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Origin and Age of Postglacial Deposits and Assessment of Potential Hazards from Future Eruptions of Mount Baker, Washington

By

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ORIGIN AND AGE OF POSTGLACIAL DEPOSITS AND ASSESSMENT OF POTENTIAL HAZARDS FROM FUTURE ERUPTIONS OF MOUNT BAKER, WASHINGTON

By JACK H. HYDE and DWIGHT R. CRANDELL

ABSTRACT

Eruptions and other geologic processes at Mount Baker during the last 10,000 years have repeatedly affected adjacent areas, and especially the valleys that head at the volcano. Most mudflows from the volcano were caused by massive avalanches of volcanic rock that had been partly altered to clay by steam and other gases. Future mudflows like these could move down valleys for distances of tens of kilometres. Floods caused by rapid melting of snow and ice by lava flows or hot rock debris could affect valley floors far from the volcano, especially if they occurred at a time of high stream discharge due to other causes. Small amounts of tephra (airborne rock debris) have been erupted at least four times during the last 10,000 years. Eruptions like these in the future probably would not seriously endanger human life except within a distance of perhaps a few kilometres of the vent. Lava flows have been erupted at least twice during the last 10,000 years, but have moved down only two valleys. Future lava flows will not directly endanger people because movement typically is so slow that escape is possible. Eruptions which caused pyroclastic flows (flows of hot rock debris) evidently occurred during only one period, and the flows were restricted to only one valley. Pyroclastic flows seriously endanger human life in areas they affect. Such flows move at speeds of as much as 100 km/hr and can bury valley floors under tens of metres of hot rock debris to distances of as much as 15 km from the volcano.

INTRODUCTION

Mount Baker is a large stratovolcano in northwestern Washington about 50 km east of Bellingham and 25 km south of the International Boundary (fig. 1). The glacier-covered cone of andesite lava flows and breccias rises 2 km above adjacent mountains carved from a complex of older rocks (Coombs, 1939; Misch, 1966; Stavert, 1971). The present cone was formed prior to the last major glaciation, which occurred between about 25,000 and 10,000 years ago (Armstrong and others, 1965; Halstead, 1968; Heusser, 1974), and probably is considerably older. It overlies rocks of an earlier eruptive center (Coombs, 1939) from which two radiometric dates of about 400,000 years have been obtained (Easterbrook and Rahm, 1970). During postglacial time clayey mudflows have been formed repeatedly, at least one of which was of large volume and moved many kilometres downvalley from the volcano. Pyroclastic flows, lava flows, and tephra were erupted from a subsidiary summit crater (Sherman Crater) during

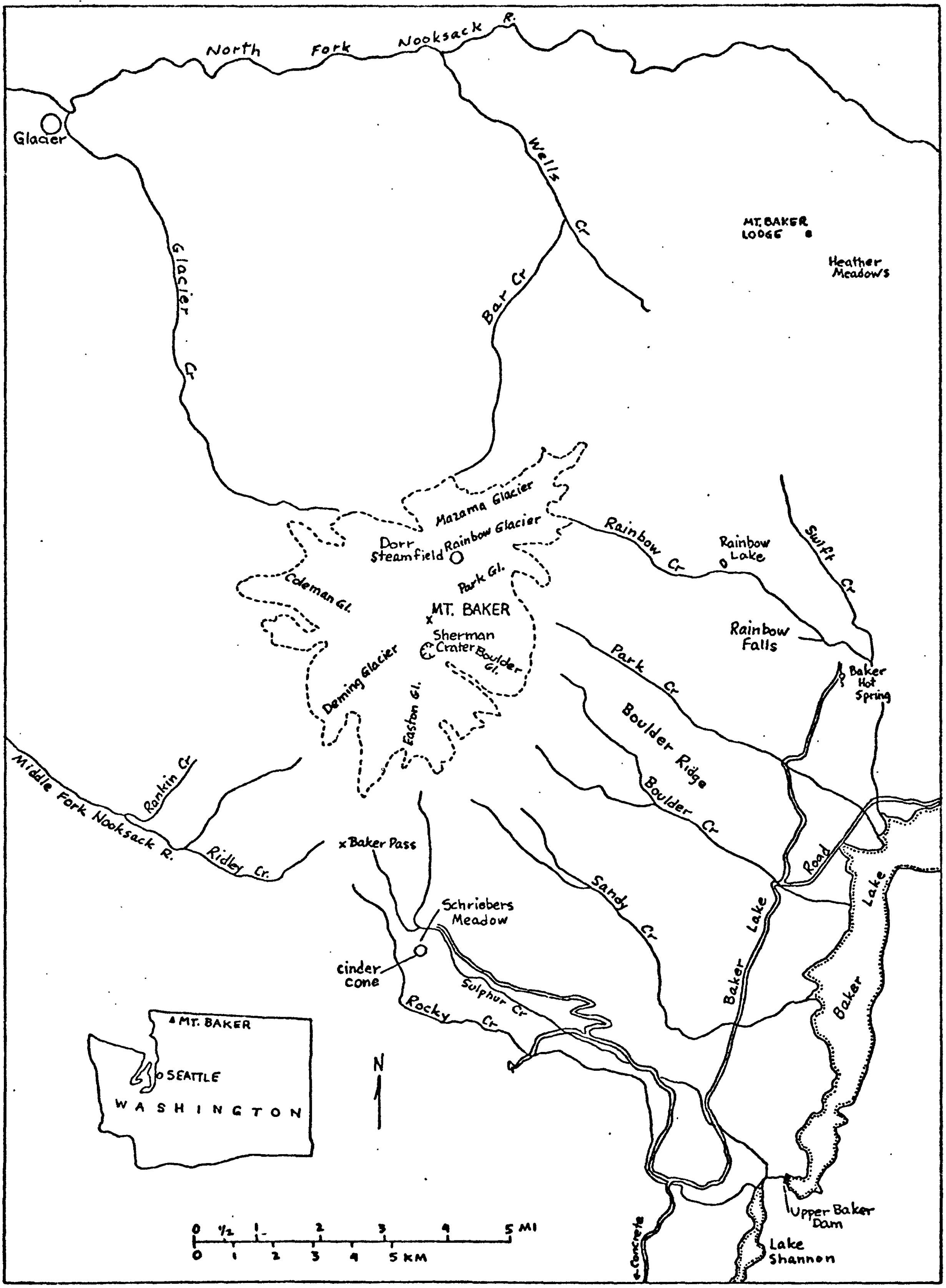

Fig. 1.--Index map of the Mount Baker area.

postglacial time, and tephra as well as one or more lava flows was erupted from a vent at Schriebers Meadow near the south base of Mount Baker.

The purpose of this report is to describe the postglacial eruptive history of the volcano as it is recorded by deposits of volcanic origin, and to appraise and forecast the hazards that could result if similar events were to recur in the future. The report is based on about 2 months' fieldwork in 1973 and 1974 by the senior author, who is responsible for the interpretation of the origin, stratigraphy, and distribution of the postglacial volcanic deposits at Mount Baker. The junior author aided in assessing potential volcanic hazards and in preparing the risk-zone maps.

The investigation was mostly limited to the east and southwest sides of the volcano, where postglacial deposits derived from Mount Baker seem to be concentrated. A reconnaissance of valleys on the north side failed to reveal such deposits; thus, detailed studies were not made there.

