GEOTHERMAL RESOURCE ASSESSMENT OF MOUNT HOOD

FINAL REPORT

U.S. DEPARTMENT OF ENERGY

CONTRACT NO. ACO6-77-ET-28369

JULY 1979

DOGAMI OPEN-FILE REPORT

O-79-8

STATE OF OREGON
DEPARTMENT OF GEOLOGY AND MINERAL INDUSTRIES
DONALD A. HULL, STATE GEOLOGIST

RLO-1040

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Principal Investigator: Donald A. Hull
Department of Geology and Mineral Industries
State of Oregon

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Department of Geology and Mineral Industries
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INTRODUCTION

On July 1, 1977, the Oregon Department of Geology and Mineral Industries began research on two geothermal resource projects with funds provided by the U. S. Energy Research and Development Administration (ERDA) (now U. S. Department of Energy) under Contract No. EG-77-C-06-1040. The projects are: (a) geothermal resource assessment of Mt. Hood Volcano in the Cascade Range; and (b) statewide inventory of low temperature geothermal resources. An application for an extension and additional funding of these projects was submitted to ERDA (DOE) on September 14, 1977, funded on December 28, 1977, and later extended to December 31, 1978. A no-cost extension to the contract was issued by DOE on January 1, 1979, with the original completion date as specified in Article II of the contract changed to June 15, 1979. Further, the contract number was changed from EG-77-C-06-1040 to AC06-77-ET-28369 as of the above date.

The Mt. Hood geothermal resource assessment project was a joint undertaking by the Department of Energy (DOE), U. S. Geological Survey (USGS), U. S. Forest Service (USFS), and Oregon Department of Geology and Mineral Industries (DOGAMI). The role each major participant of the project played in the study is set down in the signed ERDA-USGS-USFS-DOGAMI agreement under letter dated February 11, 1977, from Dr. David L. Williams, Program Manager, DGE, ERDA.

The primary objective of the project was the assessment and characterization of the geothermal resource potential of Mt. Hood. Mt. Hood was selected because: (a) it is one of the largest stratovolcanoes in the Cascade Range; (b) it has been active in the past 250 years; and (c) it is readily accessible for research. Furthermore, the volcano is approximately 50 airline miles east-southeast of the City of Portland and any substantial geothermal resource, whether low to high temperature, could be utilized by Metropolitan Portland.

Dr. Donald A. Hull, Oregon State Geologist, was the principal investigator for DOGAMI. This final report was edited and written, in part, by Dr. Joseph F. Riccio. A portion of the field studies administered by DOGAMI have been managed by its staff personnel and/or consultants, whereas other phases have been conducted by university researchers under subcontract to DOGAMI as noted below:

(1) Stratigraphy and structure of the Columbia River Basalt Group in the Cascade Range, Oregon: By Marvin H. Beeson and Michael R. Moran, Earth Science Department, Portland State University (PSU Grant No. 90-262-8126).

(2) Geology and geochemistry of Mt. Hood Volcano: By Craig M. White, Department of Geology, University of Oregon (UO Grant No. 50-262-8902).

(3) Gravity measurements in the area of Mount Hood, Oregon: By Richard W. Couch and Michael Gemperle, Geophysics Group, School of Oceanography, Oregon State University (OSU Grant No. 30-262-917).

(4) Heat flow modelling of the Mount Hood Volcano, Oregon: By David D. Blackwell and John L. Steele, Department of Geological Science, Southern Methodist University (SMU #86-09).

A geochemical study by DOGAMI and Lawrence Berkeley Laboratory (LBL), University of California (DOE Contract No.

W-7405-ENG-48) resulted in a joint publication (LBL-7092 - DOGAMI 0-79-2) entitled Geochemical studies of rocks, water, and gases at Mt. Hood, Oregon. DOGAMI's portion of the project was funded under its Contract No. EG-77-C-06-1040. A copy of the publication is enclosed.

The first technical progress report by DOGAMI for the Mt. Hood assessment was submitted in October 1977; technical progress report No. 2 was submitted in May 1978. This final report only involves DOGAMI's portion of the Mt. Hood assessment project. The final report on the Statewide Inventory of Low Temperature Geothermal Resources (AC06-77-ET-28369) was submitted to DOE under separate cover.

The geoscience researchers engaged in the joint geothermal assessment project met in Portland on January 9-10, 1979, at which time preliminary results of various aspects of the assessment effort were informally presented. This final report, including those by the university researchers under subcontract to DOGAMI, does not include any substantial input as to conclusions or recommendations presented informally or formally by the USGS.

Besides the supervision of the studies undertaken by the university researchers, DOGAMI was also charged with the drilling of temperature gradient holes on or near Mt. Hood. DOGAMI also undertook the temperature logging of available "free" holes that were within the scope of the Mt. Hood project. These data were made available to David Blackwell for heat flow determinations and for the heat flow modelling of Mt. Hood. Further, DOGAMI provided for the technical supervision of the drilling of Old Maid Flat No. 1/2. This entailed, in part, providing for the litho-logging and preservation of cuttings (which were made available to David Blackwell for rock conductivity tests and to Marvin Beeson for trace element geochemistry) from this exploratory hole; temperature logging of the hole; well-site interpretation of the several geophysical logs taken by others in this hole; and coordination and logistics between the interested parties of the assessment group relative to the drilling and logging of this hole.

Further, DOGAMI provided personnel to the USGS for the siting and staking of seismic shot holes.

DOGAMI also provided for litho-logging and cuttings preservation of Timberline No. 2. Limited drilling supervision was also provided on this hole.

Temperature gradient logging of Old Maid Flat No. 3 (Clear Fork) drilled by Northwest Geothermal Corporation was done by DOGAMI. Cuttings and temperature gradient data were submitted to David Blackwell for the heat flow studies noted above.

Water analyses from samples obtained from several of the temperature gradient holes were made available to the interested assessment parties.

STRATIGRAPHY AND STRUCTURE OF THE COLUMBIA RIVER BASALT GROUP IN THE CASCADE RANGE, OREGON

By

Marvin H. Beeson and Michael R. Moran
Earth Sciences Department,
Portland State University

Final report of work carried out under PSU Grant No. 90-262-8126 From the Oregon Department of Geology and Mineral Industries; June 1977 through March, 1978.

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FIGURES

ABSTRACT

The Columbia River Basalt Group lava flows identified in the Mt. Hood area of the Oregon Cascade Range are assigned to the Grande Ronde Basalt and Wanapum Basalt formations of the Yakima Basalt Subgroup, except for three intercalated flows of Prineville chemical type. The composite section has a stratigraphic thickness of approximately 550 m and consists of 26 flows that can be separated into eight distinct geochemical and/or magnetic polarity subdivisions.

Deformation began during the incursion of the Grande Ronde Basalt and is represented by NE trending folds traversing the Cascade Range which have structural relief of approximately 300 m and by an echelon NNW to NW trending folds and faults that occur from the Clackamas River area to Portland along the Portland Hills - Brothers fault trend. During this stage of deformation, thrust faults developed parallel to some of the anticlinal axes in patterns similar to those of the Columbia Plateau. Later deformation includes vertical N10W to N55W strike slip faulting, which, when considered with the fold trends, indicates a right lateral wrench system of regional magnitude. The Columbia Plateau style of deformation clearly crosses the axis of the Cascades with several of the larger folds being present in both provinces. A N30W trending fault located just west of the Salmon River separates the NE trending folds through the Cascades from the Portland Hills - Brothers wrench fault trend.

Distribution of the Columbia River Basalt in the area surrounding Mt. Hood and its deeper occurrences in the exploratory hole at Old Maid Flat indicates that the basalt may have been downdropped along much of the axial region of the range.

The major exposures of CRB utilized in this study are (Figure I-1):

Clackamas River Area (mapped by James L. Anderson, unpublished Master's thesis, Portland State University).

Bull Run Watershed (mapped by Beverly Vogt, unpublished Master's thesis, Portland State University).

Hood River Drainage and Hood River fault zone (mapped by Susan Timm, unpublished Master's thesis, Portland State University).

The Salmon River Area (mapped by M. H. Beeson and M. R. Moran).

The Columbia River Gorge which consists of one large exposure of CRB through the Cascade Range was not mapped for this report although some data were available from both published literature and isolated sections studied by Mr. M. R. Moran (unpublished Master's thesis, Portland State University).

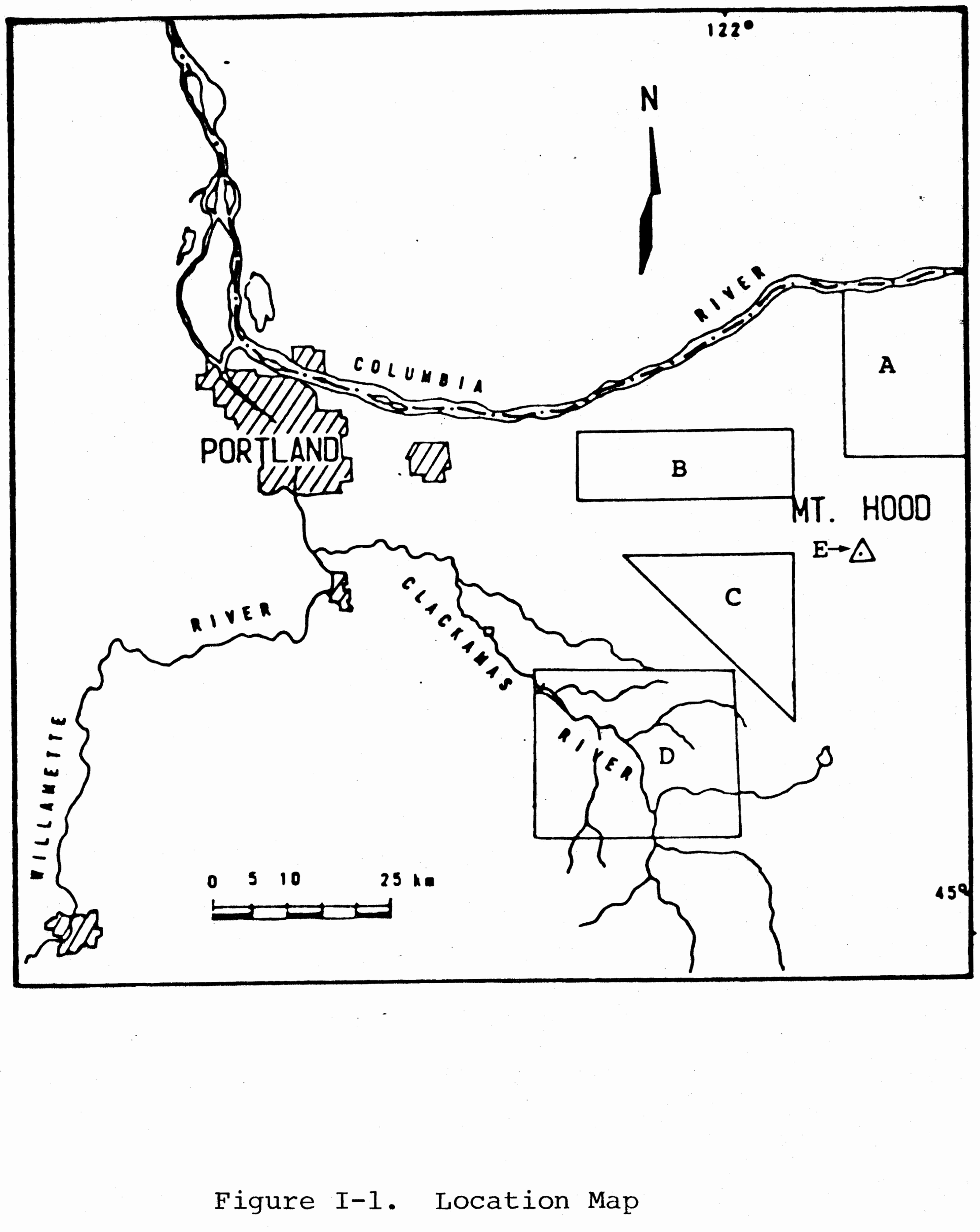


Figure I-1. Location Map

A - Hood River Area
B - Bull Run Watershed Area
C - Salmon River Area
D - Clackamas River Area
E - Old Maid Flat Exploratory Hole

II. COLUMBIA RIVER BASALT GROUP STRATIGRAPHY IN WESTERN OREGON

The Miocene Columbia River Basalt Group in Oregon, Washington, and Idaho is an accumulation of tholeiitic flood basalt flows covering approximately 2×10^5 km^2 (Figure II-1; Waters, 1962). These fluid flows spread over this region, the Columbia Plateau, as nearly horizontal sheets, attaining a total thickness of at least 1,500 m near Pasco, Washington (Asaro and others, 1978). The flows were extruded from large N to NW trending fissure systems in the eastern half of the plateau (Waters, 1961; Taubeneck, 1970; Swanson and others, 1975) between approximately 16 and 6 million years ago (Watkins and Baksi, 1974; McKee and others, 1977).

The stratigraphic subdivisions and nomenclature have undergone a number of revisions and refinements as mapping has progressed and as modern geochemical and paleomagnetic data have accumulated. Many contributions have been made to the Columbia River Basalt Group stratigraphy, some of the more noteworthy being Waters (1961, 1962); Mackin (1961); Schmincke (1967); Wright and others (1973); and Nathan and Fruchter (1974). The Group is divided into five formations (Figure II-2). Two of these, the Imnaha Basalt and the Picture Gorge Basalt, are restricted to the southeastern and southern portions of the province, respectively; the remaining three, the Grande Ronde Basalt, the Wanapum Basalt, and the Saddle Mountains Basalt, are grouped together as the Yakima Basalt Subgroup. All of the Columbia River Basalt Group flows identified west of the axis of the Cascade

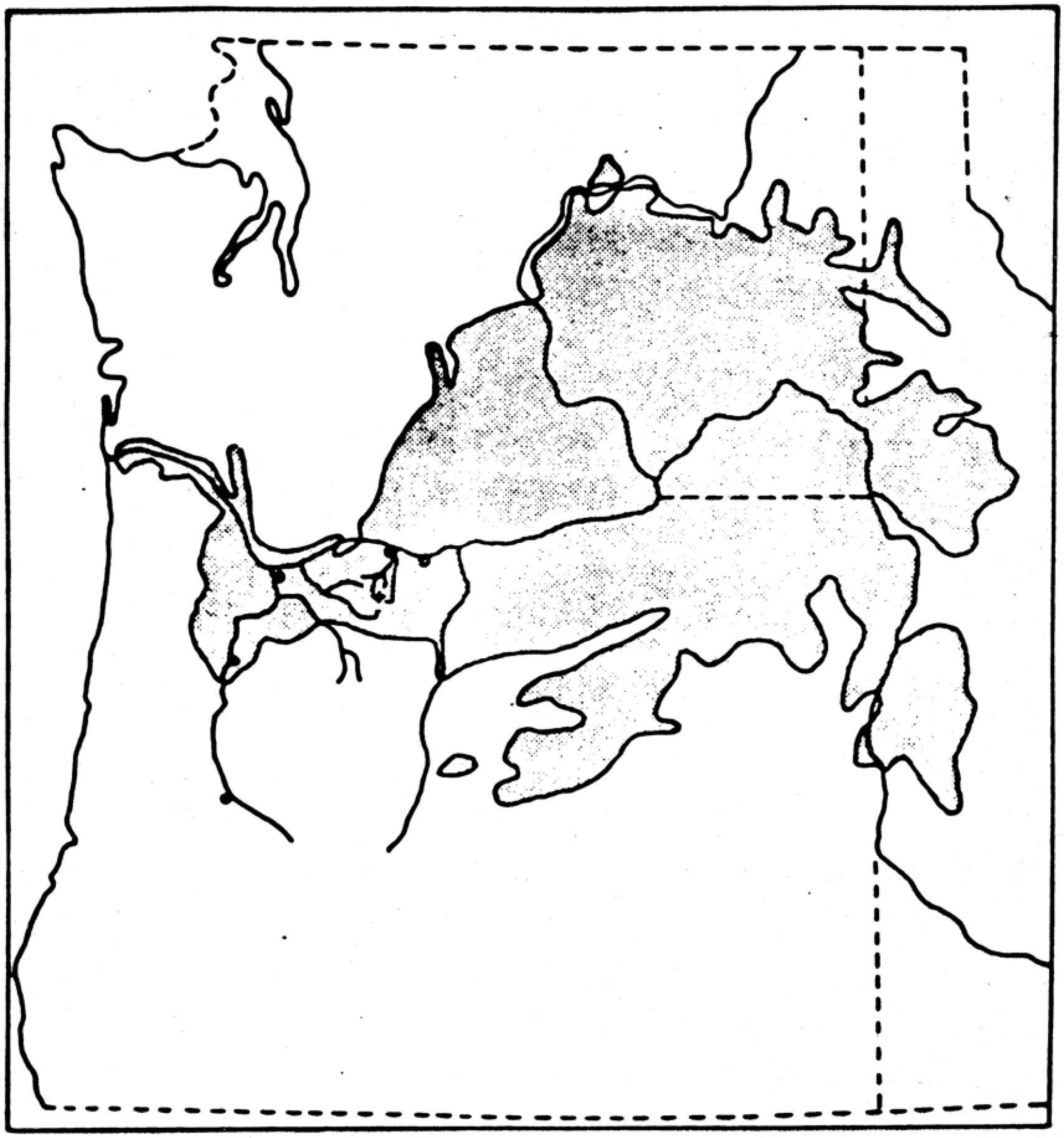


Figure II-1. Distribution of Columbia River Basalt Group in Oregon, Washington, and Idaho; + Mt. Hood.

SERIES		GROUP	SUB GROUP	FORMATION	MEMBER OR FLOW	K-Ar AGE (m.y.)	MAGNETIC POLARITY
MIOCENE	UPPER MIOCENE	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	SADDLE MOUNTAINS BASALT	LOWER MONUMENTAL MEMBER	6	N
					EROSIONAL UNCONFORMITY		
					ICE HARBOR MEMBER BASALT OF GOOSE ISLAND	8.5	N
					BASALT OF MARTINDALE	8.5	R
					BASALT OF BASIN CITY	8.5	N
					EROSIONAL UNCONFORMITY		
					BUFORD MEMBER		R
					ELEPHANT MOUNTAIN MEMBER	10.5	N,T
	MIDDLE MIOCENE				EROSIONAL UNCONFORMITY		
					MATTAWA FLOW		N
					POMONA MEMBER	12	
					EROSIONAL UNCONFORMITY		
					ESQUATZEL MEMBER		N
					EROSIONAL UNCONFORMITY		
					WEISSENFELS RIDGE MEMBER BASALT OF SLIPPERY CREEK		N
					BASALT OF LEWISTON ORCHARDS		N
					ASOTIN MEMBER		N
					LOCAL EROSIONAL UNCONFORMITY		
					WILBUR CREEK MEMBER		N
					UMATILLA MEMBER		N
					LOCAL EROSIONAL UNCONFORMITY		
				WANAPUM BASALT	PRIEST RAPIDS MEMBER		R3
					ROZA MEMBER		R3
					FRENCHMAN SPRINGS MEMBER		N2
					ECKLER MOUNTAIN MEMBER		
					BASALT OF SHUMAKER CREEK		N2
					BASALT OF DODGE		N2
					BASALT OF ROBINETTE MOUNTAIN		N2
				GRANDE RONDE BASALT			N2
	LOWER MIOCENE			GRANDE RONDE BASALT / PICTURE GORGE BASALT			R2
							N1
							R1
				IMNAHA BASALT			R1
							T
							N0
							R0

Figure II-2. Columbia River Basalt Group Stratigraphy

Mountains belong to this subgroup, with the exception of flows of the Prineville chemical type, discussed below. The coastal Miocene basalts of Oregon and Washington form three distinct stratigraphic units that are consanguineous with the three formations of the Yakima Basalt Subgroup (Snavely and others, 1973).

Some of the basalt flows originating in the eastern part of the Columbia Plateau flowed into western Oregon through a topographic low in the ancestral Cascade Mountains. This low extended from the Clackamas River drainage on the south to the present Columbia River Gorge on the north. The Yakima Basalt Subgroup, about 1,500 m thick in the Pasco Basin of Washington, thins to approximately 550 m in the Cascade Range. Many stratigraphic members recognized on the plateau are not present or comprise fewer flows in western Oregon. The Saddle Mountains Basalt, which ranges from 150 to 275 m thick in the Pasco Basin, has not been found in the Cascade Range, even though the Pomona Member is present near the Columbia River in the Coast Range of Oregon and Washington (Snavely and others, 1973; Kienle, 1971). The members of the Yakima Basalt Subgroup that occur in western Oregon are indicated in Figure II-2.

In western Oregon, the Columbia River Basalt Group comprises approximately 29 basalt flows which may be divided into three formations of the Yakima Basalt Subgroup (Figure II-3). Distinctive characteristics of each member and of other informal subdivisions are given in Figure II-4. These units are tentatively identifiable in the field on the basis

SUBGROUP	FORMATION	MEMBER	FLOW UNITS	INFORMAL UNITS	MAGNETIC POLARITY
YAKIMA BASALT	SADDLE MOUNTAINS BASALT	POMONA	1		R
	WANAPUM BASALT	PRIEST RAPIDS	2		R
		FRENCHMAN SPRINGS	7		N_2
	GRANDE RONDE BASALT	(High Mg Chemical Type)	2		
			2	WAVERLY*	
		(Low Mg Chemical Type)	1		
			1 / 1	PRINEVILLE	
			4		N_2
			2 / 2	PRINEVILLE	R_2
			3		R_2
			1		N_1

Figure II-3. Stratigraphy of the Columbia River Basalt Group in western Oregon

Figure II-4. Distinctive characteristics of western Oregon Columbia River Basalt Group stratigraphic units

STRATIGRAPHIC UNIT	FIELD CRITERIA Jointing, polarity & lithology	LABORATORY CRITERIA Geochemistry** & petrography
Pomona Member	Blocky to columnar jointing Reversed polarity Clear plagioclase phenocrysts (3-4 mm) Clots of plagioclase and pyroxene	Sm <5 La <20 Fe <8%
Priest Rapids Member	Reversed polarity Coarse sugary texture	Sm >7 La 25-30 Sc 35-40 Eu ≥2.5
Frenchman Springs Member	Well-formed colonnade Normal polarity Texture often coarse Large (1-cm) plagioclase phenocrysts	Sm >7 La 25-30 Sc 35-40 Eu ≤2.5
*High Mg Grande Ronde Basalt	Blocky and platy jointing Normal polarity Coarse texture	Sm <6 La 20-24 Sc 35-40
*Waverly flows	Upper flow - very poorly jointed Lower flow - large columns with platy jointing Normal polarity	Sm <6 La 15-18 Upper flow - clots of plagioclase and pyroxene Lower flow - pilotaxitic
*Low Mg Grande Ronde Basalt	Well-formed entablature Fine texture	Sm <7 La 25-30 Sc 30-35
*Prineville flows	Well-formed blocky to wavy colonnade Fine texture	Ba ∿2,000 Eu >4 Co <35 Abundant apatite laths

* Informal units.

** Geochemical data obtained by neutron activation analysis. All data in parts per million except where specified.

of jointing characteristics, magnetic polarity, grain size, and the presence or absence of large plagioclase phenocrysts. Laboratory data, especially major or trace element chemistry, are necessary for more accurate determinations.

Grande Ronde Basalt is the most widespread of all the Columbia River Basalt Group formations in western Oregon; occurring almost everywhere the CRB has been mapped. Of the four magnetic polarity intervals formally recognized within the Grande Ronde Basalt, only the oldest, a reversed interval (R_1), has not been found in western Oregon. The oldest normal interval (N_1) is represented by a single flow that occurs at the bottoms of the sections in Multnomah Creek and in the Clackamas River (Anderson, 1978).

Grande Ronde Basalt may also be divided chemically on the basis of magnesium content into "Low Mg" and "High Mg" flows (Figure II-3). In western Oregon, two High Mg flows occur as the top two flows of the Grande Ronde Basalt. Because of their distinctive jointing patterns and textures, the two High Mg flows are generally distinguishable in the field from the Low Mg flows, and this informal subdivision is therefore useful for geologic mapping in western Oregon. In the Columbia Plateau, however, the High Mg flows may also occur lower in the Grande Ronde Basalt section (D. A. Swanson, personal communication).

The Grande Ronde Basalt section in western Oregon also contains localized units that do not occur extensively in the plateau and are not formally recognized. In the Clackamas River area, two flows of the chemically distinctive Prineville chemical type (Uppuluri, 1974) occur at the top of the second reversed (R_2) section (Anderson, 1978). One Prineville flow, probably an N_2 flow, occurring near the top of the Low Mg Grande Ronde Basalt, has been found in the exploratory hole at Old Maid Flat. The Prineville chemical-type flows probably originated near Prineville, where 13 flows are exposed (Uppuluri, 1974), and spread northward and westward, onlapping and interfingering with flows of Low Mg Grande Ronde Basalt. Prineville flows have not been found in the Willamette Valley, but the lower part of the Grande Ronde section is not exposed in the Portland area, and few chemical analyses have been made on CRB from other parts of the valley. Prineville flows are not known to occur in the Bull Run Watershed (B. F. Vogt, personal communication) or in the Columbia River Gorge (Beeson and others, 1976).

In the Waverly Heights area near Milwaukie, Oregon, two flows which have been informally designated the Waverly flows (Beeson and others, 1976) occur between the High Mg and the Low Mg Grande Ronde Basalt flows. They are localized by structural and/or erosional lows which existed at that time. Chemically, they are very similar to the Low K_2O Grande Ronde Flows that occur at or very near this same stratigraphic horizon in the Pasco Basin (Ledgerwood, 1978) and along the Snake River in Washington. The Waverly flows are also similar chemically to the older Imnaha Basalts.

The Frenchman Springs Member of the Wanapum Basalt is widespread in the CRB occurrences in western Oregon. It is not present along some structural highs such as the Portland

Hills anticline, either because it was excluded by developing structures or because it has since been eroded. In the Columbia Plateau, Grande Ronde and Wanapum Basalts are separated by the Vantage interbed; in western Oregon, this same contact is marked by a distinctive weathering surface and an interbed of carbonaceous material. Interbeds occur between other CRB flows in western Oregon, but because the Vantage interbed is characterized by deep weathering, structural deformation, and sedimentary deposits, it must represent a longer time interval. Tree molds and carbonaceous material are common at this boundary. The first two Frenchman Springs flows above the interbed contain plagioclase megaphenocrysts which aid in positive stratigraphic determination.

