RECURRENT GEOTHERMALLY INDUCED DEBRIS AVALANCHES
ON BOULDER GLACIER, MOUNT BAKER, WASHINGTON

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Abstract.—Avalanches of snow, firm and hydrothermally altered rock and mud have been released six times since 1958 from Sherman Peak, part of the crater rim south of the main summit of Mount Baker, Wash. The avalanches traveled nearly identical paths 2.0-2.6 km down Boulder Glacier on the east slope of the volcano. Debris from at least one past avalanche can be seen as a thin bed of acidic mud in the glacier terminus. Fumaroles, thermal springs, and areas of warm ground, some of which are subglacial, are concentrated in the crater and were mapped by aerial infrared thermography. The outgoing radiant flux per unit area from a cluster of infrared anomalies within 50-150 m of the avalanche source was estimated to be 310 W m⁻² (7.620 kcal cm⁻²°⁻¹) in November 1972, which is sufficient to account for observed ice perforations. In addition vapor emission, not apparent in thermography, was observed along the source margin after the avalanche of August 1973. The principal conditions that produce the avalanches are considered to be the large accumulation of snow and firm on top of hydrothermally altered clay-rich ground at Sherman Peak and the saturation near the ground-firm interface by melt water produced both by summer snow ablation and by geothermal emission. The periodic avalanches have a potential for impounding water in the crater in addition to pended water already known to occur. Sudden release of impounded water could present a danger to the Boulder Creek valley below.

A large debris avalanche descended the Boulder Glacier from the crater rim of Mount Baker, Wash., between 0700 P.D.T., August 20, and 1000 P.D.T. August 21, 1973. Debris from past avalanches has been photographed on Boulder Glacier every few years during recent decades (fig. 1). Because both large avalanches on glaciers and noneruptive volcanic heat may initiate destructive lahars (Crandell, 1971), this preliminary study was undertaken to determine the nature, causes, and dangers of the Boulder Glacier avalanches.

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BACKGROUND

Mount Baker (48°47'N., 121°49'W.) is the northernmost of the Quaternary stratovolcanoes of the Cascade Range of northern California, Oregon, and Washington (fig. 2). Andesitic lava flows and breccias form a cone which rises 2 km above a basement complex of metasedimentary rocks (Coombs, 1939). The summit is 3,285 m above sea level and about 3,200 m above the Skagit River valley 26 km to the south. Owing to high precipitation and northern latitude the volcano is almost completely covered by glaciers which flow radially from the central summit. All the higher lava flows on the cone appear to have originated from an area now covered by a summit ice dome. In this area a crater rim is partly visible on aerial photographs taken during a time of particularly low snow accumulation—1940 (a in fig. 3). A second more prominent crater (b in fig. 3), referred to informally as Sherman crater, is centered 760 m south of and 350 m lower than the ice dome. Ice which descends from the mountain's summit to the north partly fills Sherman crater.

1Shown incorrectly as Summit Crater on some maps; the true summit crater is hidden under the central summit ice dome.
DEBRIS AVALANCHES

Since the last eruptive sequence, which occurred in the mid-1800's (Davidson, 1885, p. 262; Gibbs, 1874, p. 357-358; Pioneer Democrat [newspaper], 1859), there have been reports of several large mass movements of undetermined cause. Charles F. Easton 2 described mass movement phenomena in almost every valley heading at a Mount Baker glacier. These include a debris avalanche which traveled 11 km beyond the Rainbow Glacier terminus about 1860 and a number of either debris avalanches, debris flows, or jökulhlaups which swept 5 km below the Easton Glacier in 1911, 9 km from the Deming Glacier in 1927, and repeatedly to unspecified distances downvalley from the Mazama, Roosevelt, and Thunder Glaciers.

The first known description of an avalanche deposit similar to that which was formed in 1973 is by Easton; in 1906 he observed that the crater had been filled with rock and lava which had tumbled down from Sherman Peak” (Adams, 1919, p. 341). Later, two photographs were published which show an avalanche scar identical to that of 1973. (McNeil, 1930, 1931.)

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2 Pages 155, 215, and 316 of “Mt Baker, Its Trails and Legends,” an unpublished 262-page compilation of photographs, newspaper articles, and manuscript commissioned in 1911 by the Mount Baker Club and archived at the Whatcom County Museum of Natural History, Bellingham, Wash.
short of the glacier terminus. A graphic reconstruction of material missing from the wedge-shaped scar on Sherman Peak gave an estimate of 32,000 m³ of snow, ice, and rock involved in the avalanche, not including snow and ice added downslope.