Mount Baker is drained on the north by streams flowing into the North Fork of the Nooksack River, on the west by the Middle Fork of the Nooksack River, and on the southeast and east by tributaries of the Baker River (fig. 1), which empties into the Skagit River about 14 km southeast of Mount Baker. The Baker River is impounded by two dams; the upper dam is near the mouth of the Sulphur Creek valley and forms Baker Lake, and the lower dam is about 12 km farther downvalley and forms Lake Shannon.

Mount Baker's summit is covered by a snow and ice field and little is known of its nature or age. A prominent crater partly filled with ice, referred to as Sherman Crater (Frank and others, 1975), is 350 m lower and about 800 m south of the summit. Its east rim, above the head of Boulder Glacier, is breached by a notch about 150 m deep. Another low point, about 100 m deep, is on the southwest rim above Deming Glacier. Fumaroles and thermal springs are concentrated in the crater and solfataric activity has produced kaolinitic and opalitic alteration products (Coombs, 1939; Frank and others, 1975). Avalanches of snow, firn, and hydrothermally altered rock debris from the rim of Sherman Crater have swept down Boulder Glacier at least six times since 1958 (Frank and others, 1975).

TERMINOLOGY

The term "tephra" is used here to refer to fragmental volcanic debris thrown from a volcanic vent and transported through the air (Thorarinsson, 1954). Tephra consists of pumice or scoria, mineral crystals, dense rock fragments, or a mixture of these. Both pumice and scoria are vesicular, which means that they have a large amount of visible pore space. Scoria is somewhat less vesicular than pumice and typically is dark gray or brown, whereas pumice generally is white or yellow.

A pyroclastic flow is a hot dry flow of volcanic rock debris that moves down the flanks of a volcano. Such a flow may extend for many miles beyond the volcano's base and an accompanying cloud of fine-grained material may rise above the flow to heights of hundreds or thousands of metres. The downslope movement of pyroclastic flows is due chiefly to gravity, although the explosive force of the eruption may provide a high initial velocity. Hot air trapped within the debris or hot gases emitted by rock fragments give pyroclastic flows a high degree of mobility. The resulting deposits may consist of pumice, dense rock fragments, or both. Pyroclastic-flow deposits consisting chiefly of pumice commonly are caused by eruptions of gas-rich magma; flows mainly of nonvesicular rock fragments generally originate from avalanches of newly erupted hot rock fragments on the flanks of the volcano, or from the partial collapse of a growing volcanic dome or spine.

Ash-cloud deposits are formed by fine-grained pyroclastic flows and clouds of airborne ash that accompany such flows (Crandell and Mullineaux, 1973). These deposits are more restricted in areal distribution than tephra and usually show rapid lateral changes in thickness and grain size. The deposits consist mostly of lithic ash but pumice is common.

A mudflow is a mass of water-saturated rock debris that moves downslope as a fluid under the influence of gravity. During movement a mudflow resembles a flowing mass of wet concrete. Rock fragments in a volcanic mudflow may be either hot or cold. Mudflows that originate as a result of eruptions generally are caused by spillover of a crater lake, by large-scale melting of snow and ice by hot rock debris and steam, and by volcanic explosions which cause avalanches of saturated rock debris. Other mudflows can be caused by the saturation of loose rock debris during periods of heavy precipitation, from the avalanching of loose rock debris or rock decomposed by hydrothermal alteration, or from the sudden release of a body of water impounded by a glacier on a volcano.

DESCRIPTION OF DEPOSITS

Postglacial deposits at Mount Baker include tephra, clayey mudflows, lava flows, avalanche deposits, and pyroclastic-flow deposits (table 1). A description of the sequence of deposits in each valley follows a discussion of tephra, which is not confined to specific valleys.

Tephra

Tephra erupted by Mount Baker in postglacial time is of small volume and is restricted to the southeast, east, and northeast sides of the volcano. The deposits include, from older to younger, a rusty-brown scoria which is found in the Sulphur Creek valley, two layers of rusty-brown to black crystal-rich ash, and a layer of gray hydrothermally altered rock fragments. Mazama ash, which originated at the site of Crater Lake in southern Oregon about 6,600 years ago (Rubin and Alexander, 1960; Powers and Wilcox, 1964), is also present and serves as a useful stratigraphic marker.

Table 1.--Summary of postglacial events at Mount Baker

Event	Approximate age, or limiting dates (years ago)
Increased fumarolic activity at Sherman Crater-------	Present (1975)
Several small avalanches and mudflows extended down Boulder Glacier.	Recent past to present
Eruption of tephra consisting of hydrothermally altered rock debris from Sherman Crater.	Within the last few centuries
Two or more mudflows extended short distances down Sulphur Creek valley.	Do.
At least two mudflows extended 11 km down Boulder Creek valley.	Do.
Avalanche extended at least 9 km down Rainbow Creek valley.	Do.
A mudflow extended 14 km down Park Creek valley------	500
A mudflow (or avalanche) extended about 3 km down Middle Fork Nooksack River valley.	Between 6,000 and 300
Eruption of tephra----------------------------------	Between 6,600 and 500
A mudflow extended more than 10 km down Sulphur Creek valley.	Between 6,600 and 300
A mudflow extended at least 29 km down Middle Fork Nooksack River valley.	6,000
A mudflow extended 14 km down Park Creek valley------	6,650
Eruption of tephra----------------------------------	Between 10,000 and 6,600
A mudflow extended at least 8 km down Sulphur Creek valley.	Do.
A lava flow extended 12 km down Sulphur Creek valley.	Do.
Eruption of scoria at vent in Sulphur Creek valley---	Do.
Pyroclastic flows, mudflows, and two lava flows moved down Boulder Creek valley, some of which reached Baker River valley.	About 8,700(?)
A mudflow extended at least 6 km down Sulphur Creek valley.	10,340

Scoria in and adjacent to the Sulphur Creek valley on the southeast flank of the volcano is the coarsest and thickest of the tephra at Mount Baker. The scoria on the valley floor is covered by a lava flow, but is well exposed in cuts along the road to Schriebers Meadow. The scoria was erupted at a vent now marked by a small cinder cone at Schriebers Meadow. Distribution of the scoria suggests that the wind was from a southwesterly direction during the eruption. In the upper part of the valley the scoria is thickest on the north valley wall, and it decreases rapidly both in grain size and thickness toward the northeast. Within 1 km of the source, the scoria fragments are as large as 10 cm and the layer averages about 20 cm in thickness; 6 km to the northeast the fragments are of sand size and the deposit is no more than 3 cm thick. The scoria rests on a lahar that is about 10,340 years old (table 2), but is older than 6,600 years because Mazama ash overlies the postscoria lava flow.

The two crystal-rich tephra layers are rusty brown to black, and lie southeast, east, and northeast of the volcano. They thin rapidly away from the volcano and at a distance of 16 km are not readily visible. The thickest and coarsest part of the older tephra deposit lies along a line that trends east-southeast from the volcano, and the axis of the younger layer extends to the east-northeast.

The two layers are similar in appearance in the field, and they both contain feldspar, hornblende, and pyroxene. The upper layer appears to be the result of a single eruptive episode; however, the lower tephra consists of at least two layers of sand-sized ash separated by 1 to 2 centimetres of silt.