The Priest Rapids Member occurs in the Bull Run Watershed (B. F. Vogt, personal communication) and at Crown Point on the Columbia River as one or possibly two intracanyon flows. Priest Rapids flows have not been found in any other location in western Oregon.

The Pomona Member of the Saddle Mountains Basalt occurs along the lower Columbia River of Oregon and Washington. This flow probably traversed the Cascade Range as an intracanyon flow whose course is yet to be determined. Pomona flows have not been found in the Cascade Range or in the Portland area.

III. STRATIGRAPHY AND STRUCTURE OF THE COLUMBIA RIVER BASALT IN REGIONS WITHIN THE CASCADE RANGE

A. Hood River Area

The Hood River Valley is located 100 km east of Portland and extends north about 26 km from the northern flank of Mount Hood to the City of Hood River on the Columbia River (Figure I-1). The valley floor is nearly flat, sloping less than one degree to the north, and is overlain by glacial outwash and stream deposits at least three meters thick. The valley is flanked on the east and west by steep-sided ridges.

The entire valley and surrounding hills are underlain by CRB; however, exposures are limited to stream channels and steep hillsides. The CRB basalts have undergone weathering and a thick soil covers all but the steepest slopes. Hillside exposures are usually the result of excavations.

The valley is interrupted in its approximate center by Middle Mountain, an asymmetric hill of northeast dipping basalt.

The Hood River flows northeast along the west border of the valley with a gradient of 1 degree, providing the only outcrops of CRB from north to south within the valley. Two levels of terraces border the Hood River; the lower terraces often mark the end of an exposure of the basalts, though CRB may be found further up slope. The higher terrace consists entirely of stream-deposited glacial outwash.

<u>Stratigraphy and structure</u>

The Yakima Basalt Subgroup of the Columbia River Basalt Group exposed in the Hood River Valley consists of two low Mg R_2 flows, five Low Mg N_2 flows, and four High MgO flows of the

Grande Ronde Basalt formation and six Frenchman Springs flows and one Priest Rapids flow of the Wanapum Basalt formation. One complete section of the Wanapum Basalt underlain by two (?) High Mg flows and one Low Mg flow was sampled along Snakehead Creek in the Neal Creek drainage and analyzed for trace elements. Four High Mg flows overlain by a thin (≤ 3 m) eroded section of a Frenchman Springs flow and a thin (~ 10 m) cap of Priest Rapids at the junction of Lake Branch Creek and the West Fork Hood River was measured and analyzed. Stratigraphic sections of more than three flows in contact elsewhere in the valley were not analyzed.

The Grande Ronde Basalt is exposed along the Hood River and its tributaries west of Middle Moutain. Frenchman Springs basalt is exposed directly north of Middle Mountain along Hood River.

The entire section of Yakima Basalt in the Hood River Valley is exposed on Middle Mountain except for the Priest Rapids Member. In the southwest corner of the valley the Priest Rapids flow probably occurs as an intracanyon flow.

The Hood River area is gently folded with a general dip to the east. Frenchman Springs flows crop out at an elevation of 1600 ft in the southwest corner of the valley and at 400 ft north of Middle Mountain. Younger Pliocene (?) basalts overlie the Frenchman Springs basalt from Tucker Bridge (2N/10E-5) to the Columbia River. Frenchman Springs basalt is exposed at the mouth of Hood River.

An anticline trends north through the southwest corner of the Hood River Valley between Lake Branch Creek and the West

Fork Hood River. Another anticline trends east across the southern part of Middle Mountain and plunges to the east. No dip in the Yakima Basalt is evident along Green Point Creek.

Two main structural trends occur within the area - NE to E trending normal (?) faults and folds and NW trending faults and dikes. Two NE trending faults were mapped, one in the structurally complex Neal Creek drainage and one in the southwest corner of the Hood River Valley. South of Snakehead Creek, a breccia zone approximately 100 m wide marks a fault zone with a throw of about 150 m up to the south. Several small faults occur just north of and parallel to this breccia zone. The NE trending fault in the southwest corner is not manifest but is indicated by a stratigraphic offset in the Yakima Basalt with a throw of about 70 m down to the south.

Along the West Fork Hood River, Frenchman Springs flows are exposed at an elevation of 1350 ft (1N/9E-28); the base of the Frenchman Springs Member is not exposed. Less than one km to the north, the Vantage horizon at the base of the Frenchman Springs Member is exposed along Lake Branch Creek at an elevation of 1550 ft (1N/9E-28b).

Three small olivine basalt dikes ($\sim$1 m wide) were mapped in the High Mg Grande Ronde Basalt (1N/9E-22 & 28). They trend N10W, N15W, and N45W. A series of small faults trending N10W to N55W occur along the Hood River north of Green Point Creek. The faults have about one m wide breccia zones. The faults all occur within the Low Mg Grande Ronde Basalt section. Because Low Mg Grande Ronde flows are indistinguishable from one another, determination of direction and magnitude of movement was not possible. Due to the narrow width of the breccia zones and the generally small amount of shearing in adjacent flows, the offset was probably only a few m. One fault near Ditch Creek clearly displaced a flow 2 m down to the south.

The Hood River displays two prominent bends which are fault associated, one in (2N/9E-36d) and the other in (2N/10E-31b). In Sec. 36 displacement is visible along the fault on the east side of the river but not on the west. The dip is to the north. Not enough faulted flows were exposed to determine throw or direction of movement; however, a two m thick breccia zone occurs along the fault in Sec. 31. Direction of movement was difficult to determine but a slickenside trending N10W and dipping 52S was measured.

Between Dee (1N/10E-7) and the dam on the Hood River (2N/10E-31) a repeated exposure of two Low Mg R_2 Grande Ronde flows and three overlying Low Mg N_2 Grande Ronde flows necessitates a fault down to the southeast through Middle Mountain. The Vantage horizon is exposed on Middle Mountain at about 1600 ft elevation (1N/10E-18) and to the northeast at about elevation 2400 ft (1N/10E-8) indicating a displacement of 280 m. The fault passes between the two prominent fault-controlled river bends discussed above. The Low Mg N_2 Grande Ronde flows exposed northeast of the fault are about 230 m thick; the Low Mg N_2 Grande Ronde section to the southwest is about 130 m. thick. The increased thickness and extensive palagonite breccia on at least two Low Mg N_2 Grande Ronde flows northeast of the fault suggest that the area may have been a topographic and/or structural low when these lavas entered the Hood River Valley.

On the east side of Hood River Valley a breccia zone about 150 m wide marks the location of the Hood River fault which trends N5-15W. The throw is at least 270 m down to the southwest. The valley is cut by several NW trending faults, all down to the southwest. Hood River Valley does not appear to be a graben. A cross-section through Middle Mountain shows several tilted blocks, dipping to the east and separated by faults. The Frenchman Springs flows crop out at approximately the same elevation on the west side of Middle Mountain as they do on the east side of the Hood River fault. Although unmapped, it is believed that a fault trends approximately east-west along the south edge of Middle Mountain and is down to the south. Highly fractured basalt is exposed along the south side of Middle Mountain. Another fault may pass under Blue Ridge on the west side of the upper Hood River Valley. Either, at least 300 m of Yakima Basalt has been eroded from the upper valley, or, it has been down-faulted with respect to Middle Mountain.

Geologic History

The area which is now the Hood River Valley was a topographic low for most or all of the time the Grande Ronde flows were deposited. The lowest basalt member exposed, Low Mg (R_2) Grande Ronde, has a thick palagonite flow top, indicating contact with deep water while the flow was molten. Palagonite breccia is mixed with the flow. Beneath the palagonite, large vesicles ($\sim$ 10 cm in diameter) and vesicle columns fill the top 3 m of the flow. The flow may have been invasive--one which dives under loose sediments carrying water and sediments on top.

The Low Mg (N_2) and High Mg (N_2) Grande Ronde flows also have flow top palagonite exposed along the Hood River. The area was probably a closed basin without exterior drainage or at least with disrupted drainage.

The thicker section of Low Mg (N_2) Grande Ronde Basalts found north of the major fault through Middle Mountain likely were ponded in a confining topographic low. Because of poor exposures, it is difficult to determine if the individual flows are thicker or if there is a greater number of Low Mg (N_2) Grande Ronde flows in this area. The probability that valleys existed at the time the Low Mg flows were being extruded is supported by the existence of an intracanyon flow exposed at the junction of West and Middle Forks Hood River.

The High Mg flows have a fairly constant thickness indicating low relief at the time of extrusion except in the southwest corner of the area. Along Lake Branch Creek four High Mg Grande Ronde flows are mapped. Because only the top two m of the lowest exposed High MgO Grande Ronde flows are visible, the High Mg Grande Ronde thickness is unknown. Palagonite flow-top breccia covers the entire exposure of the lowest High Mg flow from Lake Branch Creek to Mohr Park on the West Fork Hood River. The palagonite and increased number of High Mg flows indicates the area was a structural low during the extrusion of the High Mg Grande Ronde flows.

After the High Mg Grande Ronde flows transgressed the area, a period of non-deposition ensued at around 15 my BP as indicated by the Vantage horizon.

Folding began during the accumulation of the Grande Ronde Basalt and continued, accompanied by faulting, during the deposition of Frenchman Springs flows. The NE-SW trending fault which passes between Lake Branch Creek and the West Fork Hood River occurred after the Frenchman Springs basalt had been deposited. The Frenchman Springs flows were eroded from the structural high created by the fault in the area north of Lake Branch Creek. The Priest Rapids Basalt flowed into the area filling the structural low to the south of the fault and lapped onto the up-faulted eroded Frenchman Springs basalt to the north. The Priest Rapids flow attains a thickness of about 60 m south of the fault. Further west along Lake Branch Creek the Priest Rapids flow overlies about 3 m of pillow basalt.

The NE trending fault in the Neal Creek drainage displays $\sim$10 m thick ridges of cemented breccia which are subparallel to the trend of the Hood River fault. This fault may have been associated with deep shearing which allowed hydrothermal fluids to escape upward into and cement the breccia.

Lake Branch Creek and the West Fork Hood River are separated by a late Pliocene to early Pleistocene andesite flow (Wise, 1969). The andesite laps against High Mg Grande Ronde Basalts on the northeast and against Frenchman Springs and Priest Rapids flows on the east at about the same elevation. This indicates that the NE trending fault through Lake Branch Creek-West Fork Hood River occurred prior to the andesite flow.

The NW trending faults occurred after the Priest Rapids flows were extruded and therefore are younger than the NE trending faults. Some faults appear to be contemporaneous with folding because the faults parallel the strike.

B. Bull Run Watershed Area

Introduction

The Bull Run Watershed lies within the eastern portions of Multnomah and Clackamas Counties and covers more than 390 km^2 (Figure I-1).

Lolo Pass and Mount Hood are to the east; the Columbia River Gorge, Larch Mountain, and the Benson Plateau are to the north; the town of Sandy and the Sandy River are to the west; and the communities of Alder Creek, Brightwood, Wemme, and Zigzag lie to the south. Interstate 80N passes the area on the north, U. S. Highway 26 to the south.

Access to the watershed is by permit only, and locked gates are at each of the entrances. Major approaches are from Sandy on Forest Service Road S-10, from Brightwood on Road S-224, and from Zigzag and Lolo Pass on Road N-12.

The maximum elevation of 4,600 ft is on Hiyu Mountain at the eastern boundary of the watershed. The elevation decreases toward the west; the lowest elevation, less than 500 ft is at the Sandy entrance.

The major stream in the area is the Bull Run River, which flows to the north and then to the southwest from its headwaters at Bull Run Lake. Several smaller streams in the southeast portion of the watershed join and flow into Blazed Alder, which, in turn, flows north into Bull Run River; other streams flow into this river from the east, north and south. Reservoirs No. 1 and 2 are formed by dams on the Bull Run River.

Basalt of the Columbia River Group undoubtedly underlies all of the watershed but is covered by younger geologic units and unconsolidated surficial deposits. Because stream erosion has cut through the younger material, all basalt exposures occur in proximity to rivers and streams. The highest exposure of CRB occurs at an elevation of 3100 ft northwest of Nanny Creek. Lowest exposure is at an elevation of 500 ft along the Bull Run River.

Basalt occurs along at least 80 km of the major streams, but reservoir water covers at least 10 percent of these exposures. In steep-gradient bedrock streams, exposure is often nearly continuous, but in low-gradient streams, percentage of exposure is often much less. Along roads, exposure is generally less than 10 percent.

The base of the CRB is not exposed in the watershed. The deepest part of the basalt section is exposed in Blazed Alder Creek. About 18 km to the north, outside of the watershed, CRB unconformably overlies rocks of the Eagle Creek formation.

Beaulieu (1974) maps overlying units as the Rhododendron formation in the western portion of the watershed and as Pliocene and Quaternary volcanic rocks in the eastern section. During this study, isolated patches of Rhododendron were noted but not mapped further to the east along the Bull Run River.

CRB was mapped along the Bull Run River and Blazed Alder Creek by Wells and Peck (1961) and Peck and others (1964);

more detailed mapping was done by Beaulieu (1974). Engineering studies include those by Dames and Moore (1972a, b; 1973), Patterson (1973), Ruff (1957), Schlicker (1961), Shannon and Wilson, Inc., (1958a, b; 1961, 1963, 1965, 1973), and Stevens and Thompson, Inc. (1957, 1965). A soils survey of the area was conducted by Stevens (1964).

Structure and stratigraphy

Grande Ronde Basalt flows, with a total thickness of about 150 m and Wanapum Basalt flows, with a total thickness of 137 m occur within the watershed. The basal exposed flow is a Log Mg (R_2) flow found in Blazed Alder Creek. Above it lies approximately 95 m of Low Mg (N_2) basalt comprising at least four and possibly more separate flows. These flows are difficult to differentiate either in the field or by trace element geochemistry. Rocks from these flows have extremely fine-grained textures; one of the N_2 flows is characterized by small, clear, glassy plagioclase phenocrysts. All of the flows in this group have the same kind of distinctive jointing: a small colonnade and a proportionally much larger entablature.

Two High Mg Grande Ronde flows with a total thickness of about 43 m lie above the Low Mg flows. These rocks are coarser in texture than the Low Mg flows. Rocks from the top flow are also quite open in texture. The tops of both of these flows, but particularly the upper flow, are deeply weathered. The lowest flow of the two is characterized by a blocky colonnade and multiple layers of sheet vesicles. The upper flow is characterized by well-developed columns, sections of which display, platy jointing. A thin soil zone, and, in one place, a 9 m thick interbed separates the two flows.

The Vantage interbed lies between the Grande Ronde and overlying Wanapum Basalt flows. In the Bull Run syncline, the Vantage is composed of sandy and silty sediments with local soil zones and carbonized wood. The maximum thickness is 1.5 m at Log Creek. In the Bull Run syncline, the base of the Wanapum flow above the Vantage often has up to 9 m of pillow basalt; in the anticline, the contact is flow-on-flow with no evidence of pillows, soil or carbonized wood.

Above the Vantage horizon are the Wanapum flows: six N_2 Frenchman Springs flows and one (or possibly two) R_3 Priest Rapids intracanyon flows totaling at least 137 m. The Frenchman Springs rocks are coarse in texture; three of the six flows, the first, second and fourth, have large, glassy, plagioclase phenocrysts (phyric). The third flow has occasional plagioclase phenocrysts (rarely phyric); the fifth and sixth flows are aphyric. All of these flows display well-developed colonnades and no entablatures. A red clay zone occurs locally between the two upper aphyric Frenchman Springs flows.

The Priest Rapids intracanyon flow displays reversed polarity and, where exposed along the Bull Run River, is characterized by at least 100 m of bedded palagonite, an 8 m thick colonnade and a 60 m thick entablature. Where it overflowed the canyon, the Priest Rapids flow is 12 m thick and forms massive blocky columns. This thinner part of the flow may in fact be a separate Priest Rapids flow, but poor exposures make it impossible to locate a contact.

The dominant structure is a NE trending (roughly N60E) syncline and anticline. A N60E trending, 12 degree SE dipping, thrust fault with at least 180 m of vertical offset occurs on the north limb of the anticline. The entire area displays fractures that trend in sundry directions, but particularly with trends of N10-20W, and N55-65W. The entire structure has a slight regional dip of about 2 degrees to the west-southwest.

The most northerly fold is a N60E trending syncline in which the Bull Run River flows to the southwest. The axis of the syncline lies slightly to the south of the river. The development and persistence of this syncline during the Miocene are shown by pillows that occur locally at the base of the highest High Mg Grande Ronde flow; a 9 m interbed between the two High Mg Grande Ronde flows near the main dam; a less than 30 cm thick interbed between the two High Mg Grande Ronde flows at North Fork; a soil zone of the Vantage horizon; and pillows at the lowest Wanapum flow. The intracanyon Priest Rapids flow has been found only in the syncline and its periphery.

The NE trending, thrust-faulted anticline parallels the syncline and lies south-southeast of it. It is defined by elevations and attitudes of various CRB flows, and is characterized by the absence of pillows, interbeds, and the Priest Rapids intracanyon flow. A Wanapum flow-top near the county line on Road S-154 is deeply weathered -- more than the corresponding flow-top in the syncline -- indicating a Miocene topographic high corresponding to the upper portions of the anticline. The syncline and anticline are believed to extend northeastward through Hood River Valley, where they are now broken by N-NW trending faults, to the Columbia River Gorge where they appear as the Mosier syncline and Ortley anticline.

The complete High and Low Mg Grande Ronde section does not occur in the upper reaches of Blazed Alder Creek. In the northern portion of this creek, at least four N_2 Low Mg flows overlie the R_2 Low Mg reversed flow; upstream in the southern part, High Mg flows are missing. Apparently a structure was developing in Bull Run during early CRB time. After the reverse flow entered the area, a topographic high began to develop where the present-day abbreviated section occurs. A slight relative subsidence both north and south of the high developed. The N_2 Low Mg basalt flowed around the high which was eventually covered by later High Mg flows. Gravity and magnetic maps show anomalies roughly corresponding to this abbreviated section.

The ancient high delineated by the abbreviated section in Blazed Alder Creek was evidently a zone of weakness, because as folds developed, the anticline failed at the margin of the high, producing the thrust fault with vertical offset of 180 m and net slip of at least 900 m.

The best exposure of the thrust fault is just downstream from the confluence of Boulder and Blazed Alder Creeks, where the fault plane is exposed at stream level. Below the thrust plane about 2 m of the underlying basalt flow is coarsely brecciated. Extremely finely-ground tectonic breccia occurs for about 10 m above the thrust plane.

Because of this thrust fault, CRB occurs at higher elevations and more extensively in the southeastern section of Bull Run than has been previously mapped. Highest exposure is at an elevation of 3100 ft. All the CRB in the forward section of the thrust has been disturbed, even if not actually brecciated, and therefore does not produce good outcrops in these areas. Although dense and coherent, a very minor amount of silicification was observed in the breccia of the upper thrust plate.

Linear ridges of tectonic breccia with trends of about N10-20W were observed in Blazed Alder Creek in the lower plate over which thrusting occurred. A smaller ridge also lies within the thrust zone along Boulder Creek. The linear ridges may represent an older, pre-thrust zone of weakness that brecciated during the thrusting, or both zones may be due to later fracturing which cut across the thrusted area.

A vertical fault occurs at North Fork quarry on Road S-10. The fault trends roughly N20W, but horizontal slickensides within the foot-wide fault zone trend in two directions; N30E and N30W. This fault, because of poor exposures, could not be traced for any significant distance.

Numerous fractures occur in the CRB in Bull Run. Although no attempt was made to do a statistical analysis of fracture trends, certain dominant fracture trends are apparent throughout the area. Some fractures are merely breaks in the basalt that cut through regular jointing, and in some cases, several flows; while other fractures are brecciated or contain brecciated zones.

A major fracture trend is N10-20W. Fractures with this trend are found throughout the watershed, but notable concentrations occur along the north-flowing sections of Blazed Alder Creek and Bull Run River and their tributaries. Brecciated zones with this trend also occur near the thrust fault. Along the Bull Run River just upstream from Log Creek, a large brecciated zone with this trend crops out. Aerial photographs and SLAR imagery show a linear with this identical trend that extends north along Blazed Alder Creek and Bull Run River, cuts through the glacial cirque on Falls Creek, and continues up Tanner Creek to the Columbia Gorge and into Washington State. A dike of Boring basalt with this same trend crops out along Blazed Alder Creek before curving slightly and disappearing in a side stream. At one point in Blazed Alder Creek, this dike cuts an older N55W trending breccia zone, another frequently occurring fracture trend in Bull Run.

The N55W trend is found throughout the area but seems to occur most frequently near the thrust fault. Upstream from the thrust fault, N20-55W fractures often contain breccia; these fractures, however, decrease in frequency with distance from the fault.

Other less common fracture trends include N-S, N20E and N80W. Fractures frequently affect patterns of mass wasting and erosion. For example, at the base of the falls at Falls Creek and along Road S-10 on the east side of Falls Creek, massive failure of extremely large blocks of Wanapum Basalt has occurred along N15W trends.

Fractures often control the directions in which streams flow in Bull Run. At one point Blazed Alder Creek flows in a N20W trend and then makes an abrupt turn and follows a N55W fracture. These fractures seem to be most influential in controlling stream direction when the stream is flowing across the regional anticline-syncline structure.

The path of an intracanyon flow of reversed Priest Rapids basalt has been traced from east to west through the watershed. The greatest measured thickness at any one place is 177 m but that thickness was not measured from the absolute bottom of the ancestral channel. The most easterly exposure occurs in the eastern portion of the watershed between Log and Otter Creeks. The intracanyon flow forms a mound on the bench west of Otter Creek and then is exposed by the Bull Run River at the point where the river changes directions from north to west. Again, on the north bench overlooking the river, the intracanyon flow forms large mounds of basalt. The next mapped exposure to the west is in a quarry on the south side of the Bull Run River. Further west, the flow is again cut by the Bull Run River; it then forms a ridge in a clearcut north of the river. It is last exposed in North Fork. From there, it is presumed to have flowed to Crown Point in the Columbia Gorge. It is correlated with the Crown Point intracanyon flow by similar chemistry, magnetic polarity, morphology and flow characteristics, and large amounts of bedded palagonite. Crown Point is on trend and geographically close to the intracanyon flow in Bull Run.

The intracanyon flow in Bull Run is characterized by a

100 m thick palagonite sequence which in places has been waterworked. Foreset beds indicate flow directions to the west and southwest. In other places, the palagonite is unsorted and contains large blocks of basalt up to 3 m in diameter. The flow has a relatively thin colonnade whose thickness varies from area to area but which was measured at 7.6 m along the Bull Run River. The entablature forms distinctive, flat-topped mounds which contrast with the CRB benches surrounding it.

Another distinguishing characteristic of this flow is its somewhat ambiguous remnant magnetic polarity. At some places, the flow produces a normal reading on the fluxgate magnetometer, elsewhere it is reversed. Always, however, a reversed polarity is shown at the top of the section.

The present-day river does not exactly follow the course of the ancestral river through which the intracanyon flow moved. Where the present-day river breaks into the old channel, it reveals an almost vertical, smooth, basaltic canyon wall with a U-shaped valley floor. A very small section of the ancestral valley floor is exposed in the Bull Run River and contains relatively poorly sorted, rounded to subangular basaltic pebbles, cobbles, and occasional boulders ranging in diameter from less than 1 cm to over 1.5 m.

The Bull Run Watershed region was being deformed in earliest CRB time as shown by the abbreviated section in Blazed Alder Creek. The base of the CRB is not exposed in this area to record possible earlier deformation. By High Mg Grande Ronde time, the NE trending syncline and anticline were already developing, as evidenced by the local interbed and pillows between the two High Mg flows in the syncline.

During Vantage time, as elsewhere on the Columbia Plateau, no basalt flows occurred. Instead, saprolite and soil zones developed and drainage systems evolved. When the Frenchman Springs flows entered the area, pillows formed in the syncline at the base of the earliest Frenchman flow.

Between Frenchman Springs and Priest Rapids time, a major east-west river drainage system formed. It was through this 180 m deep canyon that the Priest Rapids intracanyon flow entered the area from the east and flowed west-northwest to Crown Point in the present-day Columbia River Gorge.

Sometime during Wanapum time, and probably before Priest Rapids time, thrusting occurred on the northwest limb of the anticline. Phyric Frenchman Springs flows but not Priest Rapids flows have yet been found on the upper thrust plate. Vertical fracturing accompanied the thrusting, with most intense fracturing nearest the thrust zone.

The CRB surface was eventually covered by younger volcanic and volcaniclastic rocks. Fracturing undoubtedly continued to occur, and erosion along these fractures eventually re-exposed CRB. The most recent fracturing appears to be the N10-20W trend that is visible on SLAR imagery and air photos. Boring dikes with this same trend indicate that east-west extension accompanied or occurred after the north-south compression of the region.

C. Salmon River Area

Introduction

Located between the Bull Run River and the Clackamas River drainages is a series of small isolated outcrops of CRB which cover approximately 25 km^2 within a map area of about 250 km^2. Relationships between these exposures are difficult to determine because of structural complexities within some of the areas and because of rather extensive areas of intervening younger Rhododendron Formation and sedimentary valley fill.

Structure and stratigraphy

Like other areas previously discussed, the Columbia River Basalt Group exposed in this area is assigned to the Yakima Basalt Subgroup. As in nearly all exposures of CRB in western Oregon, the basalts in this region are mapped as Grande Ronde Basalt and Wanapum Basalt. The base of the basalt is not exposed in this region while the upper contact is unconformable with the Rhododendron Formation. The Wanapum Basalt is represented by two to four flows with an approximate total thickness of 75 m. Although a combination of intricate structure, poor accessability, and discontinuous outcrops precludes ascertaining the number of flows in the Grande Ronde Basalt, certain relationships can be determined. Two High Mg chemical type flows occupy the upper part of the formation and attain a thickness of about 70 m. The low Mg chemical type possesses an unknown number of flows but can be subdivided into the CRB N_2 and R_2 paleomagnetic intervals that are about 160 m and at least 50 m thick, respectively.

Traversing the area is the N30W trending Salmon River fault that separates the Columbia Plateau type structural trends from those of the Portland Hills-Brothers fault zone. This N30W trending fault displays a vertical displacement of about 145 m down to the west with a moderate amount of associated tectonic breccia near Arrah Wanna. However, it is believed that this apparent displacement is the result of offset of some pre-existing structure by right lateral movement because (a) near the Salmon River opposite sides of the fault lack significant vertical displacement, and (b) along this trend in the Upper Salmon River the fault displays right lateral displacement. Folds to the east of this fault trend generally N60E with the Bull Run-Ortley anticline terminating at the Salmon River fault in the vicinity of Brightwood. The upper Salmon River area is a broad asymmetric anticline with the same trend and a possible connection with the outcrops at Robinhood quarry. West of the Salmon River fault a small segment of a minor anticline occurs in the Alder Creek-Sandy River area that strikes N75W similar to the folds of the Portland Hills and is the only fold mapped in the Clackamas River drainage.

