The stratigraphy and structure of the Columbia River basalt group in the Bull Run watershed, Multnomah and Clackamas Counties, Oregon

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Portland State University

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AN ABSTRACT OF THE THESIS OF Beverly Probenius Vogt for the Master of Science in Geology presented May 1, 1981.

Title: The Stratigraphy and Structure of the Columbia River Basalt Group in the Bull Run Watershed, Multnomah and Clackamas Counties, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Martin H. Beeson, Chairman

Gilbert T. Benson

Ansel G. Johnson

Approximately 150 meters (500 feet) of Grande Ronde Basalt and 140 meters (450 feet) of Wanapum Basalt of the Columbia River Basalt Group are exposed in the Bull Run Watershed. In Bull Run, the Grande Ronde Basalt is divided into three mappable units: "low Mg" R₂ (at least one flow), "low Mg" N₂ (approximately four flows), and "high Mg" N₂ (two to three flows). The Wanapum Basalt is represented by two members: Frenchman Springs Member (six flows) and Priest Rapids Member (one flow). These units are identified by instrumental neutron
activation analysis, paleomagnetism based on measurements with a fluxgate magnetometer, petrography, lithology, jointing, and stratigraphic position.

The Columbia River Basalt Group flows entered the area from the east, moving toward western Oregon and Washington through an east-west-trending trough whose northern boundary was north of the Columbia River and whose southern boundary was in the Clackamas River area. Between the Frenchman Springs and Priest Rapids flows, a westerly flowing river carved a channel at least 174 meters (580 feet) deep that was subsequently filled to overflowing by a Priest Rapids intracanyon flow characterized by at least 105 meters (345 feet) of bedded palagonite, a 9-meter (30-foot)-thick colonnade, and a 60-meter (200-foot)-thick entablature. This flow has been identified in the Hood River Valley to the east and has been traced through the watershed. It is assumed to have continued to the northwest to the Columbia Gorge, where it appears at Crown Point.

Major structures in the Bull Run Watershed are a syncline and anticline striking N. 60° E. These folds are on strike with the Mosier syncline and the Columbia Hills anticline to the northeast and may have been continuous with them before they were broken by faulting in the Hood River Valley. A N. 60° E.-striking thrust fault that dips 12° to the southeast has produced at least 180 meters (600 feet) of vertical offset. Numerous fractures and breccia zones with trends of N. 10-55° W. cut the basalt throughout the watershed, occurring most commonly near the thrust fault. Blazed Alder Creek and the north-northwest-flowing portion of the Bull Run River follow part of a
N. 10° W.-trending lineament that extends north through Tanner Creek to the Columbia Gorge. This lineament is characterized in Bull Run by numerous fractures and breccia zones, many of which trend N. 10-20° W. Boring-type dikes trending N. 10° W. occur along Blazed Alder and Falls Creeks.

The folds, faults, fractures, breccia zones, and dikes found in the Bull Run Watershed are all consistent with a regional stress field of north-south compression and east-west extension.
THE STRATIGRAPHY AND STRUCTURE OF THE COLUMBIA RIVER BASALT GROUP
IN THE BULL RUN WATERSHED,
MULTNOMAH AND CLACKAMAS COUNTIES, OREGON

by
BEVERLY FROBENIUS YOGT

A thesis submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE
in
GEOLOGY

Portland State University
1981
TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of Beverly Frobenius Vogt presented May 1, 1981.

Marvin H. Beeson, Chairman

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Most of all, I thank my husband Paul and younger son Richard, who cheerfully sacrificed any semblance of normal family life so that I could finish this project.
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CHAPTER I

INTRODUCTION

The primary purpose of this study was to determine which units of the Miocene Columbia River Basalt Group are exposed in the Bull Run Watershed, to map their thickness and areal extent, and to delineate the structures formed since they flowed into the area and cooled. The units were to be identified on the basis of chemical composition determined by instrumental neutron activation analysis (INAA), petrographic and lithological characteristics, magnetic polarity determined by portable fluxgate magnetometer, and stratigraphic position. The end products of this study were to be this written text and a geologic map (scale 1:31,680) showing the extent of the Columbia River Basalt Group exposed in the Bull Run Watershed, the mappable units into which it was divided, and the structures which it formed.

Columbia River basalt had been mapped in the Bull Run Watershed (see Previous Work in the Bull Run Watershed in Chapter III), but only as a single, undifferentiated unit. Recent work in Columbia River basalt in the Columbia Plateau and in western Oregon, however, has shown that individual chemical groups and even individual flows within the complete Columbia River Basalt Group may now be identified and mapped over great distances, making it possible to use Columbia River basalt as stratigraphers use sedimentary units—to determine environment of deposition and subsequent structural
deformation which had affected the basalt.

As work on this study progressed, it became increasingly apparent that the Bull Run Watershed is a critical area in terms of basalt stratigraphy in the Western Cascades and western Oregon. During the Miocene, Columbia River basalt now found in western Oregon and Washington flowed from eastern Oregon, eastern Washington, and western Idaho through an east-west-trending trough whose axis was somewhere in or near Bull Run. This meant that most, if not all, of the Columbia River basalt found in western Oregon and Washington had to have flowed through Bull Run. The northern boundary of the trough was north of the Columbia Gorge in the State of Washington, the southern boundary was along the Clackamas River in Oregon. Although the Columbia River basalt is well exposed on both boundaries of the trough, the most extensive exposures between them are found in Bull Run. Therefore, the Bull Run section had to be studied to fill in the missing pieces of the story of Columbia River basalt west of the Cascades.

When geochemical and paleomagnetic techniques developed elsewhere for identifying different subgroups within the Columbia River Basalt Group were applied to the section in the Bull Run Watershed, it became possible to (1) fit the Bull Run section into the total regional basalt stratigraphy, and (2) identify structural deformation that had heretofore been unrecognized because the evidence was hidden in basalt flows that until now had been impossible to differentiate.
CHAPTER II

GEOGRAPHIC SETTING

LOCATION, CLIMATE, AND ACCESS

The Bull Run Watershed is located in northwestern Oregon within the eastern portions of Multnomah and Clackamas Counties (Figure 1). It lies within the Western Cascades Province and is west of the High Cascades divide. It covers approximately 390 square kilometers (150 square miles), occupying portions of the Cherryville and Bridal Veil 15-minute quadrangles and portions of the Tanner Butte, Wahtum Lake, Hickman Butte, and Bull Run 7½-minute quadrangles.

Lolo Pass and Mount Hood are to the east; the Columbia River Gorge to the north; the town of Sandy and the city of Portland to the west; and the communities of Alder Creek, Brightwood, Wemme, and Zigzag to the south. Interstate I-84 passes the area on the north, U. S. Highway 26 on the south.

The watershed receives large amounts of orographic rainfall each year, ranging from 430 centimeters (170 inches) per year at the higher elevations to 230 centimeters (90 inches) per year in the lower drainages on the western border. Snow generally starts to accumulate on higher elevations in late October and lasts till mid-June (U. S. Forest Service, 1976).

The Bull Run Watershed is the water supply for the city of
Figure 1. Map showing location of the Bull Run Watershed.
Portland and is jointly administered by the U. S. Forest Service (USFS), Mount Hood National Forest (Zigzag and Columbia Gorge Ranger Districts), and the City of Portland Water Bureau. Admittance to the watershed is restricted by the Exclusion Act of 1904 and is by permit only. Locked gates are at each of the entrances.

Major approaches are on USFS road S10 via a county road from Sandy, S224 from Brightwood, N12 from Zigzag and Lolo Pass, N20 from Larch Mountain, and S123 from Aims. Most of the major roads in the watershed are blacktopped; secondary roads are gravel. The U. S. Forest Service is in the process of changing road numbers throughout the Mount Hood National Forest. As the numbers have not yet been changed in Bull Run, the old numbers are used throughout this thesis. Appendix A lists the new road numbers that will be used at some as yet unspecified time in the future.

GEOGRAPHIC FEATURES

Geographic and cultural features of the Bull Run Watershed that are discussed in this thesis are shown in Figure 2. The maximum elevation of 1,380 meters (4,600 feet) is on the top of Hiyu Mountain on the eastern boundary of the watershed. The topography gradually decreases in elevation toward the west, with the lowest elevation, less than 150 meters (500 feet), along the Bull Run River at the Sandy entrance on S10.

The major river in the area is the Bull Run River, which flows first to the northwest and then to the southwest from its headwaters at Bull Run Lake on the eastern edge of the watershed. Major
Figure 2. Map showing major cultural and geographic features in the Bull Run Watershed.
tributaries to the Bull Run River include Blazed Alder, Log, Falls, and Fir Creeks and the North and South Forks of the Bull Run River. The Bull Run River is dammed twice in the lower portion of its course, forming two reservoirs. The Little Sandy River flows from east to west along the southern edge of the watershed and joins the Bull Run River just west of the western boundary of the watershed.

TOPOGRAPHY

The topographic relief of the watershed is the result of stream erosion, mass wasting, and glaciation of bedrock units of varying degrees of resistance to these processes. The Columbia River Basalt Group and the unconformably overlying Miocene, Pliocene, and Quaternary sedimentary, volcanic, and volcaniclastic rocks form a platform that slopes gently to the southwest. The platform has been dissected by rivers and streams; the more resistant High Cascade volcanic rocks and the Columbia River basalt form steep slopes and canyon walls (Figure 3); benched topography results from erosion of the softer Rhododendron Formation rocks lying between the two more resistant units (Figure 4).

Massive landslides occurring in the Columbia River Basalt Group, in the softer pyroclastic and volcaniclastic rocks of the overlying Rhododendron Formation, along contacts of Columbia River basalt and younger units, and between various younger units (Schulz, 1980) have helped to produce the broad valleys, irregular topography, and steep headscarsps characteristic of the watershed (Beaulieu, 1974).
Figure 3. Steep canyon walls along Blazed Alder Creek are produced by erosion of Columbia River basalt.
Figure 4. View to east along Reservoir No. 1. Rocks immediately above water are Columbia River basalt. More easily eroded rocks of Rhododendron Formation form gentler slopes above. Steep upper slopes are formed by more resistant Pliocene-Pleistocene volcanic rocks.
Pleistocene glaciation sculptured the upper portions of the watershed, producing the cirques in which Bull Run, Hickman, and Blue Lakes lie. The glaciation, however, affected areas probably only above elevations of about 600 meters (2,000 feet) (Beaulieu, 1974).

COLUMBIA RIVER BASALT GROUP DISTRIBUTION

Basalt of the Columbia River Basalt Group undoubtedly underlies all of the watershed but has been covered by younger volcanic and volcaniclastic units and unconsolidated surface deposits. Stream erosion has cut through the younger rocks, exposing the Columbia River basalt in the floor of the drainage basin along the river and lower portions of its tributaries. The highest exposure of Columbia River basalt occurs at an elevation of 930 meters (3,100 feet) northwest of Nanny Creek (see geologic map). Lowest exposures occur at an elevation of 150 meters (500 feet) along the Bull Run River below Reservoir No. 2.

Because of dense vegetation, younger volcanic rock cover, debris and rock slides, massive landslides, talus, alluvium, and glacial deposits, exposures of Columbia River basalt are sparse and seldom continuous over much distance. The best exposures are, of course, along streams and rivers and in some roadcuts. Erosion has produced deep canyons in the Columbia River basalt; as roads in the watershed are at the tops of the canyons, traverses on foot down into the canyons were the best way to study the basalt stratigraphy.