The lower tephra overlies the scoria deposit in the Sulphur Creek valley and thus is younger than 10,340±300 years, and the presence of the Mazama ash on top of the tephra indicates that it is older than about 6,600 years.

The younger tephra overlies Mazama ash in the Sulphur Creek valley and also at Heather Meadows, and is overlain by a 500-year-old mudflow in the Park Creek valley.

A still younger tephra produced by Mount Baker consists of gray to white hydrothermally altered rock fragments which range in size from silt and sand to 10 cm in diameter. The distribution of the tephra suggests that it was erupted from Sherman Crater. The thickest and coarsest part of the deposit extends southeast of the volcano, and is alined with the breach in the east portion of the crater rim. Individual rock fragments 4-10 cm in diameter are common about 4 km from Sherman Crater on the surface of Boulder Ridge, just beyond the terminus of Boulder Glacier. At a distance of about 10 km from the crater the tephra on Boulder Ridge is of sand size and 1-3 cm thick. The tephra deposit thins rapidly and is generally difficult to recognize more than 3 km to the north and south of the ridge.

It seems likely that the tephra was formed by a laterally directed explosion that threw altered rock from the Sherman Crater area toward the southeast.

Table 2.--Radiocarbon dates of deposits derived from Mount Baker

[Dates were determined by Meyer Rubin in the radiocarbon laboratory of the U.S. Geological Survey except that for WW-31, which was determined in the radiocarbon laboratory of Western Washington State College (Burke, 1972). The validity of the date obtained on sample WW-31 is questionable because of the small amount of material available for analysis and because of technical problems encountered when the sample was analyzed (Raymond Burke, oral commun., 1975). Thus, the date must be regarded as tentative]

Date (years before present)	Laboratory No.	Kind of sample and stratigraphic position
390±200	W-3222	Wood from base of mudflow, Boulder Creek valley.
530±200	W-2933	Wood beneath a mudflow, Park Creek valley.
5,980±250	W-2944	Wood in a mudflow, Middle Fork Nooksack River valley.
6,370±250	W-3224	Wood in a mudflow, Park Creek valley.
6,650±350	W-2971	Do.
8,700±1,000	WW-31	Wood in a mudflow, Boulder Creek valley.
10,340±300	W-2972	Wood at top of a mudflow, Sulphur Creek valley.

The volume of the tephra appears to be relatively small, probably less than 10,000 m^3. The deposit lies at the grass roots in most areas and overlies the youngest mudflow in Boulder Creek valley; thus, it is probably no more than 100 or 200 years old and may have been erupted in historic time.

Boulder Creek valley

An assemblage of pyroclastic-flow deposits, ash-cloud deposits, mudflows, lava flows, and alluvium, informally referred to as the Boulder Creek assemblage, forms an older fill in the Boulder Creek valley which has been trenched and then partly filled with younger clayey mudflows and alluvium. The assemblage is best exposed at scattered outcrops along the valley sides, 1-5 km upstream from the Baker Lake road. The assemblage forms a fan at the mouth of Boulder Creek which spreads across the Baker River valley, now mostly inundated by Baker Lake. The original extent of the assemblage down the Baker River valley is unknown; correlative deposits were not found during a brief reconnaissance of the Skagit River valley near the mouth of the Baker River.

The pyroclastic-flow deposits in the older part of the assemblage are unsorted mixtures of vesicular, nonvesicular, and glassy andesite fragments in a gray silty sand matrix. Most rock fragments are less than 60 cm in diameter, but a few are as large as 8 m. Individual pyroclastic flows are 1-8 m thick, and many contain breadcrust bombs. Interbedded deposits thought to be of ash-cloud origin consist of black sand as much as 1 m thick which commonly contains a small amount of pumice and small angular andesite rock fragments.

Mudflows in the assemblage are light gray to tan, and are lithologically similar to the pyroclastic-flow deposits; they commonly contain fragments of breadcrust bombs. Individual mudflows range in thickness from less than a metre to more than 10 m, and generally show a vertical size gradation from coarse at the bottom to fine at the top.

The best exposure of the older part of the assemblage is on the east wall of Boulder Creek valley, about 1.5 km upstream from the Baker Lake road. At least 11 pyroclastic-flow and ash-cloud deposits are interbedded there with 16 mudflows and 2 or 3 fluvial deposits. The lowest unit is 3 m or more of compact tan silty sand that contains gray andesite rock fragments as large as 1 m across. Its origin is unknown. Overlying it is a 7-m-thick succession of at least four mudflows which show a size gradation from coarse at the base to fine at the top as well as some crude stratification, and consist of andesite rock fragments as large as 60 cm in a gray silty sand matrix. The oldest visible pyroclastic-flow deposit in the sequence overlies the mudflows and is 1.5-2.5 m thick; it contains andesite rock fragments and breadcrust bombs in a loose silty sand matrix. The bombs are as large as 1 m and have glassy to vesicular interiors. Three bombs examined with a fluxgate magnetometer showed a preferred orientation of the direction of remanent magnetism which indicates that they were hot when the pyroclastic flow came to rest. A discontinuous black sand as thick as 1 m overlies the pyroclastic-flow deposit in most places. The sand is fine to coarse, and contains scattered rounded fragments of yellow pumice as well as angular nonvesicular andesite fragments as large as 2 or 3 cm in diameter. The sand is crudely stratified in a few places and probably is an ash-cloud deposit. Mudflows interbedded with pyroclastic-flow and ash-cloud deposits make up the next 24-27 m of the assemblage. Individual units are 0.5-8 m thick, medium gray to dark gray, and contain both breadcrust bombs and dense andesite fragments. Interbedded bouldery and fine-grained mudflows 0.5-4 m thick comprise the upper 15-18 m of the exposure. The deposits are tan to light gray, and some are crudely stratified.

About 1.5 km upvalley from this exposure, a porphyritic andesite lava flow 10-15 m thick is interbedded with the assemblage. The flow overlies a compact gray mudflow more than 10 m thick and in turn is overlain by mudflows and pyroclastic-flow deposits. A second lava flow of porphyritic andesite overlies these deposits. Both lava flows extend downvalley at least 5 km beyond the present terminus of Boulder Glacier.

The total original volume of the older part of the assemblage is unknown, but the part of it at and near the mouth of the Boulder Creek valley can be estimated. The bulk of the assemblage upstream from the Baker Lake road occurs in the first 3.2 km of the valley and averages about 325 m in width and 60 m in thickness. The part of the assemblage in the Baker River valley downstream from the road is fan shaped and underlies an area of at least 9 km^2. The Baker River valley, 7 km downstream from the fan, was at least 100 m lower at some time between 7,000 and 10,000 years ago (Stearns and Coombs, 1959), and 30 m seems to be a reasonable minimum average thickness for the Boulder Creek fan deposits. The volume of the assemblage estimated from these assumptions is 273 million m^3.

The nature of deposits and their volume suggest that the assemblage originated during a major explosive episode of Mount Baker. However, the restriction of the pyroclastic-flow deposits and ash clouds to the Boulder Creek valley suggests that they did not originate at the summit of the volcano. It seems more likely that the pyroclastic-flow deposits originated during the episode of volcanism that formed Sherman Crater, which is at the head of the Boulder Creek valley. The lack of hydrothermally altered rock fragments in the deposits suggests that the hydrothermal activity common in Sherman Crater today did not commence until after the older part of the Boulder Creek assemblage was formed.