The intervening synclines are not exposed except for a small area of hyaloclastic material that may mark the axis of a syncline near the confluence of the South Fork and Salmon River. The location of other synclinal axes are based on other lines of evidence and are discussed below.

Faulting has severely complicated stratigraphic relationships in all areas except Alder Creek and the upper Salmon

River. The Salmon River anticline is, however, down faulted about 75 m on the north by a NE trending normal fault.

The region between Arrah Wanna and the U. S. Highway 26 bridge crossing of the Salmon River has been deformed by several faults, all in close proximity to one another, but with different trends. A short segment of a thrust fault southwest of Arrah Wanna has displaced the basalt stratigraphically about 180 m. Associated tectonic breccias exceed 100 m in thickness; however, the thrust plane is not exposed. This fault has roughly the same trend and displacement as the Promontory Park fault in the Clackamas River and may well connect with it. The Salmon River fault is exposed an elevation of 2400 ft on Arrah Wanna trail and is responsible for the disappearance of the basalt section to the west at this locality. Displacement along this fault is not known. A N5-10W trending fault has been mapped passing near three quarries in the basalt. It is represented in the quarry in the Salmon River by a 30 m wide breccia zone and at the two quarries north of the Sandy River, near North Boulder Creek, as a much broader, less easily defined structure that has displaced the western quarry down with respect to the upper quarry.

Geologic History

The history of this region is not easily interpreted because of the lack of continuity between outcrops and the lack of exposed synclinal areas; however, certain events can be deduced. The NE trending folds are known to have formed during the incursion of the basalts because of the on-lap against anticlines of some flows and the hyaloclastic and pillow deposits found only in structurally depressed areas. These features are not observed in this area but occur in the eastward extension of the folds. Similarly the Arrah Wanna thrust fault probably formed during the later stages of the deformational episode that produced the folds as is the case with the Bull Run thrust and some of the thrusts on the Columbia Plateau.

The youngest tectonic event to have occurred is the Salmon River Fault. When projected to the south, the fault apparently has displaced Pliestocene glacial features as seen on air photos and SLAR imagery near Tumbling Creek, a tributary of the upper Salmon River.

D. Clackamas River Area

Introduction

Columbia River Basalt is exposed in the Clackamas River area within deeply cut canyons of an extensive drainage system that covers more than 700 km^2. The basalt flows form impressive cliffs with occasional waterfalls within this area some 73 km southwest of Mt. Hood (Figure I-1). The eastern part of the area is characterized by the constructional volcanic terrain of the high Cascade Range while the west is dominated by more maturely dissected western Cascade topography.

The basalts of the Columbia River Group are overlain, underlain and interfingered with volcanic and volcaniclastic rocks of local Cascadian origin. The Clackamas River valley in the vicinity of Ripplebrook Ranger Station is the approximate southern limit of these basalts, where they lap against a pre-existing topographic high formed by the Little Butte Volcanic Series. Successive flows of CRB filled relatively smooth terrain to the north of the highland and encroached progressively deeper into the foothill valleys. Sediment and distal volcanic facies in turn covered the southern perimeter of the basalt during the interflow periods to form a number of interbeds up to 46 m thick. Similarly, deposits of the Sardine Formation rapidly buried the basalt after the last flow entered the area.

Deep incision by the Clackamas River and its tributaries has exposed more than 550 m of CRB in this area. The complete basalt sequence can be seen in the cliffs forming the canyon walls in the vicinity of Three Lynx.

Structure and stratigraphy

The general geometry of the CRB in the Clackamas River area is a broad slab that is gently inclined toward the northwest. Dips over most of the area are less than 10 degrees, in part accounting for the extensive exposures that occur between Lake Harriet on the east and North Fork Reservoir on the west.

The structure of the area consists predominantly of northwest-trending faults that cut the gently tilted basalt in an en echelon pattern (Figure III-1), as is reflected in the drainage pattern of the northwest flowing Clackamas River. NE and N-S trending faults also occur, but are in the minority. Some faults are predominantly strike-slip and others are predominantly dip-slip; however, all fault planes are vertical or near-vertical. Moreover, there is an absence of

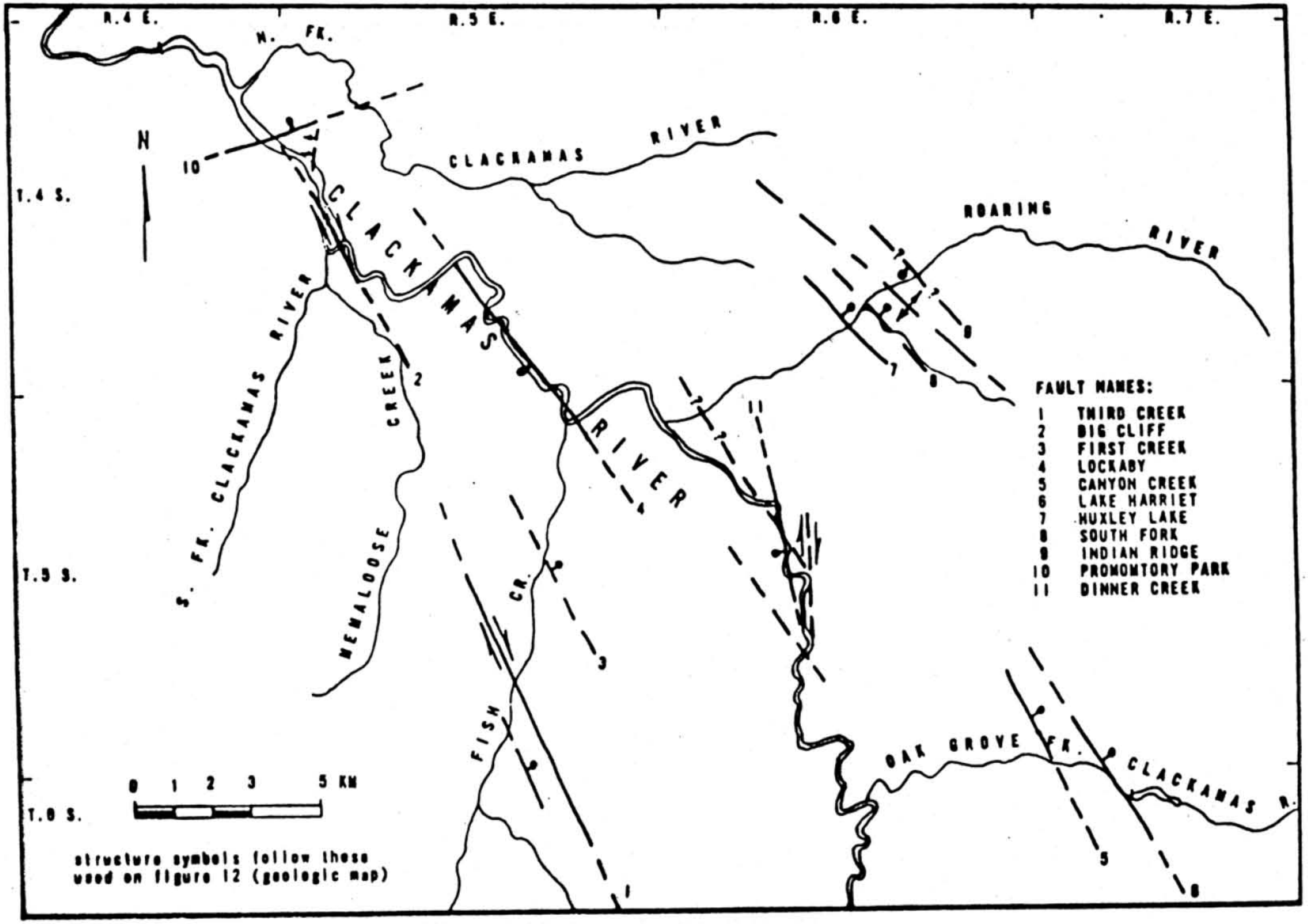


Figure III-1. Tectonic Map of the Clackamas River Area drag-folds associated with these faults.

The faults in the northeast part of the area constitute the deformed boundary of an otherwise relatively unwarped body of basalt. Dips in the Roaring River and Lake Harriet areas range between 20 and 40 degrees adjacent to faults with offsets of 200 m or more. The attitudes of flows observed within the Roaring River drainage define a northwest trending anticline with a crest that appears to be down-dropped as a block or blocks along the Huxley Lake, South Fork and the Indian Ridge faults. The Lake Harriet attitudes appear to reflect the asymmetrical east limb of the "Clackamas Anticline" of Peck and others (1964), or possibly a monoclinal fold down to the east. Faults over the rest of the area are not associated with steeply dipping flows, in distinct contrast with those on the northeast perimeter of the area. The Lockaby fault, for example, has more than 100 m of vertical offset along a very narrowly defined vertical fault plane. Flows adjacent to it are relatively undisturbed by this movement between NW trending en echelon faults. However, this simple picture is complicated by strike-slip movement along at least two of these faults.

Right lateral faults occur at Big Cliff and near Third Creek, a tributary of Fish Creek. Both of these faults define prominent air photo linears that are clearly evident within rocks of the overlying Sardine Formation. An apparent normal displacement of 15 to 30 m occurs across the Third Creek fault, but no detectible displacement can be seen at Big Cliff. The amount of horizontal offset on either of these faults cannot be deduced based upon existing data. However, many lesser fractures with horizontal slickensides can be seen throughout the area, suggesting that the collective offset on all such fractures and faults could be substantial.

The shallow dips exposed in the Clackamas River canyon are only slightly greater than the gradient of the river itself, so that abrupt changes in the stratigraphy along the river are nearly always the result of faulting rather than folding. Both the disappearance of the top of the CRB at North Fork Reservoir and the appearance of the base of the section near Three Lynx are, in part, the result of dip-slip movements on normal faults rather than dip alone. The net effect of this faulting and particularly that at North Fork Reservoir is that one does not traverse the entire CRB sequence from northwest to southeast through the Clackamas River canyon. Less than half of the 17 flows are exposed at highway level across the area due to faulting. Thus, an excursion through the Clackamas River canyon is an experience limited to the lower half of the section.

The stratigraphy of the Clackamas River area consists of Wanapum and Grande Ronde Basalt. Only the Frenchman Springs Member has thus far been identified within the former of these two formations. The Grande Ronde stratigraphy is very similar to that observed elsewhere, except that interbedded sedimentary units are more common and the distinctive Prineville chemical type is present.

The Grande Ronde Basalt in the Clackamas River area consists of at least eleven flows and five or more interbeds with a combined thickness of more than 425 m (Figure III-2). Two

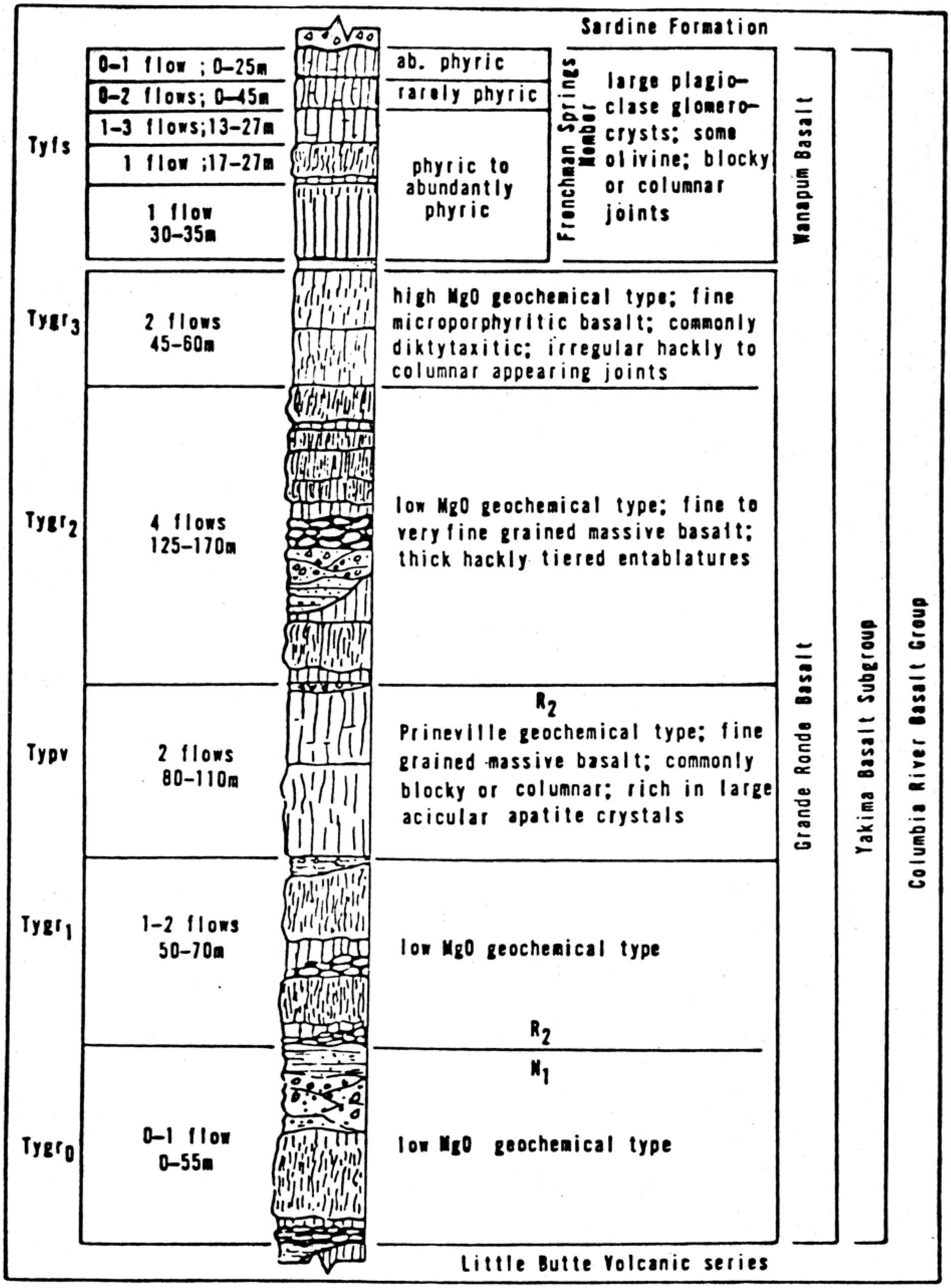


Figure III-2. Generalized Stratigraphic Column for Columbia River Basalt in the Clackamas River Area

High Mg flows occur at the top of the formation. The remainder of the Grande Ronde Basalt consists of flows of the Low Mg geochemical type separated into two approximately equal parts by two intercalated flows of Prineville chemical type. There are two paleomagnetic reversal events within the Clackamas River section that divide it into three plarity intervals. These are considered to be equivalent to the R_2/N_1 and N_2/R_2 paleomagnetic horizons recognized by previous workers elsewhere in the Columbia Plateau (Figure II-2). The N_2/R_2 paleomagnetic break coincides with the Low Mg/Prineville geochemical break, making this a well-defined stratigraphic horizon.

The Prineville flows are distinctive from the standpoint of both trace element and major oxide geochemistry. They also differ from other flows within the Grande Ronde section from the standpoint of petrography and certain physical characteristics.

The Prineville basalt type was first recognized and described by Uppuluri (1973, 1974) from exposures near Prineville Dam in central Oregon. Other flows of this chemical type were also observed by Nathan and Fruchter (1974) at Buck Creek and Tygh Ridge about 47 km north-northeast of the type locality, where they are intercalated with flows of the Low Mg Grande Ronde geochemical type. Wright, and others (1973) and Brock and Grolier (1973) noted the anomalously high P_2O_5 concentrations in these flows, as did Uppuluri at the type locality.

The Prineville chemical type flows in the Clackamas River drainage are easily distinguishable from other Grande Ronde flows by both major oxide and trace element data. Four trace elements, Sm, Eu, Ba and Co, are particularly striking as differentiators. Ba concentrations in the Clackamas River flows are higher by a factor of two to three than any of the other flows in the section. The only comparable value anywhere in the Columbia River Basalt Group is that of the Umatilla Member of the Saddle Mountains Basalt, which has Ba concentrations that are slightly higher. Conversely, Co abundances in the Clackamas River flows are 30 to 37 percent lower than all other flows in the section. It is in fact lower than in any other chemical type in the entire Columbia River Basalt Group. Eu, like Ba, has concentrations that are greater than the other flows by a factor of two to three, which is approximately equal to the Umatilla and slightly exceeded by the youngest of the two Ice Harbor flows of the Saddle Mountains Basalt. Sm concentrations are 30 to 60 percent higher than Low Mg flows and 80 to 85 percent higher than High Mg Grande Ronde flows. Major oxide distinctions include P_2O_5 concentrations that are three to four times greater, SiO_2 that is 2 to 4 percent lower, and TiO_2 that is up to 40 percent higher than other Grande Ronde types.

The Prineville flows, as their unusual chemistry would suggest, are petrographically distinguishable from other Grande Ronde flows. Their most distinctive characteristic is the anomalously long, acicular apatite crystals that occur in great abundance in all thin sections. Acicular apatite also occurs in other flows in the section but is relatively finer-grained by a factor of three to four. The presence of these crystals is a direct reflection of the anomalously high

P_2O_5 content.

The Prineville flows can also be distinguished from the rest of the Grande Ronde section on the basis of jointing characteristics. They rarely have hackly entablatures and consist almost entirely of fair-to-well-developed blocky colonnades. This contrasts dramatically with the entablature-dominant, Low Mg Grande Ronde flows above and below them.

The stratigraphy of the basalts along the Clackamas River is also characterized by interbeds, as previously noted. These units increase in number and thickness from north to south across the area. They are useful stratigraphic markers on a local basis. Although the composition of the interbeds is varied, the presence of stratified, fine-grained deposits clearly indicates that bodies of water covered much of the area. Pillow complexes up to 25 m thick commonly occur above these deposits indicating ponded water. This condition prevailed throughout CRB time in the Clackamas River area and was also the case in other peripheral areas of the Columbia Plateau as well (Swanson, 1978).

Geologic History

Very little contemporaneous structural activity is indicated during CRB time. Minor pre-reversal folding is indicated by dips that are steeper within the Prineville flows than in overlying flows in some localities. The magnitude of this folding is considered minor since the number of flows and their collective thickness within the Grande Ronde subunits is nearly constant across the Clackamas River area (Anderson, 1978). Broad basining and possible faulting is indicated by the exclusion of the upper two to three flows of the Frenchman Springs sequence from the area immediately adjacent to the southern edge of the basalt. This occurs over a distance of 1.8 to 3.7 km and involves about 67 m of section.

The major offsets observed on faults cutting CRB in the Clackamas River area are mostly post-Sardine in age.

E. Old Maid Flat Exploratory Hole

The exploratory hole at Old Maid Flat (2S/8E-15cd) on the western flank of Mt. Hood was drilled to a depth of 4,003 ft at an elevation of 2,750 ft. The hole was drilled with rotary bits and all samples collected were cuttings brought up with the circulating mud. Most samples from any given depth contained much less than 100 percent of any one rock type indicating a significant amount of uphole contamination, becoming a more serious problem with depth. From a complete set of samples split from those collected at the time of drilling, we chose samples for analysis that seemed most likely to contain a high percentage of basalt. We were guided in this choice by the lithologic log and various downhole geophysical logs. From these samples we chose seven that appeared to represent seven individual flows, most of which were greater than 30 m thick, and one sample consisting of large chips of gabbro brought up on the bit from a depth near 3500 ft. Each sample selected was thoroughly washed and sieved to obtain larger fragments which were then hand picked with the aid of a binocular microscope. The most abundant group of basaltic chips in each sample with similar physical characteristics were selected for analysis. Approximately one gram of each sample was selected and then further cleaned in an ultrasonic vibrator to remove any traces of drilling mud and other clay-sized particles. The eight prepared samples were then analyzed by instrumental neutron activation analysis (INAA) in the standard manner.

The geochemical data generated are presented in Figure III-3 and a summarized evaluation of this data in terms of identification and correlation is presented in Figure III-4. The results are summarized as follows:

1. All basalt samples analyzed are CRB and each was identified with considerable confidence as to individual chemical type.

2. Basalt occurs beneath the Old Maid Flat site at a depth interval from 2028 to 3850 ft, a total interval of 1822 ft. This composite thickness is very similar to the CRB in the Clackamas River area. We originally predicted that the thickness of CRB beneath Mt. Hood would be between 1500 and 2000 ft based on a composite thickness of all units of CRB known to occur from the Columbia River Gorge to the Clackamas River.

3. The bottom 1045 ft of this interval is bracketed by Low Mg Grande Ronde Basalt flows which is comparable in thickness to sections at Multnomah Creek (1100 ft) and in Clackamas River Area (1500 ft).

4. Sample OMF 3140 is from a Prineville chemical type flow. The position of this flow, below a Low Mg Grande Ronde flow is similar to that of the uppermost Prineville flow at Tygh Ridge (Nathan and Ruchter, 1974). No other Prineville flows are known in the Cascade Range other than those recently

SAMPLE	NA		LA		SM		CE		EU	
OMF 2072	2.05	0.04	25.7	1.80	7.52	0.14	57.00	3.00	2.18	0.09
OMF 2900	1.94	0.04	22.8	1.60	6.01	0.12	49.00	3.00	1.90	0.08
OMF 3140	2.43	0.04	23.4	1.80	8.69	0.14	53.00	3.00	3.57	0.13
OMF 3290	2.20	0.04	23.5	1.60	6.63	0.12	50.00	3.00	2.32	0.09
OMF 3518	2.02	0.04	11.1	1.20	3.12	0.08	30.00	2.00	1.10	0.06
OMF 3530	2.33	0.04	23.6	1.80	7.58	0.14	51.00	3.00	2.69	0.11
OMF 3680	2.00	0.04	26.7	1.80	6.82	0.12	58.00	3.00	1.81	0.08
OMF 3850	2.25	0.04	26.5	2.00	7.23	0.14	60.00	3.00	2.17	0.09

SAMPLE	LU		IH		HF		CO		FE	
OMF 2072	0.60	0.09	4.10	0.40	3.80	0.60	38.40	1.10	10.62	0.12
OMF 2900	0.54	0.08	5.20	0.40	3.60	0.60	38.30	1.10	8.74	0.11
OMF 3140	0.62	0.09	3.90	0.40	3.10	0.60	27.40	0.90	8.69	0.11
OMF 3290	0.62	0.09	4.40	0.40	3.40	0.60	33.00	1.00	8.44	0.10
OMF 3518	0.35	0.06	1.50	0.30	2.40	0.40	42.70	1.00	6.91	0.09
OMF 3530	0.51	0.09	4.40	0.40	3.60	0.60	30.90	1.00	8.59	0.11
OMF 3680	0.44	0.08	6.20	0.40	4.30	0.60	35.90	1.00	8.67	0.11
OMF 3850	0.58	0.09	6.60	0.50	6.00	0.70	35.30	1.10	9.34	0.12

SAMPLE	SC		CH		BA		
OMF 2072	36.60	0.20	31.00	10.00	490.00	150.00	Frenchman Springs Member
OMF 2900	33.99	0.19	17.00	8.00	550.00	140.00	Low Mg Grande Ronde Basalt
OMF 3140	36.40	0.20	8.00	7.00	2400.00	300.00	Prineville Basalt
OMF 3290	33.33	0.19	20.00	8.00	1030.00	170.00	Log Mg Grande Ronde Basalt (Contaminated)
OMF 3518	26.02	0.15	340.00	80.00	170.00	100.00	Gabbro - Not CRB
OMF 3530	35.28	0.20	31.00	10.00	1290.00	180.00	Low Mg Grande Ronde Basalt (Contaminated)
OMF 3680	31.95	0.18	17.00	8.00	590.00	140.00	Low Mg Grande Ronde Basalt
OMF 3850	33.48	0.20	21.00	9.00	630.00	140.00	Low Mg Grande Ronde Basalt

Figure III-3. Geochemical data on Old Maid Flat drill hole samples.

Elevation	Depth	Thickness	Sample	Geochemical Identification & Comments
2750'	0	2028'		Post CRB Mudflow Deposits, alluvium and volcanic sediments
722'	2028'	60'	OMF2072	Frenchman Springs Member
662'	2088'	727'		(Local volcanic episode)
-65'	2815'	167'	OMF2900	Low Mg Grande Ronde Basalt (2253-Age dated Sample - 12.2 $\pm$ 2 m.y.) #3070' Sidewall sample Normal Polarity)
-232'	2982'	208'	OMF3140	Prineville Basalt
-440'	3190'	150'	OMF3290	Low Mg Grande Ronde Basalt (contaminated w/Prineville)
-590'	3340'	170'	OMF3518	(Interbed & small intrusion) Gabbro - dike or sill
-760'	3510'	120'	OMF3530	Low Mg Grande Ronde Basalt (contamined w/Prineville)
-880'	3630'	110'	OMF3680	Low Mg Grande Ronde Basalt
-990'	3740'	110'	OMF3850	Low Mg Grande Ronde Basalt
-1100'	3850'	150'		Volcanic sediments (XLTuff - age dated 8 m.y.)
-1250'	3970'			

Total Thickness of CRB interval - 1822'; 1045' of Low Mg Grande Ronde

Figure III-4. Columbia River Basalt stratigraphy in Old Maid Flat Exploratory Hole found in the Clackamas River area (Beeson and others, 1976; Anderson, 1978).

5. Samples OMF 3290 and OMF 3530 are Low Mg Grande Ronde contaminated with approximately 40 percent Prineville basalt from uphole. This is indicated by the Low Mg Grande Ronde chemistry except for Ba, Sm, Sc, Co and Eu which have values between those of Prineville and Low Mg Grande Ronde.

These preliminary conclusions indicate that, except for local interbeds, a normal thickness of CRB occurs under Mt. Hood and that the 3850 ft sample is probably the lowest (or near to the lowest) CRB flow in this area. This suggests that the rocks below this sample are older than the CRB. It is possible that the lower 153 ft of the hole represents an interbed, but it is doubted that the CRB extends much below this level. Further study of the geophysical logs and the cuttings should be carried out to refine the thickness of basalt flows and detect possible interbeds, although inter-beds beds of significant thickness are known to occur between depths of 3340 and 3510 ft and 2088 and 2815 ft. The lower interval is complicated by a gabbroic intrusive (OMF 3518) not related to CRB. The upper interval is much thicker than any known interbed in the Cascade Range (even the Clackamas River area which is marginal to an older highland) which indicates a contemporaneous local center of andesitic volcanic activity. This local volcanic activity effectively produced a topographic high which prevented CRB flows from covering this area until the Frenchman Springs flow which occurs in the hole from 2028 to 2088 ft. It should be noted that the only volcanic interbed within the CRB in the nearby Bull Run River area is a synclinally localized, 30 ft thick, light tuffaceous sediment which occurs between two High Mg Grande Ronde flows and is within the same time interval as this major interbed at Mt. Hood. The same stratigraphic horizon in the Salmon River and Brightwood areas show no interbed.