Columbia River basalt is exposed intermittently along at least
60 kilometers (40 miles) of rivers and streams in the watershed, and reservoir water covers at least 10 percent of these exposures. In steep-gradient bedrock streams, exposure ranges from 20 to 60 percent; in low-gradient streams, the percentage of exposure is often much less or nonexistent. Most of the Columbia River basalt cropping out along roads is at the top of the section; exposures are generally poor except for outcrops on S111 at South Fork; on the north rim of Reservoir No. 1, North Fork, and Falls Creek on S10; at the east end of S10; and at the Multnomah-Clackamas County line on S154. In most cases, cross-country traverses away from streams were unproductive for this study because of dense cover of vegetation and colluvium.

RELATION OF THE COLUMBIA RIVER BASALT GROUP TO OTHER GEOLOGIC UNITS

The deepest part of the Columbia River basalt section in the watershed is exposed in Blazed Alder Creek, but the base of the section is not exposed anywhere in the watershed. However, about 17 kilometers (11 miles) to the north, outside of the watershed, Columbia River basalt unconformably overlies lower Miocene rocks of the Eagle Creek Formation.

Beaulieu (1974) mapped unconformably overlying units as the upper Miocene-lower Pliocene Rhododendron Formation in the western portion of the watershed and as Pliocene and Quaternary volcanic rocks in the eastern section. During this study, rocks of the Rhododendron Formation were observed farther to the east, and Schulz
(1980) mapped a fairly continuous sequence overlying the Columbia River Basalt Group in the southeastern portion of the watershed. Schulz also mapped Pliocene-Quaternary volcanic rocks directly overlying Columbia River basalt at North Fork and in the eastern portion of the watershed (Figure 5).

These overlying units have been grouped as unit "Tv" on the geologic map for this thesis. Landslides that are in direct contact with the Columbia River Basalt Group are indicated as unit "Qls" on the geologic map.
Figure 5. Unconformable contact between Frenchman Springs Member of Wanapum Basalt (foreground) and Pliocene-Pleistocene volcanic rock (background) on S10 east of Falls Creek.
CHAPTER III

PREVIOUS WORK IN THE BULL RUN WATERSHED

Most of the previous geologic investigations in the Bull Run Watershed have been related in some way to engineering geology. Studies related to dam construction include those by Ruff (1957), Stevens and Thompson, Inc. (1957), Shannon and Wilson (1958a,b; 1963; 1973; 1978), Schlicker (1961), and Geo-Recon, Inc. (1962). Shannon and Wilson (1965) and Stevens and Thompson, Inc. (1965) studied the Ditch Camp slide. Dames and Moore (1972a,b; 1973) and Patterson (1973) investigated the North Fork slide of 1972.

Williams (1920) and Shannon and Wilson (1961) described the geology of Bull Run Lake. Columbia River basalt was mapped as an undifferentiated unit along the Bull Run River and Blazed Alder Creek by Wells and Peck (1961) and by Peck and others (1964), who also projected an anticline into the southeastern portion of the watershed. Wise (1969) briefly discussed the Columbia River basalt he found near Bull Run Lake and in the area near the community of Rhododendron. Wise (1969) also cited Waters (1964, personal communication), who had told him he believed that all the Mount Hood area had once been flooded by Columbia River basalt. Wise noted that he had found nothing in his studies to refute Waters' statement about the distribution of the Columbia River basalt.

Wheeler and Mallory (1970) quite erroneously insisted that the basalt in the valley of the Bull Run River was not Columbia
River basalt but instead was either Quaternary "intra-canyon" basalt, intrusive rock, or pre-Columbia River basalt Little Butte or Eagle Creek-type rock. In their response to Wheeler and Mallory, Peck and others (1970), while not discussing the Bull Run exposures of Columbia River basalt directly, did question their identification of Columbia River basalt elsewhere in the Western Cascades, mentioning specific areas where Wheeler and Mallory had misidentified rock units.

Beaulieu (1974) conducted a much more comprehensive study of the geology, engineering properties of geologic units, and geologic hazards within the watershed. The purpose of his study was to provide a geologic data base that could be used by the U. S. Forest Service and the Portland Water Bureau to manage the activities within the watershed so that water quality could be maintained or improved and that geologic disaster be averted if possible—or at least minimized.

U. S. Forest Service soil surveys of the Mount Hood National Forest, including the watershed, included some discussion of bedrock geology of the watershed, but their main emphasis was, of course, on the soils found there (Stevens, 1964; Howes, 1979).

The most recent study of the Bull Run Watershed is a master's thesis by Schulz (1980). Schulz mapped the various geologic units in the watershed; studied and categorized the various types of mass movements; and showed how the mass movements were related to lithology, structure, and type of bed rock. His Columbia River basalt
stratigraphy and structure were based on this author's mapping and preliminary data given to him as a personal communication, which he acknowledged in his thesis.

This author's thesis work was summarized in a paper given to the Oregon Academy of Science in 1979.
CHAPTER IV

PROCEDURES

FIELD WORK

The first phase of this study was field mapping conducted for two months during the summer of 1976 and on weekends during August, September, and part of October in 1978. Entrance to the watershed was by written permission of the U. S. Forest Service. Along with the permit came temporary use of a key to the watershed. Use of the 1976 permit also required a court appearance before Judge James M. Burns, U. S. District Court, representatives of the Portland Water Bureau, the U. S. Forest Service, and others.

The first phase of the mapping project was reconnaissance around the Portland area to learn more about the basalt section there. Next was reconnaissance around the Bull Run Watershed to determine the general extent of the basalt outcrops and the best way of approaching the study area.

Data were plotted on an Oregon Department of Geology and Mineral Industries base map (scale 1:31,680). U. S. Forest Service low-altitude aerial photographs (scale 1:15,840) were also used for some mapping and lineation study.

Field procedure generally consisted of making traverses, taking samples, recording data in a field notebook, and plotting locations of data points on a topographic map. During the first
(1976) field season, a fluxgate magnetometer was not available all of the time to be carried into the field, so instead, oriented samples were taken from appropriate outcrops and the magnetic polarity was measured away from the watershed. This was not always a satisfactory procedure because it is preferable to use more than one sample from an outcrop to determine its magnetic polarity, so during the 1978 season, the fluxgate magnetometer was carried into the field. The original magnetic polarity of a flow may be overprinted with the earth's current field when unstable components within the flow align themselves with it (Watkins, 1965; Hooper and others, 1979); therefore, because the higher oxidation states of the titanomagnetites recording the earth's paleomagnetic field are the most magnetically stable and because samples from the more oxidized tops and bottoms of flows are most likely to give reliable readings on the paleomagnetism of that flow (Watkins and Baksi, 1974; Swanson and Wright, 1976), the magnetic polarity of flows in Bull Run was measured whenever possible from a flow top or bottom.

An altimeter was used to determine elevations of outcrops, locations of contacts, and thicknesses of units. During the first field season, an airplane altimeter with 20-foot increments was used to measure elevations; during the 1978 field season, a Thommen pocket altimeter with 20-foot increments was used. As there were no benchmarks known to be in the watershed, all elevations were set relative to a benchmark in the town of Sandy. Several trips were
made by car throughout the watershed solely for the purpose of establishing elevations of various locations.

Complete sections were measured by altimeter at Log Creek, Falls Creek, South Fork, and Dam No. 1 and are included in Chapter VI. Because of poor exposure, most of the sections have at least one offset or covered section, conditions indicated in the measured sections. The most complete section is the Log Creek section. An additional section utilizing data from core samples obtained from drilling by the Portland Water Bureau in 1978 was constructed for Dam No. 2. This section is partially based on lithologic descriptions and cross sections drawn by Richard Gaps, formerly of the Portland Water Bureau.

LABORATORY METHODS

The laboratory phase of this project consisted of two parts: instrumental neutron activation analysis (INAA) and petrography. Fifty samples were analyzed by INAA for this study. Discussion of the INAA procedure is included in Appendix B. Five additional analyses conducted by Beeson and others (1975) for the Portland Environmental Geology (PEG) project are also included in this thesis in the appendix. All INAA data are printed in Appendix C, and sample locations are shown on the geologic map.

Thirty-eight samples were analyzed as experiment 7-V by this author in 1977. The samples were irradiated by the TRIGA reactor at Reed College in Portland on January 12, 1977. Because of instrument problems, the first count could not done on the Reed
College Ge(Li) detector as planned, and instead the samples were counted on January 20, 1977, on three detectors at the Center for Volcanology, University of Oregon, Eugene. The University of Oregon system had to be modified to produce data in a form usable by the Portland State University computers, and during this process some data were lost. The second count was conducted without mishap on March 15, 1977, at Reed College. Because of these problems, 11 samples were analyzed again, and an additional 12 samples were analyzed by Beeson and Moran in 1978 as parts of their experiments 7-7, 7-9, and 7-10.

Because the samples used for this study were not all irradiated at the same time and were not all counted on the same detector, the data are listed in two different ways in the appendix: (1) one comprehensive list, and (2) a series of different lists, one for each experiment and each different detector. Because there were apparently some minor differences in some of the experiments which produced some generally higher or lower values for some elements, the second listing was more helpful in determining relative abundances of elements of different chemical groups within the Columbia River Basalt Group.

Once the concentrations of selected elements were determined for these 55 samples, each sample was assigned to a certain chemical group within the Columbia River Basalt Group. The chemical data were supplemented by paleomagnetic, lithologic, petrographic, and field data. Classification of each sample is included with the INAA data in Appendix C.
PETROGRAPHY

One hundred and twenty-three thin sections were prepared for this study. Identification of chemical groups of basalt by petrography was no more reliable than regular hand-sample identification, and therefore petrography was not used for identification and correlation of chemical groups in this study. General petrographic characteristics of the chemical groups are given in Chapter VI, along with other more significant characteristics.
CHAPTER V

REGIONAL COLUMBIA RIVER BASALT GROUP STRATIGRAPHY

GENERAL

The Miocene Columbia River Basalt Group is a sequence of tholeiitic flood basalts that cover approximately \( 2 \times 10^5 \) square kilometers (78,000 square miles) in Oregon, Washington, and Idaho (Waters, 1962) (Figure 6). This basalt, which was erupted from north- to northwest-trending fissures in northeast and eastern Oregon, eastern Washington, and adjacent areas of western Idaho, flowed generally toward the west, accumulating on the Columbia Plateau to a maximum thickness of 1,500 meters (4,950 feet) near Pasco, Washington (Asaro and others, 1978). Ages of the flows range from 16.5 to 6 m.y. (Holmgren, 1970; Baksi and Watkins, 1973; Watkins and Baksi, 1974; Atlantic Richfield Hanford Co., 1976; and McKee and others, 1977).