The extent of weathering and one radiocarbon date suggest formation of the assemblage in early postglacial time. The assemblage is clearly younger than glacial drift deposited during the Fraser Glaciation, which ended about 10,000 years ago (Armstrong and others, 1965; Halstead, 1968; Heusser, 1974). The time when Fraser ice disappeared from the Boulder Creek valley is not known, but by 10,000 years ago the valley probably was free of ice below about 1,200 m, which is the approximate altitude of the mudflow in the upper Sulphur Creek valley from which a radiocarbon sample dated at 10,340 years was obtained (table 2). A radiocarbon sample, dated at about 8,700 years (table 2), was obtained by Burke (1972) from a mudflow beneath the lava flow that is interbedded with the assemblage. This date may be representative of the age of most or all of the older part of the assemblage, inasmuch as no evidence has been found of intervals of weathering or erosion during its formation.

The younger part of the assemblage includes mudflows interbedded with fluvial deposits which partly fill a trench eroded into the older assemblage. These deposits form nearly continuous terraces along the Boulder Creek valley for a distance of about 6 km upstream from Baker Lake. The terraces are as much as 10 m above Boulder Creek in the upper part of the valley, 3-4 m near the Baker Lake road, and merge with the surface of the Boulder Creek fan about 1 km downstream from the road.

Two mudflows separated by a buried soil and duff zone as thick as 8 cm crop out in the south bank of Boulder Creek at and downstream from the Baker Lake road. The lower mudflow is as thick as 3 m and consists of andesite rock fragments as large as 2 m across in a matrix of gray silty sand. Hydrothermally altered fragments are common in the matrix, and about 20 percent of the larger fragments also are altered. Wood fragments are abundant throughout the deposit, and stumps and logs 30-80 cm in diameter are common near the base of the mudflow. The mudflow overlies as much as 1 m of rusty-brown to gray fluvial sand and gravel in which the stumps are rooted. The composition of the upper mudflow is similar to that of the lower one, but rock fragments in it are no more than 50 cm in diameter. The upper mudflow is 50 cm thick at the upstream end of the exposure and thins downstream.

Both mudflows seem to be relatively young. A radiocarbon date of about 390 years was obtained from wood incorporated near the base of the lower mudflow. The presence of a weathered zone at the top of the lower mudflow, overlain by a layer of organic material, suggests that the mudflows were separated by a time interval of one or two centuries' duration. The upper mudflow forms the fan surface and supports a first-generation forest near the edge of the creek. Ring counts of several tree stumps and comparison of tree diameters indicate that the forest is no older than 125 or 150 years.

Park Creek valley

A clayey mudflow crops out along the east side of the Park Creek valley along the road to Baker Hot Springs, about 1 km above its junction with the Baker Lake road. The mudflow is bluish gray and has a brown oxidized top, and contains rock fragments as large as 2 m across in a clayey matrix. The deposit is as thick as 5 m and in most places overlies glacial outwash, sand, and gravel. A wood fragment from the mudflow at this locality yielded a radiocarbon age of about 6,650 years (table 2). A lakeside exposure of what is probably the same mudflow occurs on the east side of the Park Creek fan near the mouth of Swift Creek, where it is overlain by as much as 2 m of fluvial sand and gravel which forms the surface of the fan. The mudflow contains abundant wood fragments, from which a radiocarbon date of about 6,370 years was obtained.

The mudflow veneers hills and valley walls to heights of 15-20 m in the lower Park Creek valley, upstream from the Baker Lake road. The deposit is more than 7 m thick at the lakeside exposure on the east side of the Park Creek fan. Thus, an average thickness of 5 m seems reasonable over an area of 5 km^2 in the lower part of the Park Creek valley. The thickness of the mudflow in the upper part of the valley is not known, but reasonable estimates of area and thickness suggest a volume there of no more than 2 million m^3. The overall original volume of the mudflow is estimated to be at least 25 million m^3.

Following an interval of about 6,000 years, a second clayey mudflow moved down Park Creek and reached the mouth of the valley. The stump of a tree that was growing on the surface covered by this mudflow near the Baker Lake road yielded a radiocarbon date of about 530 years (table 2). The mudflow is mottled gray and rusty brown, and consists of compact clayey and sandy silt which contains rock fragments as large as 30 cm in diameter. About 20 percent of the fragments are hydrothermally altered. The deposit is well exposed in streambanks at the Baker Lake road crossing of Park Creek, where it is 1-2 m thick and overlies several centimetres of carbonized wood fragments and black to brown sand. About 1 m of fluvial sand and gravel and bedded gray silt underlies the sand. Although the mudflow covered the flood plain to a depth of at least 15 m at some localities, its distribution is limited, and its original volume was probably no more than 1 or 2 million m^3.

The clayey mudflows most likely were caused by avalanches of hydrothermally altered rock from the flank of the volcano in the area of the Dorr Steamfield (fig. 1).

Rainbow Creek valley

Within the last few hundred years, several large masses of rock debris have avalanched into the upper part of Rainbow Creek valley, at least one of which continued as far as 9 km. The resulting deposits veneer the valley sides and form hummocky surfaces on the valley floor; shallow basins in the deposits are occupied by lakes and small ponds. The debris forms large conspicuous deposits at four localities on the valley floor. Rainbow Lake, about 4.5 km below the head of the valley, is impounded by one of the largest deposits.

About 0.5 km upvalley from Rainbow Falls the deposit consists of rock fragments as large as 5 m across in an unstratified, reddish-brown, silty sand matrix. Near the valley wall the matrix is clayey. Rock fragments are mainly andesite, less than 5 percent of which are hydrothermally altered. The surface of the deposit is hummocky and has as much as 15 m of relief. Steeply sloping ridges of rock debris as much as 40 m above stream level are present downstream from the falls near the mouth of the creek.

The volume of debris in the Rainbow Creek valley is estimated to be at least 13 million m^3. This figure is based on an assumption that the larger deposits on various segments of the valley floor have average thicknesses of 2, 10, and 15 m.

The avalanche deposit near Rainbow Falls supports a first-growth forest. By comparison with trees of known age in the same area, the oldest trees probably are no more than about 450 years old.

The most recent deposit in the valley originated when a large mass of rock broke loose from the south valley wall near the terminus of Rainbow Glacier. The resulting rock debris veneers a glacial moraine on the opposite valley wall to a height of 180 m and extends downvalley at least 1.5 km. This rockfall may have occurred within the last hundred years.

Sulphur Creek valley

The oldest mudflow in the Mount Baker area is exposed in Sulphur Creek valley, 1.5 km north of Schriebers Meadow. A radiocarbon date of about 10,340 years was obtained from carbonized wood 2-4 cm below the top of the mudflow. The deposit consists of more than 2 m of gray silty sand and rock fragments, less than 10 percent of which are hydrothermally altered. Here, the mudflow is overlain by 70 cm of rusty-brown scoria and another mudflow.