The steep (≥30°) slope of Sherman Peak was stripped bare of snow and firm over an area of 7,400 m². An ice escarpment overlooking the bare slope and appeared decidedly unstable, making close examination of the scar area hazardous. However, on September 3, 1973, a field reconnaissance was made of marginal portions of the source area as well as the remaining avalanche path. Hydrothermally altered rocks and light-brown to dark-gray soil were freshly exposed in the source area. Near the margin of the bare slope vapor slowly emanated from a few small vents, while snow and ice melt water coursed down the exposure. Just below the source area an outcrop of altered breccia was sheathed by intact sulphur stalactites as much as 1 m long indicating past emission of volcanic gases or fluids. Huge avalanche firm blocks and normal snow accumulation had filled the east breach of the crater rim to an estimated depth of 10 m. The nature of this deposit is of considerable importance as will be shown later.

On the upper half of Boulder Glacier, avalanche debris consisted largely of firm and snow blocks as much as several meters across. Firm (snow which was at least 1 year old) composed most of the debris. Thin patches of rock and mud covered much of the slide path. Samples from the path midpoints contained gray, angular, slightly to highly hydrothermally altered rock fragments generally less than 5 mm in diameter. These fragments were embedded in a matrix of extremely sticky dense gray mud. Although the avalanche terminus was not examined, aerial photographs indicate that debris in that area included much larger rock fragments. Snow and firm cored levees, 1 to at least 5 m thick and visible in photographs as dark stripes, extended along the avalanche path. The levees appeared to have been produced by both scoriage and debris deposition on the snow-covered glacier surface.

Although none of the avalanches since 1958 reached the glacier margin at the time of their occurrence, there is now a considerable accumulation of mud at the terminus. The glacier front is active and about 10 m high, so that several upper ablation horizons may be recognized easily. In the upper part of the ice face a thin horizontal layer of medium-gray sticky mud was exposed. Debris from this source completely covered the lower two-thirds surface of the north part of the terminal face. Field inspection showed no distinctive difference between mud from the August avalanche.

Figure 2.—Regional setting of Boulder Glacier, Mount Baker, Wash.
Figure 3.—Vertical view of the upper cone of Mount Baker. The southwest rim of a crater (a) partly protrudes from a broad summit ice dome. Sherman crater (b), a partly ice-filled crater to the south, is the site of numerous ice perforations caused by heat emission (d and e are ice perforations mentioned in text). Sherman Peak (c) is the southeast rim of Sherman crater. At the time of the photograph, snow had slumped on the northeast slope of Sherman Peak, although a full-scale avalanche had not occurred. Debris visible on Boulder Glacier is due to nearly continuous rockfall from an outcrop unrelated to Sherman Peak. Vertical aerial photograph W-1232-236, September 1940.
Figure 4.—Avalanche paths on Boulder Glacier and relationship to thermal features in adjacent crater. Dates refer to time of photography used to map avalanche paths. Exact time of avalanche release is unknown. a, crater buried beneath summit ice dome; b, Sherman crater; c, Sherman Peak; f, g, h, debris sample sites.
and mud incorporated in the glacier ice. Subsequent acidity analyses (table 1) of mud debris from the terminus, the 1973 avalanche, and the crater rim also were similar. All samples had a high acidity (pH <2.3) consistent with pH determinations of hydrothermally altered rock in the crater walls (Bockheim and Ballard, 1973).

Acidic material at the Boulder Glacier terminus
Table 1.—Acidity values for debris samples at Mount Baker

<table>
<thead>
<tr>
<th>Sample site</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>East breach debris cone (site f)</td>
<td>2.0</td>
</tr>
<tr>
<td>Middle avalanche surface (site g)</td>
<td>1.9</td>
</tr>
<tr>
<td>Bonide Glacier terminus (site h)</td>
<td>2.2</td>
</tr>
<tr>
<td>Crater soil (Bockheim and Ballard, 1978)</td>
<td>1.2-8.7</td>
</tr>
</tbody>
</table>

Note.—Measurements were made of mixtures of 50 ml of distilled water (pH=6.7) and 50 g of air-dried debris. Sample sites are shown in figure 4.

probably came from the crater rim and represents a stratigraphic record of a past avalanche. The August 1973 avalanche thus is not an isolated incident but rather the latest episode of mass wasting of the crater rim. It is suggested here that these recurrent events are related to heat emission and solfataric alteration in the crater area.