Some of the Columbia River basalt flowed through a topographic low extending from the present-day Columbia River Gorge on the north to the Clackamas River on the south, spread south into what is now the Willamette Valley and north into the State of Washington, flowed farther west, and possibly even reached the present-day coast (Beeson and others, 1979). The Bull Run Watershed lies within the topographic low through which the basalt flowed, and this study is concerned with the basalt found there.
Figure 6. Map showing areal distribution of Columbia River Basalt Group (stippled area) in Oregon, Washington, and Idaho. (After Swanson and others, 1979)
DEVELOPMENT OF COLUMBIA RIVER BASALT GROUP STRATIGRAPHY

In 1893, Russell gave the name "Columbia lava" to lavas ranging in age from Eocene to Recent that covered portions of eastern Washington, eastern Oregon, southern Idaho, and north­eastern California. In 1900, he gave the name "Columbia River lava" to four "sheets" of basalt flows of different ages in the Yakima region of central Washington. In 1901, he applied the name Columbia River basalt to the basaltic lavas of the Pacific Northwest.

Merriam (1901) believed that the name Columbia River basalt should be used only for the "horizon that is most prominent along the Columbia River." He restricted the use of the name to those lavas that form a "well-defined series between the John Day and Mascall formations" in the John Day basin of central Oregon.

Smith (1901), working also in the Yakima area, saw the necessity of being able to divide the basalts into different units of different ages and used the name "Yakima basalt" for basalts exposed in the canyon of the Yakima River. Lindgren (1901) suggested that the name "Columbia River lava" be restricted to Miocene lavas only.

Waters (1961) divided the Columbia River basalt into the older Picture Gorge Basalt and the younger Yakima Basalt on the basis of field, petrographic, and chemical characteristics. He (1962) and other workers, particularly Mackin (1961), Bond (1963), Schmincke (1967), Swanson (1967), Wright and others (1973), and Nathan and Fruchter (1974), continued to subdivide the Columbia
River basalt on the basis of chemical, petrologic, paleomagnetic, and/or lithologic characteristics. In 1979, Swanson and others published a much-needed revised stratigraphic nomenclature, dividing the group into one subgroup, five formations, and 14 members (Figure 7), based on major-element and paleomagnetic characteristics and stratigraphic position; and their nomenclature is used in this thesis.

Several other workers, including Osawa and Goles (1970), Beeson and others (1975, 1976), and Beeson and Moran (1979a,b) have demonstrated the value of using trace-element abundances for identification of different chemical groups within the Columbia River Basalt Group; and it was on the basis of trace- and major-element abundances, paleomagnetism, lithology, and stratigraphic position that units within the Bull Run Watershed were identified.

Basalts belonging to three formations of the Yakima Basalt Subgroup of the Columbia River Basalt Group are found either within the Bull Run Watershed or at least in the topographic low of which it is a part. These formations are the Grande Ronde, Wanapum, and Saddle Mountains Basalts (Figure 7), which correspond to the Yakima Basalt of Waters (1961) and to the lower, middle, and upper Yakima Basalt of Wright and others (1973).

GRANDE RONDE BASALT

The Grande Ronde Basalt is the most widespread formation within the Yakima Basalt Subgroup (Swanson and Wright, 1981) (Figure 8).
<table>
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<tr>
<th>Series</th>
<th>Group</th>
<th>Sub-group</th>
<th>Formation</th>
<th>Member</th>
<th>K-Ar age (m. y.)</th>
<th>Magnetic polarity</th>
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<td>Imnaha</td>
<td>Basalt</td>
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Figure 7. Columbia River Basalt Group stratigraphic column. Dashed line indicates units found in western Oregon (Beeson and others, in press). Dotted line indicates units found in Bull Run. In western Oregon, Vantage Member overlies Grande Ronde Basalt and is in turn overlain by Wanapum Basalt. (After Swanson and others, 1979)
Figure 8. Maps showing distribution of members of Columbia River Basalt Group found in Bull Run. Stars indicate location of Bull Run. (After Swanson and others, 1979)
It is also the most voluminous, constituting between 90 and 95 percent of the total volume of the Yakima Basalt Subgroup (Choiniere and Swanson, 1979). The thickest section, about 1,000 meters (3,000 feet) thick, is found in drillholes DH-4 and DH-5 in the Pasco Basin, Washington (Ledgerwood and others, 1973; Myers, 1973; Atlantic Richfield Hanford Co., 1976).

The Grande Ronde Basalts form a chemically distinct group that is characterized by relatively low FeO and higher SiO₂ relative to MgO than the other chemical groups. On the basis of major- and trace-element chemistry, the Grande Ronde Basalt chemical group may be divided into two groups, called informally "high Mg" and "low Mg" basalts in this thesis. Throughout most of the Columbia Plateau, these high and low Mg flows interfinger. However, in southwest Washington and western Oregon, flows of the high Mg chemical type overlie the low Mg section. As there are different chemical, lithologic, and jointing characteristics for each of these two chemical subgroups, they are mappable units in this region.

With some exceptions (see section on Grande Ronde Basalt, Chapter VI), most of the basalts in the Grande Ronde Basalt chemical group are very similar in hand specimen and thin section and are generally fine grained and aphyric, with rare plagioclase microphenocrysts and plagioclase-clinopyroxene clots. Olivine is present in very small amounts (less than 0.5 percent) in the groundmass (Swanson and others, 1979).

Swanson and others (1979) divide the Grande Ronde Basalt into
four magnetostratigraphic units (R₁, N₁, R₂, and N₂) on the basis of natural remanent magnetism (Figure 7). These paleomagnetic divisions are also mappable units. In western Oregon, the high Mg subgroup mentioned above falls into the N₂ magnetic interval, the low Mg subgroup into the N₁, R₂, and N₂ magnetic intervals.

VANTAGE MEMBER

A sedimentary interbed called the Vantage Member of the Ellensburg Formation (Swanson and others, 1979) overlies the deeply weathered uppermost high Mg Grande Ronde Basalt flow. Farther to the east, this interbed is a sandstone; in the western Columbia Plateau, western Oregon, and southwestern Washington, the Vantage Member is variable in nature, having at different locations clastic and volcaniclastic sediments, a soil zone, and carbonized wood. Where the interbed is not present, a thin saprolite commonly occurs.

The Vantage Member represents a hiatus in the outpouring of Columbia River basalt—a period long enough for soil to develop on the uppermost Grande Ronde Basalt flow, for forests to grow, and for drainages and some geologic structures to develop. It also separates two chemically distinct groups of Columbia River basalt, the Grande Ronde Basalt and Wanapum Basalt, and is a major stratigraphic horizon in the Bull Run Watershed and throughout the Columbia Plateau and western Oregon and Washington.
The Wanapum Basalt (Figure 7) is less voluminous than the Grande Ronde Basalt, accounting for approximately 5 percent of the total volume of the Yakima Basalt Subgroup (Choiniere and Swanson, 1979). It is, however, the unit that is exposed most extensively at the surface in the Columbia Plateau (Swanson and Wright, 1981) and in western Oregon.

The Wanapum Basalt is characterized by generally higher FeO and TiO₂ values relative to MgO (Wright and others, 1973) and on the basis of petrography and magnetic polarity has been divided into four members, from oldest to youngest, the Eckler Mountain, Frenchman Springs, Roza, and Priest Rapids Members. Only the Frenchman Springs and Priest Rapids Members have been identified with certainty in western Oregon.

In general, Wanapum Basalt samples are medium grained, olivine bearing, and either aphyric or sparsely, variably, or abundantly plagioclase phyric. The distribution of plagioclase phenocrysts is one means by which some individual Wanapum flows may be recognized in western Oregon.

The Wanapum Basalt spans the N₂ and R₃ magnetic intervals (Figure 7), and magnetic polarity of flows is also useful in identifying different Wanapum Basalt members.
Considerable work has been done on the Columbia River Basalt Group in areas surrounding the Bull Run Watershed. Early workers in the Columbia River Gorge to the north include Williams (1916), Barnes and Butler (1930) and Allen (1932), who mapped the Columbia River basalt as a single, undifferentiated unit, and Waters (1973), who subdivided it, tentatively identifying the intracanyon flow at Crown Point as "Late Yakima" Priest Rapids petrographic type.

As work on the chemical differentiation of various units within the Columbia River Basalt Group progressed on the Columbia Plateau, Beeson and others (1975, 1976, and in press) and Beeson and Moran (1979a,b) were able to work out the basalt stratigraphy in the Western Cascades and western Oregon, using INAA and trace-element abundances to identify the different chemical groups. Their work also led to theses by Anderson (1978) in the Clackamas River drainage to the south, Timm (1979) in the Hood River Valley to the east, this author in the Bull Run Watershed, and Tolan (in progress) in the Columbia Gorge to the north.

Beeson and Moran's mapping in the Salmon River area; their INAA analyses of basalt chip samples from the first drillhole at Old Maid Flat on the west side of Mount Hood; and thesis work by Anderson, Timm, and this author were all included in an Oregon Department of Geology and Mineral Industries open-file report (Beeson and Moran, 1979b) and are part of an as yet unpublished paper (Beeson and
others, in press). Locations of these study areas and other relevant peripheral locations are shown in Figure 9.

Work currently underway by Anderson in the Hood River Valley and by Beeson and Tolan in the Columbia River Gorge and the Willamette Valley will help complete the Columbia River Basalt Group picture in western Oregon.
Figure 9. Map showing locations of Columbia River basalt discussed in this thesis. Individual outlined areas were mapped as follows: A--Clackamas River area, Anderson (1978); B--Salmon River area, Beeson and Moran (1979b); C--Bull Run Watershed, this thesis; D--Hood River Valley, Timm (1979) and Anderson (1981, personal communication); E--Old Maid Flat drillhole, Beeson and Moran (1979b); F--Columbia River Gorge, work in progress by Tolan; G--Multnomah Falls, Beeson and others (1975); H--Crown Point, Waters (1973); I--Portland, Beeson and others (1975).
CHAPTER VI

COLUMBIA RIVER BASALT GROUP STRATIGRAPHY IN THE BULL RUN WATERSHED

GENERAL

All of the Columbia River basalt that has been identified with certainty in the Bull Run Watershed belongs either to the Grande Ronde Basalt (approximate exposed thickness of 150 meters (500 feet)) or the Wanapum Basalt (approximate total thickness of 140 meters (450 feet)). A generalized stratigraphic column of the Columbia River basalt in Bull Run appears in Figure 10.

Parameters and identifying criteria for these chemical groups in western Oregon were developed by Beeson and others (1975, and in press) and Beeson and Moran (1979a,b) and are presented in modified form in Table I.

In Table II, elemental abundances of samples from different chemical groups identified in Bull Run are compared with analyses of samples of the same chemical groups found on the Columbia Plateau. Because of instrumental problems, elemental abundances in the Bull Run analyses did not always correspond closely to those in the Plateau analyses. It was useful, however, to compare relative amounts of elements, and the relative amounts of elements found in different chemical groups in Bull Run are presented graphically in Figure 11.