The scoria was erupted from a vent at Schriebers Meadow, which subsequently was the source of one or more lava flows. The lava flow extended 12 km down the Sulphur Creek valley, forced the Baker River against its east valley wall, and temporarily dammed it. The lava is a dark-gray basaltic andesite (Stavert, 1971) and commonly displays aa structures; some pressure ridges were noted near the terminus of the flow. Stearns and Coombs (1959) found three lava flows in the Baker River valley and noted that the oldest flow was recognized only in drill holes and seems to be considerably older than the others. The two younger flows apparently were not erupted at the same time, as there is evidence of an erosional interval between them. Only one lava flow is exposed at Schriebers Meadow. The lava flow in the lower part of the valley was not examined in detail during this study, and the existence of two separate flows was not confirmed.

The stratigraphic relation of the pre-lava flow scoria to the old mudflow north of Schriebers Meadow shows that the flow is less than 10,340 years old, and the presence of Mazama ash on top of the flow indicates an age of more than 6,600 years.

Two clayey mudflows in the Sulphur Creek valley are younger than the scoria and lava flow, and are separated from each other by 3 cm of Mazama ash. The pre-Mazama mudflow consists of gray silty and clayey sand and rock fragments, a few percent of which are hydrothermally altered; this deposit was seen only at an outcrop along Sulphur Creek, 1.5 km north of the cinder cone. The post-Mazama mudflow is mottled gray to rusty brown, and contains more than 10 percent of hydrothermally altered rock fragments. It is evidently of considerable extent. Near Baker Pass it is more than 7 m thick and overlies very compact brown till(?), and at Rocky Creek bridge, 4 km south-southeast of Schriebers Meadow, it directly overlies the lava flow. The distribution of the deposit in the area between Schriebers Meadow and Rocky Creek bridge indicates that the mudflow was at least 10 m deep during movement. Still farther downvalley, a deposit thought to be the same mudflow underlies a terrace near the Baker Lake Road.

The presence of the post-Mazama mudflow near Baker Pass suggests that it is correlative with a large clayey mudflow, described subsequently, that moved down the Middle Fork Nooksack River valley about 6,000 years ago.

Bouldery deposits along Sulphur Creek at Schriebers Meadow probably were formed by repeated mudflows during the last century or two. These deposits are not clayey and do not contain altered rock fragments; they probably were formed at times of high runoff caused by heavy rainfall or rapid snowmelt.

Middle Fork Nooksack River valley

The largest and longest clayey mudflow at Mount Baker originated about 6,000 years ago on the southwest side of the volcano and moved more than 29 km down the valley of the Middle Fork of the Nooksack River. The mudflow consists of a mottled gray and rusty-brown mixture of sand, silt, and clay containing angular and subangular andesite rock fragments, more than 10 percent of which are hydrothermally altered. The deposit underlies terraces along the valley and ranges in thickness from less than a metre to more than 10 m. It crops out in roadcuts in the Middle Fork valley near the mouth of Clearwater Creek, where as much as 8 m of it forms a terrace about 100 m above the valley floor. At this locality the mudflow contains abundant wood, one fragment of which yielded a radiocarbon date of about 5,980 years. Near river level in the same area the mudflow is 15 m thick and contains boulders as large as 1 m across. The mudflow was also seen near the mouth of Ridley Creek in the upper part of the valley, and in streambanks on the west side of Middle Fork Nooksack River, 1.5 km south of the community of Kulshan (fig. 4). The mudflow probably reached at least as far downstream as the mouth of Middle Fork.

At most places the mudflow overlies fluvial sand and gravel or glacial drift, and near Ridley Creek and on the west side of Middle Fork near Kulshan it overlies as much as 4 cm of Mazama ash.

The original volume of the mudflow in the Middle Fork valley is difficult to determine, because its exposed thickness is highly variable and nowhere does it form a broad thick fill. Outcrops near the mouth of Clearwater Creek indicate that the mudflow was temporarily at least 100 m deep there, which suggests movement downvalley as a wave, similar in manner to that described for clayey mudflows at Mount Rainier (Crandell, 1971). The mudflow is estimated to have had an original volume of 40 or 50 million m^3.

The mudflow probably originated when hydrothermally altered rock debris avalanched from near the summit of Mount Baker, swept down the Deming Glacier, and flowed down the Middle Fork valley.

A younger mudflow, consisting mainly of fragments of volcanic breccia, originated on the southwest flank of Mount Baker and moved more than 3 km down the Middle Fork valley. The deposit forms a broad, hummocky terrace about 15 m above the Middle Fork flood plain near the mouth of Ridley Creek, and farther west it displaces the mouth of Rankin Creek nearly 1 km downstream. The deposit consists predominantly of fragments of volcanic breccia as much as 5 m across in a matrix of brownish-gray sand and silt. The mudflow probably resulted from the collapse of part of the nearly vertical west valley wall 1-2 km upvalley from the terminus of Deming Glacier. The deposit is estimated to underlie an area of at least 0.5 km^2, to average about 2 m in thickness, and to have a volume of about 1 million m^3. The mudflow is old enough to support a second-generation forest, and is younger than the 6,000-year-old mudflow in the Middle Fork valley.

POTENTIAL GEOLOGIC HAZARDS

Although Mount Baker was formed prior to the last major glaciation and has erupted only infrequently since, repetition of some events that have occurred at the volcano during the last 10,000 years could threaten human life and cause property damage. A problem inherent in many evaluations of geological hazards is the long time interval between events--long, that is, in comparison to the human lifespan. At Mount Baker, for example, the interval between successive mudflows in a given valley may have been as long as several thousand years. Nevertheless, a potentially dangerous mudflow could occur at virtually any time. Another problem is the far-reaching effect of certain kinds of volcanic events. Although the areas of greatest potential hazard are close to the volcano, tephra, mudflows, and floods can affect areas tens of kilometres downwind or downvalley. For example, the most extensive mudflow from Mount Baker moved downvalley at least 27 km, and some mudflows from other volcanoes in Washington have traveled more than 100 km.

There are few people in areas close to the volcano during much of the year, but late spring, summer, and early fall months see a large increase in the transient population, especially within Mount Baker National Forest. On the basis of 1974 visitor-use figures compiled by the U.S. Forest Service, during a summer weekend there might be 2,000 persons or more within an area that could be covered by a mudflow of moderate size. Such an event might occur without warning.

Potentially hazardous events that could occur at Mount Baker include the formation of mudflows and avalanches and the eruption of tephra, hot pyroclastic flows, and lava flows. Possible dangers associated with each of these events are described in the following sections.

Mudflows and avalanches of rock debris

At Mount Baker, the greatest potential geologic hazard is that of avalanching of rock debris from the slopes of the volcano, and movement of the resulting mass downvalley as a mudflow. Mudflows could originate without warning and without any associated volcanic activity, although an eruption would greatly increase the probability of such an event.

Mudflows can move at speeds of 15 to more than 30 km per hour and bury everything in their path under mud and rock debris. Roads, bridges, and other structures could be destroyed or severely damaged. A mudflow moving into a reservoir would displace an equivalent volume of water, and could result in flooding downstream from the dam.

Many of the mudflows at Mount Baker contain hydrothermally altered rock fragments and clay. The distribution of the mudflows suggests that they originated either in the Sherman Crater area or in the vicinity of the Dorr Steamfield on the northeast flank of the mountain. Future mudflows presumably will be caused by avalanches of altered rock from these or other areas.