The CRB at Old Maid Flat occurs between an elevation of 772 ft above and 1100 ft below sea level. Therefore, it is likely that considerable down faulting occurred about Mt. Hood in addition to earlier folding of CRB. The presence of a Prineville basalt flow locally suggests that the area was structurally low, although not the lowest point in the structure as no hyaloclasitic materials were noted in the cuttings from the Old Maid Flat hole.

A sample of the uppermost Grande Ronde flow from 2953 ft was dated by 40K/40Ar with the resulting age determined to be 12.2 $\pm$ 2 my which seems to conflict with the relative age from stratigraphic criteria. It is believed that the data is compatible because the age may be within the limits of analytical error and the possibility of Argon loss at elevated geothermal temperatures which probably existed in the geologic past is exceedingly great. Atlantic Richfield Hanford Company (p. 49, 1976) dated approximately 300 samples of Yakima Basalt by the 40K/40Ar method. They state:

> "The apparent ages of the samples below Rosa range in erratic fashion from about 11 to 15 million years B.P. Investigations as to the cause for the erratic relationship between potassium-40 and argon-40 revealed that the variation in apparent age increased as the glass content increased and was highly erratic in those samples in which glass had altered to palagonite."

Low Mg Grande Ronde flows, as a group, are finer grained and contain more glass than other units.

IV. GENERALIZED STRUCTURAL MODEL OF THE CRB IN THE CASCADE RANGE

A. Introduction

Although the exposures of CRB are somewhat limited in the general Mt. Hood area, certain consistencies lead the authors to believe that a generalized structural model can be presented that is at least a first order approximation of the actual geologic structure.

The structural model which is proposed consists of 1) several NE trending folds passing through the Cascade Range and merging with folds of the Columbia Plateau (at least one of the anticlines is faulted and thrust in places); 2) a wrench fault zone exposed in the Clackamas River area which is aligned with the Brothers fault zone and the Portland Hills fault zone and along which NW trending en echelon faults and a few NW trending folds occur; and 3) N-NW trending fractures and faults some of which display right lateral movement, the more northerly oriented often being the locus of dike injection; 4) Cascade upwarp and cauldron-type faulting around Mt. Mood.

B. NE Trending Folds and Thrust Faults

The most dominant and consistent structural trend in the CRB is the NE trending folds. Most strike from N40 to 65E which is similar to those along the Columbia River from Hood River to The Dalles. Because the structure began to develop during the time that the CRB was still spreading over the area, it is assumed that fold trends project across the present Cascade Range and merge with those of the plateau. The mapping of CRB in the Hood River Valley area tends to confirm this premise.

The characteristics of the NE-trending folds are generalized as follows:

1. They are asymmetrical with gentle dips (5-15 degrees) on the SE limbs of the anticlines and steep dips (25-35 degrees) on the NW limbs.

2. The anticlines are occasionally thrust faulted on the NW limb with thrusting from SE to NW.

3. Folding began by High Mg Grande Ronde time. Pillow lavas and interbeds often occur in synclines; abbreviated sections occur in crests of anticlines.

4. Folding continued to build structural relief long after the last CRB flow (Priest Rapids) entered the area. Total structural relief on the folds in the Bull Run Watershed is on the order of 300 m.

5. These folds seem to change trend and/or terminate near the N30W trending Salmon River fault.

6. Near the anticline hingeline, zones of brecciation which parallel flow layers are common.

These folds are similar in trend, age, and physical characteristics to those in CRB on the western margin of the Columbia Plateau (Kienle and others, 1978) which strongly suggests that they belong to the same episode of deformation.

An extrapolation of Columbia Plateau folds southwestward across the Cascade Range, provides the following structural correlations:

1. The Mosier syncline extends up the West Fork Hood

River and becomes the Bull Run syncline.

2. The Ortley anticline extends into the Bull Run anticline which then curves southward to Brightwood where it terminates against the N30W trending Salmon River fault. This anticline is known to be faulted on the NW limb where it crosses the Columbia River. The NW limb is also thrust-faulted in the Bull Run Watershed area.

3. The Dalles syncline has no equivalent fold exposed west of the Cascades, but it should project under Mt. Hood. It is suspected that this is the major syncline through the Cascades in this area, and possibly contains western Oregon CRB flows not found in other exposures of the Cascades, such as the Waverly flows and the Pomona flow.

4. The south limb of this syncline may be the north limb of the anticline that is mapped in the upper Salmon River. No thrust fault has been observed in this anticline, but tectonic breccias occur just northwest of this anticline near the south Fork Salmon River.

Thrust zones parallel to the NE fold structures have not been previously noted. A major thrust on the NW limb of the Bull Run anticline and fragments of thrust zones on the South Fork Salmon River (?) and in the vicinity of Arrah Wanna have been mapped. The characteristics of these thrust faults are as follows:

1. Thick (100-200 m) massive fine to coarse breccia zone above thrust plane.

2. Thin (1-3 m) coarse breccia zone below the thrust plane.

3. Low angle ($\sim$12 degrees SE) thrust plane.

4. Magnitude of thrusting is approximately one km with approximately 200 m of throw.

5. Within the breccia zone flow contacts and attitudes are obscured.

6. Dip of the thrust faults changes along strike and may become faults which appear to have mostly vertical movement in the same sense as the thrust movement.

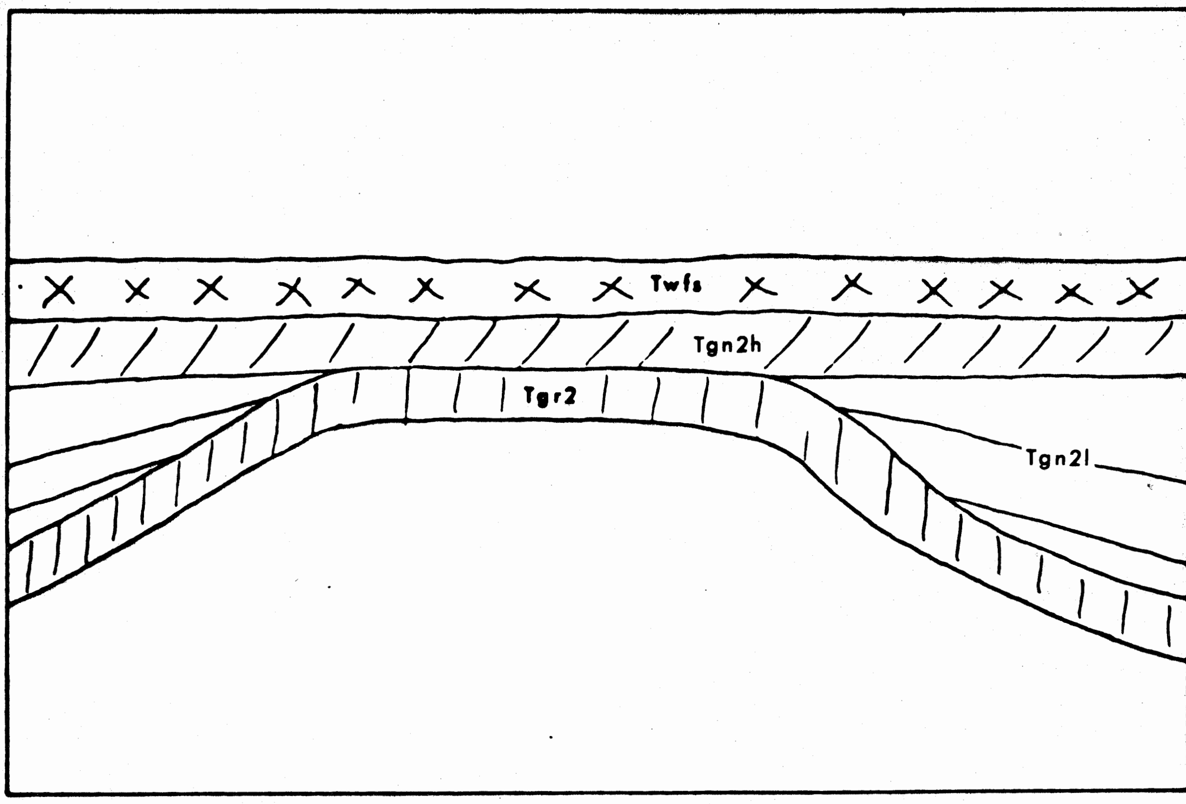
7. Thrust faults are associated with pre-existing zones of weakness in the basalt such as thinned CRB sections or vertical faults.

8. NW trending fractures (N20W) appear to cut thrust zone breccias which have resulted in cemented zones which now stand out as resistant ridges as a result of differential weathering.

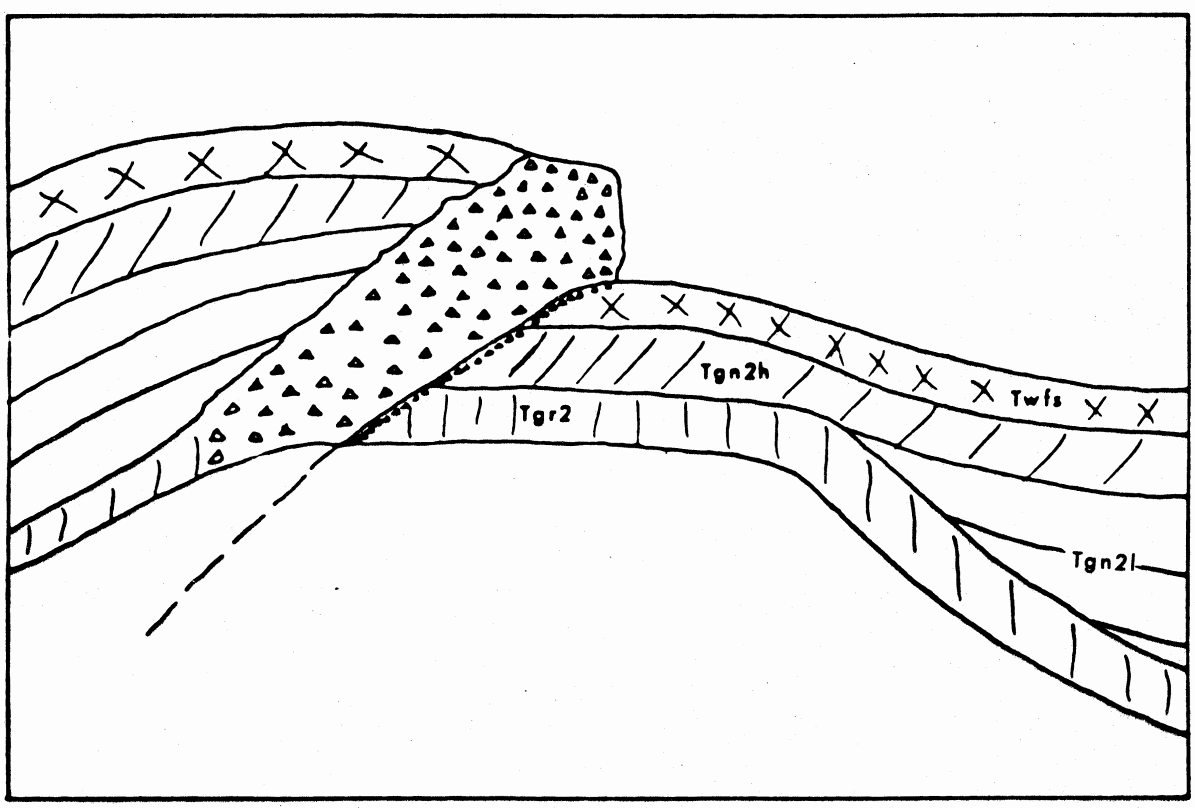
9. Breccias of thrust zones are massive and show coherent but little hydrothermal alteration or cementation except for the N20W trending ridges.

Detailed stratigraphy in the Bull Run Watershed area reveals an abbreviated section of CRB adjacent to the thrust fault. It is believed that this thinned section is directly related to the development of the thrust fault in this area (Figure IV-1).

It is concluded that the thrust faults represent fairly shallow, thin-skinned deformation of the brittle, competent basaltic flows in response to N-NW to S-SE compression. These faults may not extend to a great depth below the basaltic layer because the underlying less competent rocks may have



a)



b)

Figure IV-1. Development of Bull Run thrust fault. Sketches show cross-sections (a) pre-thrust and (b) post-thrust failed more by folding. There is no evidence to indicate that these zones extended through the lithosphere to provide paths for magmas to migrate to the surface.

C. Wrench Fault Zone

The second major feature of this structural model is a wrench fault zone exposed in the Clackamas River area. This wrench zone which is on trend with the Brother's fault zone - Portland Hills fault zone has the following characteristics:

1. En echelon faults, both right lateral and normal, which are oriented about N30W, slightly different than the trend of the wrench zone itself ($\sim$N45W).

2. A few NW trending folds occur such as the one in Roaring River and the Portland Hills. The trend of these folds is slightly more westerly than that of the wrench itself. Fold of this trend seem to be restricted to the southwest of the N30W trending Salmon River fault. The wrench zone seems to be more convergent (more folds) near Portland and more divergent (more faulting) in the Clackamas River area.

D. NW Trending Faults and Fractures

Another structural feature that appears to occur throughout the entire area is a system of N-NW trending fractures and faults. Some of these faults display slickensides which indicate that right lateral movement has occurred. These fractures and faults may be subdivided roughly into three dominant trends:

1. N10-20W - Have little if any vertical offset; fault zones are narrow ($\sim$5 m), brecciated and cemented; cavity

fillings are common; Boring-type (Plio-Pleistocene) basaltic dikes usually occur in fractures having this orientation; fractures with this orientation cut across the flows and breccia zone.

2. N30W - Have wide breccia zone (10-30 m); some cavity fillings; no dikes; occasional considerable vertical offset.

3. N55W - Trends occur most commonly near the thrust zone in the Bull Run Watershed Area; no vertical offset observed; little breccia in a narrow ($\sim$1 m) zone.

These fractures seem to vary considerably in length, but the N30W and the N10-20W are more extensive than the N55W fractures. Individual fractures seem to connect to those of another trend which gives the impression that the lithosphere has rifted along an irregular line bounded by fractures of different orientations (Figure IV-2). Detailed observations along streams show that stream trends are often the result of two trends which intersect one another (Figure IV-3). We interpret these trends to indicate predominantly extension along N10-20W zones and right lateral movement along N30W zones. The N55W zones show little evidence of movement and may be a secondary effect concentrated near existing thrust faults.

E. Cascade Upwarp and Subsidence

The CRB dips gently away from the High Cascades on both the west and east flanks of the Cascades in the vicinity of Mt. Hood. This broad feature is probably related more to the nature of subduction beneath the Cascades than to coupled

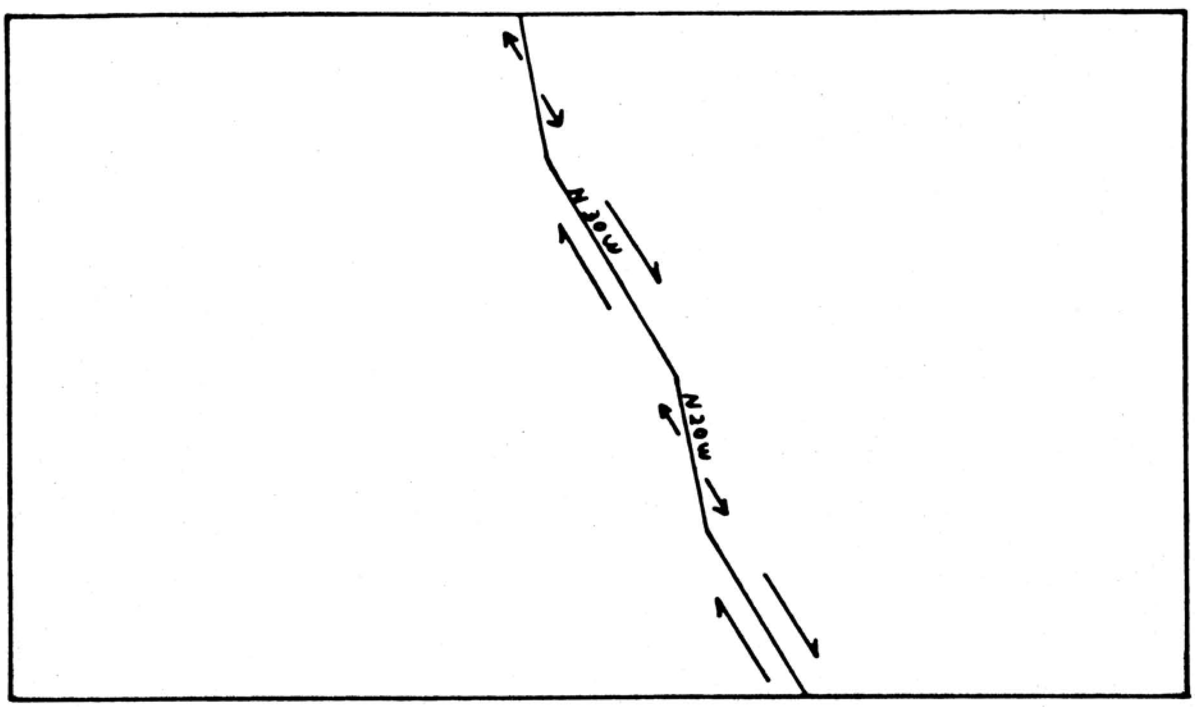


Figure IV-2. Pattern of faulting. N20W trend is zone of extension and dike emplacement.

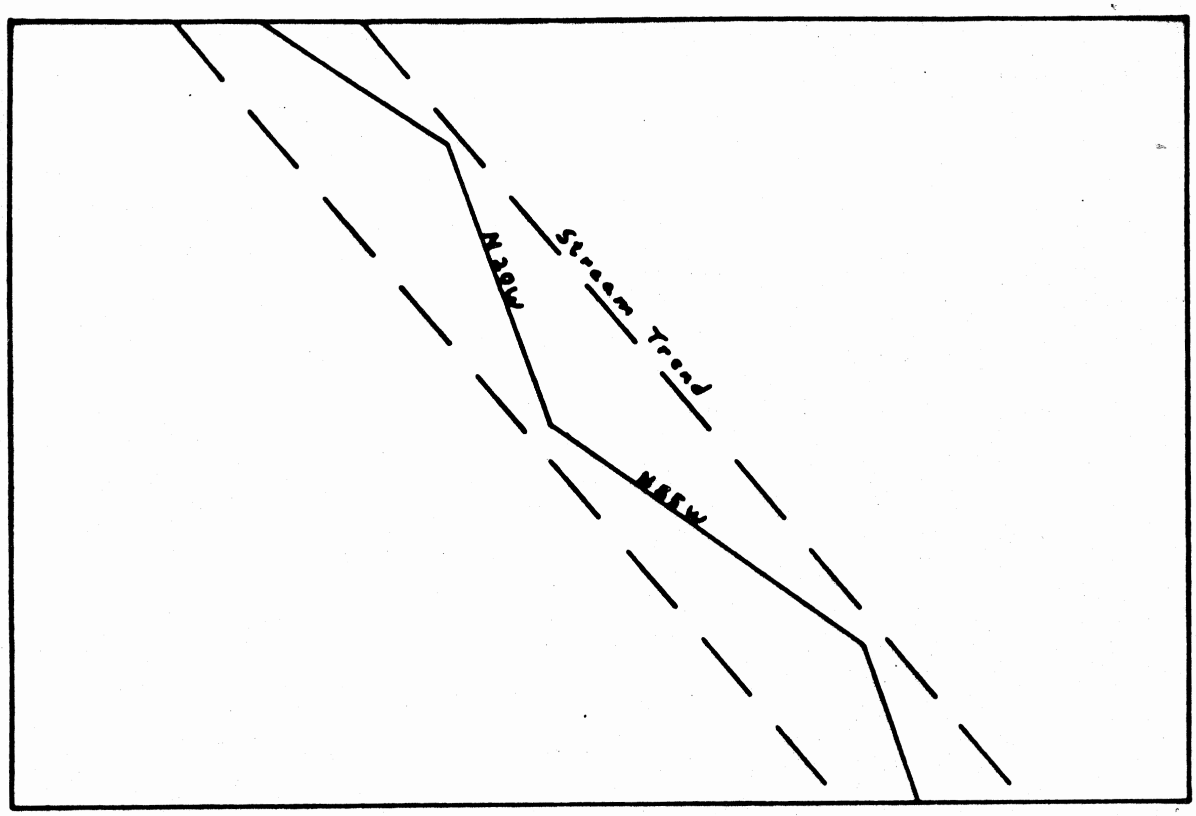


Figure IV-3. Fracture pattern controlling stream trend in upper Blazed Alder Creek.

wrenching of the continental lithospheric plate. We assume that active subduction occurred during most of the Cascade volcanism which resulted in intrusion and extrusion of intermediate composition melts which heated and swelled the crust producing upwarping. Lack of present day seismicity argues against an active subduction zone and subsidence of the crest of the range may indicate recent extension.

North-trending faults within the Hood River fault zone contain slickensides which indicate right lateral movement with a vertical component. We believe that the Cascade Range, due possibly to its higher than normal heat flow, has behaved anomalously to the regional stresses resulting in a right lateral wrenching along this zone. Deeper rocks along the Cascade Range may behave more plastically to wrenching, than the cooler, more brittle rocks near the surface. This wrenching combined with E-W extension may have produced the series of eastward tilted blocks in the Hood River area. It also seems possible that the extension may have caused partial melting at the base of the crust thereby produting magma to supply the High Cascade volcanoes in the absence of an active subduction zone.

The top of the CRB at an elevation of 2028 ft in the Old Maid Flat exploratory hole suggests the possibility that cauldron-type subsidence has occurred. Extension of the Cascade Range and magmatization at depth may both be instrumental in producing the subsidence. The margins of the subsidence are not well known due to extremely sparse data, but the abrupt termination of the CRB south of Middle Mountain and the general physiography would suggest that subsidence is largely confined between the Hood River fault zone on the east and a NE-trending line from Dee to Zigzag on the west. North of Dee to the Columbia River, tilted blocks towards the Hood River fault zone may reflect the termination of graben-type subsidence. Radiometric ages of andesite near the Hood River fault decrease northward suggesting progression of faulting to the north. The southern margin of subsidence is even more poorly defined, but it does terminate north of the Salmon River.

V. GEOLOGIC HISTORY OF THE MOUNT HOOD AREA

A. Pre-Columbia River Basalt

Geologic evidence as to the nature of the area prior to CRB time (16 my BP) is limited largely to exposures of the Eagle Creek Formation and the in part, time-equivalent, Little Butte Volcanic Series. The Eagle Creek formation is composed mostly of mudflow deposits and conglomerates and ubiquitous basaltic andesite flows derived from volcanoes of the western Cascades, located north of the Columbia River Gorge and south of the Clackamas River. The Little Butte Volcanic Series consists primarily of mudflow deposits and tuffs. The lowland area between the aforementioned highs must have contained one or more westwardly-flowing streams. Perhaps the John Day Formation - correlative in part to the Eagle Creek and Little Butte Formations - may have extended as a wedge into this low area or gap. The lowest section from the Old Maid Flat exploratory hole is similar to rocks of the John Day Formation which crops out near Warm Springs, 50 km to the southeast.

The Portland Hills fault - Clackamas River wrench zone was probably already active and expressed topographically, judging from the distribution of the CRB northwest of Portland (Beeson and others, 1976) and its abrupt termination in the Clackamas River area.

B. Columbia River Basalt

During the middle Miocene (16-14 my BP) approximately 29 different flows of the Columbia River Basalt Group entered the area. The maximum number of flows in any one section is about 20 flows which means that approximately one flow entered the area every 100,000 years; however, there apparently was variation in time between successive flows. Flows present represent the N_1, R_2, N_2, and R_3 magnetic polarity intervals and longer than normal intervals exist between flows at the Vantage horizon and between the Frenchman Springs and Priest Rapids Members of the Wanapum Basalt. At least one N_1 flow occurs in the Columbia River Gorge and in the Clackamas River indicating that some of the earliest flows to pass through the Cascades covered the entire gap. This same distribution generally characterizes most succeeding units up through the Frenchman Springs flows.

After Frenchman Springs time, either uplift in the Cascade Range, subsidence in the Columbia Plateau, or NE trending folds prevented later flows from covering extensive areas across the Cascades. The Rosa flows apparently did not extend into the area because they are not present in any of the CRB sections; and Priest Rapids flows have only been found locally along the Mosier syncline in the Bull Run Watershed area where they are partly confined as intracanyon flows.

During the time that the CRB flowed through the Cascade Range several geologic events took place which are detailed as follows:

1. Invasion of the Prineville Basalt flows - While the Low Mg Grande Ronde Basalt flows were flowing through the Cascades from the east, eruptions of basalt in the vicinity of the Prineville, Oregon, produced approximately 13 flows (Uppuluri, 1974), three of which flowed northwestward into the Cascade region to interfinger with the Grande Ronde Basalt. Two Prineville flows (stratigraphically at the top

of R_2) extended into the Clackamas River area and northward to Tygh Ridge. Later (near top of Low Mg Grande Ronde N_2), one flowed northward to Tygh Ridge and by an unknown route into the Mt. Hood area.

2. Local andesitic volcanic center near Old Maid Flat - Eruption began during the interval between High Mg and Low Mg Grande Ronde time and probably continued throughout CRB time even though one Frenchman Springs flow finally covered at least part of this andesitic center.

3. NE trending folds - The Waverly flows near Milwaukie seem to be localized flows that were probably channeled by a syncline or stream canyon developed within a structural depression or zone of weakness. Waverly flows have not been discovered as yet in the Cascades. A possible path for these two flows is The Dalles - Mt. Hood syncline. In the Bull Run watershed area the omission of all Low Mg N_2 flows in the Blazed Alder Creek exposures indicate structural development during CRB time.

4. Priest Rapids Intracanyon Flow - Priest Rapids lava flowed through the Mosier syncline and into canyons cut into CRB as deep as Low Mg Grande Ronde. The former stream valley extended from the West Fork Hood River through the Bull Run Watershed to Crown Point. The Priest Rapids flows overfilled the canyons and completely obliterated the former drainage, probably defeating the stream and shifting it to another location.