The ratios of La to Na of all samples except for sample 18,
<table>
<thead>
<tr>
<th>FLOW AND THICKNESS</th>
<th>MEMBER</th>
<th>FORMATION</th>
<th>SUBGROUP</th>
<th>GROUP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRIEST RAPIDS INTRACANYON</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>FLOW 12-124m (40-580ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(5) PHYRIC 9m (30ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(4) PHYRIC (VARIABLY) 30m (100ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(3) PHYRIC 30m (100ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(2) PHYRIC 9-12m (30-40ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(1) PHYRIC 9-40m (30-130ft)</td>
<td>PRIEST RAPIDS (R2)</td>
<td>FRENCHMAN SPRINGS (N2)</td>
<td>WANAPUM</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>(-1, -2) HIGH MG 2-3 FLOWS 66m (220ft)</td>
<td>&quot;HIGH MG&quot; (N2)</td>
<td>VANTAGE</td>
<td>YAKIMA BASALT</td>
<td>COLUMBIA RIVER BASALT GROUP</td>
</tr>
<tr>
<td>LOW MG N2 4(7) FLOWS 86m (270ft)</td>
<td>&quot;LOW MG&quot; (N2)</td>
<td>GRANDE RONDE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LOW MG R2</td>
<td>&quot;LOW MG&quot; (R2)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 10. Generalized stratigraphic column for the Columbia River Basalt Group in the Bull Run Watershed.
<table>
<thead>
<tr>
<th>STRATIGRAPHIC UNIT</th>
<th>FIELD CRITERIA</th>
<th>CHEMICAL CRITERIA²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Priest Rapids Member</td>
<td>Jointing, polarity, and lithology</td>
<td>Fe &gt; 10%</td>
</tr>
<tr>
<td></td>
<td>Reversed polarity</td>
<td>Sm &gt; 7</td>
</tr>
<tr>
<td></td>
<td>Coarse sugary texture in overflow portion</td>
<td>La 25-30</td>
</tr>
<tr>
<td></td>
<td>As intracanyon flow characterized by</td>
<td>Sc 35-40</td>
</tr>
<tr>
<td></td>
<td>thick sequence of bedded palagonite</td>
<td>Eu 2.5</td>
</tr>
<tr>
<td></td>
<td>at base, relatively thin colonnade,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and thick entablature</td>
<td></td>
</tr>
<tr>
<td>Frenchman Springs Member</td>
<td>Jointing, polarity, and lithology</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Well-formed colonnade</td>
<td>Fe &gt; 10%</td>
</tr>
<tr>
<td></td>
<td>Normal polarity</td>
<td>Sm &gt; 7 (generally)</td>
</tr>
<tr>
<td></td>
<td>Texture often coarse</td>
<td>La 25-30</td>
</tr>
<tr>
<td></td>
<td>Some flows have large (1-cm)</td>
<td>Sc 35-40</td>
</tr>
<tr>
<td></td>
<td>plagioclase phenocrysts</td>
<td>Eu 2.5</td>
</tr>
<tr>
<td>&quot;High Mg&quot; Grande Ronde Basalt³</td>
<td>Blocky and platy jointing</td>
<td>Fe &lt; 10%</td>
</tr>
<tr>
<td></td>
<td>Normal polarity</td>
<td>Sm &lt; 7 (generally)</td>
</tr>
<tr>
<td></td>
<td>Coarse texture</td>
<td>La 20-24 (generally)</td>
</tr>
<tr>
<td></td>
<td>Upper flow--inflated texture</td>
<td>Sc 35-40</td>
</tr>
<tr>
<td>&quot;Low Mg&quot; Grande Ronde Basalt³</td>
<td>Well-formed entablature</td>
<td>Fe &lt; 10%</td>
</tr>
<tr>
<td></td>
<td>Fine-grained texture</td>
<td>Sm &lt; 7</td>
</tr>
<tr>
<td></td>
<td>Upper flow(s)--plagioclase phenocrysts</td>
<td>La 25-30</td>
</tr>
<tr>
<td></td>
<td>Divided into two units on basis of</td>
<td>Sc 30-35</td>
</tr>
<tr>
<td></td>
<td>normal or reversed polarity</td>
<td></td>
</tr>
</tbody>
</table>

¹Criteria developed by Beeson and others (1975), Beeson and Moran (1979a,b), and others (in press). A few of the Bull Run samples deviated slightly from these values because of instrumental values but still show the same relative differences between chemical groups.

²Chemical data obtained by instrumental neutron activation analysis. All data in parts per million except where specified.
³Informal units.
TABLE II

COMPARISON OF TRACE ELEMENT ABUNDANCES OF SAMPLES FROM BULL RUN,
THE COLUMBIA PLATEAU, AND THE CROWN POINT INTRACANYON FLOW

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ba</td>
<td>783.0</td>
<td>1240.0</td>
<td>496.0</td>
<td>992.0</td>
<td>564.0</td>
<td>1000.0</td>
<td>503.0</td>
<td>460.0</td>
<td>534.0</td>
<td>690.0</td>
<td>510.0</td>
<td>500.0</td>
</tr>
<tr>
<td>Co</td>
<td>36.9</td>
<td>36.0</td>
<td>41.3</td>
<td>40.3</td>
<td>39.4</td>
<td>31.9</td>
<td>37.5</td>
<td>41.7</td>
<td>37.7</td>
<td>39.8</td>
<td>41.1</td>
<td>42.3</td>
</tr>
<tr>
<td>Cr</td>
<td>11.7</td>
<td>15.0</td>
<td>100.1</td>
<td>43.0</td>
<td>33.1</td>
<td>20.0</td>
<td>54.6</td>
<td>66.0</td>
<td>15.6</td>
<td>25.0</td>
<td>96.7</td>
<td>23.0</td>
</tr>
<tr>
<td>Hf</td>
<td>5.2</td>
<td>4.7</td>
<td>3.7</td>
<td>3.7</td>
<td>4.35</td>
<td>4.5</td>
<td>4.3</td>
<td>4.2</td>
<td>5.4</td>
<td>4.1</td>
<td>4.6</td>
<td>5.9</td>
</tr>
<tr>
<td>Th</td>
<td>6.1</td>
<td>5.8</td>
<td>3.5</td>
<td>2.8</td>
<td>3.7</td>
<td>4.4</td>
<td>3.8</td>
<td>4.2</td>
<td>4.1</td>
<td>4.0</td>
<td>3.3</td>
<td>4.5</td>
</tr>
<tr>
<td>Sc</td>
<td>31.20</td>
<td>32.8</td>
<td>37.04</td>
<td>37.0</td>
<td>36.39</td>
<td>35.7</td>
<td>35.45</td>
<td>37.8</td>
<td>36.69</td>
<td>38.77</td>
<td>36.44</td>
<td>39.7</td>
</tr>
<tr>
<td>La</td>
<td>28.7</td>
<td>26.5</td>
<td>18.2</td>
<td>19.5</td>
<td>26.5</td>
<td>23.4</td>
<td>27.0</td>
<td>26.8</td>
<td>34.0</td>
<td>30.03</td>
<td>29.0</td>
<td>31.7</td>
</tr>
<tr>
<td>Ce</td>
<td>58.6</td>
<td>52.0</td>
<td>38.0</td>
<td>35.0</td>
<td>52.5</td>
<td>54.0</td>
<td>55.0</td>
<td>59.0</td>
<td>69.0</td>
<td>66.0</td>
<td>59.0</td>
<td>59.0</td>
</tr>
<tr>
<td>Sm</td>
<td>7.7</td>
<td>6.15</td>
<td>5.4</td>
<td>5.07</td>
<td>7.2</td>
<td>6.61</td>
<td>7.0</td>
<td>7.55</td>
<td>-</td>
<td>9.03</td>
<td>8.7</td>
<td>8.87</td>
</tr>
<tr>
<td>Eu</td>
<td>2.18</td>
<td>2.02</td>
<td>1.68</td>
<td>1.79</td>
<td>2.27</td>
<td>2.17</td>
<td>2.34</td>
<td>2.16</td>
<td>2.81</td>
<td>2.62</td>
<td>2.59</td>
<td>2.4</td>
</tr>
<tr>
<td>Lu</td>
<td>0.60</td>
<td>0.56</td>
<td>0.50</td>
<td>0.49</td>
<td>0.63</td>
<td>0.6</td>
<td>0.61</td>
<td>0.72</td>
<td>0.73</td>
<td>0.75</td>
<td>0.63</td>
<td>0.9</td>
</tr>
</tbody>
</table>

1 Swanson and Wright (1981)
2 Average of five samples.
3 Average of three samples.
4 Average of two samples.
5 Analysis by Beeson and Moran, 1976.
Figure 11. Graph showing relative amounts of some key elements used in identification of different chemical groups of Columbia River basalt in Bull Run. Numbers at tops and bottoms of columns are maximum and minimum values found in Bull Run analyses. As there were systematic shifts of elemental abundances in some experiments, there are no absolute high, medium, or low values for each element. Instead, elemental abundances were compared separately for each experiment. Na and Fe are in percent; other numbers are in parts per million.
which was identified as a Boring chemical-type sample because of its high Na and Cr content and because of its occurrence as a dike cutting through Columbia River basalt, are plotted against the ratios of Sc to Th in Figure 12; the same ratios are plotted by experiment in Figures 13a-g. The chemical fields for Wanapum and high and low Mg basalt are indicated in the figures. Figure 12 shows that there are several samples in the wrong fields. When the samples are plotted by experiment, however, it becomes apparent that there was a systematic shift in the PEG and 7-9 experiments (Figures 13a and f). Slight shifting of the boundaries of the fields in these graphs resolved most of the inconsistencies. Samples falling onto a line separating chemical groups or into the wrong field or having a large enough error to be considered part of another group were classified instead by paleomagnetism, lithology, or stratigraphic position; such samples are circled on the graphs, and the final classification is indicated.

Certain descriptive terminology used in this thesis is very familiar to all who work with Columbia River basalt but may not be known by others. For that reason, a few definitions are included here. The word "phyric" is used to describe the texture of a rock sample and means the presence of megascopically visible crystals in a groundmass of much finer crystals or volcanic glass. The word "aphyric" means there are no such large crystals. Rocks discussed in this thesis are described as aphyric, rarely phytic, variably phytic, or abundantly phytic.

As lava flows into water or onto wet ground, it reacts
Figure 12. Ratios of Na to La plotted against ratios of Sc to Th for all samples. Numbers indicate map locations of samples. Fields of the three major chemical groups are separated by solid lines. Samples with circles belong to different chemical groups than where they appear in this diagram, and their final classifications are indicated by appropriate letters. Samples are plotted by experiment and detector in Figures 13a-g.
Figure 13a. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by Beeson and Moran (1975) as part of PEG project. Plot shows systematic shift of values for some elements in this experiment. Sample 52 is known to be Wanapum Basalt on basis of lithology and stratigraphic position, so dashed lines show appropriate boundaries of chemical groups for this experiment.
Figure 13b. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by author in 1977 as experiment 7-V and counted on green detector at University of Oregon.
Figure 13c. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by author in 1977 as experiment 7-V and counted on orange detector at University of Oregon.
Figure 13d. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by author in 1977 as experiment 7-V and counted on red detector at University of Oregon.
Figure 13e. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by Beeson and Moran in 1978 as experiment 7-7. Sample 19 is discussed in Chapter VI (Blazed Alder Creek Section).
Figure 13f. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by Beeson and Moran in 1978 as experiment 7-9. Diagram shows systematic shift of some elements in this experiment, and dashed lines show appropriate boundaries after they have been shifted. Sample 45 was classified as Wanapum Basalt on basis of Fe content, lithology, and stratigraphic position.
Figure 13g. Ratios of Na to La plotted against ratios of Sc to Th for samples analyzed by Beeson and Moran in 1978 as experiment 7-10. Sample 20 is discussed in Chapter VI (Blazed Alder Creek Section).
violently, shattering and forming glassy fragments that are soon altered to yellow or reddish-brown waxy material called "palagonite."