An avalanche of rock debris from high on the volcano conceivably could move downslope at a very high speed, like the 1970 avalanche of ice and rock from Huascarán Mountain in Peru (Plafker and others, 1971). That avalanche had a volume of at least 50 million m^3 and descended through a vertical distance of about 3,500 m in traveling 14.5 km. Its average speed over that distance was between 280 and 335 km/hr. Rapid movement might have been facilitated by a friction-reducing cushion of air that was trapped and compressed beneath the mass as it hurtled over ramplike obstacles along its path. Within a short distance of its source, the avalanche became a highly fluid and mobile mass of mud and boulders. When the main body of the avalanche came to rest, a large destructive wave of water and debris from it traveled more than 135 km farther downvalley at an average speed of about 35 km/hr (Plafker and others, 1971, p. 559).

The only large deposit from Mount Baker which probably moved downvalley as an avalanche is in the Rainbow Creek valley. That avalanche descended at least 1,740 m vertically within a distance of about 9 km.

The areas in which an avalanche of rock debris would have the most serious consequences are the Boulder Creek valley and Baker Lake. Rock masses having a volume of as much as 30 million m^3 could avalanche onto Boulder Glacier from cliffs both north and south of Sherman Crater. The rock masses are at altitudes of 2,900 to 3,050 m, and for the first 2 km below them the slope of the volcano ranges from 30° to 38°. The slope of the floor of the Boulder Creek valley flattens to less than 5° near Baker Lake. The distance from the potential source areas to the lake is about 12.5 km, and the vertical difference in height is about 2,670 m.

The sliding or falling of rock masses of this size from Mount Baker probably would require an eruption, a steam explosion, or a strong local earthquake. Some of these events probably would also impart an initially high velocity to the mass.

The paths of avalanches from Mount Baker probably would be restricted to the zone of high risk from mudflows and floods; in addition, a large avalanche moving into Baker Lake could cause one or more waves which would threaten areas along the shoreline and which might overtop the dam.

The likelihood of large avalanches from Mount Baker cannot be realistically assessed, nor can volume or distance of movement be anticipated. Nevertheless, the possibility of such a mass reaching as far as Baker Lake should not be disregarded. Even though this distance seems great, an avalanche moving this far would require a "coefficient of friction" (vertical drop divided by horizontal distance) of .21, which is nearly the same as that of the avalanche from Huascarán Mountain (Plafker and others, 1971, p. 558). Such a great distance of movement probably requires exceptionally favorable conditions, such as a very large volume of material, a high velocity which could be provided by a steep initial drop or an explosion, and the development of a cushion of compressed air beneath the moving avalanche.

Tephra

Hazards from tephra are greatest downwind and close to the vent, and depend on the volume, rate, and duration of the eruption, the strength and direction of wind, and distance from the volcano (Wilcox, 1959; Mullineaux, 1974). The respiratory system and eyes could be affected by toxic fumes and ash close to the volcano, and vegetation may be damaged or killed. Reduced visibility, contamination of surface-water supplies, and damage to machinery may also occur. Deposition of tephra more than a few centimetres thick could impede or halt highway traffic, especially if accompanied by rainfall.

The main fallout area of tephra during future eruptions of Mount Baker probably will be in the sector between NNE and SE, which is the sector toward which, annually, about 65 percent of the winds blow at altitudes between 3,048 and 9,144 m (10,000 and 30,000 ft) (fig. 2). Only about 11 percent of the annual winds at these altitudes blow in westerly directions toward densely populated areas in northwestern Washington and southwestern British Columbia.

Pyroclastic flows

Pyroclastic-flow deposits were found only in the valley of Boulder Creek, and they seem to have been formed during only one eruptive period. The infrequency in the past of eruptions which produced pyroclastic flows suggests that the danger from similar events in the future is not great. However, if pyroclastic flows were to occur during future volcanic activity, they could move at least as far as 15 km down any valley that heads on the volcano.

The main danger from pyroclastic flows results from the basal flow of hot rock debris, an accompanying cloud of hot ash and gases, and the possible high speed of both the flow and the cloud. Pyroclastic flows commonly move at speeds of 50-100 km/hr, and have temperatures of hundreds of degrees C. Mixtures of hot rock fragments and ash could bury valley floors to depths of many tens of metres, and the cloud of hot ash and gases could cause asphyxiation, burning of the skin, and injuries by impact of rock fragments. Forest fires could be started by the hot debris. Eruption of hot pyroclastic flows onto snowfields or glaciers could result in rapid melting, followed by floods and mudflows. Valley floors would be the areas of greatest danger from the basal flow, and the accompanying cloud of hot