CRATER HEAT EMISSION

Aerial thermal infrared images acquired for the U.S. Geological Survey’s volcanic thermal monitoring project show the extent of surface infrared anomalies in the Sherman crater (Friedman and Frank, 1974). Figure 6 is a predawn thermographic image of the crater obtained by the U.S. Forest Service on April 29, 1973, using an aircraft-mounted RS-7 line scanner sensitive to radiant emission in the 8-14 μm spectral band. For geographic reference it is approximately the same scale as the vertical photograph (fig. 3). This springtime thermographic image shows clusters of infrared anomalies which cover 7500 m², about 6 percent of the crater area. These anomalies occupy 90 percent of the maximum anomalous area recorded 6 mo earlier during a period of relatively lower snowpack and are coincident with areas of warm ground, fumaroles, and boiling pools. Typical warmer temperatures in the crater are measured by bimetallic thermometers during the summers of 1972 and 1973 are 90°C for vapor, 60°C at <1 cm ground depth, and 90°C at 50 cm ground depth. Since these were isolated measurements, they do not indicate the full thermal range but do suggest that the boiling point of water (90°C at 3,000 m alt) limits the maximum fumarole temperatures. Coincident solfataric activity has effectively transformed crater rock to kaolinitic and opalitic alteration products (Coombs, 1939, p. 1500).

The most active part of the crater fumarole field (d, e in fig. 6) is located within ice perforations which occur just inside the east breach of the Sherman crater rim and 50-150 m downslope from the avalanche source. Solfataric ground is flanked on the west by the crater glacier and on the east by a wedge of avalanche debris and snow which has accumulated in the east breach. A stream fed by snow and ice melt water and thermal springs issues from the crater glacier, flows across the fumarole area, and disappears beneath the avalanche deposit in the east breach. The most impressive feature here is a roaring fumarole on the streambank which forcefully ejects vapor and water 1-10 m from sulfur-encrusted crevices a few centimeters in diameter in a rock outcrop. Warm ground, boiling pools, and numerous smaller fumaroles cover the remaining area. Small fumaroles also permeate the margins of the avalanche deposit in the east breach and extend up the slope of Sherman Peak to the south and around the base of the rock exposure to the north. These thermal features to the north appear as two dim point anomalies in the thermographic image (f in fig. 6). The warmest areas which extend up Sherman Peak are also portrayed on the thermographic image (d in fig. 6). However, no anomalies in the image correspond to vapor vents observed in September 1973 on the upper avalanche scar area. This may be due to the thick snowpack on Sherman Peak at the time of the aerial infrared survey.
HEAT FLOW REQUIRED TO MELT SNOW AND ICE IN THE EAST BREACH AREA

An earlier thermographic overflight was made November 20, 1972, by the NASA NP3-A earth resources aircraft using an internally calibrated RS-14 line scanner sensitive to radiation in the 8-14 \( \mu \)m band. Line-scan thermographic images were film recorded on board the aircraft with a 10-step gray scale calibration strip which gave black-body radiation temperatures ranging from 283 to 373 K (20°-100°C). In addition, uncalibrated images encompassing the total temperature range of the scanner were reproduced from videotape. The total area, on video-processed images, of the infrared anomalies in Sherman crater was measured by planimeter to be 8,800 m\(^2\). Of this area, 3,800 m\(^2\) is included in the east breach sector. On the calibrated images 230 m\(^2\) registered more intense than the first gray step or higher than 293 K (20°C). Background radiation temperature for nearby nonanomalous ice areas averaged 255 K (–18°C) as measured along a Barnes PRT-5 infrared-radiometer traverse carried out simultaneously from the NP3-A aircraft along the axis of the infrared-scanner ground swath.

Table 2 is based on the calibrated thermographic images and gives the estimated radiant flux from the east breach anomalies. The following expression for the Stefan-Boltzmann equation is used here:

\[
M = \sigma(T^4)
\]

where \( \sigma = 5.679 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4} \) (Reynolds, and others, 1963),

\( \epsilon = 1 \) (for black body),

\( T \) is given in K in the table, and

\( M \) is the outgoing radiant flux per unit area.

