signals occurs at DOG; this can be attributed to the exceedingly low local velocity mentioned earlier.

Visually distinct from the low frequency events are the much less frequently recorded tectonic events, which show the usual tectonic microearthquake characteristics of impulsive S and P phases. The tectonic event at the bottom of Figure 3 was recorded on the 1973 array, which was about three diameters larger than that used in 1974. Comparing arrivals at DOG, BLZ, and SUM for the shots and low frequency events with arrivals at BOO, LIZ, and SUM for tectonic events shows a much higher apparent velocity for the tectonic event, indicating a deeper source. While the tectonic event located at a hypocentral distance of between five and six kilometers from all array stations, the dispersive effect is not as great as it was for the nearer explosion and low frequency event. This difference in character of tectonic events and low frequency events at outlying stations makes counting low frequency event occurrence quite reliable, since the events are easily distinguished from the much less frequent tectonic events on helicorder records written at some distance from the glaciers.

Figure 1, in addition to the station distribution, presents a summary of well-recorded event locations. The major point shown is that low frequency events occur only on the glacier clad side of the mountain and have very shallow depths. No low frequency events were observed with arrivals which would allow locations on the south side of the mountain. The locations of the tectonic events tend to be southwest of the summit at depths exceeding one kilometer. The locations were determined using the layered velocity structure described earlier, and the accuracy of the locations was assessed by locating several of the explosions not used in the model construction. Generally the solutions are accurate to within a hundred meters in the plane of the mountain slope and within two hundred meters in the depth.

Better depth control for several isolated events was obtained with the high frequency array, since all the stations were on glacier ice. A constant velocity half space, with the appropriate P-wave velocity of 3.18 km/sec, was used for these locations. The resulting solution for the depth of two low frequency events is 45 meters $\pm$ 20 meters, which is approximately the ice thickness in the high frequency array area.

The above locations are for only a few selected, well-recorded events; however, we feel they are representative of most of the low frequency events. From an examination of helicorder records, the maximum amount of activity occurred between the BOO and LIZ stations. Lower frequency emersive arrivals were always recorded at MUD, TIM, and SHW in agreement with the dispersive picture outlined above. Generally, the impulsive nature of the first arrivals was only evident at most at one station for each event and never observed at TIM, SHW, or MUD. The low frequency event locations can be summarized as extremely shallow and confined to the glacier areas of Mt. Saint Helens.

Summary

The evidence for many of the low frequency events being the result of discrete glacier movement is compelling. The character of the events is due to their shallow sources in a highly stratified velocity structure, i.e., path effect rather than source effect. We have found no events which do not fit this hypothesis, though out of the thousands recorded only a few hundred have been looked at in detail. There may be some events which have volcanic-related sources, though we have found none in the sample we used for detailed analysis. This reflects directly on the problem of using the level of low frequency activity as a warning indicator for volcanic eruptions on volcanoes with active glaciers. We must find a simple discrimination technique between glacier noises and volcanic earthquakes if a volcano warning system using seismic techniques is to be effective on the northern Cascade volcanoes.

Acknowledgement

This work was supported by NSF Grant GA-41395.

References

Blank, H. R., M. M. Brown, T. Matumoto, and J. K. Westhusing, Seismicity investigations in the Cascade Mountains and vicinity, Oregon, NASA Tech. Rept., NASA/MSC Contract NAS 9-9690, 1971.

Crandell, D. R. and D. R. Mullineaux, Late recent age of Mt. Saint Helens volcano, Washington, U.S. Geol. Survey Prof. Paper 400-B, 307-308, 1960.

Endo, E. T., P. L. Ward, D. Marguez, R. V. Allen, and D. Harlow, A prototype global volcano surveillance system monitoring seismic activity and tilt: Part 1 Implementation (abstr.), EOS, 54, 1143, 1973.

Matumoto, T. and P. Ward, Microearthquake study of Mt. Katmai and vicinity, Alaska, J. Geophys. Res., 72, 2557-2568, 1967.

Minakami, T., S. Hiraga, T. Miyazaki, and S. U ibori, Fundamental research for predicting volcanic eruptions, II, Bull. Earthquake Res. Inst. Tokyo Univ., 47, 893-949, 1969.

Minakami, T., S. Utibori, S. Hiraga, T. Miyazaki, N. Gyoda, and T. Utsunomiya, Seismometrical studies of volcano Asama, I, Bull. Earthquake Res. Inst. Tokyo Univ., 48, 235-301, 1970.

Shimozuru, D., A seismological approach to the prediction of volcanic eruptions, in The Surveillance and Prediction of Volcanic Activity, UNESCO, no. 8, Paris, 1971.

Shimozuru, D., T. Minakami, and N. Gyoda, Volcanological survey of Indonesian volcanoes, Part II, Bull. Earthquake Res. Inst. Tokyo Univ., 47, 969-990, 1969.

Unger, J. D. and J. M. Coakley, Microearthquakes near Lassen Peak, California, U.S. Geol. Survey Prof. Paper 750-C, 156-157, 1971.

Unger, J. D. and R. W. Decker, The microearthquake activity of Mt. Rainier, Washington, Bull. Seis. Soc. Amer., 60, 2023-2035, 1970.

Figure Captions

Figure 1. Map of upper slopes of Mt. Saint Helens with 500 meter contours. The active glaciers are stippled. Seismic stations used for the 1973 array are shown as open triangles and as closed triangles for 1974. Station SUM was used both years. The closed circles are locations of low frequency events (depths less than 200 m). The stars are locations of tectonic earthquakes (depths between 1 and 3 km). Both were located using the 1973 array.

Figure 2. Travel time plot of arrivals from explosions. Solid circles are first arrivals. The stars are second arrivals for all rock paths under the Nelson Glacier. Our interpretation of the travel time curves are on the right, tipped at an angle corresponding to the slope of the mountain in the Dogshead area.

Figure 3. Seismograms of three types of events recorded on Mt. Saint Helens. The tectonic earthquake was recorded on an array larger than that used to record the low frequency event and the explosion.