5. Pomona flow (12 my BP) - After Priest Rapids time,

structural development of the NE trending folds continued and volcanism in the Cascades filled structural valleys to the east with volcanic debris which was partially water deposited. An example of the latter is the Selah Member of the Ellensburg formation (Kent, 1978). The Pomona flow passed through the Cascade Range, probably channeled by structural and erosional valleys, in a yet to be determined location.

C. Post-Columbia River Basalt

Volcanism and plutonism continued in the Cascades area in post-CRB time. Larger volcanic centers were probably concentrated on The Dalles - Mt. Hood syncline. The Still Creek (11.6 my BP) and Laurel Hill (8 my BP) plutons must have been emplaced in The Dalles - Mt. Hood syncline which probably defeated any stream which might have flowed within the structure. Perhaps it was during this time interval that the Columbia River was shifted to its present course. In post-CRB time several geologic events occurred:

1. Continued development of NE trending folds and thrust faulting in places. At least 300 m of structural amplitude exists along north-south cross-sections in the Bull Run Watershed, most of which developed after the last Frenchman Springs flow (approximately 14-15 mp BP). Even more relief may be present on the extension of The Dalles syncline, buried under Mount Hood.

2. Rhododendron volcanism - Most Rhododendron deposits were produced as a result of eruption from andesitic volcanic centers. Much of the products preserved occur as sedimentary

deposits that accumulated in synclinal depressions in the CRB.

3. Development of NW trending faults and fractures - NW trending faults appear to have been active after most of the NE trending events occurred. The N30W trending Salmon River fault cuts off the NE trending folds. Considerable displacement occurs on N30W trending faults at Arrah Wanna and on Middle Mountain. A N15W fracture in Blazed Alder Creek and Tanner Creek is extremely linear across the Bull Run syncline. N10-20W fractures also cut the thrust zone breccias.

4. Uplift of the Cascade Arch - Uparching of the Cascade Range occurred sometime subsequent to the CRB eruptions (14-15 my BP). Insufficient data are available to determine when the major uplift occurred. Perhaps uplift was most active during subduction which resulted in thickening of the crust, emplacement of plutons and heating and possible hydration of the lithosphere. Most plutons and extrusions in the Mt. Hood Area range in age from 11.6 to 4 my BP.

5. Boring Lava volcanism - Boring lava was erupted from centers and widely scattered N-N20W trending dikes which are common from Hood River to Portland (Allen, 1977). Boring volcanism seems to be associated with E-W extension throughout the area.

6. Subsidence along the High Cascades - The Hood River fault probably resulted from right lateral wrenching and subsequent subsidence after the earlier erupted Boring-type lavas (reversed polarity, perhaps 3 my BP). Some of these flows are tilted about 10 degrees to the east towards the

Hood River fault.

7. High Cascade volcanism - This was perhaps the last major event and may have been associated with subsidence around Mt. Hood.

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GEOLOGY AND GEOCHEMISTRY OF
MT. HOOD VOLCANO

By

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ABSTRACT

The lavas that comprise Mt. Hood volcano can be divided on the basis of their age and modal composition into three suites: (1) the sequence of pyroxene and hornblende andesites that was erupted prior to the last glaciation and which comprise about 90 percent of the volcano; (2) the post-glacial hornblende dacites that were erupted primarily as hot avalanche flows from domes near the summit; and (3) the flows of olivine andesite that were erupted from several satellite vents on the flanks of Mt. Hood. This report presents new compositional data for the Main-Stage lavas and the post-glacial dacites.

Samples of Main-Stage lavas were obtained from five subaerial flow sequences and from the Timberline exploratory hole. Major and trace element analyses indicate that the sequentially erupted lavas in any one section are not related as member of a simple fractional crystallization series. The occurrence of siliceous lavas near the base of some sections indicates that Main-Stage magma reservoirs may have been compositionally zoned. When the trace element abundances in all Main-Stage lavas are compared, at least two discrete magma batches can be identified.

Eruption of the post-glacial dacties took place during three eipsodes at approximately 10,000 yrs, 2,000 yrs, and 200 yrs BP. Each eruptive episode produced a geochemically

distinct series of lavas. Within each age group, sequentially erupted lavas appear to be related by small degree of fractionation of the observed phenocryst phases. It is suggested that the contrasting processes of differentiation indicated for the post-glacial versus the Main-Stage magmas (fractional crystallization vs magma zonation) may be related to the considerable differences in volumes and cooling rates inferred for their respective reservoirs.

Estimates of the conditions of equilibration of the post-glacial dacites were made by comparing the phenocryst compositions in a dacite sample with experimental equilibria data. The calculations yielded the following results: temperature = 910 to 920°C; logarithm of oxygen fugacity = -10.5; minimum load pressure = 3.5 to 7 kb (approximately equal to 10 to 20 kilometers depth).

Because of the inferred small volumes and deep residence levels of the post-glacial magma reservoirs, it is unlikely that they would generate a significant geothermal anomaly within or immediately beneath Mt. Hood. Nonetheless, because of the very young age of the most recent eruptions (100 - 200 yrs BP), a local heat source could be provided by magma that is still residing at shallow depths within the volcanic conduit. In addition, deep-seated magma chambers associated with the Main-Stage volcanism could, if of sufficient volume, continue to affect the regional geothermal gradient in the vicinity of Mt. Hood.

INTRODUCTION

Mt. Hood is the northernmost of the large composite volcanoes that form the crest of the Cascade Range in Oregon. The volcano is predominantly andesitic in composition and consists of about 180 cubic kilometers of flows and pyroclastic debris. Although there are no well-documented accounts of historic eruptions at Mt. Hood, the continuous near-summit fumarolic activity indicates that the volcano is still active.

In his major study of the Mt. Hood area, Wise (1969) divided the volcano into three lava groups; a voluminous series of andesitic lavas that was erupted prior to the last glaciation, a post-glacial group of dacitic plug domes and pyroclastic flows, and several post-glacial satellite cones of olivine andesite. Crandall and Rubin (1977) subdivided the dacitic rocks by delineating three age units within the pyroclastic facies. The lowermost block and ash flows are interbedded with glacial till and outwash, and on this basis, their age is estimated to be about 10,000 to 12,000 years BP. These flows are overlain by two younger pyroclastic sequences that contain charcoal which have yielded radiocarbon dates of 1,700 years and 200 years BP.

The schematic column of the Mt. Hood section (Figure 1) summarizes the stratigraphic divisions made by Wise (1969) and Crandall and Rubin (1977). For this report, the pre-glacial

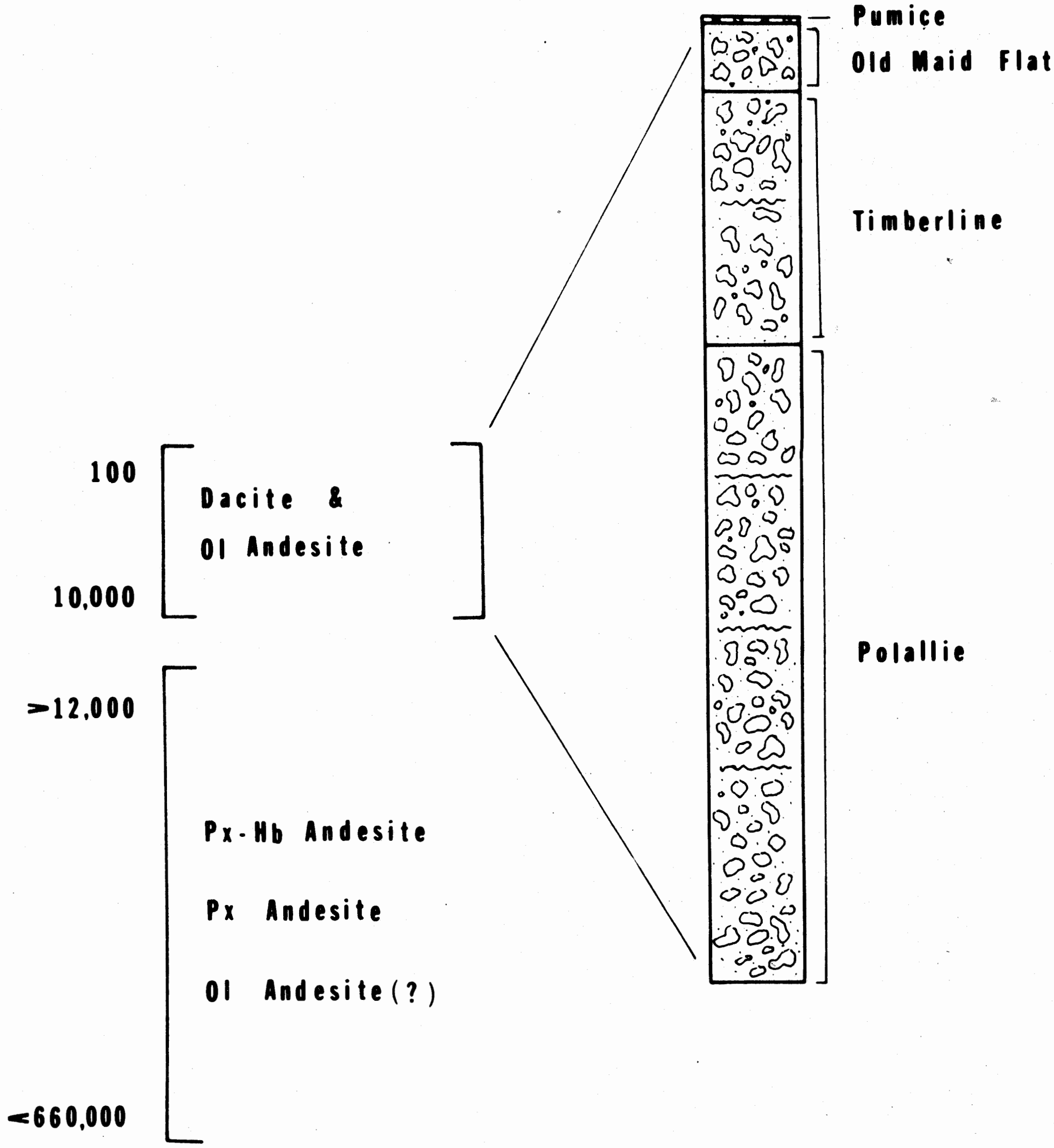


Figure 1. Schematic column of the Mt. Hood Section. The thickness of the post-glacial pyroclastic section is roughly proportional to the volumes of each age group.

Mt. Hood sequence will be called the Main-Stage lavas and the post-glacial silicic rocks will generally be referred to as dacites, although some andesitic rocks do occur in the sequence. The names, Polallie, Timberline, and Old Maid Flat have been applied by Crandall (pers. comm.) to the 10,000-12,000 yr, 1,700 yr, and 200 yr-old block and ash flows, respectively, and these names will be used in place of the absolute age designations.

Scope

The present day study was initiated in order to apply recently developed techniques in petrology and geochemistry to the problem of the late-stage magmatic evolution of the Mt. Hood lavas. Because knowledge of the order of eruption of lavas is critical in evaluating competing petrological models, new analyses of rock samples have been made only where the relative ages of flows in a section have been determined by field observation, drilling, or radiometric dating. The goal of the study is to aid in the assessment of Mt. Hood as a potential geothermal resource area and, for this reason, emphasis has been placed on the evolution of the young, silicic rocks at Mt. Hood, even though they are volumetrically less important than the Main-Stage lavas.

Analytical Procedures

Concentrations of eight major elements in all the Mt. Hood samples were determined by X-ray flourescence spectrometry of fused glass discs. Sample splits were analyzed for

Na and Mg by use of a Varian model 175 atomic absorption unit. Zr, Sr, Rb, and Ni concentrations were determined by X-ray flourescence analysis of pressed powders; all other trace element analyses were made by use of instrumental neutron activation. Complete trace element analyses were made by counting irradiated samples for two and six hours on a 4096 channel germanium crystal detector. Less precise analyses were obtained for most of the dacitic rocks by counting samples for two hours on a 2048 channel detector; a procedure that is more rapid and less costly than that used for the complete analyses but which yielded reliable values for Th and La. Mineral analyses were made with an electron microprobe.

POST-GLACIAL DACITES

Post-glacial dacitic lavas at Mt. Hood occur primarily as voluminous pyroclastic debris flows which fill radial drainages and mantle the lower slopes of the volcano. The abundance of prismatically jointed blocks throughout the pyroclastic section and the uniform magnetic orientation of blocks in some flows indicate that most of the debris was deposited at elevated temperature; in some cases at temperatures above the Curie point. The flows probably originated from explosive eruptions at the sides or base of an episodically active dome, the remnants of which cap most of the near-summit ridges.

The Polallie block and ash flows are the oldest and most voluminous of the post-glacial pyroclastic deposits. They occur primarily on the east and northeast sides of the volcano where they are well exposed in sections up to 150 meters thick in the canyons of Polallie and Cold Spring Creeks. Flows of Polallie age have not been identified on the south, west, or northwest slopes of Mt. Hood. A crumble-breccia that occurs at the 9500-foot level on Cooper Spur may represent a portion of the Polallie dome that was undermined by the repeated block and ash eruptions.

In contrast to the Polallie eruptions, the explosive activity that produced the Timberline and Old Maid Flat flows was strongly directed to the south and west. The 1,700-year-old Timberline pyroclastic flows mantle the south slope of Mt. Hood in the vicinity of Timberline Lodge and form thick sections in the upper reaches of the Zigzag and Sandy Rivers. The 200-year-old flows of the Old Maid Flat group overlie flows of Timberline age in exposures along the Sandy River where a twenty-centimeter-thick ash layer marks the contact. It is likely that rocks of Old Maid Flat age also form the noticeably steeper portion of the south slope between the 8000-foot level and the base of Crater Rock. The large blocks in this area are similar in their mineralological and chemical composition to blocks from other Old Maid Flat sections and they probably were formed by the collapse of a young dome that occupied the Devils Kitchen amphitheater, just south of the present summit (Figure 2).

The hornblende dacite plug dome that forms Crater Rock is the site of the most intense fumarolic activity in the summit region. Its extrusion probably followed the explosive activity that produced the Old Maid Flat flows and caused the collapse of the Devils Kitchen dome. Additional evidence of very young activity was found by Crandall (pers. comm., 1979), who recognized small pumice fragments on the surface of the Old Maid Flat flows in the upper portions of the White River valley. The pumice is unlike that erupted from neighboring volcanoes and was almost certainly produced by a minor eruption of Mt. Hood, possibly during the reported activity in the middle 1800s.

Petrography

All of the post-glacial dacitic rocks at Mt. Hood contain abundant phenocrysts of plagioclase and ferromagnesian minerals

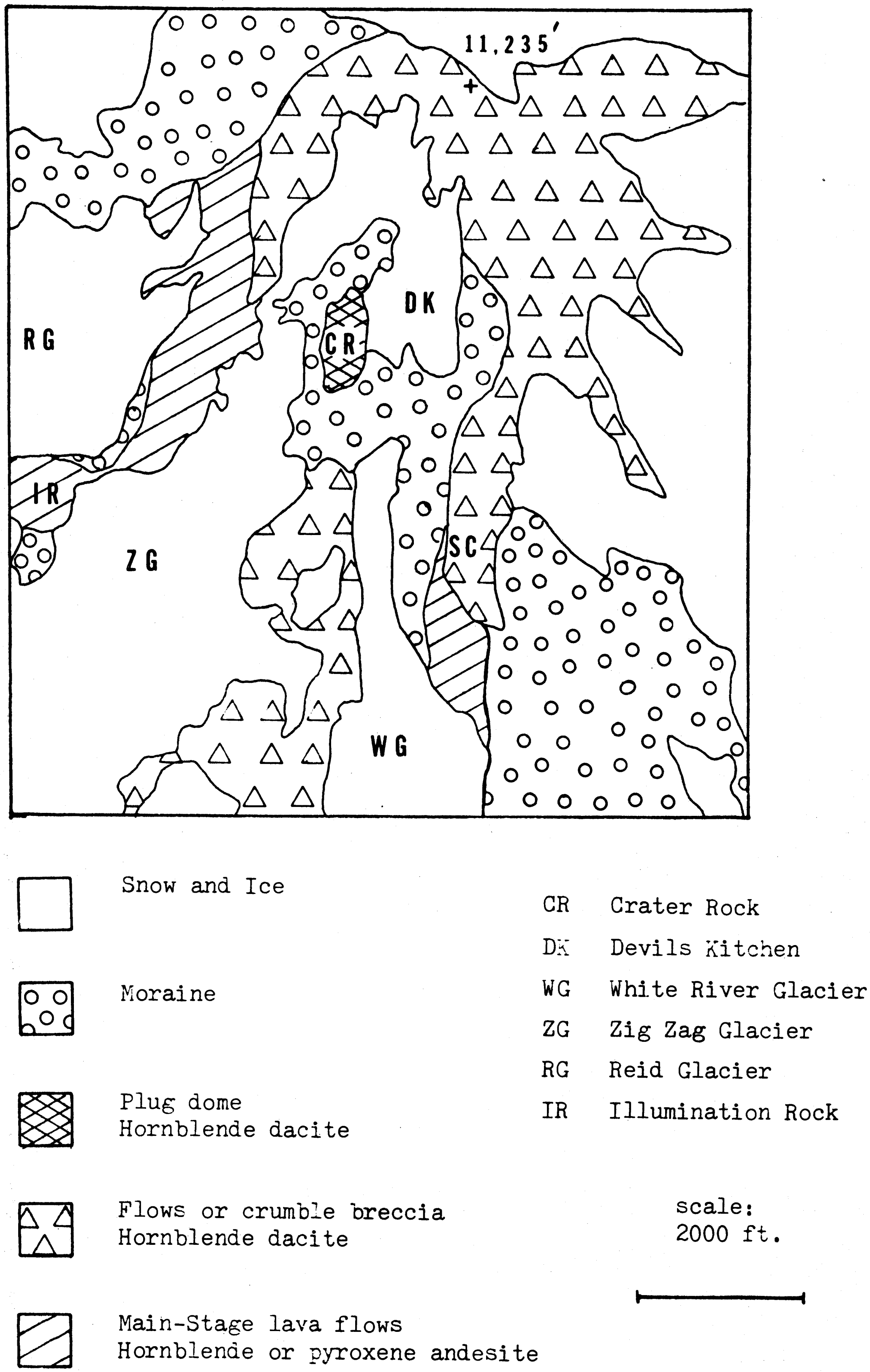


Figure 2. Geologic sketch map of the summit area of Mt. Hood

in a groundmass of fine-grained crystals, crypto-crystalline material and, rarely, light brown glass. Phenocrysts and microphenocrysts of plagioclase and orthopyroxene $\pm$ amphibole $\pm$ clinopyroxene form between 30 and 35 percent of the mode in nearly all observed samples.

Although most phenocryst grains are optically zoned, the range of mineral compositions as revealed by the electron microprobe (Table 1) is relatively narrow. Most phenocrysts are fresh and display subhedral or euhedral crystal outlines; however, amphibole grains are commonly rimmed by fine-grained aggregates of opaque minerals and, in some rocks, may be totally replaced by this material. Clinopyroxene is generally the smallest and least abundant of the phenocryst minerals and its occurrence in a given specimen appears to be inversely related to the abundance of hornblende.

It would be impossible to assign a specimen to one of the three age groups on the basis of petrography alone; nonetheless, general petrographic characteristics can be recognized in each of the pyroclastic units. Blocks from the Polallie flows commonly contain much less modal amphibole and greater amounts of modal clinopyroxene than blocks from the two younger units. In addition, amphibole phenocrysts are generally quite fresh in the Old Maid Flat blocks but appear to be progressively more resorbed in the older units. These characteristics may reflect the small but progressive increase in the silica contents of the post-glacial dacitic rocks with time.

TABLE 1

Mineral Compositions Used in Equilibria Calculations

Pyroxenes

	core opx A	core cpx A	rim opx A	rim cpx A	gr mass opx B	gr mass cpx B
SiO2	52.62	52.10	52.54	52.45	52.82	51.83
TiO2	.05	.34	.05	.39	.17	.51
Al2O3	.67	1.73	.84	1.45	.96	2.04
FeO	22.66	9.12	21.25	9.15	22.63	8.91
MgO	22.90	14.57	22.64	14.77	22.30	14.33
MnO	.69	.28	.68	.28	.65	.25
CaO	1.11	21.70	1.25	21.70	1.19	21.39
total	100.70	99.85	99.25	100.18	100.71	99.26
EN	65	14	67	14	65	14
FS	35	42	33	42	35	42
WO	--	44	--	44	--	44

Plagioclases

	core plag A	rim plag A	core plag B	rim plag B	gr mass plag C	gr mass plag D
SiO2	56.45	54.53	56.39	54.45	54.19	54.34
Al2O3	27.07	28.14	26.96	28.13	28.54	28.13
FeO	.32	.41	.26	.45	.38	.53
MgO	.10	.11	.08	.12	.11	.09
CaO	9.52	10.55	9.55	10.67	11.16	10.89
Na2O	5.79	5.31	5.92	5.22	5.18	5.20
K2O	.19	.18	.23	.20	.16	.20
total	99.44	99.23	99.41	99.29	99.75	99.35
AN	48	52	47	53	54	54

Oxides

	ilm A	ilm B	ilm C	mt A	mt B
SiO2	.02	.31	.31	.80	.69
TiO2	39.90	35.95	39.04	4.54	8.21
Al2O3	.29	.50	.45	2.78	2.22
FeO	56.50	60.06	56.04	84.44	82.13
MgO	2.80	2.32	2.88	1.88	2.06
MnO	.10	.06	.08	.14	.14
Cr2O3	.06	.08	.07	.26	.26
V2O3	.71	.87	.68	.39	.39
total	100.39	100.19	99.55	95.30	96.17
HM	27	34	28	--	--
IL	73	66	72	--	--
MT	--	--	--	85	75
ULV	--	--	--	15	25

All analyses were made with an electron microprobe using a 3 micron beam width. All phases are from sample CR-55A; a prismatically jointed block from near the middle of the Polallie Canyon section.

Geochemistry

The major and trace element compositions of 27 post-glacial silicic lavas from Mt. Hood are given in Table 2. Although some overlap in major elements does occur among the three age groups, a general trend can be seen in which rocks from the younger units are slightly richer in SiO_2 and poorer in MgO, CaO, and Fe_2O_3.

In contrast to the major elements, the concentrations of K_2O, Zr, Th, and La bear a more complex relationship to the age of the sampled unit. This behavior is illustrated in Figure 3, in which the abundances of the four excluded elements are plotted versus a schematic scale of decreasing age. Because the Polallie canyon exposure offered the opportunity to sample a thick continuous section, the samples of Polallie age have been plotted in five positions, according to their stratigraphic height. In contrast, the stratigraphic position of the Timberline and Old Maid Flat samples within their respective units cannot be determined in the field, and for this reason, analyses of these rocks are plotted as if they were exactly time-equivalent. Analyses of the Crater Rock plug dome and the post-Old Maid Flat-age pumice are plotted as the youngest samples.

Examination of the lower portion of Figure 3 reveals a general trend of increasing K_2O, Zr, Th and La upward through the Polallie Canyon section. In a similar way, the Old Maid Flat--Crater Rock--pumice samples show an increase in excluded element concentrations with time. This trend is reversed at

TABLE 2

	Blocks in Polallie Pyroclastic Flows							Blocks in Old Maid Flat Pyroclastic Flows					Basal Old Maid Flat Ash
	HD-83	HD-84	CR-55A	HD-85	HD-4	HD-5	HD-6	HD-2	HD-28	HD-29	HD-30	HD-31	HD-48
SiO_2	61.99	61.93	61.26	62.73	62.56	62.82	62.90	63.77	63.26	63.34	63.22	63.49	60.70
TiO_2	.74	.78	.74	.77	.75	.76	.76	.72	.71	.72	.72	.71	.86
Al_2O_3	17.52	17.65	19.17	17.42	17.05	17.13	17.04	16.84	17.27	17.11	17.06	16.95	17.35
M_gO	2.71	2.41	2.28	1.68	2.41	2.30	2.26	2.24	2.21	2.26	2.36	2.28	3.01
Fe_2O_3	5.90	5.68	5.42	5.74	5.50	5.82	5.44	5.26	5.17	5.29	5.26	5.18	6.28
MnO	.09	.09	.07	.09	.07	.07	.07	.07	.07	.07	.08	.07	.09
CaO	5.53	5.67	5.36	5.60	5.46	5.42	5.40	5.16	5.30	5.29	5.25	5.18	5.98
Na_2O	3.97	4.26	3.86	4.21	4.41	4.17	4.36	4.37	4.48	4.35	4.48	4.56	4.21
K_2O	1.39	1.39	1.65	1.55	1.59	1.63	1.59	1.43	1.39	1.42	1.41	1.44	1.34
P_2O_5	.17	.16	.18	.20	.19	.19	.18	.15	.14	.15	.15	.14	.18
Rb	22	21	26	26	27	25	27	22	17	20	20	20	19
Sr	672	626	609	621	600	596	598	552	558	551	555	546	633
Zr	143	144	169	156	179	176	175	137	140	146	145	145	155
Th	3.5	3.3	4.1	4.5	4.3	5.3	n.d.	2.9	2.6	n.d.	2.7	n.d.	n.d.
La	18.3	18.3	20.2	22.2	22.2	22.2	n.d.	15.9	15.6	n.d.	14.0	n.d.	n.d.