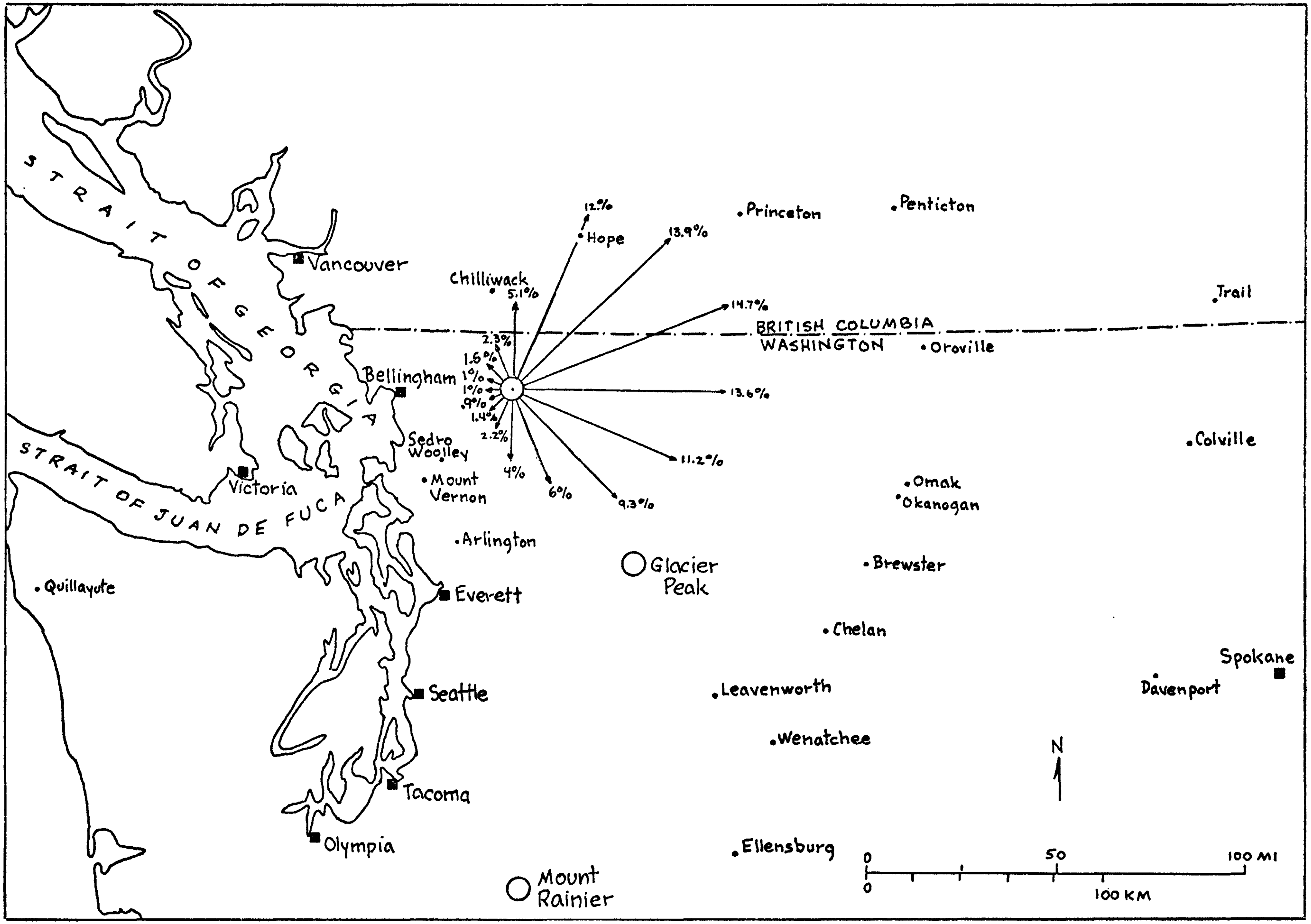

Fig. 2.--Average annual frequency of winds in northwestern Washington which blow toward directions indicated. Wind directions are centered on Mount Baker, but were determined at Quillayute, and are based on a 20-year record of winds at altitudes of 10,000, 14,000, 18,000, and 30,000 feet, averaged. Squares indicate some large cities, dots represent certain smaller communities.

ash and gases could extend to heights of hundreds of metres on valley sides. Pyroclastic flows might be directed down one valley by the location or configuration of the vent, or they might stream radially down all sides of the volcano.

Lava flows

If the volcano continues to behave as it has in the past, future hazards from lava flows will be minimal. However, an eruption similar in scale to that of the Sulphur Creek lava flow would endanger campgrounds and other developed areas on the floors of valleys within 15 km of the volcano. These areas include most of the community of Glacier, northwest of Mount Baker. A lava flow that reached the mouth of Glacier Creek might block the only road available for evacuation of some of the developed areas; however, the downvalley movement of a lava flow would be slow enough to permit evacuation long before the highway was threatened. Lava flows could endanger resorts, campgrounds, and U.S. Forest Service facilities along Baker Lake, but they would threaten property rather than lives. Upper Baker Dam and associated service facilities near the mouth of Sulphur Creek would not be directly affected unless very large volumes of lava were erupted.

The indirect effects of an eruption of lava can be more serious than the direct effects. Eruption of lava onto a snowfield or glacier could generate disastrous floods and mudflows. Although lava flows also could start forest fires and cover roads, lava from volcanoes like Mount Baker generally moves so slowly that people could be evacuated from endangered areas.

DISCUSSION OF RISK ZONES

The eruptive behavior of Mount Baker during the last 10,000 years suggests that the eruption of lava flows and pyroclastic flows in the future is less likely than the eruption of tephra and the formation of mudflows; thus, these two general categories of potential hazards are distinguished from one another. Figure 3 shows areas which could be affected by lava flows and pyroclastic flows like those of the last 10,000 years. Only a few valleys were affected in these ways during that period, but the potential risk zones are extended down each valley that heads at the volcano because it is not possible to predict that any one valley is more likely to be affected in the future than others. The potential risk zone from ash clouds is shown to extend high on valley walls and farther downvalley than pyroclastic flows or lava flows. This kind of distribution is little more than a best guess, but is based in part on studies of ash-cloud deposits at Mount St. Helens volcano (Crandell and Mullineaux, 1973), and on the effects of ash clouds associated with some historic pyroclastic flows elsewhere in the world (Taylor, 1958; Davies, 1972). The actual extent of the areas that would be affected would depend on such factors as volume, speed, and direction of the pyroclastic flows, local topography, and speed and direction of winds.

Areas around the volcano are not subdivided according to differing degrees of risk from pyroclastic flows and lava flows, but, in general, relative risk is greatest on the flanks of the volcano and on valley floors within

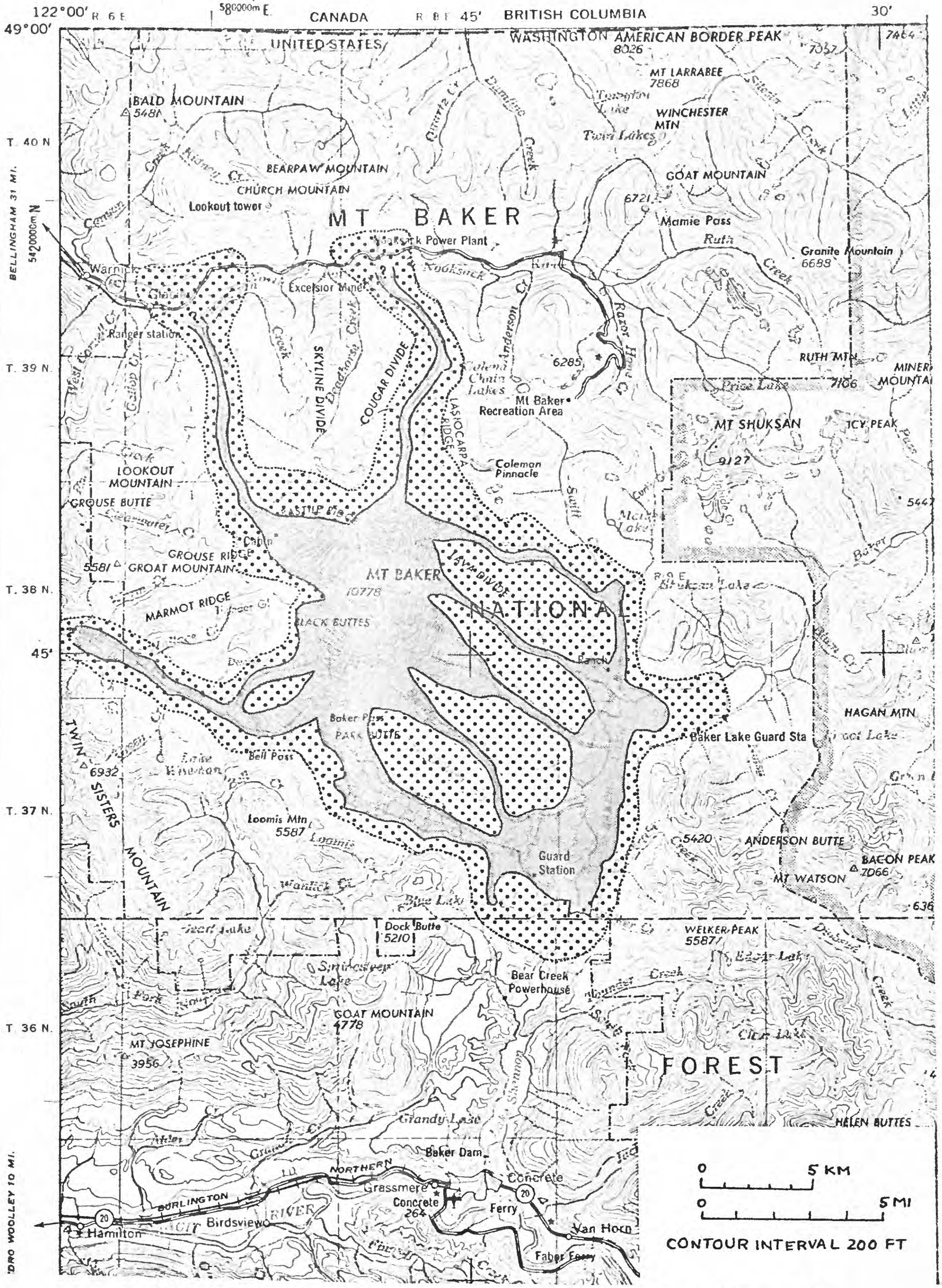

Fig. 3.--Areas which could be affected by lava flows and pyroclastic flows erupted by Mount Baker (shaded area) and by ash clouds associated with pyroclastic flows (stipple pattern).

a few kilometres of the base of the volcano. The degree of risk decreases away from the volcano, and, at any point in a specific valley, with increasing height above the valley floor.