TU

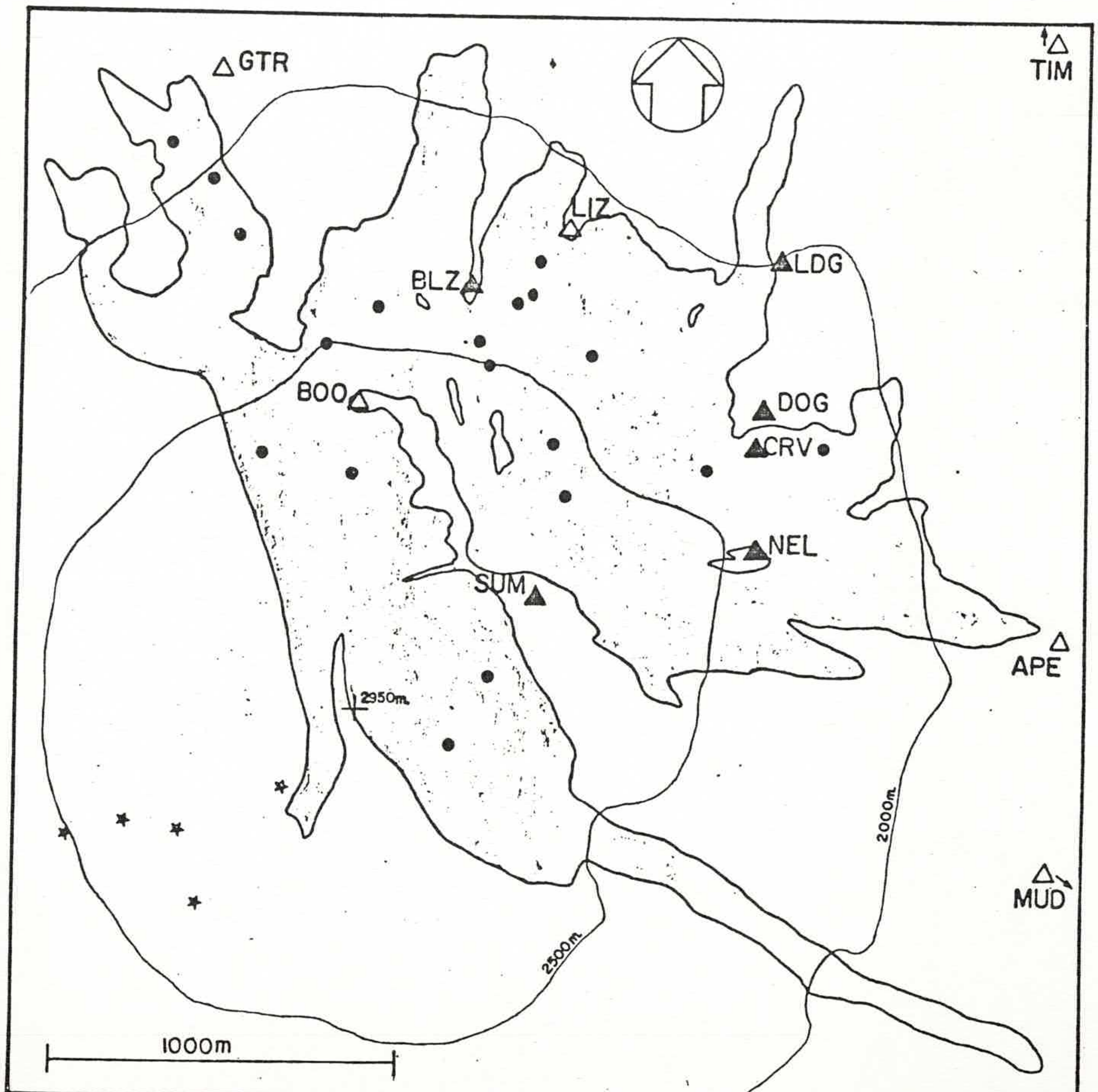
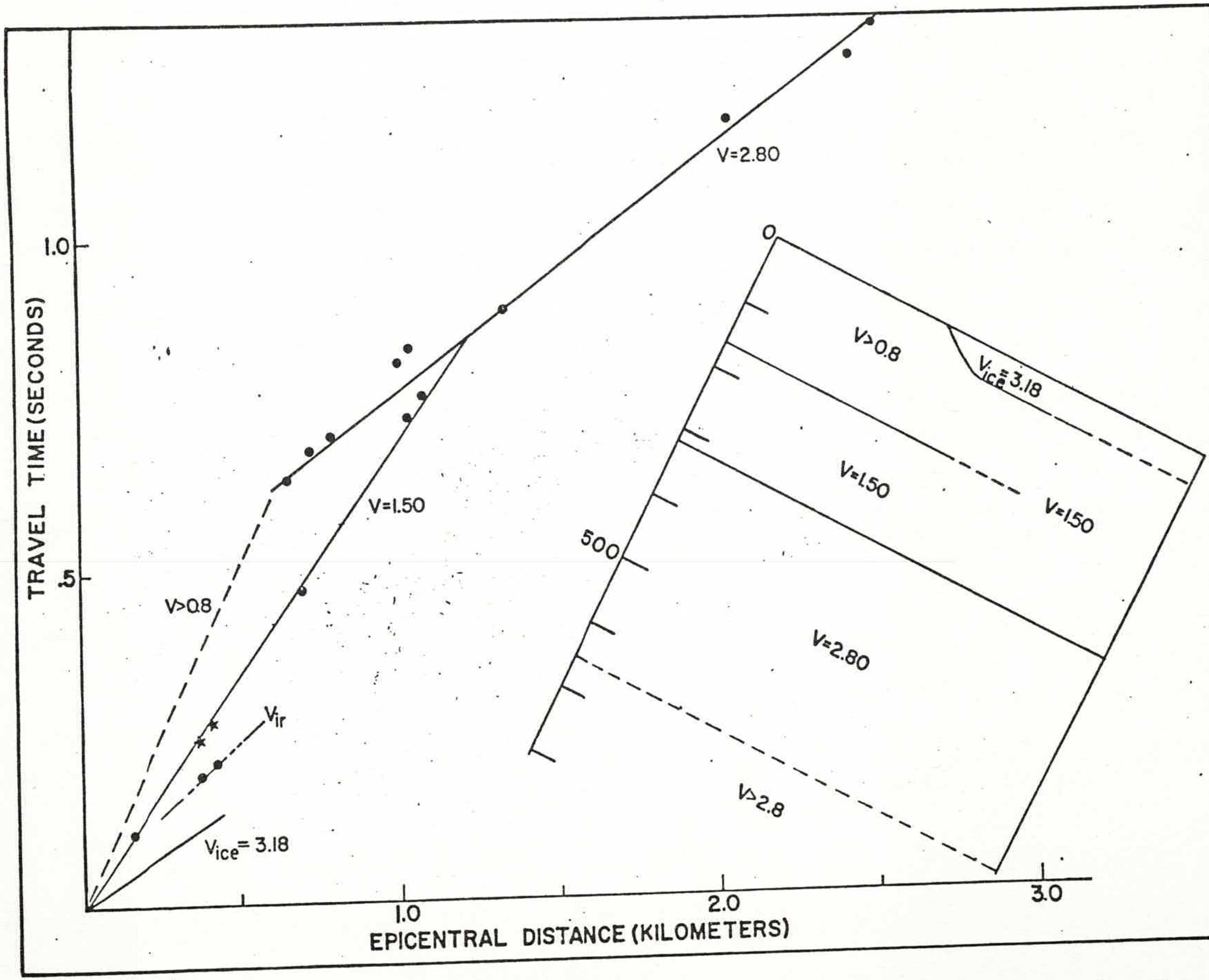