The average outgoing radiant flux per unit area based on data in table 2 is 319 W m\(^{-2}\) (7,580 kcal cm\(^{-2}\)s\(^{-1}\)), equivalent to a total radiant flux for the east breach area of 1.15 \( \times \) 10\(^6\) W (275,000 cal s\(^{-1}\)). Although no data exist for snow accumulation in the crater, a minimum estimate can be made of snow melted by the thermal zones. Various snow course data for lower altitudes are available. The Martin Lake snow survey site 7 km from the crater and 1,100 m in altitude was selected for the following estimates. On April 28, 1973, 1.5 m water equivalent of snow was measured at Martin Lake (Davis, 1973) and is assumed to approximate the minimum snow accumulation in the east breach. Actual accumulation was probably much greater because of wind-deposited snow. On April 29, 1973, thermographic images showed about 3,000 m\(^2\) of anomalous snow-free ground (fig. 6) from which a volume of 4,500 m\(^3\) water equivalent of snow would have been melted if accumulation was 1.5 m. This would have required an energy input of 0.5 \( \times \) 10\(^6\) J m\(^{-2}\) (12,000 cal cm\(^{-2}\)) over the principal accumulation period of 4 mo (January–April, fig. 7). The east breach radiation anomalies, however, yielded 3.5 \( \times \) 10\(^6\) J m\(^{-2}\) (79,000 cal cm\(^{-2}\)) over a 4-mo period, clearly enough to melt assumed snow accumulation in the east breach area, not taking into account additional melting caused by advective heat transfer from subglacial melt-water streams. Moreover, at no time during the year has the east breach area been seen to be completely snow covered, which indicates snow probably melts as fast as it falls in the core area of the anomalies. White (1969, p. 5198) has suggested that in such areas total heat-flow rates are at least 419 W m\(^{-2}\) (10,000 kcal cm\(^{-2}\) s\(^{-1}\)). If this estimate is correct, table 2 shows that radiant flux alone is sufficient to keep at least 230 m\(^2\) of ground in the east breach free of snow the year round.

AVALANCHE CONDITIONS

Although there is insufficient evidence to determine the ultimate trigger for the avalanches, the probable contributing conditions may be examined. Factors that have been considered are storms, large annual accumulations of snow, seasonal production of melt water, and geothermal heat emission.

A close estimate of the time of release has been obtained for only one avalanche; that is, August 20–21, 1973. Observations from various local weather stations indicate that a previous storm had ended August 16 and that weather patterns for the following 6 d were generally partly cloudy with no sharp air temperature fluctuations. Thus the most recent avalanche evidently was not caused by rapidly changing weather. If it is assumed that the similarity of past avalanches indicates a common cause, short-term weather effects may be neglected as an important factor.

Long-term weather patterns also do not seem very important. If the local 16-y record of snow accumulation at Martin Lake (fig. 7) is taken as an index
of the yearly winter precipitation pattern at Mount Baker, there is no apparent relationship between avalanche release and snowpack peaks. Snow, judged to be due largely to wind drift, readily covers the avalanche source area in 1 yr. This is enough to build up the snowpack on Sherman Peak to the volume present at the time of avalanche release. For example, photographs show that the amount of snow covering the avalanche source in late summer 1963, 1 yr after an avalanche, is not appreciably different from the amount in late summer 1965, 1 yr preceding the next avalanche, even though there was an intervening season of extremely heavy snowfall. It appears that wind conditions quickly produce a stable shape for the snowpack and that excess snow is blown off and deposited elsewhere. The snowpack at the avalanche source area thus soon attains a nearly constant volume which provides the major load on the slope, but which is insufficient by itself to cause avalanche release.

Photographs show that all but one observed avalanche path lie on top of snow accumulated during the previous winter. Therefore, most avalanches must have occurred during the ablation season, after the time of maximum snowpack. A late spring or summer occurrence indicates that seasonal melting is probably an important factor. Moreover conditions at or near the ground-firm interface are also important, as avalanche release appears to have taken place either at the interface or in the ground itself. Because much of the ground on Sherman Peak contains clay-rich material which results from hydrothermal alteration, major causes of instability probably are water saturation of this clay-rich material as well as water lubrication at the ground-firm interface. The main source of water is from the melting of snow and firm as a result of both summer ablation from above and ground heat emission from below. Heat emission at the avalanche source likely occurs at a low level—enough to produce the localized vapor emission observed along the source margin after the 1973 avalanche but not enough to prevent rapid thick snow accumulation. Thus the important conditions are that (1) a large quantity of snow accumulates on Sherman Peak, (2) rock is hydrothermally altered to clay-rich material, and (3) melt water, which is produced by summer snow ablation and by geothermal heat emission, saturates the ground and firm. Every 2 to 4 yr a combination of these conditions leads to the release of snow, firm, and a surface layer of rock and mud from Sherman Peak.