As it flows into water, lava may also form discrete, ellipsoidal bodies of lava called "pillows," which are characterized by internal radial jointing, glassy rinds, and flattened tops.

Finally, as lava flows cool, jointing patterns develop, breaking the rock into various patterns that have been given names, some of which have been taken from architectural terminology. Figure 14 shows some of these features. The vertical columns may be columnar or blocky and may undulate or pinch and swell. The columns may be broken into shorter prismatic sections by horizontal joints called "platy jointing" because they resemble stacks of plates. Within a flow, the zone made up of vertical columns is called the "colonnade." Elsewhere in a flow, jointing may be much more irregular, with thinner columns broken much more irregularly by more cross joints; this portion of a flow is called the "entablature."

GRANDE RONDE BASALT

Introduction

The base of the Grande Ronde Basalt section is not exposed in Bull Run. However, Grande Ronde Basalt overlies the lower Miocene Eagle Creek Formation in the Columbia Gorge to the north (Waters, 1973) and overlies and interfingers with the upper Oligocene to lower Miocene "Beds of Bull Creek" (Eagle Creek Formation) in the Clackamas River area to the south (Hammond and others, 1980).

From bottom to top, the exposed Grande Ronde Basalt section in
Figure 14. Typical jointing found in basalt of the Columbia River Basalt Group. (After Swanson, 1967)
Bull Run consists of one low Mg flow (map symbol Tglr) belonging to the \( R_2 \) paleomagnetic interval, approximately four \( N_2 \) low Mg flows (map symbol Tgln) belonging to the \( N_2 \) paleomagnetic interval, and two to three \( N_2 \) high Mg flows (map symbol Tgh). General chemical, lithological, and jointing criteria used for identifying high and low Mg samples are shown in Table I.

**Low Mg Grande Ronde Basalt**

There are at least five low Mg (one \( R_2 \) and four \( N_2 \)) Grande Ronde flows in Bull Run with a thickness exceeding 90 meters (300 feet) (Figure 15).

Petrographically (Figure 16a) and in hand sample, rocks from most of these flows look very much alike: fine-grained, dense, aphyric with occasional plagioclase microphenocrysts, very fine-grained pyroxene and some olivine in the groundmass, and both equant and elongated opaque minerals. For comparison, photomicrographs of samples from the other map units are shown in Figures 16b-g. One and possibly two flows at the top of the \( N_2 \) Grande Ronde section have white elongated plagioclase phenocrysts up to 0.5 centimeters (0.2 inches) in length and are very similar in appearance, chemistry, and stratigraphic position to the Winter Water flow that has been mapped on Tygh Ridge in Wasco County, Oregon (Vandiver-Powell, 1978), in the Columbia Gorge (Bentley, 1978, personal communication), and in Portland and the Willamette Valley (Beeson, 1980, personal communication).

Individual low Mg Grande Ronde flows tend to have a relatively thin colonnade and proportionally much thicker entablature(s)
Figure 15. Waterfall over N. low Mg Grande Ronde Basalt section in Blazed Alder Creek, just upstream from its confluence with Nanny Creek.
Figure 16a. Photomicrograph of low Mg Grande Ronde Basalt sample, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16b. Photomicrograph of -1 high Mg Grande Basalt sample, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16c. Photomicrograph of -2 high Mg Grande Ronde Basalt, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16d. Photomicrograph of +1 Frenchman Springs Member of Wanapum Basalt, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16e. Photomicrograph of +4 Frenchman Springs Member of Wanapum Basalt, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16f. Photomicrograph of Priest Rapids Member of Wanapum Basalt. Sample taken from entablature that formed within canyon. Photo taken under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
Figure 16g. Photomicrograph of overflow portion of Priest Rapids Member of Wanapum Basalt, under crossed nicols (upper photo) and plane polarized light (lower photo), x30 (approximately).
(Figure 17). With the exception of the Winter Water flow(s), most of the low Mg Grande Ronde flows look very much alike. Because of limited exposure and similar appearance of these flows, the total number of Grande Ronde flows present in Bull Run could be estimated only.

Areal extent of the R₂ and N₂ low Mg flows is shown on the geologic map. The Winter Water basalt was not mapped as a separate unit but was observed along the northerly flowing portion of the Bull Run River downstream from its confluence with Blazed Alder Creek (Figure 18) and also in Nanny Creek.

Part of the N₂ low Mg section is missing in Blazed Alder Creek (see section on Folds in Chapter VII), where it is believed that N₂ low Mg flows surrounded but did not cover a structural high of R₂ low Mg basalt.

High Mg Grande Ronde Basalt

Two, and in one location possibly three, high Mg Grande Ronde flows occur stratigraphically above the low Mg Grande Ronde flows in Bull Run. For convenience in this thesis, the uppermost flow is called "-1," the lower flow "-2" (Figure 19). The high Mg section is approximately 60 meters (200 feet) thick. These flows have normal magnetic polarity and belong to the N₂ paleomagnetic interval. Chemical and other characteristics of these flows are presented in Table I.

In thin section (Figure 16b), samples from the -1 flow have microphenocrysts of pyroxene, both equant and elongated opaque minerals, and a relatively coarse plagioclase groundmass. The -2 flow is finer
Figure 17. Part of the N₂ low Mg Grande Ronde section exposed on east side of Bull Run River just downstream from Log Creek confluence. Irregular jointing is characteristic of these flows.
Figure 18. N$_2$ low Mg Grande Ronde Basalt flow exposed at confluence of Bull Run River and Blazed Alder Creek. This occasionally phryic flow is similar in lithology and stratigraphic position to Winter Water flow of Vandiver-Powell (1978).
Figure 19. Lowest Frenchman Springs flow (+1) and two high Mg Grande Ronde Basalt flows (-1 and -2) exposed at north side of Dam No. 1. Vantage Member is between +1 and -1 flows.
grained and has pyroxene primarily in the groundmass, a larger proportion of equant opaque minerals, and plagioclase microphenocrysts (Figure 16c). Both flows have textures ranging from intersertal to hyalopilitic.

In hand sample, the high Mg samples tend to be coarser in texture than the low Mg samples. The -1 flow is diktytaxitic in texture; the -2 flow is slightly finer, denser, and more vesicular (Figure 20).

The jointing of these two flows is quite distinctive (Figure 21). The -1 flow has well-developed columns, sections of which display platy jointing. The columns, some of which pinch and swell, range from between 1.5 to 2.5 meters (5 to 8 feet) in diameter. Columns of the -2 flow are blocky, often smaller in diameter than those of the flow above, and have zones of sheet vesicles. The -2 flow is slightly darker in color, whereas the -1 flow has a brighter, yellowish-red hue on the surface of outcrops.

A separate flow unit or what could be a third flow occurs at the base of the -1 flow only at Log Creek. Although a horizontal break occurs in this flow, there is no sign of a soil zone, vesicular zone, or baked contact which would be characteristic of a contact between separate flows. Because elsewhere in Bull Run only two high Mg flows were observed, it seems likely that this is a flow unit instead of another flow.

The nature of the contact between the two high Mg flows indicates that some type of topographic relief was developing during high Mg time. This contact is most easily observed along S10 at the North
Figure 20. Lower flow (-2) of the two high Mg Grande Ronde flows. This outcrop along the Bull Run River shows characteristic vesicularity of the upper portion of this flow.
Figure 21. Contact (dashed line) between -1 (above) and -2 (below) high Mg Grande Ronde Basalt flows at North Fork quarry on S10. Almost vertical fault (dotted lines) with horizontal slickensides is directly above figure in left photo.
Fork quarry. There a thin soil zone separates the two units and the top of the -2 flow is deeply weathered. Approximately 2.2 kilometers (1.4 miles) to the west-southwest near the Reservoir No. 1 boat-house, a 9-meter (30-foot)-thick tuffaceous sandy and silty interbed occurs at this same contact. Finally, 7 kilometers (4.4 miles) southwest of Dam No. 1, core samples taken from the pond below Dam No. 2 indicate a 3- to 6-meter (10- to 20-foot)-thick tuffaceous interbed, also between the two high Mg flows. A few pillows are present at the base of the -1 flow at North Fork and also at the base of the flow unit at Log Creek. Drilling below Dam No. 2 also indicated that thickness of the -1 high Mg flow and the elevation of the top of the -2 flow are quite variable. The presence of the local interbeds, pillows at the base of the -1 flow, and the irregular surface of the -2 flow suggest that a structure, or at least a drainage pattern, was developing during the time that high Mg flows were entering the area. The pillows locally at the base of the -1 flow indicate that there the flow came in contact with water. The tuffaceous interbed occurs within the same time interval that andesitic volcanism was occurring in the vicinity of the Old Maid Flat drillhole to the east (Beeson and others, in press) and may represent tuffaceous sediments that were washed into a topographic low during Miocene volcanic episodes.

The top of the upper high Mg flow is deeply weathered, often to a depth of 5 to 10 meters (15 to 30 feet) (Figure 22). On this deeply weathered surface, which represents a long period during which no basalt entered the area, the Vantage Member was deposited (see below).
Figure 22. Contact between Wanapum and Grande Ronde Basalt at north side of Dam No. 1. Dashed line indicates Vantage Member. Carbonaceous material and only slight suggestion of pillows are found here. Left photo shows color of units; right photo shows deeply weathered top of -1 flow.
Distribution of the high Mg Grande Ronde Basalt flows is shown on the geologic map.

VANTAGE MEMBER

The Vantage Member (Figure 23) is the interbed that separates the high Mg Grande Ronde Basalt section from the overlying and chemically distinct Wanapum Basalt. It is easily identified in the Bull Run Watershed because the basalt below is diktytaxitic and aphyric and the basalt above is abundantly phryic (Figure 24). The interbed is up to 1.5 meters (5 feet) thick and is composed of sandy and silty sediments with local soil zones, tree molds (Figure 25), and pieces of carbonized wood.

The high Mg flow top beneath the Vantage is deeply weathered. On the Columbia Plateau (Bentley, 1977) and along the Clackamas River (Anderson, 1978), this deeply weathered zone is often capped with a saprolite that has acted as a slip face over which the Wanapum Basalt has tended to fail and move downslope, leading to the formation of a topographic bench on the Vantage Member that can be mapped on the basis of topographic expression (Anderson, 1978). This tendency of the Vantage to form topographic benches was not as apparent in Bull Run for several reasons: (1) The best and most continuous exposures are in the trough of a syncline (see section on Folds in Chapter VI), where sliding is least likely to have occurred. (2) On the limbs of the fold, where sliding and subsequent benching is most likely to have taken place, the interbed is thin or virtually absent. Furthermore, products of more recent volcanism have covered evidence
Figure 23. Part of measured section at Log Creek. Here Vantage (dotted line) separates +1 Frenchman Springs flow from high Mg Grande Ronde section (-1, -1a, and -2, separated by dashed lines). Note sheet vesicles in -2 flow.
Figure 24. Vantage at Log Creek. Here water falls over a Frenchman Springs flow with undulating columnar jointing and about 9 meters (30 feet) of pillows. Soil zone of Vantage is about 1.5 meters (5 feet) thick here.
Figure 25. Standing on Vantage Member at Log Creek, J. L. Anderson is holding hammer handle in large, horizontal, east-west-oriented Miocene tree mold.
of any sliding along dip slopes that may have taken place.