TIM
GTR
LIZ
BLZ
LDG
BOO
DOG
CRV
NEL
SUM
APE
MUD
2950m.
2000m.
2500m.
1000m

Fig 1



TRAVEL TIME (SECONDS)
1.0
.5
EPICENTRAL DISTANCE (KILOMETERS)
1.0
2.0
3.0
V=2.80
V=1.50
V>0.8
V_ir
V_ice= 3.18
0
500
V>0.8
V_ice= 3.18
V=1.50
V=1.50
V=2.80
V>2.8

figure 2

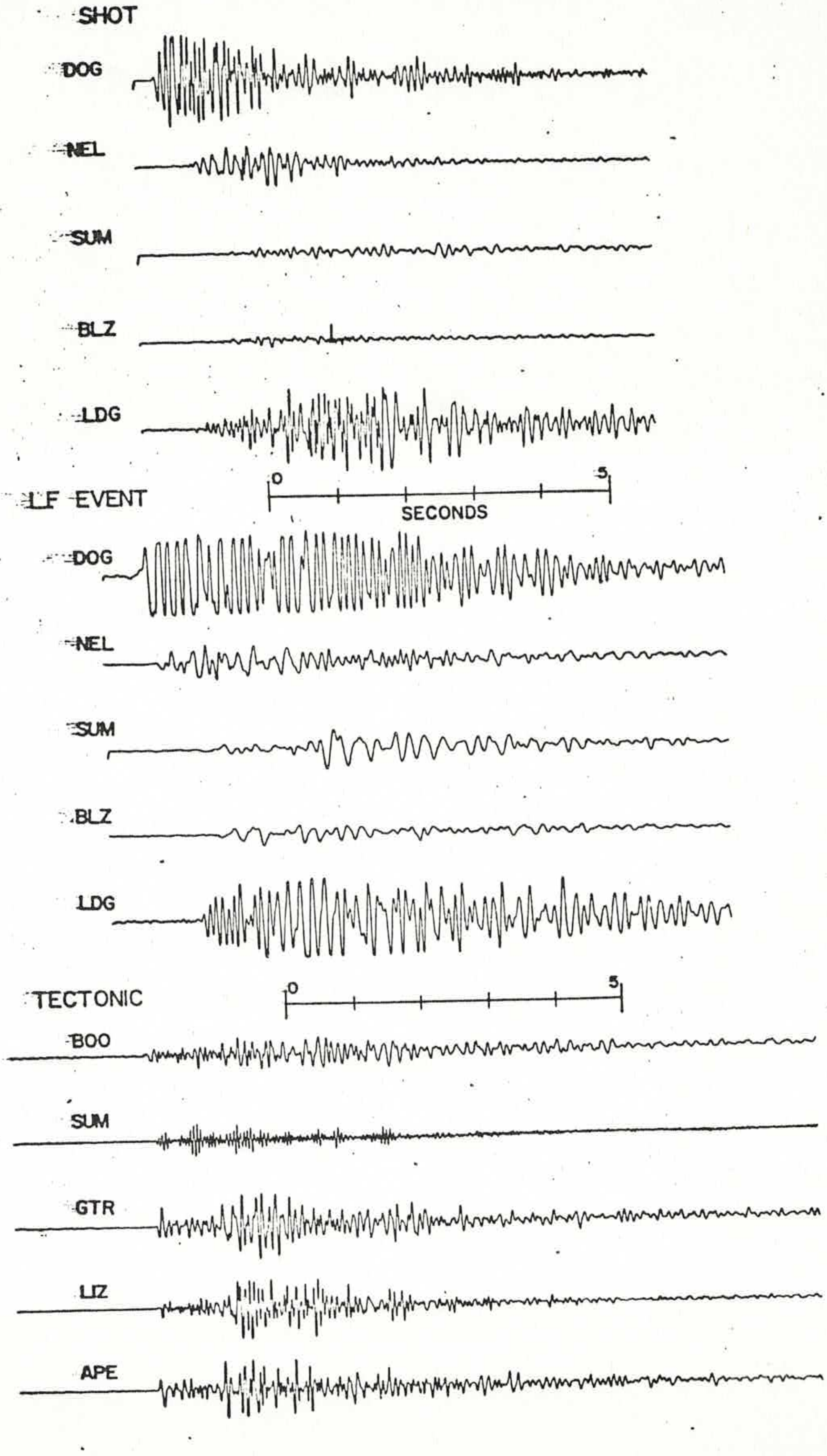

SHOT
DOG
NEL
SUM
BLZ
LDG
LF EVENT
0
5
SECONDS
DOG
NEL
SUM
BLZ
LDG
TECTONIC
0
5
BOO
SUM
GTR
LIZ
APE

figure 3

Increased Heat Emission From Mount Baker, Washington

Stephen D. Malone and David Frank

In late afternoon on March 10, 1975, Roy Ashe, operator of the Upper Baker Dam at the Baker Lake hydroelectric reservoir, reported than an unusually large dark gray plume of vapor was rising above the rim of the Sherman Crater near the top of Mount Baker, 21 km upstream. A flurry of aerial observations the following day noted distinct changes from previously known fumarolic activity in the icecovered crater. New fumaroles, ice pits, semicircular crevasses, and ponded water in the crater had appeared, as well as a thin dusting of gray debris 100 to 300 m outside the crater. The apparently sudden change in the thermal regime of Mount Baker was obvious as well as ominous.

Geologic History

Mount Baker (48°46'N, 121°49'W) in northwestern Washington is a moderately eroded stratovolcano, which rises 2 km above older metasedimentary and volcanic rock (Figure 1). In an initial study of the geology, *Coombs* [1939] found the lavas to be largely pyroxene andesite with the earliest eruptions of probable Pleistocene age. Volcanic rocks erupted near the same volcanic center, but thought to be older than Mount Baker proper, were reported by *Easterbrook and Rahm* [1970, p. 20] to have K/Ar dates of 400,000 ± 100,000 B.P. *Hyde and Crandell* [1975] studied postglacial deposits from the past 10,000 years and examined the potential volcanic hazards. They found evidence for at least four eruptions of tephra, two of lava, and one episode of pyroclastic flows, in addition to many mudflows, some of which may have accompanied eruptions. A radiocarbon date of 390 ± 200 years reported by *Hyde and Crandell* [1975, p. 7] limits the most recent tephra deposit on the east side of the volcano to within the past few hundred years.

Historical reports suggest that the last eruptive period was probably in the mid-1800's. *George Gibbs* [1874, pp. 357–358], a geologist with the International Boundary Commission, reported Indian stories of an eruption that resulted in a massive fish kill in Baker River, volcanic ash, and a large forest fire east of the volcano in 1843. In 1858, *Gibbs* [1874, p. 334] received reports from local miners of lava and an apparent lahar on the plain now submerged by Baker Lake.

> At the foot of the mountain was a level plain two or three miles wide, of black volcanic rock and sand, upon which were vast piles of half-burned timber, apparently swept down by a current of, as they supposed, lava, but more probably water.
>
> A stream of lava was visible on the side of the mountain, and also on the plain, and sulphur was found scattered over its surface. They saw smoke ascending on the eastern side, about two-thirds the distance above the snow line.