CONTINUATION OF TABLE 2

	Blocks in Timberline Pyroclastic Flows					Near-Summit Dacite Flows				Crater Rock	Pumice
	HD-17	HD-18	HD-19	HD-26	HD-27	HD-23	HD-25	HD-8	HD-60	HD-9	HD-10
SiO_2	63.19	63.26	62.91	63.58	63.56	62.40	62.26	62.76	62.93	64.11	62.88
TiO_2	.71	.72	.71	.70	.70	.77	.78	.77	.80	.69	.73
Al_2O_3	17.00	16.99	17.06	16.92	16.89	17.25	17.16	17.11	17.67	16.94	17.71
M_9O	2.40	2.34	2.43	2.29	2.35	2.40	2.45	2.42	2.24	2.11	2.18
Fe_2O_3	5.36	5.34	5.38	5.16	5.13	5.72	5.68	5.59	5.44	5.12	5.36
MnO	.07	.08	.07	.07	.07	.08	.08	.08	.08	.08	.08
CaO	5.45	5.36	5.36	5.22	5.25	5.44	5.41	5.46	5.59	5.10	5.30
Na_2O	4.17	4.24	4.44	4.39	4.42	4.40	4.68	4.19	3.53	4.21	4.08
K_2O	1.49	1.52	1.50	1.53	1.49	1.38	1.32	1.43	1.54	1.49	1.50
P_2O_5	.15	.15	.14	.13	.15	.17	.18	.17	.18	.15	.19
Rb	20	21	21	22	23	18	18	21	24	23	21
Sr	572	579	562	537	557	550	545	555	561	534	545
Zr	146	159	152	152	154	163	151	160	149	148	174
Th	2.9	n.d.	n.d.	3.0	3.5	2.9	n.d.	n.d.	n.d.	3.3	3.8
La	16.8	n.d.	n.d.	15.6	18.2	16.7	n.d.	n.d.	n.d.	15.8	17.7

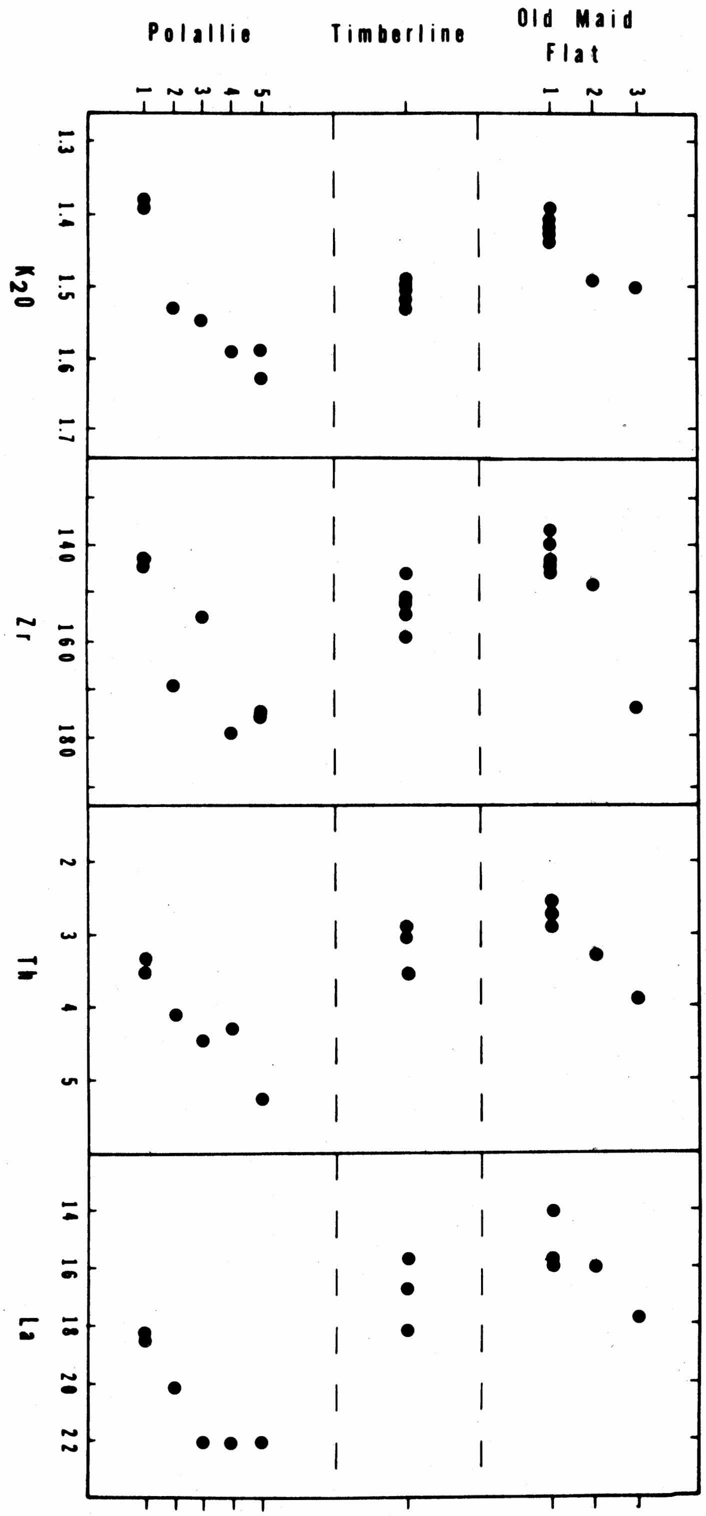


Figure 3. A plot of the concentrations of K_2O (wt. %), zirconium (ppm), thorium (ppm), and Lanthanum (ppm) versus a schematic scale of stratigraphic height. Samples are from prismatically jointed blocks in post-glacial pyroclastic flows.

the major time breaks where the initial products of each eruptive episode are depleted in these elements relative to last-erupted lavas of the preceding episode.

The trends within the Polallie section and the Old Maid Flat-Crater Rock-Pumice lava group are consistent with small degrees of fractional crystallization; however, the occurrence of a geochemical reversal at each of the major time breaks indicates that the Polallie, Timberline and Old Maid Flat lavas are probably not related to one another through a simple Bowen-type fractionation process. Because the younger rocks are neither less siliceous nor more phenocryst rich than the older ones, it is also unlikely that the three eruptive groups are related through progressively deeper tapping of a simply-zoned magma chamber. Although a single, complexly-zoned magma chamber cannot be ruled out as a source of all of the post-glacial dacitic lavas, it is more likely that each of the three major eruptive episodes tapped discrete magma batches. The distinct geochemical character of the lavas of each eruptive episode is emphasized by plotting the excluded elements versus silica. Plots of potash and thorium values are shown in Figures 4 and 5.

In order to further investigate the relationship among the post-glacial dacitic rocks, several least-squares mixing calculations were made in which the major-element compositions of rocks in the Polallie eruptive group were used as end members. These calculations test the possibility that one rock composition could be generated from another by subtraction of the observed phenocryst phases. It can be seen from the results

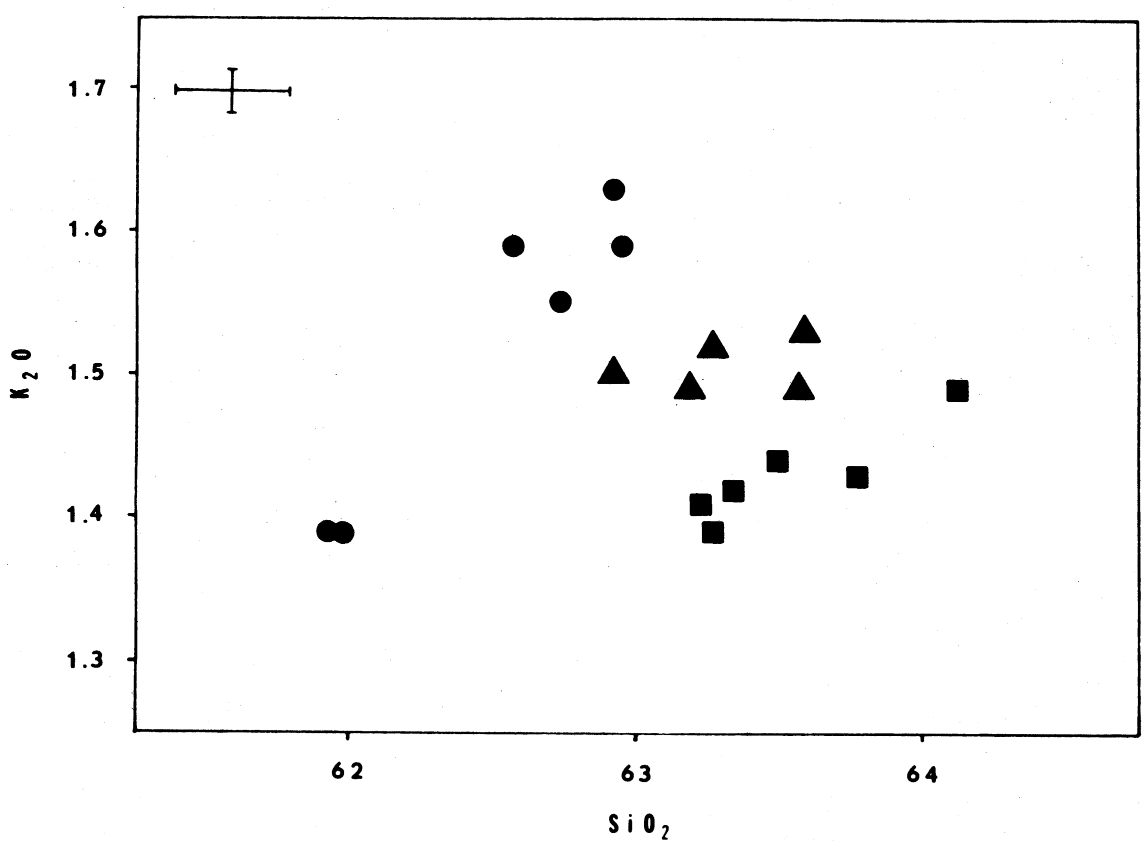


Figure 4. A plot of the concentration of SiO_2 versus K_2O. Circles are analyses of Polallie blocks, triangles are analyses of Timberline blocks, squares are analyses of Old Maid Flat blocks. 1 sigma error bars are given in the upper left of the figure.

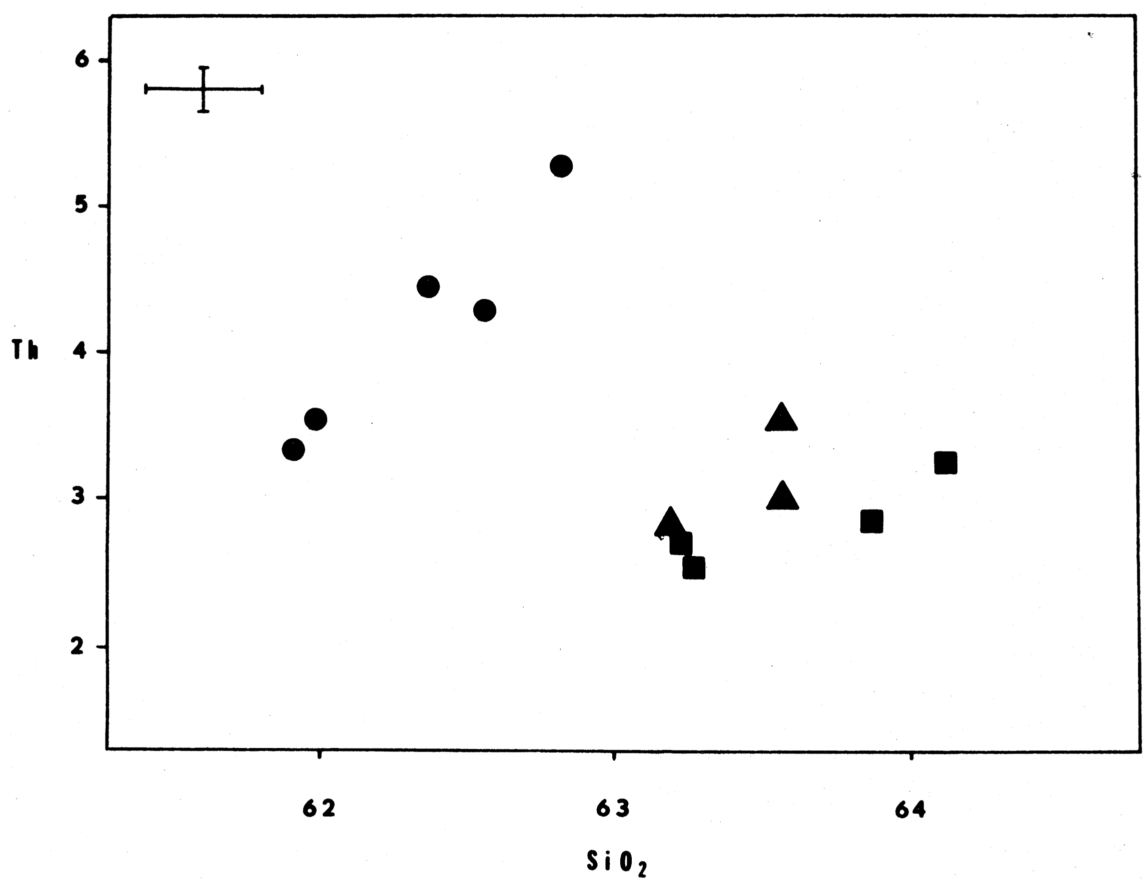


Figure 5. A plot of thorium concentration (ppm) versus SiO_2. Symbols are the same as those in Figure 4.

presented in Table 3 that the range of rock compositions through the Polallie canyon suite could be generated by about 10 percent fractional crystallization of plagioclase and orthopyroxene. When an attempt is made to relate the rocks of the Timberline group to those from the upper portion of the Polallie section a reasonable fractionation model cannot be obtained.

In summary, the geochemical data from the post-glacial silicic lavas indicate that eruptions of discrete magma batches took place at 12,000-10,000 yrs, 1,700 yrs, and 200 yrs BP. Because the lavas are very similar in mineralogical and major-element chemical composition, it is likely that successive magma batches equilibrated under similar conditions. During each eruptive episode the magmas were differentiated to a small degree by the removal of phenocryst minerals from the melt.

Conditions of equilibration

The temperature, pressure, water content, and oxygen fugacity of the dacitic magmas can be estimated by comparing the mineral compositions of the natural rocks with experimental data on crystal-crystal and crystal-liquid equilibria. A sample (CR-55A) from a prismatically jointed block near the middle of the Polallie Canyon section was selected for these calculations and an extensive analysis was made of its phenocryst and groundmass phases.

Pyroxene Geothermometer

Distribution of the component $Mg_2Si_2O_6$ between calcium-

TABLE 3

LEAST SQUARES MIXING MODEL FOR LAVA COMPOSITIONS OF POLALLIE BLOCKS

	F	X PLAG	X OPX	r^2
Parent (HD-83) to:				
HD-4	.041	.021	.020	.081
HD-6	.068	.039	.029	.633

LEASE SQUARES MIXING MODEL FOR LAVA COMPOSITIONS OF OLD MAID FLAT BLOCK, AND DACITE FROM CRATER ROCK

	F	X PLAG	X AMPH	r^2
Parent (HD-30) to:				
HD-9	.034	.013	.021	.647

Least squares mixing calculations are based on major element analyses of whole rocks and microprobe analyses of phenocryst phases. F is the total percent of the crystals removed from the magma. r^2 is the sum of the errors between the calculated daughter composition and the analyzed composition. Note that the Polallie magmas appear to have fractionated plagioclase and orthopyroxene whereas the Old Maid Flat magma differentiated by removal of plagioclase and amphibole.

rich pyroxene and magnesian orthopyroxene has been shown to be temperature dependent. Because they are relatively unaffected by pressure, the compositions of co-existing pyroxenes in the igneous rocks can be used as a geothermometer. From experimental equilibria studies, Wood and Banno (1973) showed that temperature is related to simple pyroxene compositions by

$$T(^{o}K) = \frac{-10202}{\ln(X^{cpx}_{Mg_2Si_2O_6}/X^{opx}_{Mg_2Si_2O_6}) - 7.65\, X^{opx}_{Fe} + 3.88(X^{opx}_{Fe})^2 - 4.6}$$

When the compositions of three pyroxene pairs from sample CR-55A (Table 1) are substituted in the above equation, the calculated temperatures are:

Pyroxene cores............................910° C
Pyroxene rims.............................920° C
Groundmass pyroxenes......................918° C

The temperatures fall within a remarkably narrow range and, although they may be somewhat low for low-silica dacites, they are in general agreement with temperature estimates made for dacitic magmas at Mt. Lassen.

Iron-Titanium Oxide Geothermometer

The iron-titanium oxide geothermometer utilizes the co-existing solid-solution phases ulvospinel-magnetite and ilmenite-hematite. When these minerals crystallize under equilibrium conditions, their compositions are uniquely determined by both temperature and the fugacity of oxygen (fO_2). Buddington and Lindsley (1964) published a series of calibration curves from which the temperature and the logarithm of fO_2 of a system can be estimated from the mole fraction of hematite and ulvospinel in the co-existing oxide phases.

When the compositions of these minerals in sample CR-55A are compared with the curves in Figure 6, it can be seen that the ilmenite solid-solution ratio falls outside the range calibrated by Buddington and Lindsley. Although it is not possible to precisely interpolate the curves, an estimate of fO_2 can be made by using the co-existing magnetite composition and the equilibrium temperature obtained from the two pyroxene geothermometers. These values intersect at point A on Figure 6 and a corresponding value for log fO_2 of -10.5 can be determined from the ordinate. It should be noted that a reasonable interpolation of the ilmenite curves at Hm_{25}-Hm_{30} would pass close to point A and thereby further confirm the pyroxene-based temperature estimates.

Plagioclase Geothermometer

The compositional dependence of plagioclase on both temperature and water pressure has long been established by petrologists. Kudo and Weill (1970) successfully formulated an expression by which this relationship could be used to determine the equilibration temperature of plagioclase-liquid pairs at several different water pressures. If temperature can be estimated by an independent method, then the Kudo-Weill equations can be used to estimate the partial pressure of water in a magma at the time of plagioclase crystallization.

The temperatures obtained by the Kudo-Weill method for sample CR-55A, listed as a function of water pressure, are:

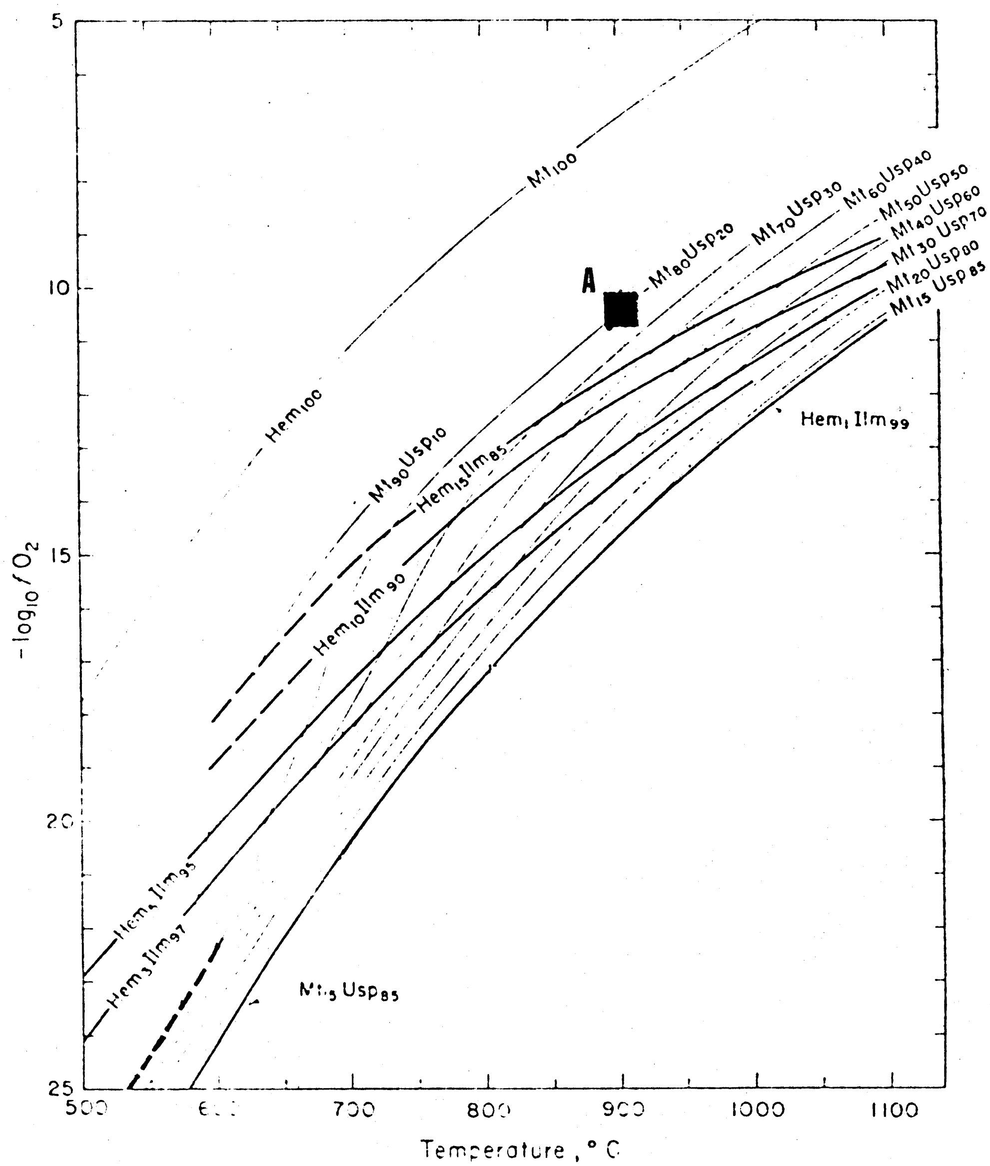


Figure 6. Compositions, in mole percent, of co-existing ilmenite-hematite and magnetite-ulvospinel solid solutions as a function of temperature and oxygen fugacity (after Buddington and Lindsley, 1964). Point A shows the intersection of the magnetite-ulvospinel compositional range in sample CR-55A with the temperature of equilibration of the Polallie magma as calculated from the two pyroxene geothermometer.

P_{H_2O}	Dry	0.5 kb	1.0 kb	5.0 kb
T^oC (pheno)	1148	1095	1057	765
T^oC (gmass)	1178	1129	1091	803

An estimate of P_{H_2O} can be made from these data by interpolating the values at a temperature of 915°C. This procedure yields a P_{H_2O} value of 3.0 kb for the phenocryst temperatures and 3.5 kb when the groundmass plagioclase temperatures are used.

Because the partial pressure of water in a magma cannot normally be greater than the total load pressure, the P_{H_2O} estimates represent the lowest pressures at which the Polallie magma could have equilibrated with plagioclase. If the magma was not water saturated, then P_{total} would, of course, have to be greater than 3-3.5 kb, and the depth of the magma chamber would exceed 10 kilometers.

Geobarometry

An estimate of the minimum load pressure under which the Polallie magma last equilibrated can be made by using equations developed by Carmichael and his co-workers (1971) for the activity of silica in magmatic systems. Because for many reactions the silica activity is dependent on T and fO_2 as well as P_{total}, independent estimates of these variables must be made before Carmichael's equations can be used.

The procedure by which a pressure estimate may be obtained from mineral composition data is well documented elsewhere and a list of the pertinent equations will not be given in this report. For the Polallie lavas, a value for log α liquid_{SiO_2} can be estimated from the reaction

$$1/3\ fe_3O_4 \ + \ SiO_2 \ = \ FeSiO_3 \ + \ 1/6\ O_2$$

in which $FeSiO_3$ is the ferrosilite component of the orthopyroxene. By substituting the compositional data for magnetic and orthopyroxene (Table 1) and the independent estimates for T and fO_2 into Carmichael's equations, a value of 6.7 kb is obtained as a minimum load pressure for the equilibration of the Polallie magma. This pressure corresponds to a depth of about 20 kilometers for the location of the magma chamber immediately prior to the eruption of the Polallie lavas.

MAIN STAGE LAVAS

More than 90 percent of the volume of Mt. Hood volcano is composed of a preglacial series of flows, breccias, and pyroclastic rocks; the great majority of which are andesitic in composition. Unlike the composite cones of the central Oregon Cascade Range, Mt. Hood is not built on an extensive platform of Pleistocene basaltic flows, but rather rests directly on volcanic rocks of Pliocene and Miocene age. The age of Mt. Hood volcano is not known; however, because lavas having reversed remnant magnetism have not yet been found, an age of 660,000 yrs should be considered as a maximum date for the onset of eruption.

In order to best understand the magmatic evolution of the Main Stage lavas, surface samples were taken for analysis only where four or more flows could be sampled in unambiguous stratigraphic order. In addition, the Timberline drill hole (3S/9E-7aac) offered a unique opportunity to sample eleven flows through a vertical section of about 1,400 feet. A detailed log of this drill hole is attached (Appendix I).

Petrography

All of the observed Main Stage lavas contain phenocrysts of plagioclase, orthopyroxene and, in lesser abundance, clinopyroxene. Amphibole occurs in about 66 percent of the samples and is generally partially or completely replaced by pseudomorphic mats of fine-grained opaque minerals. In contrast to the observation by Wise (1969) that amphibole-bearing andesite flows occur only in the upper portion of the volcano, the present study indicates that there is no relationship between the stratigraphic height of a flow and its amphibole content. Microprobe analyses were not made of phenocryst phases in the Main Stage lavas; however, mineral analyses and petrographic descriptions are presented by Wise (1969) and a flow-by-flow description of the mineralogy of the cuttings from the Timberline drill hole is given in Appendix I.

Geochemistry

The major and trace element composition of samples from five sections and the Timberline drill hole are given in Table 4. The analyses in each set are presented in order of increasing stratigraphic height. The drill hole samples probably represent a complete flow sequence; however, because of lack of continuous exposure, it is unlikely that all flows in the subaerial sections have been sampled.

Major Elements

In contrast to the post-glacial silicic lavas, the Main Stage flows show little systematic chemical variation through individual measured sections. The behavior of silica in six sections is given as an Example in Figure 7. Although it is clear from this figure that there is no serial variation of SiO_2 concentrations upward through the sections, there is a general tendency for the flows at the lowest projected stratigraphic elevations (< 4900 ft.) to be relatively enriched in silica ($> 62\%$ SiO_2).