(3) The Bull Run Watershed is a considerable distance from sources of sediments, such as the highlands that supplied sediments to the interbeds of the Clackamas River. The interbeds of Bull Run, including the Vantage Member, are much thinner, certainly more uncommon, and much less likely to cause failure of the overlying units and subsequent benching. (4) Bull Run was covered by younger volcanic rocks; consequently, the Columbia River basalt has not been as deeply eroded as were the flows along the Clackamas River, and benches have not had the opportunity to become as well developed.

For these reasons, therefore, the Vantage Member could not be as readily identified in the Bull Run Watershed on the basis of topography. It was mapped instead on the basis of lithology of the overlying and underlying units.

WANAPUM BASALT

Introduction

Seven Wanapum Basalt flows with a total thickness of at least 140 meters (470 feet) overlie the Vantage Member in the Bull Run Watershed. The lower six flows belong to the \( N_2 \) Frenchman Springs Member; the uppermost flow is an intracanyon flow of the \( R_3 \) Priest Rapids Member.

General chemical characteristics that are useful in identifying flows of this chemical group are shown in Table I. In general, Wanapum rocks are coarser in texture than Grande Ronde rocks. Swanson and others (1979) describe them as "generally medium-grained olivine-
bearing commonly slightly to moderately plagioclase-phyric flows, most of which have high Fe and Ti contents."

Identifying properties of the two members and individual flows belonging to one of the members are discussed below.

Frenchman Springs Member

Six $N_2$ Frenchman Springs flows with a total thickness of 150 meters (430 feet) were observed in Bull Run. For convenience, they are numbered +1 to +6, from oldest to youngest, in this thesis.

Chemically, the Frenchman Springs and Priest Rapids Members of the Wanapum Basalt are quite similar, except that the Eu and Sm values of the Frenchman Springs Member are generally lower than those of the Priest Rapids Member.

In thin section, Frenchman Springs rocks have both equant and elongated opaque minerals, small rounded olivine blebs, and blocky pyroxene microphenocrysts (Figure 16d). Three of the flows have large plagioclase phenocrysts and glomerocrysts (Figure 16e). Textures range from intersertal to hyalopilitic.

The Frenchman Springs flows are most easily recognized in the field by their coarse texture and the fact that three of the flows are abundantly phryic. The two lowest flows (+1 and +2) contain abundant plagioclase phenocrysts ranging from 0.6 to 1.3 centimeters (0.25 to 0.5 inches) in length; the third flow (+3) has very rare phenocrysts of the same size; the fourth flow (+4) contains variable amounts of phenocrysts that are generally larger (up to 3.75 centimeters (1.5 inches) in length) and more nearly equidimensional in shape than those of the other two abundantly phryic flows; and the
two uppermost flows (+5 and +6) are essentially aphyric. The number of phenocrysts in the +4 flow varies greatly, even over a relatively short distance in the same outcrop. For example, the +4 flow in one continuous outcrop near the county line on Sl54 appears to be aphyric in one area and extremely phyric in another portion. The large size of the phenocrysts, their blocky shape, and their variable abundance make it possible to recognize this flow where there are good exposures; however, the extreme variability of phenocryst abundance meant that a poorly exposed aphyric sample might be from either an aphyric +5 or +6 flow or from the variably phyric +4 flow. East of the Cascades where there are good continuous exposures, these individual Frenchman Springs flows would be mappable units. In the Bull Run Watershed, however, the poor exposure made it impossible to treat them as individual mappable units.

Pillows found locally at the base of the lowest Frenchman Springs (+1) flow indicate areas where the basalt flowed into water or onto wet ground. The thickest sequence of pillows is about 9 meters (30 feet) thick at Falls and Log Creeks. Pillows were also observed in core samples from below Dam No. 2, along the south shore of Reservoir No. 2 (Figure 26), at Deer Creek, on Sl0A, and on a small unnamed tributary to North Fork. This same contact at Dam No. 1 has only a slight suggestion of pillows; on Boulder and Nanny Creeks, and the east end of Sl0, the base of the +1 flow has no pillows.

All of the Frenchman Springs flows have colonnades, but no entablatures were observed in the Frenchman Springs section. In some cases, flows had well-developed columnar jointing; more frequently,
Figure 26. Pillows at base of +1 Frenchman Springs flow poorly exposed at water level in sec. 30, T. 1 S., R. 6 E., north of mouth of South Fork, Reservoir No. 2.
the columns were blocky. The columns of the +1 flow are somewhat undulatory (Figure 24) and are from 1 to 2 meters (3 to 6 feet) in diameter. The top of the +1 flow at Log Creek is highly vesicular and has a ropy surface (Figure 27).

The +2, +3, and +4 flows also have blocky columns. The columns of the +4 flow are at least 1.2 meters (4 feet) wide, with some platy and hackly jointing near the top of the flow. A narrow red clay zone separates the +4 and +5 flows upstream on Log Creek (Figure 28) and on an unnamed spur just northwest of Log Creek. The +5 flow has a highly vesicular flow top and columns 0.6 to 0.9 meters (2 to 3 feet) wide with some platy jointing. The +6 flow has blocky columns 0.6 to 1.2 meters (2 to 4 feet) wide.

The above characteristics of the six Frenchman Springs flows were observed in very small and discontinuous outcrops and may be only local, not widespread, properties. Therefore, chemistry, lithology, stratigraphic position, and magnetic polarity were the only reliable criteria for identification of Frenchman Springs flows in Bull Run.

Although all of the Frenchman Springs flows in Bull Run are classified as N2 flows, paleomagnetic work by R. Simpson (1980, personal communication) records a paleomagnetic excursion in the +1 and +2 Bull Run flows similar to that observed by Simpson in the same flows in the Portland area and by Choiniere and Swanson (1979) in the chemically similar Cape Foulweather Basalt cropping out along the northern Oregon coast.

Work by Beeson and others (1976) and Anderson (1978) suggests that the Bull Run Frenchman Springs flows may be correlated on the
Figure 27. Top of +1 Frenchman Springs flow above biggest falls at Log Creek. Flow top is vesicular and has pahoehoe surface.
Figure 28. Contact between phytic (+4) and aphyric (+5) flows of Frenchman Springs Member, on Log Creek between S10 and S155. This contact here and at short unnumbered spur road to west is marked by presence of red clay.
basis of lithology, chemistry, and stratigraphic position to specific Frenchman Springs flows described by Bentley (1977) on the Columbia Plateau: the +1 and +2 flows are similar to the abundantly phryic Ginkgo Flow, the +3 flow to the aphyric Sand Hollow flow, the variably phryic +4 flow to the moderately phryic Kelley Hollow flows, and the aphyric +5 and +6 flows to the aphyric Union Gap (=? Sentinal Gap) flows.

Distribution of the Frenchman Springs Member in Bull Run is shown on the geologic map.

Priest Rapids Member

Stratigraphically overlying the Frenchman Springs flows in Bull Run is the magnetically reversed Priest Rapids Member, which occurs as an intracanyon flow that overfilled its canyon, undoubtedly forcing later rivers to cut channels farther to the north. This paleomagnetically reversed Priest Rapids Member belongs to the R₃ magnetic interval.

Chemically, the Priest Rapids Member is similar to the Frenchman Springs Member except for differences shown in Table I. On the Columbia Plateau, the Priest Rapids Member has been divided into two chemical types, the older Rosalia and younger Lolo chemical types (Table II); the Priest Rapids flow in Bull Run is classified as Rosalia chemical type on the basis of its relatively high Fe and low Cr contents.

In hand sample, Priest Rapids rocks are dense, dark, and aphyric, with the overflow portion of the flow coarser grained and slightly lighter in color than the portion that cooled within the old canyon. The Priest Rapids rocks from the overflow portion of the flow look
very much like the aphyric Frenchman Springs samples in both hand sample and in thin section (Figures 16f and g); therefore, the reversed magnetic polarity and morphology of the unit where it is an intracanyon flow were used to identify the Priest Rapids flow in Bull Run. Where exposed along the river, the intracanyon flow (Figure 29) is characterized by at least 105 meters (345 feet) of stratified palagonite (Figure 30), a thin colonnade that may be up to 9 meters (30 feet) thick, and a 60-meter (200-foot)-thick entablature. The intracanyon flow is 174 meters (580 feet) thick at the only place it could be measured along the Bull Run River; its total thickness must have been greater, however, for the base of the flow was not exposed at this point.

Where the intracanyon flow overfilled the canyon and cooled directly on the older Frenchman Springs surface, the unit is only 12 meters (40 feet) thick and forms thick blocky columns 1.5 to 3 meters (5 to 10 feet) in diameter, with zones of platy jointing. Best exposures of the overflow portion of the intracanyon flow are at the Southside quarry on S111 (Figure 31). Best exposures of the intracanyon flow itself are along the Bull Run River and in the upper reaches of North Fork.

Waters (1973) tentatively and correctly identified basalt cropping out to the northwest at Crown Point in the Columbia Gorge as part of a Priest Rapids intracanyon flow (Figure 32). The Priest Rapids flow in Bull Run is correlated to that flow on the basis of similar chemistry (Table II), magnetic polarity, flow characteristics, and general morphology (Figure 33). The flow at both locations is
Figure 29a. Looking almost due west at Priest Rapids intra-canyon flow in Bull Run. Bull Run River is at bottom of photo. Note bedded palagonite in foreground and rounded slopes formed by entablature. Here flow is 174 meters (580 feet) thick, but base of flow is not exposed. Figure 29b is telephoto shot of circled area and shows colonnade of flow.
Figure 29b. Telephoto photograph of area circled in Figure 29a. Arrow points to colonnade of Priest Rapids intracanyon flow.
Figure 30. Bedded palagonite of Priest Rapids intracanyon flow exposed along the Bull Run River.
Figure 31. Priest Rapids intracanyon flow, where it overfilled its canyon and poured onto the surrounding lowlands. The overflow portion of the flow is exposed at Southside quarry on the south side of the Bull Run River between Reservoirs No. 1 and 2 on SLII.
Figure 32. Sketch of Crown Point intracanyon flow (Priest Rapids chemical type) (Waters, 1973). Note relative proportions of palagonite, colonnade, and hackly entablature, similar to proportions of intracanyon flow in Bull Run. At Crown Point, canyon was more than 200 meters (680 feet) deep (Waters, 1973).
Figure 33. Aerial photographs of Priest Rapids intracanyon flow at Bull Run (above) and Crown Point (below). Arrows point to colonnades.
approximately the same thickness and has large amounts of stratified palagonite.

The Priest Rapids flow was also identified to the east of the watershed in the Hood River Valley (Timm, 1979), and its course has been partially traced by Anderson (1981, personal communication) through the Hood River Valley toward the Bull Run Watershed (Figure 34).

The course of the Priest Rapids intracanyon flow has also been traced through Bull Run (see geologic map). The most easterly exposure of the intracanyon flow occurs west of S10 between Log and Otter Creeks. It then forms a great mound on the enclosing Frenchman Springs bench west of Otter Creek (Figure 35) and then is exposed by the Bull Run River where the river changes directions from flowing northwest to flowing southwest. Again, on the north bench overlooking the river, the intracanyon flow appears as a large basalt mound. The next mapped exposure is on the south side of the Bull Run River in a quarry at the end of S111 (Figure 36). The intracanyon flow again crops out along the Bull Run River and then forms a ridge in a clearcut south of S10 in sec. 12, T. 1 S., R. 6 E. The intracanyon flow appears last in North Fork, upstream from the quarry on S10 (Figure 37). From there, it is presumed to have flowed to the northwest to Crown Point in the Columbia Gorge.