Many other reports can be found of observations from the distant Puget Sound and Georgia Strait lowland areas. *Hopson et al.* [1962], in considering historical activity at Mount Rainier, suggested that such reports should be examined cautiously because of the tendency for excited lowlanders to base supposed eruption observations on inconclusive evidence. Accordingly, some distant reports of activity at Mount Baker seem more reliable than others. In 1854 *George Davidson* [1885], a West Coast geographer and historian with the Coast Survey, saw from a distance masses of dense smoke rise 600 m above the mountain and after a few days of

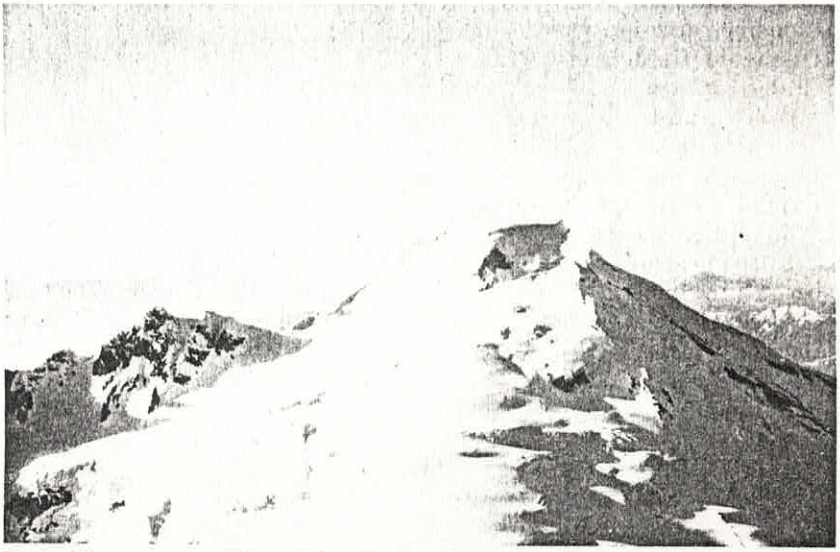


Fig. 1. The south slope of Mount Baker. Sherman Crater, to the south of the summit, is the location of the increased fumarolic activity first observed on March 10, 1975. The large vapor plume rises about 200 m above the summit from the east breach of the Sherman Crater rim. (Aerial photo by Austin Post, May 28, 1975.)

cloudy weather observed what he considered to be either 'ash and scoria' or bare ground on the upper 600 to 900 m of the cone. He reported that later in 1858 residents of Victoria, B.C., observed brightly illuminated eruption clouds over Mount Baker at night. John Tennent, territorial legislator from Whatcom County reported hearing from residents of Semiahmoo (now Blaine) that for a few days in 1859 'Two large and bright jets of flame were seen, having the appearance as if issuing from separate openings or fissures. . .' [*Pioneer Democrat*, 1859]. Thus the historic literature describes what may be tephra (in 1843, 1854, 1858), lava (in 1843), incandescence (in 1858), and fire fountains (in 1859). In addition to these dates, published reference has been found for 'eruptions' in 1846, 1856, 1870, 1872, 1964, and 1969, but these reports are quite vague and are unconfirmed. Thus we feel that eruptions may have occurred in the 1840's and 1850's but definitely have not occurred in the 20th century.

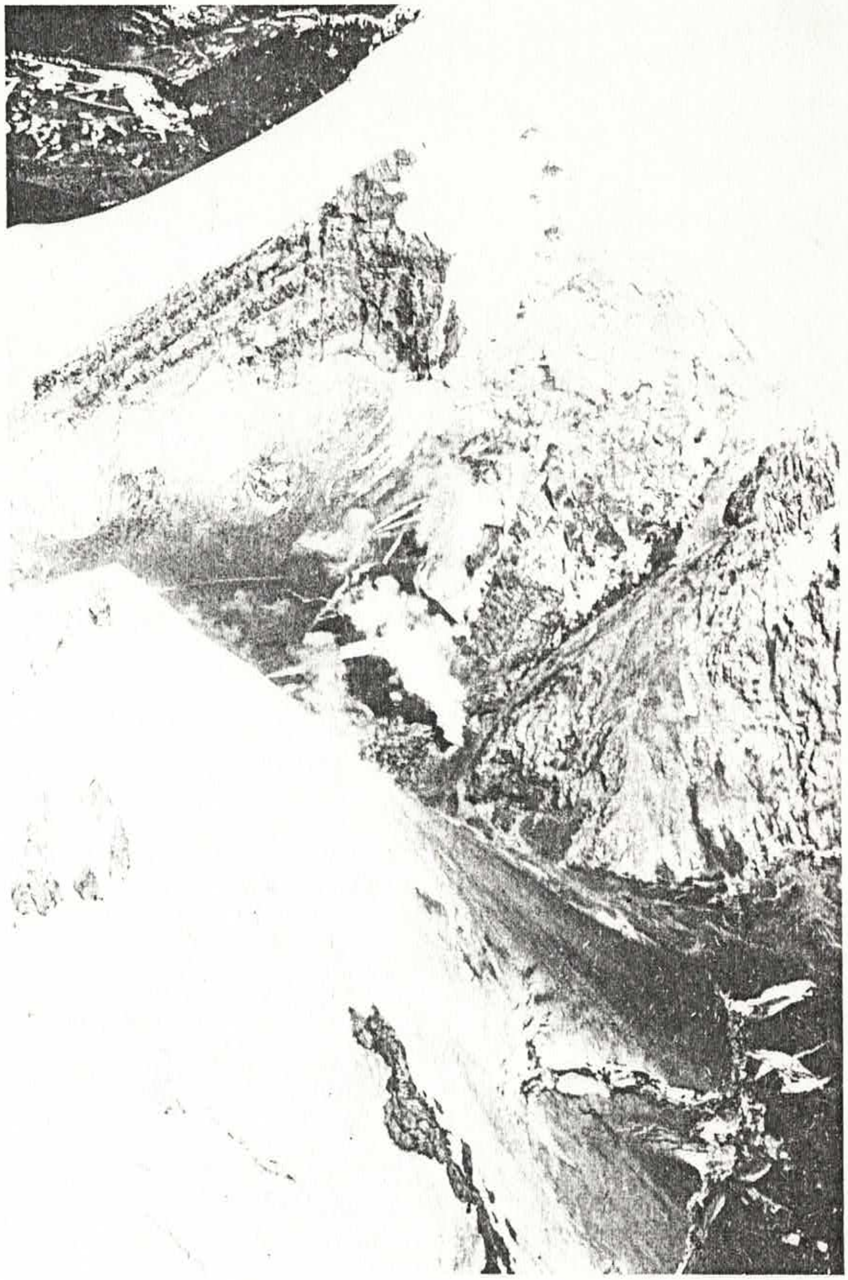


Fig. 2*a*. Sherman Crater. This view to the northeast shows typical summer snow conditions prior to the March increase in fumarolic activity. Ice pits are visible along the east and west margins of the crater and are melted out by clusters of small fumaroles. Ice at the top center of the picture is a small glacier which flows down from the summit and terminates at the east breach of the crater rim, to the right center. (Aerial photo by Jack Hyde, Tacoma Community College, August 1973.)