The extent of the area that could be affected by the deposition of tephra (fig. 4, in pocket) is based on the assumption that tephra erupted in the future by Mount Baker will be of similar volume and extent as that erupted during the last 10,000 years. It is not possible to assess the likelihood that future eruptions of tephra will be of much greater volume than those of the past. However, if a substantially greater volume were to be erupted, a zone of relatively high risk to human life should replace that of moderate risk, and the moderate risk zone should be shifted outward accordingly.

The greater extent of the tephra risk zones east of the volcano than to the west is based on the probability that the wind will be blowing from the southwest, west, or northwest during an eruption (fig. 2), particularly if the eruption lasts more than a few hours or a few days.

Mudflow and flood hazard zones beyond the flanks of the volcano are limited to valley floors, and the degree of risk varies according to distance from the volcano, height above valley floors, and the location of known areas of hydrothermally altered rock on the volcano. The zone of moderate risk from mudflows would extend down the Baker River valley at least to its mouth except for the presence of two dams which would trap a mudflow moving down the east side of the volcano. However, if a mudflow or an avalanche moved into one of the lakes rapidly it could create waves that might endanger people in boats and along shorelines. If lake levels were high, large waves might overtop a dam.

The areas of low risk in the Nooksack River and Skagit River valleys indicate in a general way the extent of flooding that could result from an eruption during a period of unusually high stream discharge. If an eruption occurred during a time of dry weather, excessive melting of snow and ice probably would affect only the high-risk zone on the map (fig. 4). But if an eruption occurred during a time of excessive rainfall, or during rapid melting of snow owing to meteorological conditions, major flooding could extend far downstream.

The limit of potential flooding shown in the Skagit River valley is based on a discharge of 275,000 ft^3/s, which has an estimated recurrence interval of once every 200 years (U.S. Army Corps Engineers, 1967). The potential flood area in the Nooksack River valley assumes a discharge of 83,000 ft^3/s, which is roughly twice the measured discharge at Deming during the largest flood on record, in 1951 (U.S. Army Corps Engineers, 1964).

REFERENCES CITED

Armstrong, J. E., Crandell, D. R., Easterbrook, D. J., and Noble, J. B., 1965, Late Pleistocene stratigraphy and chronology in southwestern British Columbia and northwestern Washington: Geol. Soc. America Bull., v. 76, no. 3, p. 321-330.

Burke, R. M., 1972, Neoglaciation of Boulder Valley, Mt. Baker, Washington: Bellingham, Wash., Western Washington State Coll. unpub. M.S. thesis, 47 p.

Coombs, H. A., 1939, Mt. Baker, a Cascade volcano: Geol. Soc. America Bull., v. 50, no. 10, p. 1493-1509.

Crandell, D. R., 1971, Postglacial lahars from Mount Rainier volcano, Washington: U.S. Geol. Survey Prof. Paper 677, 75 p.

Crandell, D. R., and Mullineaux, D. R., 1973, Pine Creek volcanic assemblage at Mount St. Helens, Washington: U.S. Geol. Survey Bull. 1383-A, 23 p.

Davies, R. A., 1972, The 1970 eruption, in Johnson, R. W., Davies, R. A., and White, A. J. R., Ulawun volcano, New Britain: Australia Bur. Mineral Resources, Geology and Geophysics Bull. 142 (Bull. PNG 5), p. 17-28.

Easterbrook, D. J., and Rahm, D. A., 1970, Landforms of Washington: Bellingham, Wash., Western Washington State Coll., 156 p.

Frank, David, Post, Austin, and Friedman, J. D., 1975, Recurrent geothermally induced debris avalanches on Boulder Glacier, Mount Baker, Washington: U.S. Geol. Survey Jour. Research, v. 3, no. 1, p. 77-87.

Halstead, E. C., 1968, The Cowichan ice tongue, Vancouver Island: Canadian Jour. Earth Sci., v. 5, no. 6, p. 1409-1415.

Heusser, C. J., 1974, Quaternary vegetation, climate, and glaciation of the Hoh River Valley, Washington: Geol. Soc. America Bull., v. 85, no. 10, p. 1547-1560.

Misch, Peter, 1966, Tectonic evolution of the Northern Cascades of Washington State--A west-cordilleran case history, in A symposium on the tectonic history and mineral deposits of the western Cordillera, Vancouver, B.C., 1964: Canadian Inst. Mining and Metallurgy Spec. Vol. 8, p. 101-148.

Mullineaux, D. R., 1974, Pumice and other pyroclastic deposits in Mount Rainier National Park, Washington: U.S. Geol. Survey Bull. 1326, 83 p.

Plafker, George, Ericksen, G. E., and Concha, J. F., 1971, Geological aspects of the May 31, 1970, Peru earthquake: Seismol. Soc. America Bull., v. 61, p. 543-578.

Powers, H. A., and Wilcox, R. E., 1964, Volcanic ash from Mount Mazama (Crater Lake) and from Glacier Peak: Science, v. 144, no. 3624, p. 1334-1336.

Rubin, Meyer, and Alexander, Corrinne, 1960, U.S. Geological Survey radiocarbon dates, [Pt.] V: Am. Jour. Sci., Radiocarbon Supp., v. 2, p. 129-185.

Stavert, Larry, 1971, A geochemical reconnaissance investigation of Mount Baker andesite: Bellingham, Wash., Western Washington State Coll. unpub. M.S. thesis, 60 p.

Stearns, H. T., and Coombs, H. A., 1959, Quaternary history of the upper Baker Valley, Washington: Geol. Soc. America Bull., v. 70, no. 12, pt. 2, p. 1788.

Taylor, G. A., 1958, The 1951 eruption of Mount Lamington, Papua: Australia Bur. Mineral Resources, Geology and Geophysics Bull. 38, 100 p.

Thorarinsson, Sigurdur, 1954, The eruption of Hekla, 1947-1948, v. 2, pt. 3, The tephra-fall from Hekla on March 29, 1947: Vísindafélag Íslendinga Rit, 68 p.

U.S. Army Corps of Engineers, 1964, Flood plain information study, Nooksack River, Summary report: Seattle, Wash., U.S. Army Corps Engineers, 12 p.

______1967, Flood plain information study, Skagit River Basin, Summary report: Seattle, Wash., U.S. Army Corps Engineers, 17 p.

Wilcox, R. E., 1959, Some effects of recent volcanic ash falls, with special reference to Alaska: U.S. Geol. Survey Bull. 1028-N, p. 409-476.