The flow in Bull Run is characterized by the 105-meter (345-foot)-thick palagonite section that has been waterworked. Foreset beds indicate flow to the west and southwest. Locally the palagonite is unsorted and contains large blocks of basalt up to 3 meters (10 feet) in diameter. The basal contact of the intracanyon flow with the older
Figure 34. Map showing mapped occurrences of the Priest Rapids intracanyon flow from the Hood River Valley, through Bull Run, to Crown Point. Data are from the following sources: A--J. L. Anderson (1981, personal communication); B--Timm (1979); C--(Vogt, this thesis); D--Waters (1973).
Figure 35. Top of intracanyon flow exposed west of Otter Creek and north of Bull Run River on S10F. Mound is intracanyon flow; bench in foreground is top of a phryic Frenchman Springs flow.
Figure 36. Entablature of intracanyon flow exposed in quarry at east end of S111.
Figure 37. Bedded palagonite of intracanyon flow at North Fork. Upper photo shows bedding in palagonite; lower photo shows palagonite changing to compact lava within the intracanyon flow.
basalt through which it flowed is exposed in only one place along the Bull Run River, in sec. 7, T. 1 S., R. 7 E. (Figure 38), where the base of the flow has been undercut by the Bull Run River, forming overhanging ledges. The very small exposed section of the ancient valley floor has relatively poorly sorted, rounded to subangular basaltic pebbles, cobbles, and boulders with a diameter of up to more than 1.5 meters (5 feet).

When the flow entered the Bull Run area, it was moving through a channel cut at least as deep as the N₂ low Mg Grande Ronde Basalt. Farther to the west along the Bull Run River, the base of the channel is only as deep as the high Mg section. This suggests that between Grande Ronde and Priest Rapids time, more uplift and subsequent downcutting by the river had occurred on the east end of the watershed than on the west.

The present day rivers and streams in Bull Run do not follow the course of the ancient river channel through which the intracanyon flow traveled. When the present-day river breaks into the old river channel, as in the upper reaches of North Fork, it reveals an almost vertical, smooth, basaltic canyon wall (Figure 39).

The Priest Rapids Member is thought to occur only in the northern portion of the watershed in proximity to the Bull Run River and North Fork. In the southeast portion of the watershed, however, sample 31 taken from a small isolated outcrop on S154 shows some similarity to the Priest Rapids chemistry. It is clearly Wanapum in chemistry and lies amid Frenchman Springs flows, which is how it was originally identified. Recent refinements in the chemical identifi-
Figure 38. Old valley floor of river channel through which Priest Rapids intracanyon flow moved. Floor was covered with unsorted basaltic pebbles, cobbles, and boulders and is exposed at westernmost extent of intracanyon flow along the Bull Run River.
Figure 39. Contact between old Columbia River basalt canyon wall and Priest Rapids intracanyon flow. Old canyon wall here is of ~1 high Mg Grande Ronde basalt and is exposed on North Fork, upstream from the quarry on S10.
cation of different members of the Wanapum Basalt suggest that this sample has Priest Rapids affinities. It is the only analyzed sample in the southeast portion of the watershed with these chemical characteristics, and more mapping and more analyses would be necessary to prove that Priest Rapids does, indeed, occur in this portion of the watershed.

BLAZED ALDER CREEK SECTION

Two samples from poorly exposed outcrops in the heart of the R2 low Mg Grande Ronde Basalt section in Blazed Alder Creek present problems of identification. One, sample 19, shows some similarities to the Pomona Member of the Saddle Mountains Basalt, mapped as an intracanyon flow in the Columbia Gorge by Anderson (1980) and by Tolan (1980, personal communication). It is low in Eu, Sm, and La and high in Cr, as are Pomona samples. It is, however, not a fresh sample and has vesicle fillings. Poor exposure made it impossible to say if this sample came from an intracanyon flow or not.

The other sample, sample 20, has chemistry typical of Wanapum Basalt and is phyric, as are some of the Frenchman Springs flows. It has reversed magnetic polarity, however, which is not like the Frenchman Springs flows. The one phenocryst in the sample is 0.7 centimeters (0.3 inches) long, and no such type of phenocryst was observed in the other Priest Rapids samples from Bull Run. Furthermore, Priest Rapids is the only other type of Wanapum Basalt known to be in Bull Run. In the Columbia Gorge, phenocrysts have been observed in the Priest Rapids basalt (Beeson, 1981, personal communication), so
this sample may be from part of a Priest Rapids intracanyon flow that backed up into a side canyon. The inclined columns of the poorly exposed outcrop from which the sample was taken are similar in appearance to those frequently found in intracanyon flows, but such an intracanyon relationship was definitely not proven.

Sample 20 does not resemble the Pomona Member. It does bear some lithological, chemical, and jointing similarity to the Roza Member (Figure 7 and Table II) (Tolan, 1980, personal communication), but the Roza has not been reported as far west and south as Bull Run—and certainly not as an intracanyon flow.

These problems of identification surfaced after my permit to enter Bull Run had expired and can therefore not be resolved at this time. Because of poor and discontinuous exposure along Blazed Alder Creek, analysis of many samples will probably be required before these relationships can be worked out.

MEASURED SECTIONS IN THE BULL RUN WATERSHED

Figure 40 shows the locations of measured sections in the Bull Run Watershed. The sections and their relative elevations are shown in Figure 41; correlations between the sections are shown in Figure 42.

In Figures 41 and 42, the flows are numbered from +1 to +6 in ascending order from the Vantage Member and from -1 to -4 in descending order from the Vantage. Flows +1 to +6 are Frenchman Springs flows of Wanapum Basalt; flows -1 and -2 are high Mg Grande Ronde Basalt, and flows -3 and -4 are low Mg Grande Ronde Basalt. Offsets and cover are indicated in the sections.
Figure 40. Map showing locations of measured sections in Bull Run. A = Dam No. 2; B = South Fork; C = Dam No. 1; D = Falls Creek; E = Log Creek.
Figure 41. Measured sections in Bull Run, shown at elevations where they occur. Flows +1 to +6 are Frenchman Springs flows. Flows -1, -la, and -2 are high Mg Grande Ronde, and -3 and -4 are low Mg Grande Ronde.
Figure 42. Correlation of measured sections in Bull Run. Flows +1 to +6 are Frenchman Springs flows; flows -1, -la, and -2 are high Mg Grande Ronde, and -3 and -4 are low Mg Grande Ronde.
It was impossible to measure or construct a more complete low Mg section because of poor exposure and similarity of appearance of the low Mg flows. The number of low Mg flows in the Bull Run Watershed was estimated by comparing poorly exposed contacts along Blazed Alder Creek.

Differences in thickness of various individual flows and the presence of interbeds locally may be related to structural development that may have been occurring during Columbia River basalt time (see section on Folds in Chapter VII). The interbed between the -1 and -2 high Mg Grande Ronde flows is only local. The -1 flow is variable in thickness in cores taken from below Dam No. 2, and the top of the -2 flow varies in elevations in the same cores. These differences also appear in the sections measured elsewhere in the watershed. The Vantage Member varies in thickness and character within the watershed. The thickest sequence of Frenchman Springs basalt appears at Falls Creek, and the thick sequence of pillows at Log Creek and elsewhere near the Bull Run River attests to the presence of water at those locations. The absence of pillows on the southeast portion of the watershed implies a difference in topographic relief or else a drainage development. Clearly, the basalt surface formed by each of these flows did not always remain featureless and undisturbed before the incursion of succeeding Columbia River basalt flows.

COMPARISON WITH SECTIONS FROM SURROUNDING AREAS

Considerable work on Columbia River Basalt Group stratigraphy has been done in the areas surrounding Bull Run (see section on
Columbia River Basalt Group Mapping Peripheral to the Bull Run Watershed in Chapter V). Figure 43 compares the number of flows found in the areas around Bull Run with the Bull Run section. Comparison of these stratigraphic columns indicates the following:

1. Only one of the Wanapum flows, the variably phytic +4 flow, found in Bull Run did not reach the Portland area. Otherwise, the Bull Run and Portland sections are quite similar.

2. The Grande Ronde sections in Bull Run and the Clackamas River area are also quite similar, except that no Prineville basalt interfingers with the Grande Ronde Basalt in Bull Run as it does in the Clackamas River area. Differences in the Clackamas River Wanapum section suggest that structural development occurring during Wanapum time began excluding some of the basalt flows from the edges of the trough in the Clackamas River area, although they continued to pour through the center of the trough—the Bull Run area.

3. There is not enough overlap with the Multnomah Falls section in the Columbia Gorge to be able to make many comparisons. At least one of the low Mg flows in Blazed Alder Creek is similar in appearance to one of the low Mg flows in the Multnomah Falls section (Beeson, 1976, personal communication), but there was no way to actually correlate these flows, many of which resemble each other chemically, magnetically, and lithologically.
4. Comparison with the Old Maid Flat drillhole shows that a Prineville flow came close to but did not enter the Bull Run area. The Old Maid Flat volcanic episode recorded between the low Mg Grande Ronde and Frenchman Springs times may have been the cause of the tuffaceous interbed between the two high Mg Grande Ronde flows in Bull Run.

5. Comparison with the Hood River section indicates that fewer high Mg flows reached the Bull Run area than were found in the Hood River Valley. The differences in the distribution of phryic and aphyric flows in the Frenchman Springs sections may be more a function of variability in the number of phenocrysts in flows rather than real differences in the distributions of the flows themselves, because a total of six Frenchman Springs flows occurs in both areas. The Priest Rapids intracanyon flow has been traced through the Hood River Valley and the Bull Run Watershed toward Crown Point in the Columbia Gorge.

These comparisons show how well the Bull Run section corresponds to those of nearby areas, thereby verifying the areal extent of the basalt flows and demonstrating the effects of structural deformation on their distribution.
CHAPTER VII

STRUCTURE

GENERAL

The major structures in the Bull Run Watershed are a syncline and anticline striking roughly N. 60° E. (Figure 44). On the north limb of the anticline, a N. 60° E.-striking thrust fault that dips 12 degrees to the southeast has produced at least 180 meters (600 feet) of vertical offset of the Columbia River basalt.

Numerous fractures and breccia zones trending N. 10-55° W. cut the basalt throughout the watershed. Blazed Alder Creek and the north-northwest flowing portion of the Bull Run River follow a N. 10° W.-trending lineament that is apparently the result of movement along the N. 10-20° W. fractures occurring in this zone. Other fracture trends are north-south, N. 20° E., and N. 80° W.

The folds in the Bull Run Watershed generally plunge about 2° to the west-southwest as the result of Cascadian uplift.

FOLDS

Folds were delineated in the Bull Run Watershed on the basis of elevations of different Columbia River basalt units, nature of contacts between flows, presence or absence of interbeds, and, to a certain extent, attitudes of beds. Because of the very poor exposure and the undulatory nature of basalt flow tops, dips and strikes
Figure 44. Map showing major structures in the Bull Run Watershed.
were, in most cases, somewhat approximate. The most reliable attitudes were taken from contacts that were visible over some distance.