Fumarolic Activity Prior to 1975

From the mid-1800's to the present, fumarolic activity has been prevalent, as there has been repeated historical reference to variable amounts of vapor issuing from Mount Baker. During the past century, mountaineering journals and newspapers have contained numerous descriptions of two large fumarole fields: one, Sherman Crater, located just south of the summit, and the other, Dorr Fumarole Field, located midway up the north side of the cone and named after an early visitor William Henry Dorr.

Until good aerial photography became available for Mount Baker in 1940, few significant changes in thermal patterns were noted in historical descriptions. Thermal patterns evident in 1940 photographs are very similar to more recent patterns with the exception of an additional ice pit, which developed in the southwest quadrant of Sherman Crater sometime between 1940 and 1956 [*Frank et al.*, 1975, pp. 80, 82]. Annual aerial photography from 1958 to the present and aerial infrared thermography from 1970 to 1973 acquired by the U.S. Geological Survey show virtually no significant change in thermal patterns through 1974 (Figure 2*a*). Intermittent ground investigation from 1972 to 1974 showed that the fumaroles which produced snow-free ground and melted large ice pits typically formed in clusters and had openings from 1 cm to as much as 50 cm in diameter. Typical temperatures were 90°C in Sherman Crater (2900 to 3200 m altitude) and 91°C at the Dorr Field (2350 to 2440 m altitude), the boiling points of water for the respective altitudes. Additionally, *Frank et al.* [1975] reported:

1. Acidic snow melt from Sherman Crater was channeled into a single stream that flowed through the east breach of the crater rim,

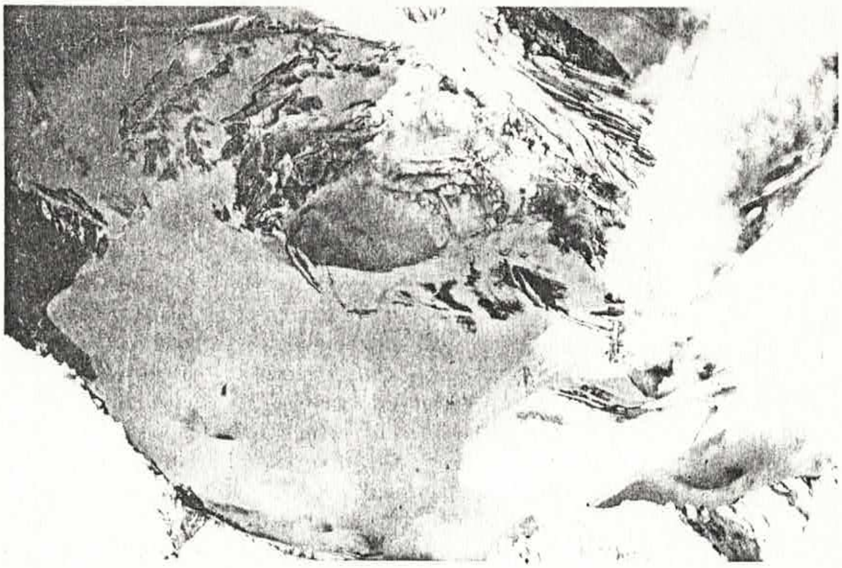


Fig. 2*b*. Sherman Crater. This view similar to Figure 2*a* and also to the northeast shows the development of the new north ice pit which has formed at the base of the icefall. The central ice pit to the lower right center is the location of a shallow lake. The third major location of new activity is in the east breach of the crater rim at the top right. In this photo a recent snowfall has covered much of the ash. A seismic station is located on the crater rim just off the lower right of the photo; the gas sensor is located in one of the fumaroles in the steamy area along the bottom of the photo. (Aerial photo by Austin Post, U.S. Geological Survey, May 28, 1975.)

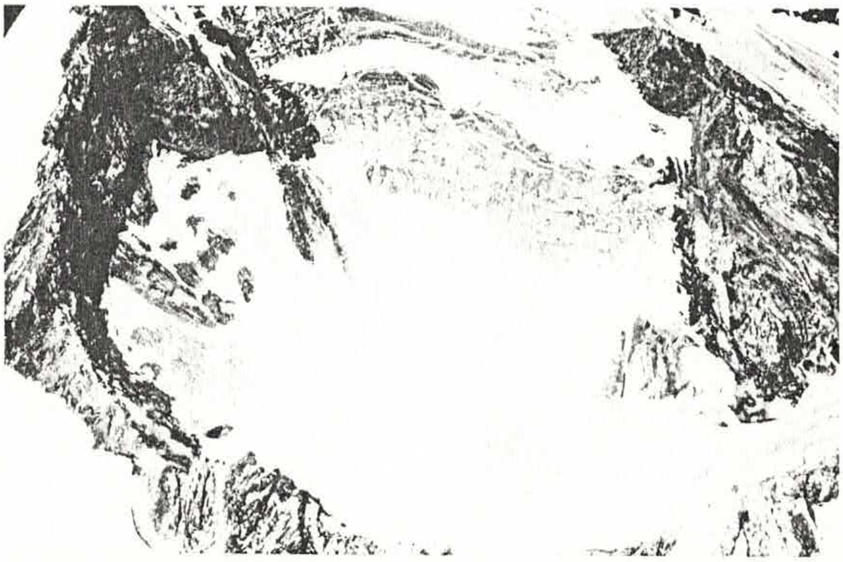


Fig. 3. New fumarolic activity in Sherman Crater. In this view to the northwest, Sherman Peak is in the left center, Lahar Lookout to the right center. A prominent plume about 100 m long issues from the new main fumarole at the base of Lahar Lookout. A comparison with Figure 1 illustrates the extreme variability in the main vapor plume. Other new ice pits and crevasses in addition to old ice pits are evident. Dark gray dust thinly coats the snow surface and provides a stark contrast to older, clean snow as particularly evident in crevasses. (Aerial photo taken July 3, 1975.)

subglacially into the Boulder Creek valley below.

2. The largest, most pressurized fumarole on Mount Baker was located in this stream bed between two prominent remnants of the crater rim, Sherman Peak to the south and Lahar Lookout to the north.

3. A surficial ice depression and observed ponding marginal to this depression suggested the presence, possibly intermittent, of a subglacial crater lake.

4. Fumarolic activity in the east breach of the crater rim was partly responsible for small recurrent debris avalanches which traveled from Sherman Peak down Boulder Glacier.

Thermal Changes in 1975 Through July

Since March 10 an interdisciplinary effort, both ground-based and airborne, by various university and federal scientists has documented specific changes that have taken place in Sherman Crater (Figure 2*a* and 2*b*). Examination of snow stratigraphy in Sherman Crater during the initial ground investigation on March 31 revealed that the first dust layer was probably deposited near the time of the first observation of unusual steam emission on March 10. Most of the dust emission has been from a large new fumarole located on the base of Lahar Lookout about 10 m upslope from the old main fumarole (Figure 3). This new fumarole, which was about 1 m in diameter in March, developed into a 1 × 5 m fissure by June. The dust, composed largely of fumarolic sublimates and products of hydrothermal alteration, plus a very minor amount of old lithic and glassy particles (R. Wilcox, 1975, oral communication), has apparently issued continuously from the main fumarole and at least at some times from some of the other fumaroles. Dust thickness was still ≤1 cm over most of the crater by July.