The occurrence of siliceous rocks at the base of the Mt. Hood section is inconsistent with a Bowen-type model of

TABLE 4

MAJOR AND TRACE ELEMENT ANALYSES OF MAIN STAGE LAVAS

	TIMBERLINE DRILL HOLE										
	TDH-11	TDH-10	TDH-9	TDH-8	TDH-7	TDH-6	TDH-5	TDH-4	TDH-3	TDH-2	TDH-1
SiO_2	64.79	62.03	63.71	62.30	60.73	61.90	61.11	62.33	60.77	59.89	59.73
TiO_2	.66	.78	.74	.73	.85	.81	.74	.80	.82	.76	.85
Al_2O_3	16.61	17.85	17.13	17.81	17.67	17.11	17.86	16.91	17.92	17.90	17.75
MgO	2.16	2.19	1.95	2.50	2.79	2.61	2.74	2.58	2.63	4.07	3.41
Fe_2O_3	5.33	5.72	5.18	6.01	6.35	6.07	6.34	5.92	6.07	6.27	6.36
MnO	.08	.08	.08	.08	.10	.09	.10	.08	.09	.10	.10
CaO	4.69	5.76	5.35	5.24	5.96	5.70	5.74	5.60	6.22	5.65	6.27
Na_2O	3.96	4.06	4.38	4.09	4.20	4.25	4.24	4.19	4.09	4.14	4.15
KaO	1.59	1.38	1.34	1.11	1.18	1.29	.99	1.42	1.22	1.06	1.20
PaO_5	.13	.16	.15	.13	.18	.16	.15	.17	.17	.15	.18
Rb	27	27	21	17	19	20	17	20	17	18	13
Sr	427	471	585	513	507	471	532	538	542	544	505
Zr	151	127	133	157	143	137	135	141	133	132	123
Ni	36	17	27	32	41	42	49	42	41	43	43
Sc	11.2	11.3	11.4	11.9	12.9	12.6	12.9	12.9	12.7	13.4	14.1
Co	14.5	14.9	13.3	16.2	18.4	17.6	18.8	17.6	18.0	19.2	19.5
Hf	4.5	3.7	3.8	3.6	3.9	3.7	3.8	4.2	3.7	4.1	3.8
Ta	1.0	.7	.7	.6	.6	.8	.4	n.d.	n.d.	n.d.	.6
U	1.4	1.4	1.1	n.d.	2.6	.9	n.d.	n.d.	1.2	1.0	1.4
Th	4.8	n.d.	3.4	2.4	2.4	2.6	2.3	3.3	2.7	2.5	2.6
Ba	430	309	360	378	249	308	250	358	335	292	298
La	20.4	16.1	18.6	13.7	15.4	15.1	15.0	17.0	16.3	15.8	15.9
Ce	41.8	33.6	36.9	28.4	30.8	32.4	31.9	37.1	34.3	33.4	33.4
Nd	n.d.	n.d.	20	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.
Sm	4.1	3.9	4.1	3.5	4.0	3.9	3.9	4.0	3.9	3.8	3.9
Ev	1.0	1.1	1.2	1.0	1.2	1.1	1.1	1.1	1.1	1.2	1.1
Tb	n.d.	.6	.5	.4	.6	.7	.5	n.d.	.5	n.d.	.6
Yb	1.2	1.4	.8	.8	1.6	1.0	1.3	1.3	1.2	1.3	1.3
Lu	.3	.2	.2	.2	.3	.2	.2	.2	.2	.2	.2

TABLE 4 CONTINUED

	ELIOT BRANCH - COOPER SPUR SECTION						YOCUM RIDGE SECTION			
	HD-66	HD-67	HD-68	HD-69	HD-74	HD-72	HD-78	HD-79	HD-80	HD-81
SiO_2	62.71	60.58	60.73	60.67	60.90	60.14	59.89	59.27	59.98	63.30
TiO_2	.74	.91	.90	.85	.87	.93	.93	.98	.80	.77
Al_2O_3	17.70	17.22	17.08	17.68	17.28	17.69	18.10	17.65	18.54	17.12
MgO	1.85	2.77	2.74	2.74	2.67	2.66	2.77	3.19	2.78	1.92
Fe_2O_3	5.91	6.20	6.10	6.10	6.18	6.14	6.67	6.70	6.61	5.46
MnO	.09	.09	.09	.10	.10	.09	.10	.10	.11	.09
CaO	5.55	6.06	6.02	5.86	5.92	6.34	6.16	6.45	6.02	5.31
Na_2O	4.16	4.35	4.47	4.25	4.34	4.23	4.29	4.10	4.14	4.27
K_2O	1.14	1.55	1.58	1.47	1.50	1.49	.98	1.33	.86	1.61
P_2O_5	.16	.27	.31	.28	.25	.28	.18	.24	.15	.15
Rb	18	21	25	23	20	19	12	19	13	29
Sr	593	807	811	908	1040	1116	583	679	582	572
Zr	147	185	209	170	160	152	135	150	114	137
Ni	24	23	27	28	27	25	n.d.	n.d.	n.d.	n.d.
Sc	11.6	11.6	11.6	11.6	13.6	11.6	11.9	n.d.	12.5	10.8
Hf	4.0	4.8	4.8	4.7	4.6	4.3	3.5	4.0	3.4	4.3
Ta	1.4	1.8	1.4	1.6	1.4	1.1	1.0	.9	.9	1.3
U	1.4	4.5	1.9	2.1	1.8	1.6	2.9	n.d.	5.2	2.4
Th	3.1	4.8	5.1	4.9	4.4	4.3	1.9	3.1	1.5	3.9
Ba	300	463	436	476	450	496	235	331	200	240
La	17.5	28.3	28.4	28.6	31.5	32.9	13.2	19.3	n.d.	18.6
Ce	36.3	57.7	59.7	58.4	66.4	69.0	36.1	39.3	25.6	39.5
Nd	n.d.	42	n.d.	31	42	44	18	n.d.	n.d.	n.d.
Sm	4.1	5.8	5.8	5.5	6.6	6.5	4.5	4.6	3.5	4.3
Eu	1.2	1.5	1.6	1.5	1.6	1.7	1.2	1.3	1.1	1.0
Tb	.6	.7	.7	n.d.	.6	.5	.5	.6	.5	.5
Yb	1.1	1.3	1.4	1.5	1.3	1.3	1.2	1.2	1.4	1.6
Lu	.2	.2	.2	.2	.3	.2	.2	.2	.2	.3

TABLE 4 CONTINUED

	ZIGZAG CANYON-MISSISSIPPI HEAD SECTION					MT. HOOD MEADOWS SECTION					
	HD-89	HD-88	HD-87	HD-86	HD-1	HD-16	HD-15	HD-14	HD-13	HD-12	HD-11
SiO_2	61.43	61.16	60.11	61.85	62.98	59.52	59.96	60.07	59.65	60.55	61.75
TiO_2	.78	.85	.88	.77	.76	.94	.95	.92	.93	.87	.77
Al_2O_3	17.26	17.43	17.78	17.74	16.95	17.87	17.55	17.53	17.59	17.47	17.39
MgO	3.03	2.63	3.06	2.12	2.38	2.80	2.84	2.90	3.07	2.82	2.60
Fe_2O_3	6.34	6.27	6.42	6.36	5.56	7.00	6.79	6.64	6.81	5.92	5.80
MnO	.10	.09	.09	.09	.07	.09	.09	.09	.09	.08	.08
CaO	5.55	5.80	6.23	5.52	5.46	5.99	5.96	5.95	6.12	5.99	5.75
Na_2O	4.15	4.25	3.93	4.16	4.21	4.30	4.22	4.27	4.17	4.51	4.27
K_2O	1.19	1.31	1.34	1.22	1.48	1.26	1.40	1.41	1.36	1.55	1.43
P_2O_5	.16	.21	.16	.17	.16	.23	.25	.22	.23	.24	.17
Rb	23	21	22	21	23	15	20	19	18	18	22
Sr	524	571	580	580	568	596	574	589	562	928	603
Zr	167	154	159	161	158	158	183	175	178	152	150
Ni	n.d.	n.d.	n.d.	n.d.	n.d.						
Sc	12.8	11.6	13.6	11.5	11.5						
Hf	4.3	4.5	4.6	4.0	4.3						
Ta	1.4	1.6	1.4	1.4	.9						
U	1.3	1.3	1.8	1.5	n.d.						
Th	3.2	1.8	3.7	3.3	3.8						
Ba	329	333	310	321	327						
La	20.5	19.2	19.8	18.7	18.1						
Ce	40.1	38.3	39.5	37.7	39.3						
Nd	22	20	20	n.d.	n.d.						
Sm	4.4	4.3	4.4	4.3	4.0						
Eu	1.2	1.2	1.2	1.2	1.1						
Tb	.5	.5	.5	.5	.4						
Yb	1.4	1.5	1.4	1.3	1.0						
Lu	.2	.2	.3	.2	.2						

TABLE 4 CONTINUED

	COE BRANCH-BARRETT SPUR SECTION				LANGILLE CRAGS SECTION		
	HD-43	HD-46	HD47	HD-45	HD-75	HD-76	HD-77
SiO_2	63.70	60.19	60.96	62.31	61.95	62.51	60.82
TiO_2	.70	.85	.87	.79	.89	.88	.85
Al_2O_3	17.44	17.77	18.00	17.19	16.98	16.47	17.59
MgO	2.04	2.98	2.61	2.48	2.36	2.35	2.54
Fe_2O_3	4.84	6.44	5.99	5.70	5.70	5.75	6.21
MnO	.07	.09	.07	.08	.08	.09	.09
CaO	5.23	6.05	5.73	5.53	5.81	5.61	5.88
Na_2O	4.33	4.07	4.50	4.23	4.15	4.26	4.30
K_2O	1.50	1.40	1.11	1.53	1.78	1.79	1.46
P_2O_5	.15	.17	.17	.16	.30	.29	.25
RB	21	24	11	20	23	26	23
Sr	550	575	615	636	927	881	909
Zr	152	177	135	157	197	193	177

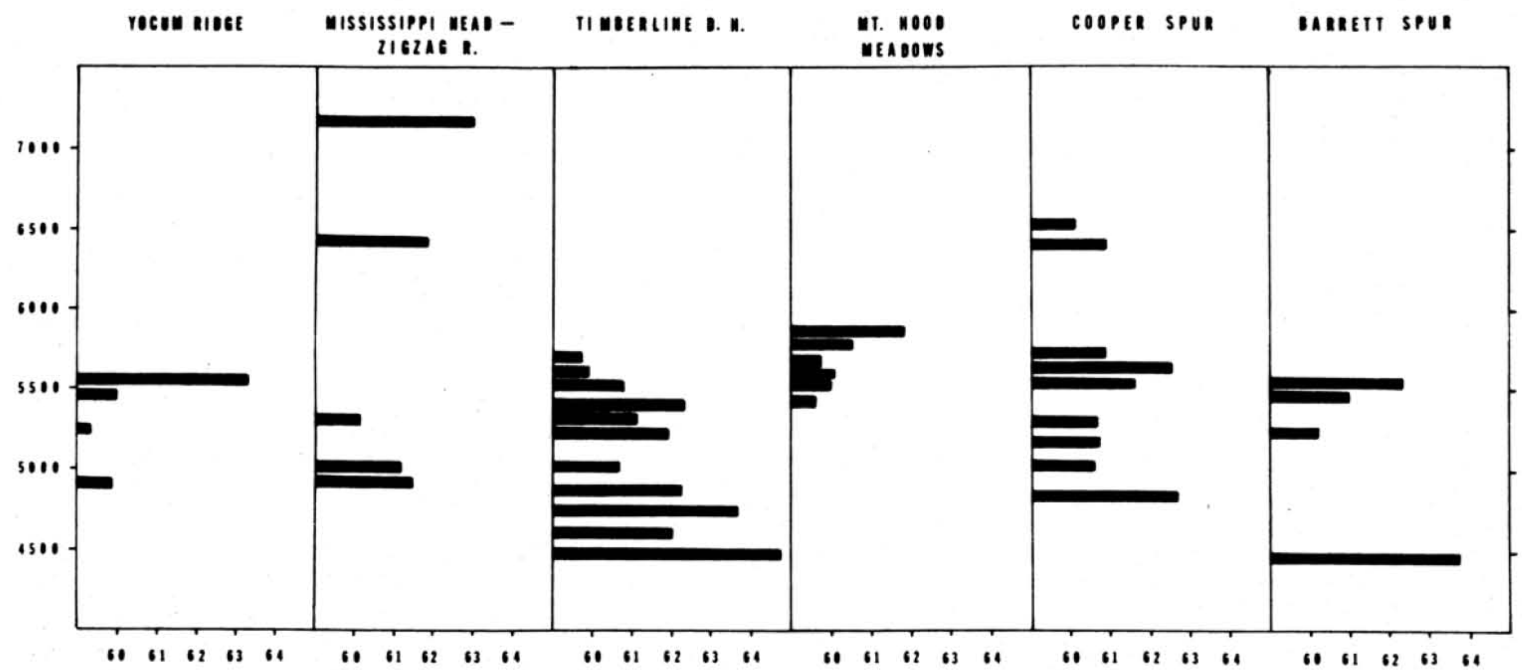


Figure 7. A graph of weight percent SiO_2 in Main Stage Mt. Hood lavas. The surface section has been projected with an initial dip of 10° to a distance from the summit that is equal to that of the Timberline drill hole.

fractional crystallization; however, numerous other examples exist of volcanoes in which the initial eruptions produced the most siliceous lavas in a sequence. At Hekla volcano in Iceland, this cycle has been repeated many times and the silica content of the initial products of each eruptive episode has been shown to be proportional to the length of the quiescent period between eruptions (Thorarinsson, 1954). An analysis of this kind cannot be made for the Main Stage Mt. Hood lavas because the absolute time intervals between eruptions are not known. Nonetheless, the eruption of siliceous lavas during the earliest stages of volcanism indicates that at least the initial magma chamber beneath Mt. Hood was compositionally zoned. The recurrence of rocks of dacitic composition at higher intervals in the Main Stage sequence may mark the initiation of later eruptive episodes.

Trace Elements

In general, the trace element compositions of the Main Stage lavas tend to reflect the major element contents in any one section of the flows. This tendency can be seen by comparing the trace element trends in Figures 8 and 9 with the trends for SiO_2 and MgO given in Figure 10. As might be expected, the excluded elements mimic the silica trend whereas the trends of Ni, Co, and Sc are similar to that of magnesia. The relatively consistent covariation of the major and trace elements in the drill hole section indicates that these flows may be genetically related, perhaps as differentiates of a common parental melt.

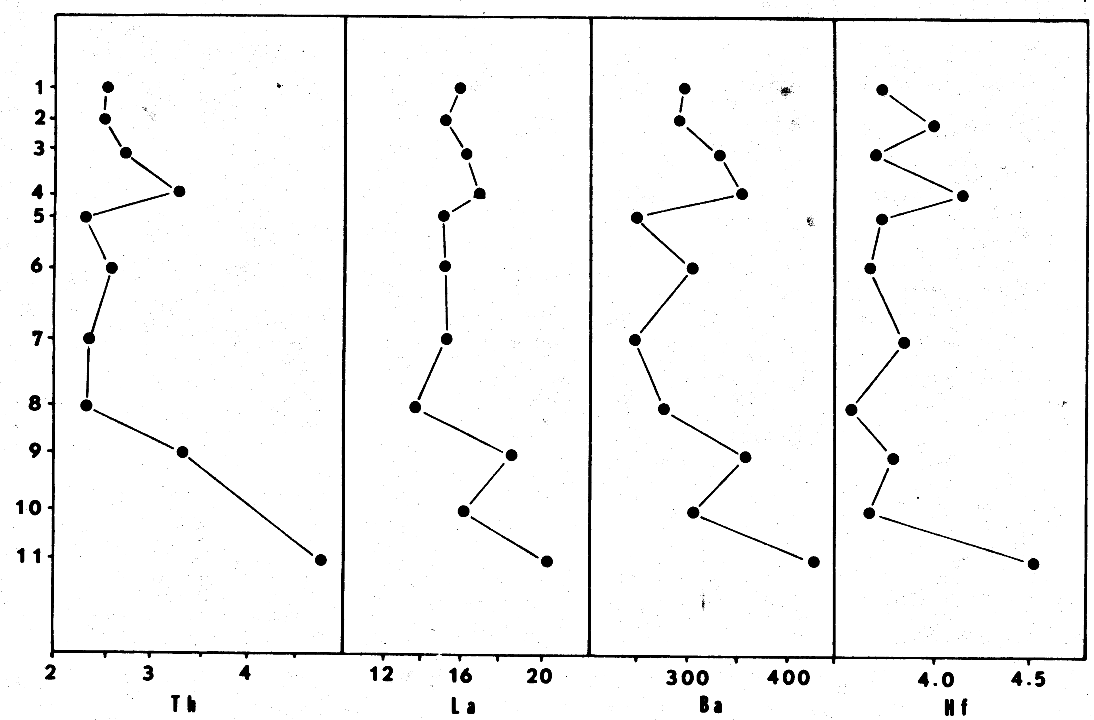


Figure 8. A plot of the concentrations of selected excluded trace elements versus flow number for the Timberline drill hole section.

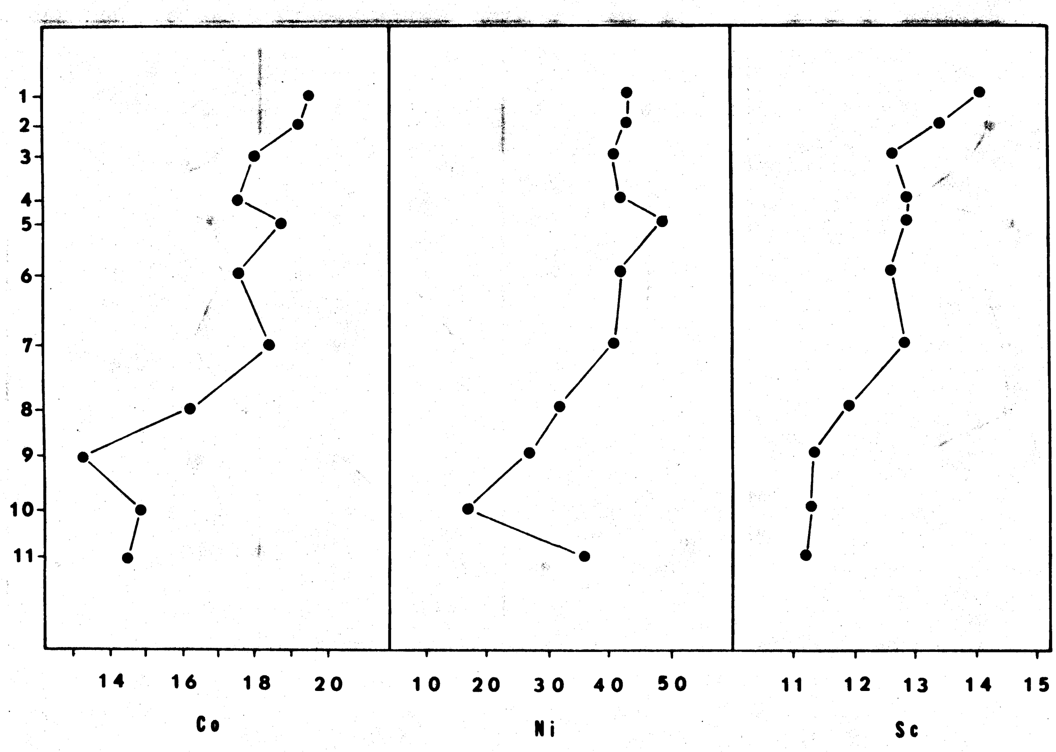


Figure 9. A plot of the concentrations of selected included trace elements versus flow number for the Timberline drill hole.

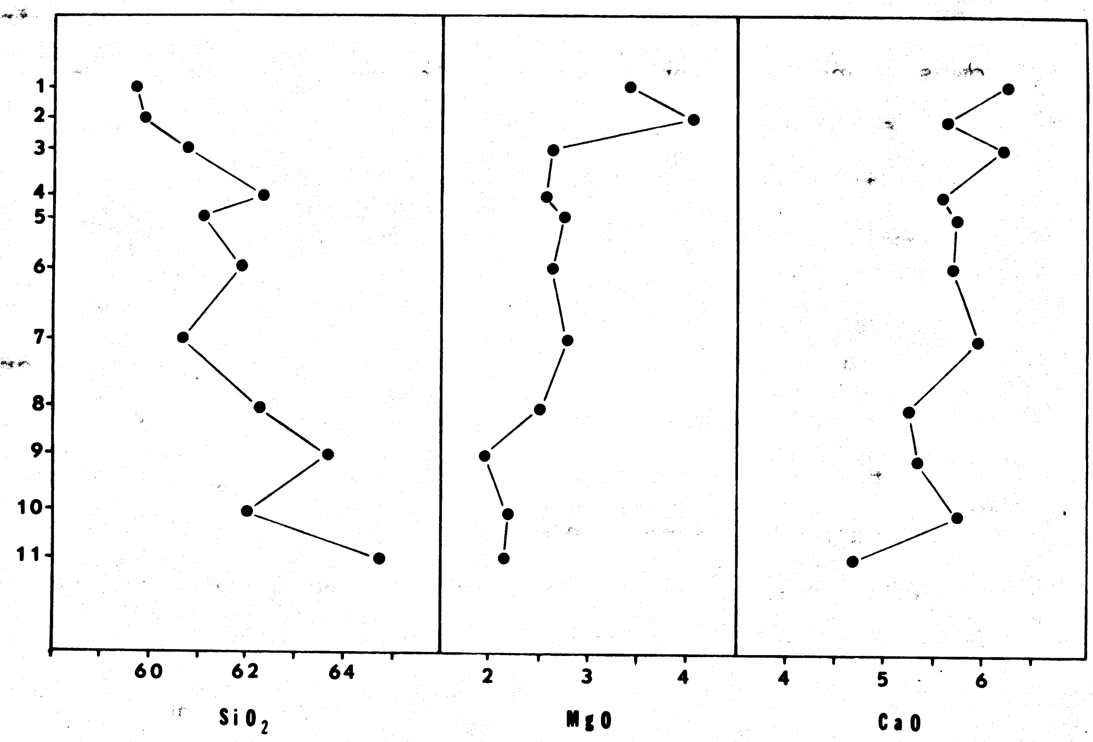


Figure 10. A plot of the concentrations of selected major elements versus flow number for the Timberline drill hole.

When the trace element compositions of flows from different sections are compared, chemical differences appear that cannot be readily explained by late stage differentiation processes. As shown by Figure 11, some flows are noticeably enriched in K_2O and the excluded trace elements compared to other Main-Stage lavas with similar major element compositions. With the exception of the basal flow (HD-66), the lavas in the Eliot Branch-Cooper Spur section have the highest excluded element contents whereas the Timberline drill hole samples contain the lowest concentrations of these elements. Flows from other sections fall within one or the other of these trends or occupy intermediate positions.

The existence of geochemically distinct lava suites in asymmetrical distribution around the volcano indicates that Mt. Hood was probably built by periodic eruptions of discrete magma batches from several different vents. Those flows that have intermediate concentrations of excluded trace elements may represent separate magma batches or may be mixtures of two or more end-member parent compositions. The variability in abundance in trace elements in lavas with similar SiO_2 contents could be caused by differences in the proportion of partial melting that produced each magma batch. Because of the eutectic nature of partial melting, small differences in the amount of melting would not affect the major element composition of the liquid; however, a parental magma that is produced by small degree of melting would have considerably higher abundances of the excluded trace elements than one representing a greater proportion of melt.

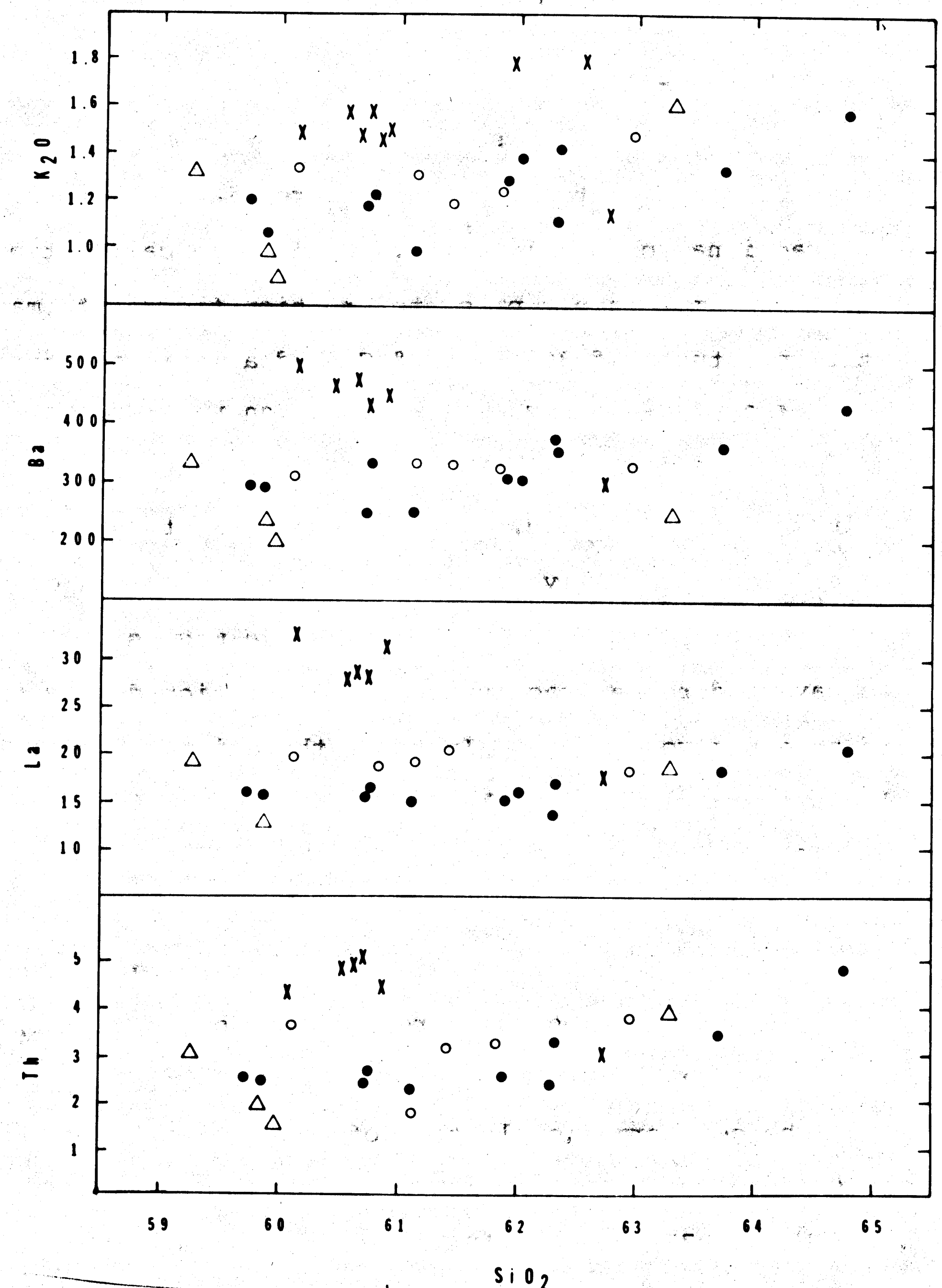


Figure 11. A plot of selected excluded elements versus SiO_2 in Main Stage lavas. Solid circles = Timberline d.h.; open circles = Mississippi Head-Illumination Rock section; triangles = Yocum Ridge section; X = Eliot Branch-Cooper Spur Section.

SUMMARY AND GEOTHERMAL IMPLICATIONS

The post-glacial silicic lavas were erupted during three temporally distinct episodes, each of which tapped a discrete batch of magma that was being differentiated by small amount of fractional crystallization. Equilibria calculations indicate that immediately prior to eruption the dacite magmas were at temperatures of 900 to 920° C, had a maximum water saturation of 30 percent and were at least 20 km beneath Mt. Hood.