Avalanche Significance and Potential for Crater Lake Formation

Since the major component of debris from known avalanches has been snow and firm and only a limited quantity of snow accumulates prior to release, the amount of debris has been insufficient to flow beyond the Boulder Glacier terminus and into the lower Boulder Creek valley. The rate of solfataric alteration of the crater area may be significant in this con-
nection since, if the rate is increasing, greater amounts of rock would become susceptible to structural failure. Furthermore, as the avalanches erode into the middle part of Sherman Peak (fig. 5), the upper part will be undercut so that conceivably a large volume of Sherman Peak above the avalanche source could eventually break loose. The inclusion of this rock mass, estimated at $5 \times 10^6$ m$^3$, in a single future avalanche would increase the amount of debris by at least 100 times compared with the last avalanche and would likely extend well into the lower Boulder Creek valley in a manner similar to large rock avalanches which fell from Little Tahoma Peak, Mount Rainier, in 1963 (Crandell and Fuhnestock, 1965). At present the most obvious hazard posed by debris avalanches is to mountain climbers traveling on Boulder Glacier or following the established Boulder Creek route to the summit of Mount Baker (American Alpine Club committee, 1961, p. 241-242). The avalanches probably are released during the most popular climbing season.

Avalanches have occurred at fairly regular intervals since 1958. This suggests that a debris avalanche of comparable magnitude could occur on Boulder Glacier sometime between 1975 and 1977 and every 2 to 4 yr thereafter, as long as current thermal activity is maintained. Greater potential danger would exist if avalanche debris should dam the crater outlet in the east rim and form a lake. This, like many glacier-dammed lakes, would be subject to sudden release from dam failure (Post and Mayo, 1971). Some ponding is known to occur in the crater even when avalanche debris does not form a dam. A schematic profile of Sherman crater, based on field observations, is presented in figure 8. In September 1973, in the larger ice perforation (e), a small alcove was melted into the edge of the glacier wall where ponded water extended beneath the ice for an unknown distance. During an aerial photographic over-flight in September 1963, a lake emitting vapor was observed in this same ice perforation. Assuming a normal funnel-shaped crater floor, the existence of a sizable body of water under the ice is implied. Furthermore a superficial depression in the ice in the center of the crater, similar to that found above the lake in the west crater of Mount Rainier (River and Steele, 1972), suggests the presence of either a central source of heat emission or a subglacial lake.

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**Figure 8.** Schematic section of Sherman crater. A stream fed by melting snow and ice and by thermal springs was observed in ice perforation $d$, and ponding was observed in perforation $e$.  

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**EXPLANATION**

- Avalanche debris
- Thermal activity
- Inferred glacier bed
- Inferred crater lake
The drainage from such a lake, whatever its size, combines with other crater runoff and flows through a narrow gorge in the east breach of the crater rim. Debris from the avalanches plus normal snow accumulation maintain a wedge-shaped deposit of snow and ice at least 10 m thick in this gorge. In August 1972 and September 1973 surface streamflow discharged from the crater at an estimated 10 1·s⁻¹ and continued into an ice tunnel beneath the avalanche debris deposit. In September 1973 there was no blockage of water by the avalanche deposit as demonstrated by an injection of tracer dye which flowed subglacially from the crater to the Boulder Glacier terminus within 3 h.

Should a future avalanche in the ice tunnel in the east breach, water will be impounded in addition to that ordinarily contained in the crater. At least 30,000 m³ of water could be contained in the perfrations if the water level reaches the top of the 1973 avalanche deposit. The volume of ice missing from the perfrations is estimated to be of the same order of magnitude as the deposit in the east breach. Thus, if the present vertically directed heat flow were diverted horizontally toward the avalanche deposit, as by a warm lake, rapid melting and water percolation through the deposit would result in a lake outburst. Destructive potential in the Boulder Creek valley from failure of an ice dam would depend on such factors as (1) rapidity of release of floodwaters, (2) availability of additional stored water within the crater ice and within Boulder Glacier, (3) availability of loose debris as water moves downvalley, (4) temporary storage and diversion capability of debris, and (5) possibility of release during seasons when flood conditions already prevail.

REFERENCES CITED

McNell, F. H., 1980, Backtracking old trails: Mazama, v. 12, no. 12, p. 6-10.

Note by scanner (6/2012): Several debris flows have been documented post 1973. Information at MBVRC website: www.mbvrc.wordpress.com/bakerfacts.