In April the central ice depression noted previously developed into a 40 m deep ice pit in which a 50 × 70 m shallow acidic lake quickly formed (Figure 4). This lake was measured at 34°C and *p*H 2.5 on July 11. By July a second shallow lake of smaller size developed in the east part of the crater. Drainage from both lakes as well as other snowmelt in the crater continued to flow through the east breach of the crater rim and into the lower Boulder Creek valley. The *p*H of Boulder Creek, 11 km from the breach, has been consistently below 4.5 since March 10 and as low as 3.4 at times. A sampling and analysis program for water and debris has been established by the U.S. Geological Survey and University of Washington personnel.

By far the most impressive change in Sherman Crater has been in ice breakup and melt (Figures 2*b* and 4). As the summer ablation season progressed, each new appearance of snow-free ground was accompanied by previously unobserved fumaroles. Whether the overall fumarolic area has gradually continued to increase since March 10 or has merely been partly hidden by snow cover is not entirely clear, but at least locally, particulary around the central lake and the main fumarole, new fumaroles have continued to develop over the past few months.

Geophysical Monitoring

Because the recent increased thermal activity might be a premonitory indication of an eruption, a number of geophysical monitoring efforts have been started. Many scientists from several institutions have begun investigations of various aspects of the new activity. A partial list of the investigations we are aware of is included in the appendix. Data from some experiments are continuously telemetered to the University of Washington for recording and interpretation, and other studies require on-the-site observations. A brief description of the individual experiments we are involved in follows.

Photography. One of the simplest yet most valuable data gathering techniques is still and motion photography. On every trip to the crater and at many other times from the air, numerous photo-

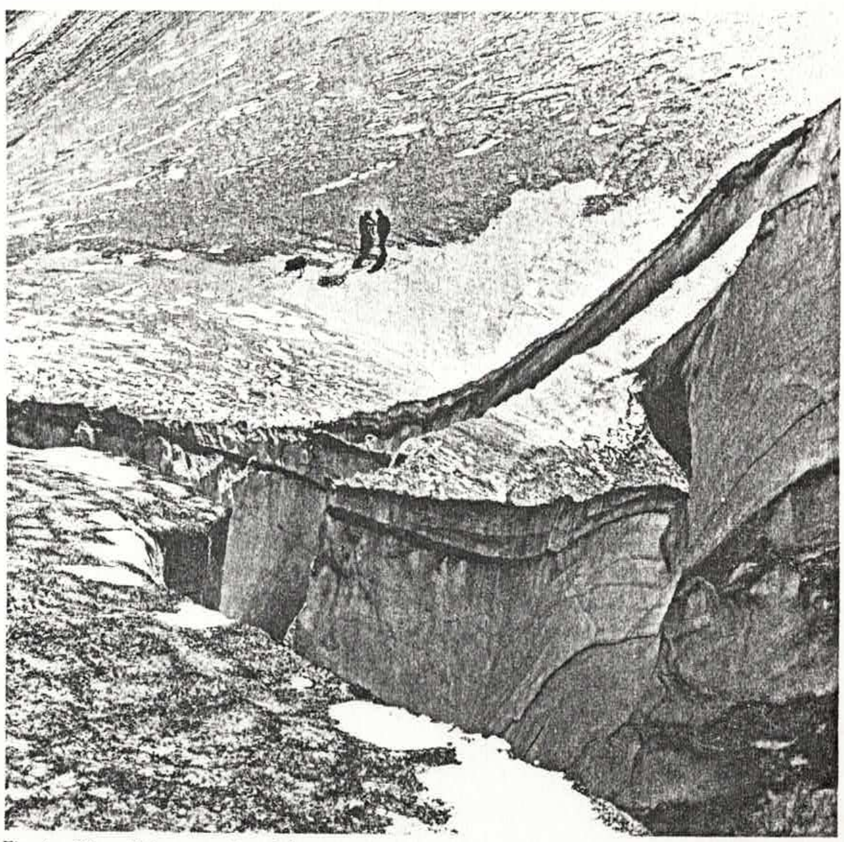


Fig. 4. View of the east edge of the central pit. Steve Malone and Al Rohay are preparing instruments to be lowered into the central pit lake 40 m below.

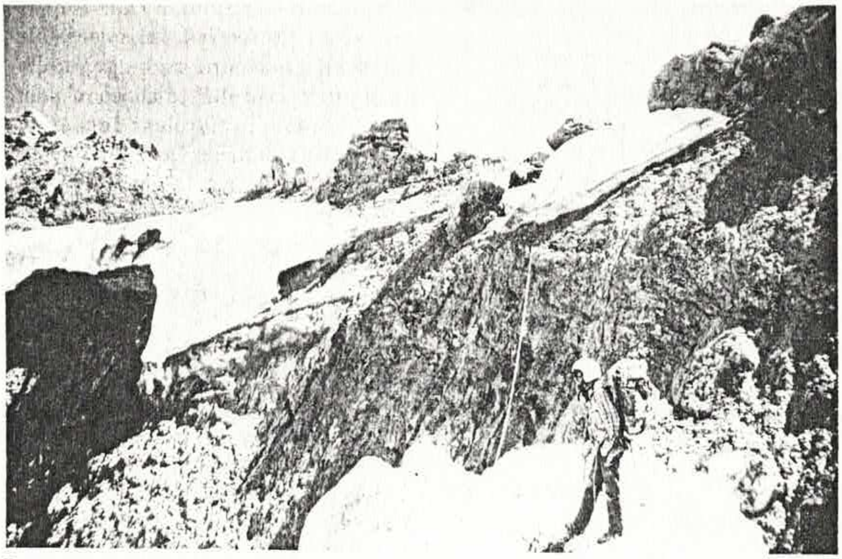


Fig. 5. View of a section of the inside of the south rim of Sherman Crater showing the antenna for the seismic station and the newly exposed rock where the crater ice has pulled away from its usual position. Don Swanson of the U.S. Geological Survey is examining ice features. (Photo July 10, 1975.)

graphs are taken from many different vantage points to document the changes that take place in the crater over periods of weeks to months. A few of these pictures are reproduced here.

Seismicity. Data from the Western Washington regional seismic net are capable of locating earthquakes in the Mount Baker area down to about magnitude $M_L = 2.5$. In addition to these seismic stations there are now two stations located on Mount Baker proper, which lower the detection threshold to less than $M_L = 0$. One station (MBW) is located about 6 km from the summit on the west side at 1830 m elevation and was installed in 1972 as part of the U.S. Geological Survey's volcano monitoring program. On March 31, 1975, a station (SCW) was established on the south rim of Sherman Crater, less than 500 m from the new main fumarole (Figure 5). These stations are on independent telemetry links, and their data are recorded on helicorders at the university's geophysics laboratory to facilitate rapid detection of changes in seismic activity.