The Main Stage lavas comprise about 90 percent of the volume of Mt. Hood and, like the young dacites, represent several geochemically distinct magma batches. In contrast to the post-glacial magmas, the Main-Stage magmas do not appear to have undergone fractional crystallization during the course of an eruptive episode. Instead, the existence of silica-rich lavas near the base of the Mt. Hood sequence indicates that the Main-Stage magma chambers may have been compositionally zoned. It is suggested that processes resulting in zonation of a magma may be more likely to occur in large Main-Stage chambers than in those representing the more rapidly cooled, small, post-glacial magma bodies.

The geothermal evaluation of an igneous system is based on the age, volume and depth of possible magma chambers. Smith and Shaw (1975) suggest 10 km as a maximum depth for magma chambers associated with potential geothermal resources. If the late-stage Mt. Hood magmas last equilibrated at depths greater than 20 km, as suggested by the equilibrium calculations, then residual magma in the chamber would probably have little influence on near-surface geothermal systems. Because of the young age of the most recent eruptions, a local heat source could be provided by magma that is still residing at shallow depths within the volcanic conduit. Calculations indicate that a cylindrical conduit which has the diameter of Crater Rock plug dome would contain about 0.3 km^3 of magma in the upper 10 km of its length.

The geothermal significance of the Main-Stage volcanism cannot be precisely evaluated because the age and depth of the associated magma chambers is not known. Estimates of the age and volume of the residual magmas indicate that they may still be associated with major geothermal anomalies (Figure 12); however, there is no reason to believe that these magmas are located at shallow depths. Deep-seated magma bodies could have considerable effect on the regional geothermal gradient in the Mt. Hood area, although it is unlikely that they would significantly affect the thermal regime of the volcanic edifice. Potential resources associated with a high regional anomaly would more likely be found along deeply penetrating structures.

In summary, the geological and geochemical evidence indicates that geothermal anomalies may exist at two levels in the Mt. Hood area; a shallow, localized anomaly associated with the young volcanic conduit, and a deep, regional anomaly associated with residual magmas from the Main-Stage volcanism of Mt. Hood.

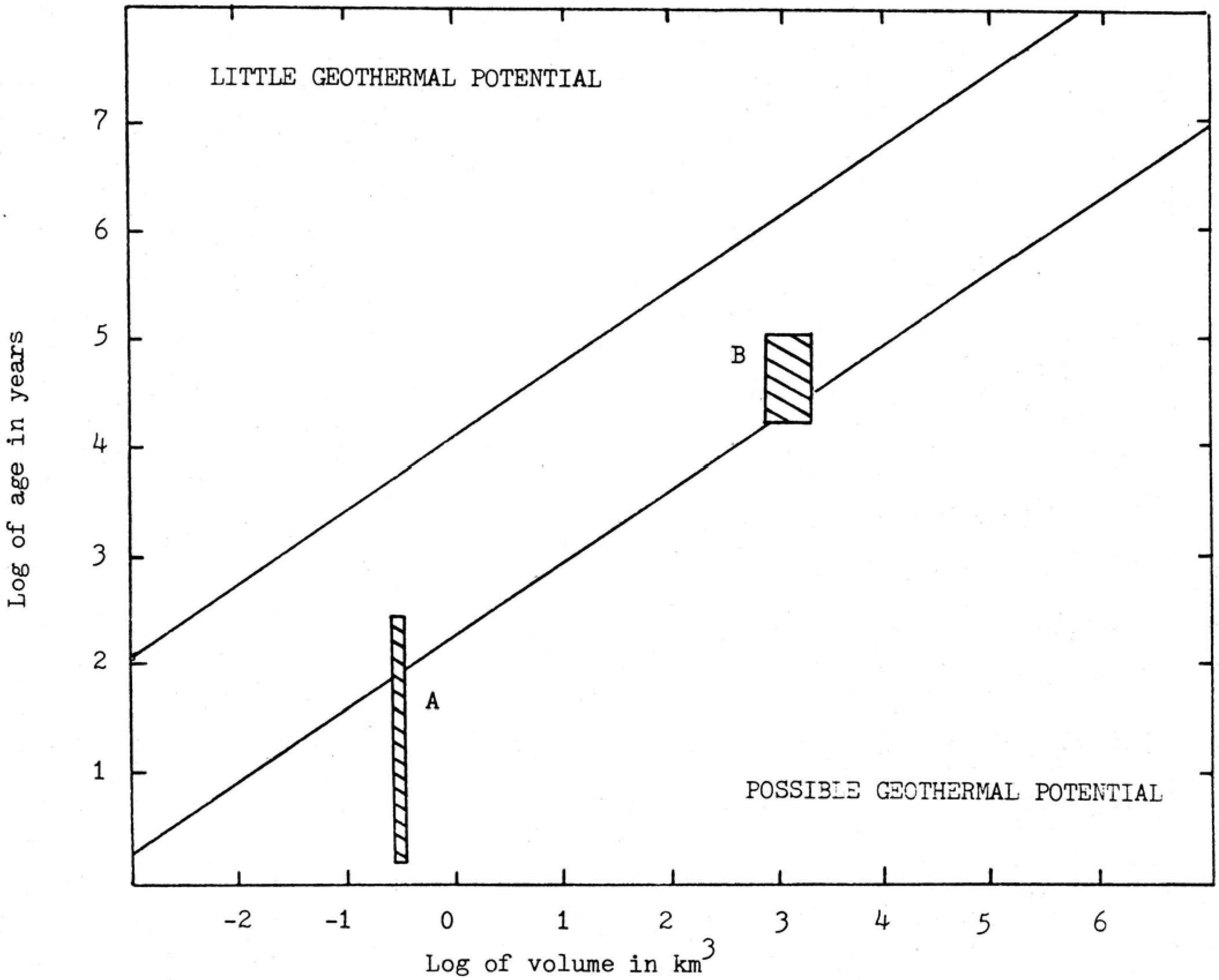
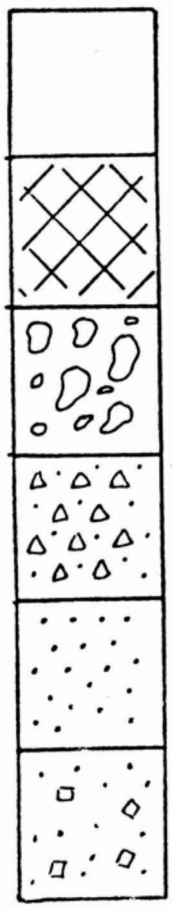


Figure 12. Graph of theoretical cooling time versus volume for magma bodies. Systems having magma chambers with large molten fractions would plot below the diagonal lines; systems that are now approaching ambient temperatures would plot above the diagonal lines; systems that may now be approaching a completely crystallized state would plot between the diagonal lines (after Smith and Shaw, 1975). Field A shows the age and volume range for a shallow volcanic conduit beneath Mt. Hood. Field B shows a range of ages (15,000 yrs - 100,000 yrs) and volumes (assuming that the erupted volume = 10-20% of the total magma reservoir) of a hypothetical Main-Stage magma chamber.

APPENDIX I

LITHOLOGIC LOG TIMBERLINE LODGE DRILL HOLE, 1978

Lithologic Symbols



Lava flow

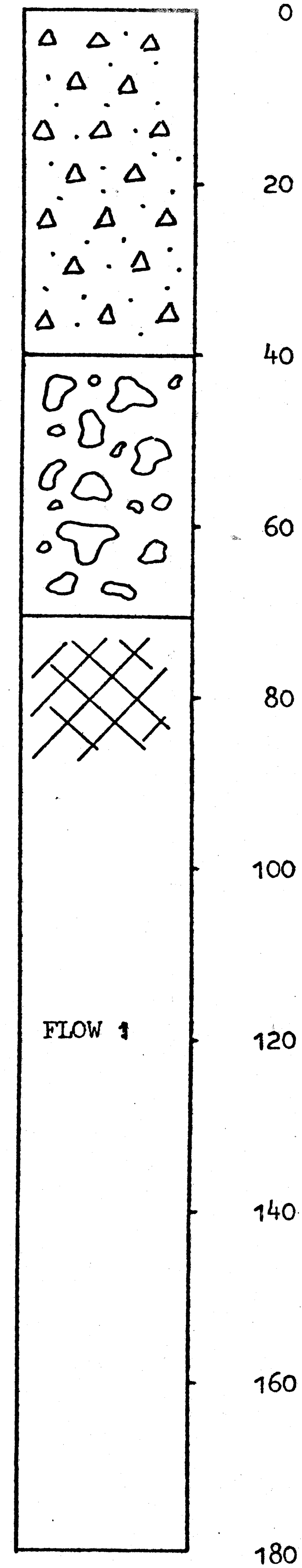
Brecciated lava flow

Mud flow or interflow colluvium

Dacitic block and ash flow

Lapilli

Crystal tuff



Plag Px Am Dacite. Large Am phenocrysts occur in chips from first 10 feet of hole, whereas the remaining 30 feet is composed of dacite with small Am phenocrysts and a higher proportion of Cpx.

Heterogeneous mixture of dacite and andesite. Large fragments in return.

FLOW #1. Light gray andesite with large Pl phenocrysts, abundant small crystals of honey to medium brown Opx, and less abundant phenocrysts of green-brown Cpx. Matrix is sugary in texture and has a salt and pepper appearance.

T. S.* **Plag = Opx >> Opaq > Cpx > Am**
Amphibole is present as small relict grains composed of finely granular opaque minerals.

* Relative modal proportions of phenocryst and microphenocryst minerals were determined by observation of thin sections of drill hole cuttings; description following flow # is from the field log and was made with the aid of a binocular microscope.

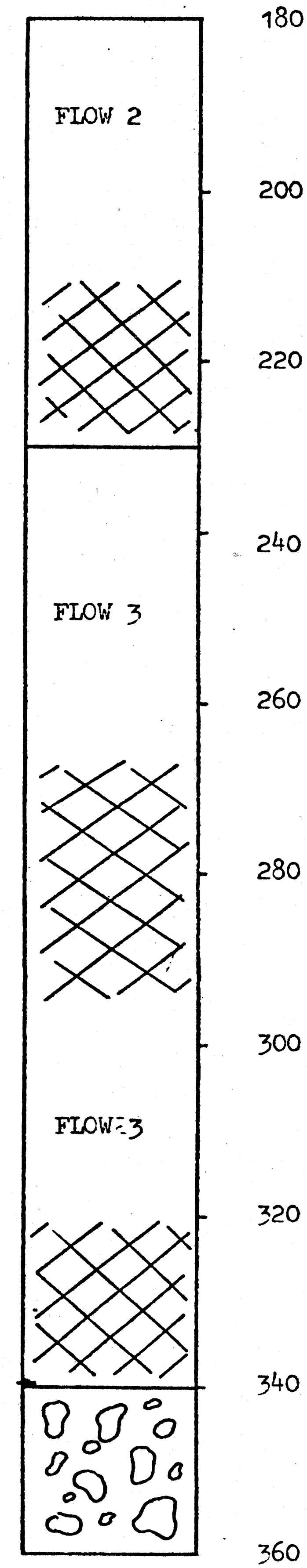
FLOW 2. Brown andesite with large phenocrysts of brown Opx and less abundant Cpx. The matrix has been altered to a light brown color by oxidation.

T. S. Plag > Opx > Cpx >> Opaq > Am
Amphibole present as small relict grains similar to those in flow #1.

FLOW 3. Medium brown andesite with phenocrysts of Pl, medium brown Opx and green Cpx. Matrix is fine-grained and gray-brown in color. A large proportion of the flow is vesicular and has been oxidized to a hematite-red color. Much of the flow has probably been autobrecciated.

T. S. Plag >> Opx = Cpx > Opaq
Plagioclase contains inclusions of brown glass. No amphibole was observed.

Heterogeneous mixture of highly oxidized andesite and black glassy andesite.



FLOW 4. Dense, light gray andesite with large Pl phenocrysts and smaller phenocrysts of brown pyroxene. Two pyroxene types are not descernible. Matrix is gray with some irregular patches of pink oxidation alteration.

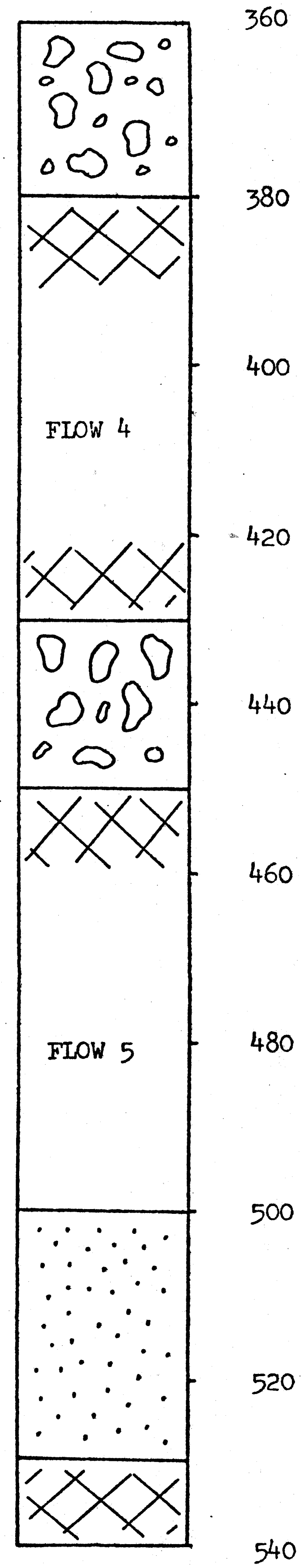
T. S. Plag > Opx >> Cpx >> Am?
Amphibole is present only as indistinct relicts.

Oxidixed heterogeneous mixture of andesites.

FLOW 5. Vesicular, medium gray-pink andesite with phenocrysts of Pl, brown Opx and green Cpx.

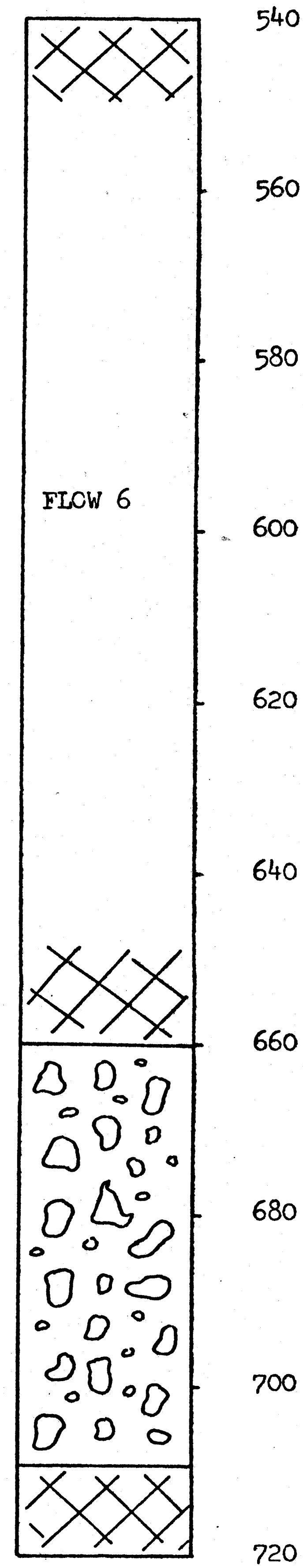
T. S. Plag > Opx >> Opaq = Cpx

Highly oxidized, bb-sized, black glassy lapilli.



FLOW 6. Dense light gray andesite with large phenocrysts of Pl, euhedral medium brown phenocrysts of Opx, and small honey-colored microphenocrysts of Opx. Matrix is very light gray.

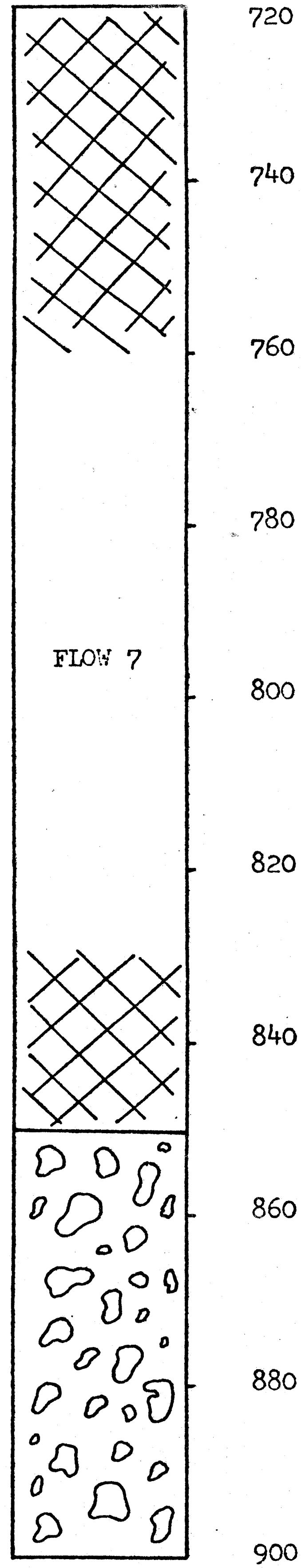
T. S. Plag > Opx > Am > Cpx =Opaq
Amphibole occurs as large phenocryst grains that have been completely converted to granular opaques + px? + plag?



Heterogeneous mixture of gray andesite, brown andesite and highly oxidized glassy fragments.

FLOW 7. Dark gray andesite with large Pl phenocrysts and small, dark brown pyroxene phenocrysts. Matrix is dark in color and probably contains a large proportion of glass.

T. S. **Plag > Opx >> Cpx = Opaq**



Heterogeneous mixture of at least three types of andesite, the most abundant of which has a distinctive limonite-yellow colored groundmass.

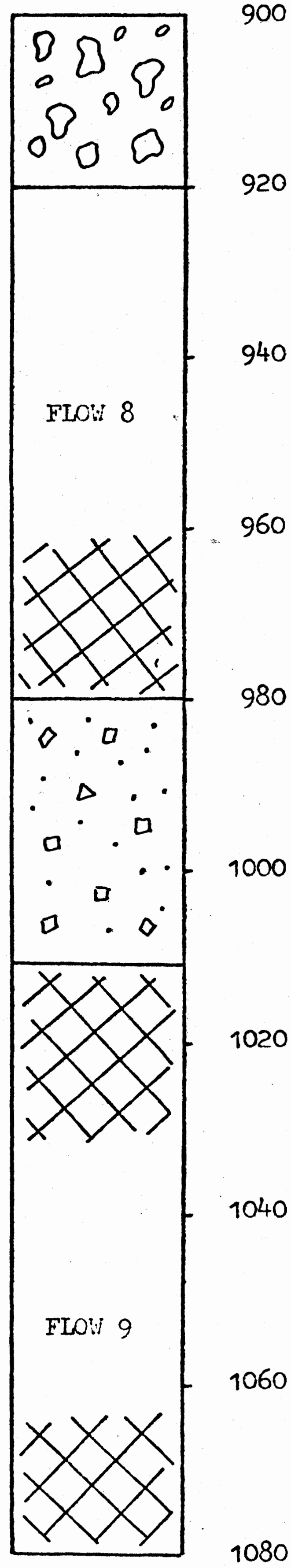
FLOW 8. Black, glassy andesite with large Pl phenocrysts, rare, large, dark brown Opx crystals, and a distinctive dark gray spotted matrix.

T. S. Plag > Opx > Cpx > Opaq
Orthopyroxene grains are rimmed with Cpx.

Crystal tuff with Pl crystals in a matrix of light gray to yellow ash and lapilli. Pyrite is a very abundant alteration mineral in this rock.

FLOW 9. Medium gray andesite with large phenocrysts of Pl and small crystals of red-brown pyroxene. Much of this flow is brecciated and oxidized. Pyrite is present as an alteration mineral but is less abundant than in the crystal tuff just above.

T. S. Plag > Opx = Am
Amphibole occurs as large grains of oxyhornblende that is rimmed with granular opaque minerals. This is the first occurrence of amphibole in the drill hole section that is not totally altered.

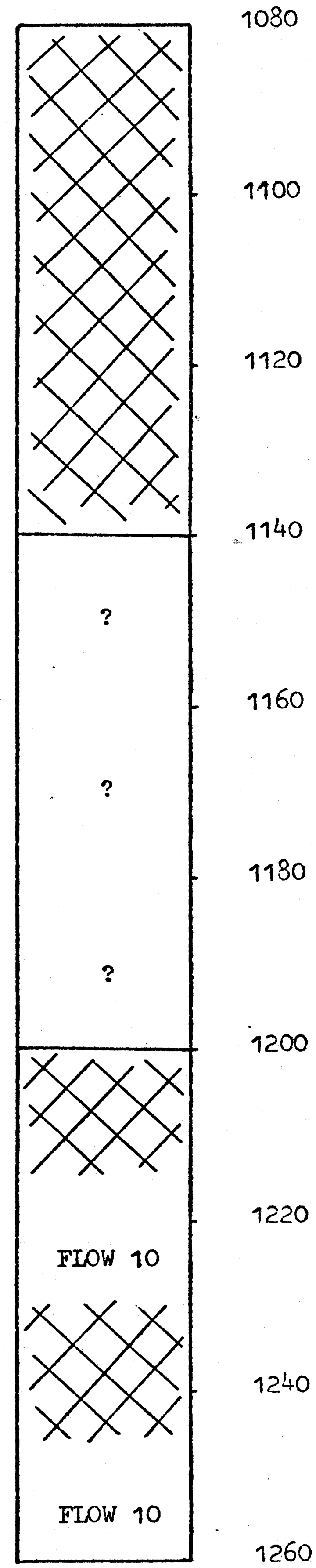


Continued brecciated flow 9.

(Convert to mud circulation at 1140'. Return is very mixed with a large proportion of oxidized lapilli and pyritic crystal tuff similar to units described above. It is likely that down-hole contamination from the more easily eroded units has masked the lithology in this interval. All return below this point probably contains a significant proportion of contamination from above)

FLOW 10. Medium gray andesite with large glassy-looking phenocrysts of Pl and small honey-colored crystals of Opx. Matrix is sugary with a salt and pepper appearance.

No thin section

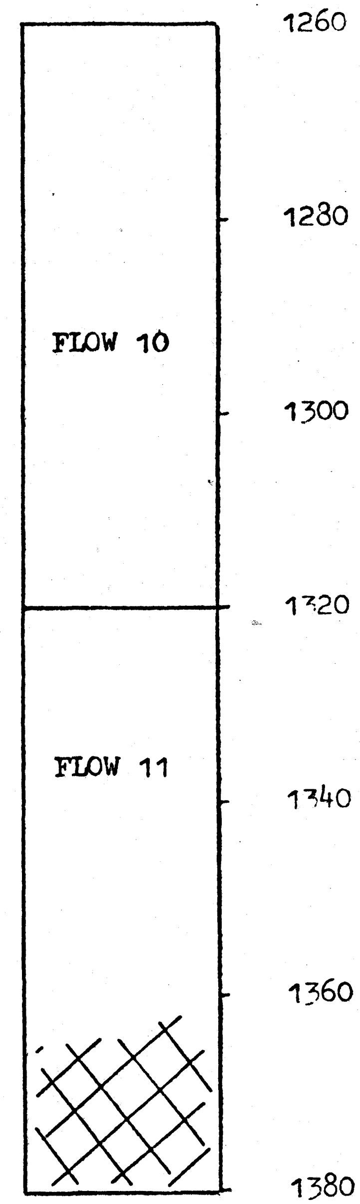


Continued flow 10.

FLOW 11. Light gray andesite with small phenocrysts of Pl and Opx in a holocrystalline light gray matrix. Return contains abundant oxidized rock starting at 1360' which indicates that the base of the flow may be just below the bottom of the drill hole.

No thin section

Bottom of hole at 1380'.



APPENDIX II

Radiometric Dating

Three samples of cuttings from the Old Maid Flat drill hole (2S/8E-15cd) were dated by the potassium/argon method. Samples OMF-2953 and OMF-3530 are from basaltic units that have been identified by optical and geochemical methods as members of the Columbia River Group (Beeson and Moran, 1978). OMF-3970 is from an andesite flow below the Columbia River Basalt. All three dates (Table 5) are anomalously young; the dated units most likely suffered loss of radiogenic argon as a result of one or more post-Miocene thermal events.

Two potassium/argon dates also were obtained from whole rock samples from pre-Mt. Hood units. HD-64 is a sample of hornblende dacite from the northwest peak of Mill Creek Buttes (1S/10E-27d d). Wise (1969) identified two domes and several associated flows at Mill Creek Buttes and, because of their constructional form, believed them to be of Pleistocene age. The K/Ar dates obtained for the present study indicate that these rocks are considerably older than Wise's estimate and were probably erupted toward the end of the episode of volcanism that produced the lower Pliocene Rhododendron and Dalles formations.

Sample HD-62 is from a lava flow that is exposed in a road cut just north of Still Creek (3S/8E-29d). The flow is intruded by the Still Creek granodiorite. Because the sample was taken within 100 yards of the contact, it is likely that the date may reflect the age of the thermal event associated with the

TABLE 5

RADIOMETRIC DATES

Sample No.	% K	Ar (cc/g)	% Ar	A (m.y.)
OMF-2953	1.1577	5.5205×10^{-7}	4.75	12.2 ± 2.0
OMF-3530	1.2935	2.9802×10^{-7}	4.38	5.9 ± 1.1
OMF-3970	0.8711	2.6895×10^{-7}	7.62	7.9 ± 0.8
HD-64	0.7170	2.0786×10^{-7}	13.57	7.5 ± 0.4
HD-62	1.1170	4.0346×10^{-7}	20.76	9.3 ± 0.3

Still Creek - Laurel Hill plutonism. The 9.27 m.y. date does in fact fall within the age range cited by other authors for the Laurel Hill pluton (Bickerman, 1971).

It should be noted that the major element composition of the flow from which sample HD-62 (Table 6) was taken is unlike that of any previously reported lower Pliocene lava. The high ratio of total Fe/Mg and the high TiO_2 content are suggestive of Columbia River Basalt composition; however, the altered nature of the sample precluded a confident geochemical correlation.

TABLE 6

MAJOR ELEMENT COMPOSITION

	HD-64	HD-62
SiO_2	62.89	51.62
TiO_2	.71	1.82
Al_2O_3	17.42	14.43
MgO	2.79	4.77
Fe_2O_3	5.20	13.41
CaO	6.04	8.75
Na_2O	3.87	3.69
K_2O	.85	.99
P_2O_5	.14	.30

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