Comparisons of the seismicity at the older station, MBW, before and after the beginning of the increased thermal activity in early March showed no initial change. No increase in seismic activity was detected, and in fact no earthquakes originating near Mount Baker have been detected since MBW was installed in 1972. This absence of activity is in contrast to Mount Rainier and Mount St. Helens, two other Cascade volcanoes, which both typically have several locatable and numerous detectable earthquakes in their vicinity each year.

The new crater station, SCW, writes records with very different characteristics than those from MBW. Again there have been no events that can definitely be identified as earthquakes. However, there have been transient events that could be mistaken for earthquakes if we did not already have experience identifying various types of seismic events on glacier-clad volcanoes. In previous studies, seismic stations were established high on both Mount Rainier and Mount St. Helens. These stations as well as the Sherman Crater station record transient events with a low-frequency character similar to that of volcanic 'type B' earthquakes as described by *Minakami* [1974] as well as many other authors. Extensive detailed studies on Mount St. Helens have led us to conclude that these low-frequency events are largely if not entirely due to the movement of glaciers [*Weaver*, 1975; *Weaver et al.*, 1974; *Weaver and Malone*, 1974]. Our work this spring on Mount Baker suggests glacier or ice movement as the source for the low-frequency events recorded both at SCW and to a lesser degree at MBW. The signatures of the low-frequency events and the waveform dispersions between the two stations have identical characters to ice events studied previously.

In addition to the transient events on SCW, there is an interesting character to the seismic background noise. The noise level during most of April was at a moderate level for a seismic station located at 3130 m on a mountain subject to storms and strong winds. On April 27 a dramatic increase in the background noise was observed that persisted at a very high level for several hours before moderating slightly. Since then periodic increases in the noise level have been observed. The source for these noise level changes is presumably a variation in the venting mechanism of the fumaroles. Weather or wind effects can be ruled out, for there is no correlation between observed weather in the Baker area and the seismic noise levels. Wind noise has a different character and much lower amplitude than fumarolic noise. Large changes in the pressure and volume of vapor coming from the fumaroles have been observed from time to time, but the observations are scattered and subjective enough to prohibit rigorous comparison with the seismic noise level changes.

Gravity. During the trip to the crater on May 12, two gravity stations were established, one on the south rim near the seismic station and the other on the west rim near the gas sensor. A Lacoste and Romberg G gravity meter is being used to reoccupy there stations periodically along with control stations at the base of the mountain and at the University of Washington. A set of gravity readings is repeatable to better than 0.05 mGal, and the instrument drift seems to be quite linear at less than 0.1 mGal per month. We expect to be able to reliably detect changes of the order of 0.2 mGal after correcting the data for earth tides. This corresponds to vertical displacement at the crater rim of about 1 m,

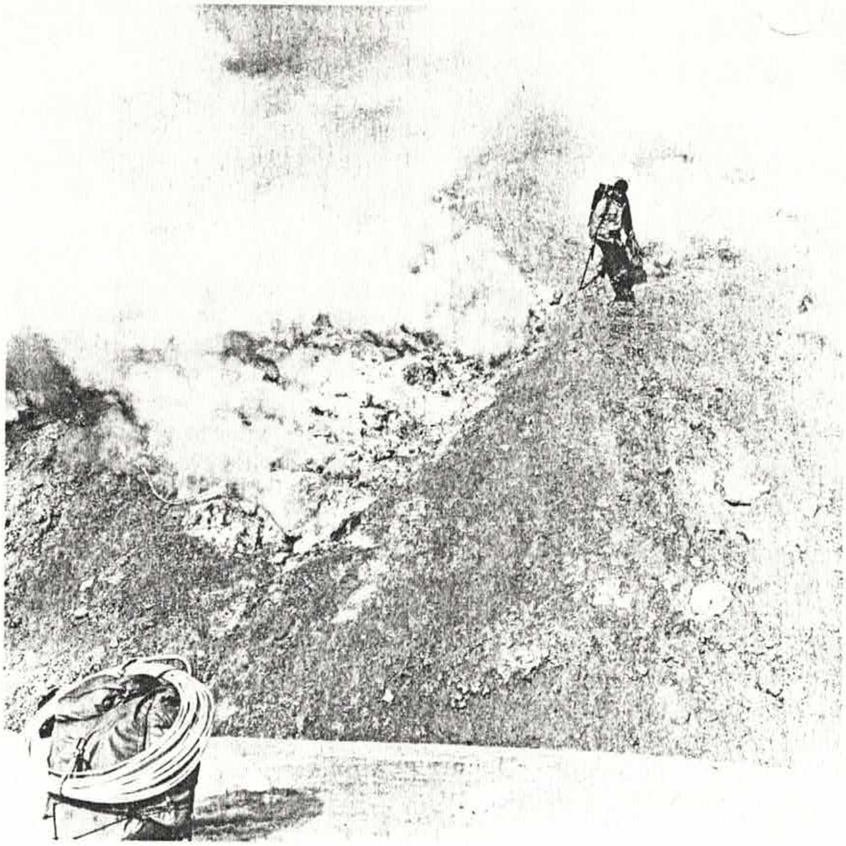


Fig. 6. View of a fumarolic cluster on the west rim. The white tubing running out of the vapors on the far left goes between the gas sensor located in one of the fumaroles and the electronics package located on the rim above. Descending the slope is Al Rohay of the University of Washington.

which would have an equivalent maximum tilt on the side of the mountain of more than 200 μrad if purely elastic deformation is assumed. This much tilt should be easily detectable with simple tilt meters. The gravity data thus far are not extensive enough to define any pattern or trend.

Gas and Temperature. We are providing technical advice and logistical support for Motoaki Sato of the U.S. Geological Survey, who has built and installed a continuous gas and temperature sensor in a fumarole on the west rim of Sherman Crater (Figure 6). This device monitors the reducing capacity of the fumarolic gas and produces a signal that is proportional to the concentration of H_2 and H_2S. The detector also contains a thermistor, which measures the gas temperature. The data from this sytem are multiplexed with the seismic data for transmission to the university recording facilities.

Additionally, an H_2S meter provided by the U.S. Geological Survey has been continually used in work areas on the crater rim and in camp to monitor concentrations of toxic gas. Since the H_2S levels in open air frequently go well over 10 ppm, we have often found it necessary to use respirators for protection. Self-contained breathing devices would be needed for prolonged work near the fumaroles.

A predawn thermal infrared survey was flown by the U.S. Forest Service in cooperation with the University of Washington on March 26 shortly after the initial observations of increased activity. The images showed an approximate increase in the area of warm ground of 50% in comparison with previous infrared surveys by the same aircraft flown in cooperation with the U.S. Geological Survey. Measurements of a small part of the crater fumarole field have been made with a ground-based infrared radiometer to aid in the calibration of the March airborne survey as well as future surveys. Also during the various trips to the crater, thermometer measurements have been made of fumaroles in accessible locations and found to be generally at 90–91°C, similar to those of past years. Some fumaroles, including the main fumarole, are still inaccessible and may be hotter than 91°C.

Future Monitoring Activities

The monitoring experiments mentioned above, as well as other observation programs, will continue for the foreseeable future. Expansion is planned of both the seismic and the temperature-probe arrays. A grant from the U.S. Geological Survey will provide support for five or six additional seismic stations to be located on and around the mountain, and telemetry will be available for additional temperature and water quality data. Some monitoring of unstable rock masses, which pose a potential avalanche hazard, is planned, and a modest glaciological survey to map ice movement in the crater is now under way.

Two important research programs by others are airborne thermal infrared surveys and tilt measurements. A number of institutions have made and are planning infrared overflights. High-quality images have already been obtained by groups at Los Alamos Scientific Laboratories and Oregon State University. Also, high-precision tilt stations are being installed by the U.S. Geological Survey at three sites on Mount Baker's flanks. Additional experiments under way are listed in the appendix with addresses for contacting the individuals involved.

The increased thermal activity on Mount Baker is dramatic and scientifically interesting. It is the largest known thermal increase at one of the Cascade volcanoes since the Lassen Peak eruptions from 1914 to 1917. Whether the Mount Baker activity will continue and lead to an eruption or will eventually die away, no one can yet say. Even if the activity were to cease today, the data gathered thus far provide an exciting glimpse into the dynamic processes of Cascade volcanoes.

Appendix

Categories of research on Mount Baker exclusive of the geophysics program of the University of Washington. The numbers in parentheses refer to the names listed below.

Aerial photography (1, 5, 7, 9)
Hazard analysis and mapping (1, 4, 8, 13)
Stream flow and water quality (10, 13, 16)
Airborne thermal infrared imagery (5, 7, 10)
On-site gas analysis and samples (3, 5, 6)
Tilt stations and tilt meters (2, 11)
Time lapse photography (1, 5)
Debris analysis (3, 5, 14, 15)
Ice caves study (6)
Airborne cloud physics and air quality studies (12)

Names and addresses of individuals participating in some aspect of the Mount Baker research. This list is not necessarily complete.

1. Dr. Mark F. Meier
U.S. Geological Survey
1305 Tacoma Avenue S.
Tacoma, WA 98402
2. Dr. Don Swanson
U.S. Geological Survey
345 Middlefield Road
Menlo Park, CA 94025
3. Dr. Motoaki Sato
Mail Stop 959
National Center
U.S. Geological Survey
Reston, VA 22092
4. Dr. Dwight Crandell
U.S. Geological Survey
Federal Center
Denver, CO 80225
5. Dr. John Eichelberger
Mail Stop 978
Los Alamos Scientific Lab
P. O. Box 1663
Los Alamos, NM 87544
6. Dr. Gene Kiver
Department of Geology
Eastern Washington
State College
Cheney, WA 99004
7. Dr. Charles Rosenfeld
Department of Geography
Oregon State University
Corvallis, OR 97331
8. Dr. Jack Hyde
Department of Geology
Tacoma Community College
5900 South 12th Street
Tacoma, WA 98465
9. Dr. Don Easterbrook
Department of Geology
Western Washington
State College
Bellingham, WA 98225
10. Don Campbell
Forest Supervisor,
Baker-Snoqualmie
National Forest
1601 Second Avenue
Seattle, WA 98101
11. Dr. Bruce Nolf
Science and Mathematics
Central Oregon Community College
College Way
Bend, OR 97701
12. Lawrence Radke
Atmospheric Sciences AK-40
University of Washington
Seattle, WA 98195
13. Duane Wegener
State Department of Ecology
4350 150th N.E.
Redmond, WA 98052
14. Dr. Fiorenzo Ugolini
Forest Resources AR-10
University of Washington
Seattle, WA 98195
15. Dr. Ray Wilcox
U. S. Geological Survey
Federal Center
Denver, CO 80225
16. Jack McCall
U.S. Geological Survey
1305 Tacoma Avenue S.
Tacoma, WA 98402

Acknowledgments

Our work on Mount Baker has been dependent on cooperation and help from many individuals and institutions. In particular, we express our appreciation to Mark Meier and his colleagues at the U.S. Geological Survey in Tacoma, Washington, for their sharing of photographs, maps, and other pertinent information. Also, Motoaki Sato and Don Swanson of the U.S. Geological Survey kindly provided helicopter support for some of our trips to the crater. Financial support was provided by National Science Foundation grant DES-73-00458 (formerly GA-41395) for the study of seismic activity of the Cascade volcanoes.

References

Coombs, H.A., Mt. Baker, a Cascade volcano, *Geol. Soc. Amer. Bull., 50,* 1493–1510, 1939.

Davidson, G., Recent volcanic activity in the United States: Eruption of Mount Baker, *Science, 6,* 362, 1885.

Easterbrook, D.J., and D.A. Rahm, *Landforms of Washington,* 156 pp., Western Washington State College, Bellingham, Wash., 1970.

Frank, D., A. Post, and J.D. Friedman, Recurrent geothermally induced debris avalanches on Boulder glacier, Mount Baker, Wash., *U.S. Geol. Surv. J. Res., 3,* 77–87, 1975.

Gibbs, G., Physical geography of the northwestern boundary of the United States, *J. Amer. Geogr. Soc. N.Y., 4,* 298–302, 1874.

Hopson, C.A., A.C. Waters, V.R. Bender, and M. Rubin, The latest eruptions from Mount Rainier volcano, *J. Geol., 70,* 635–647, 1962.

Hyde, J.H., and D.R. Crandell, Origin and age of postglacial deposits and assessment of potential hazards from future eruptions of Mount Baker, Washington, *Open File Rep. 75–286,* 22 pp., U.S. Geol. Surv., Washington, D.C., 1975.

Minakami, T., Seismology of volcanoes in Japan, in *Physical Volcanology,* edited by L. Civetta, P. Gasparini, G. Luongo, and A. Rapolla, pp. 1–28, Elsevier, New York, 1974.

Pioneer Democrat (newspaper, Olympia, Washington Territory), *8*(1), 2, Nov. 25, 1859.

Weaver, C.S., Seismic events on Cascade volcanoes, Ph.D. dissertation, 145 pp., Univ. of Wash., 1975.

Weaver, C.S., and S.D. Malone, Glacier sources for low-frequency seismic events recorded at Mount St. Helens volcano (abstract), *Eos Trans. AGU, 55,* 1151, 1974.

Weaver, C.S., S.D. Malone, and S.W. Smith, Anomalous seismic events on Cascade volcanoes (abstract), 70th Annual Meeting Program, Seismol. Soc. of Amer., 1974.

Stephen D. Malone is a Senior Research Associate in the geophysics program at the University of Washington. He received his B.A. in physics from Occidental College and Ph.D. in geophysics from the University of Nevada. He has conducted a number of detailed microearthquake studies at several Cascade volcanoes as well as in the Columbia River basin. He is presently the secretary-treasurer of the Pacific Northwest section of AGU and as such is organizing a special session at the October 1975 meeting on volcano monitoring.

David Frank studied geology at North Carolina State University and is continuing his graduate study at the University of Washington. He has been a geologist with the U.S. Geological Survey since 1972; during this time he has concentrated his work on the relationships between thermal activity and mass movement on quiescent volcanoes.