The most northerly structure is a N. 60° E.-striking syncline through which the southwestward-flowing reach of the Bull Run River flows. The axis of the syncline may lie slightly south of the river, at least at South Fork, where the beds are almost horizontal, and at Dam No. 1, where the Vantage Member is at least 12 meters (40 feet) lower on the south side of the river than on the north (Figure 45).

The existence of this syncline during the time that the Columbia River basalt was entering the area and its location are shown by (1) pillows that occur locally at the base of the -1 high Mg Grande Ronde flow, indicating the presence of a local topographic low containing some water; (2) the variably thick and very localized tuffaceous interbed between the two high Mg flows, indicating the location of a topographic low in which tuffaceous sediments accumulated during high Mg time; (3) the well-developed Vantage Member of varying thickness, complete with a soil zone and carbonized wood at such widespread locations as Falls, Deer, and Log Creeks, also suggesting topographic development with different thicknesses of soil developing on different types of slopes; and (4) thick sequences of pillows found locally at the base of the +1 Frenchman Springs flow, indicating the presence of water locally within topographic lows. The intracanyon Priest Rapids flow and the main body of its overflow are found in proximity to the syncline, indicating that by Priest Rapids time, a well-developed drainage had formed within the syncline, as it
Figure 45. Vantage Member (dashed line) on south side of Dam No. 1. Here the Vantage is about 12 meters (40 feet) lower than on the north side of the dam, suggesting that the axis of the Bull Run syncline may be slightly south of the Bull Run River at this point.
has also done at the present time.

A northeast-trending, thrust-faulted anticline parallels the syncline and lies south-southeast of it. The anticline is defined on the basis of elevation of various Columbia River basalt units, absence of pillows and interbeds, and attitudes of beds. One Wanapum flow top exposed near the county line on S154 is deeply weathered--more than the corresponding flow top in the syncline, suggesting a Miocene topographic high corresponding to the upper portions of the anticline. The total Wanapum section appears to be thinner in the anticline, but this impression may be due to poor exposure rather than thinner or missing flows. The complete section of Wanapum Basalt is not exposed at any one place in the anticline.

Structural deformation may have begun as early as low Mg Grande Ronde time. The complete Grande Ronde section is not present in the upper reaches of Blazed Alder Creek in secs. 14 and 23, T. 1 S., R. 7 E. In the northern part of Blazed Alder Creek, approximately four N2 low Mg flows overlie the R2 low Mg flow. In the southern portion of Blazed Alder Creek, high Mg flows overlie the R2 low Mg flow, and the N2 low Mg flows are missing (see Plate 2, cross section A-A'). This abbreviated section seems to indicate that a structure was developing in Bull Run even during early Columbia River basalt time. After the R2 low Mg flows entered the area, a topographic high began to form, either as a fold or a horst. The younger N2 low Mg flows surrounded the high but were not able to cover it and are not found there today. Eventually, however, the high Mg flows and the Wanapum Basalt did cover the old high.
The folds often influence the nature of the streams flowing through or across them. Although waterfalls are found throughout the watershed, they are most common where the streams are cutting through beds that are nearly horizontal or are dipping upstream, such as along the upper reaches of Blazed Alder and Nanny Creeks.

FAULTS

The major fault in the Columbia River basalt in the Bull Run Watershed is a thrust fault on the north limb of the Bull Run anticline. The fault plane is best exposed on Blazed Alder Creek, just downstream from its confluence with Boulder Creek (Figure 46), and it is here that the attitude of N. 60° E. 12° SE was measured on the fault plane.

Below the thrust plane, about 2 meters (7 feet) of the underlying high Mg flow has been coarsely brecciated. About 10 meters (30 feet) of finely ground tectonic breccia occurs immediately above the thrust plane (Figure 47) in the low Mg basalt that was thrust above the high Mg flows. Above the zone of finely ground breccia is much coarser tectonic breccia, with a total thickness of more than 150 meters (500 feet).

Breccia produced by this thrusting is exposed along some of the roads in the watershed: on Sl54 from about 0.5 to 1 kilometer (0.3 to 0.6 miles) northwest of the county line (Figure 48); in a small patch just northwest of the great andesite talus slope on Sl54 in sec. 19, T. 1 S., R. 8 E.; and along the east end of Sl0 from 0.8 to 2 kilometers (0.5 to 1.25 miles) west of the north junction.
Figure 46. Bull Run thrust fault, exposed on Blazed Alder Creek just downstream from its confluence with Boulder Creek. Here thrust fault strikes N. 60° E. and dips 12° to the southeast. Low Mg Grande Ronde Basalt has been thrust over high Mg Grande Ronde Basalt exposed at water's edge in foreground. About 10 meters (30 feet) of finely ground breccia and 150 meters (500 feet) of coarse breccia are exposed above thrust plane at this point.
Figure 47. Closeup of thrust fault showing coarse breccia of thrust plane and extremely finely ground breccia above it.
Figure 48. Tectonic breccia of thrust fault exposed along SI54 northwest of county line. Thrust plane of this thrust fault is exposed 150 meters (500 feet) below on Blazed Alder Creek.
of S10 and S154 in secs. 18 and 19, T. 1 S., R. 8 E., where fairly competent beds of Frenchman Springs and Grande Ronde Basalt are interspersed with zones of tectonic breccia (Figure 49). This same alternation of breccia zones and competent beds of basalt occurs upstream from the thrust fault on Boulder Creek, where at least three low Mg flows have been thrust over the high Mg flows, suggesting that imbricate thrusting along several planes of weakness—probably flow contacts in the basalt—may have occurred above the main thrust zone. Thin horizontal bands of tectonic breccia were also observed in the high Mg flows near the base of the waterfall below the thrust plane.

The ancient R2 low Mg topographic high described earlier (see section on Folds) resulted in a thinner section and may well have been a zone of weakness that influenced the location of failure on the anticline, for it is just downstream from where the thrusting occurred.

The minimum vertical offset on this fault is 180 meters (600 feet), with a dip slip of at least 900 meters (3,000 feet). This amount of offset was measured from the top of the basalt on the upper thrust plate to the top of the similar units of basalt in the underlying plate over which thrusting occurred. If imbricate thrusting did occur, even more shortening took place.

The age of the thrusting is not known because of poor exposure. Some folding must have occurred before Priest Rapids time, because most, if not all, of the Priest Rapids basalt is found in or near the syncline. Schulz (1980), observing the irregular thickness of the Rhododendron Formation on the Columbia River basalt, notes that "a
Figure 49. Tectonic breccia zone along east end of S10. Here breccia zones alternate with coherent layers of Grande Ronde and Wanapum Basalt as the result of thrusting on the Bull Run thrust fault.
period of erosion, and probably some broad folding, intervened between the last Columbia River basalt flows and the first Rhododendron pyroclastic flows." Schulz also states that the relief on the Columbia River basalt surface was probably greater than several hundred feet by Rhododendron time."

Deformation probably continued into late Miocene and on into Pliocene time, with folding affecting some of the Rhododendron rocks as well. K. Manning (1981, personal communication) measured an attitude of N. 48° E. 66° SE on Rhododendron sandstone and siltstone also in Bull Run along the Little Sandy River in secs. 5 and 8, T. 2 S., R. 7 E., right on strike with the Bull Run anticline and thrust fault. In a small stream that is northwest of the quarry at the curve on S10 (SW 1/4 sec. 18, T. 1 S., R. 8 E.), Manning (1981, personal communication) has observed rocks that look like Rhododendron Formation rocks that appear to be part of the breccia zone associated with the thrust fault. Determination of the age of thrusting will require more detailed mapping of overlying units and due to the poor exposure and lack of good marker beds in Bull Run may well be impossible.

Because of the thrust fault, Columbia River basalt occurs at higher elevations than had been mapped before. New exposures were found at an elevation of 930 meters (3,100 feet) (see geologic map) and along the upper reaches of Cedar Creek. Exposures on the upper portion of the thrust plate are very poor because of brecciation and may be more extensive than were found in this study. All of the Columbia River basalt in the forward section of the thrust plate has been disturbed, if not actually brecciated, and therefore does
not produce good outcrops. For example, one very small outcrop of Columbia River basalt on S127 north of Nanny Creek appeared to be fairly solid, but all of the pieces of basalt in it were loose and could be picked up without using a hammer to break them.

Some silicification in the thrust-plate breccia was observed in an old clearcut north of S10, but no mineralization was observed in the breccia of the upper plate. Some silica was found along Blazed Alder Creek below the waterfall in the lower plate over which thrusting occurred.

Linear ridges with trends of N. 10-20° W. are associated with the thrust zone. In Blazed Alder Creek, a tectonic breccia ridge at least 50 meters (160 feet) wide occurs in the high Mg flow of the lower plate (Figure 50) and probably represents a zone of weakness almost normal to the thrust that brecciated during or after thrusting. This breccia ridge appears to terminate abruptly on the apparently undisturbed portion of the flow directly beneath it. Within the thrust zone of the upper thrust plate, a smaller ridge about 5 meters (15 feet) wide stands out from the rest of the breccia of the thrust zone. This ridge also trends roughly N. 20° W. and must have formed later than the thrusting.

An almost vertical fault occurs at the North Fork quarry on S10 (Figure 21). It trends roughly N. 20-25° W. One meter (3 feet) of fault gouge is associated with this fault, and nearly horizontal slickensides lying in several planes suggest strike-slip motion, with right-lateral motion probably the last direction of movement. This fault is visible only at the quarry and could be traced no farther.
Figure 50. Photo looking to south-southeast at tectonic breccia ridge in Blazed Alder Creek that trends approximately N. 15° E. This ridge is part of the lower plate over which thrusting occurred and may represent a zone of weakness which failed as thrusting was occurring.
The amount of horizontal displacement along this fault could not be determined.

Prior to discovery of the Bull Run thrust fault, no faults had been recognized in the watershed. With additional logging and more roadbuilding, it is entirely possible that more faults will be found.

**FRACTURES**

Numerous fractures are found throughout the Bull Run Watershed. No analysis of fracture trends was done for this study because of poor exposure, but certain dominant fracture trends are very apparent. Some fractures are merely breaks in the basalt that cut through regular jointing and in some cases several flows; other fractures are brecciated or contain breccia zones.

One of the most pronounced trends is the N. 10-20° W. trend. Fractures with this trend are found throughout the watershed, but notable concentrations of them occur along the northwest-flowing sections of the Bull Run River and Blazed Alder Creek. Breccia zones with this trend are found on both sides of the Bull Run River just upstream from the Log Creek confluence; fractures with this same trend are found also in Log Creek (Figure 51). In fact, numerous fractures trending N. 10-20° W. unite to form a N. 10° W.-trending fracture zone that is part of a clearly defined lineament that extends along Blazed Alder Creek and the Bull Run River (Figure 52), northward through a similarly aligned drainage in the glacial cirque of Falls Creek and across the divide into the aligned Tanner Creek. This lineament is visible on SLAR imagery. Although tectonic breccia
Figure 51. Fractures occurring along Log Creek. Color photo shows N. 20° W. fractures; black-and-white photo shows N. 10° W. fractures.
Figure 52. View to the south from Sl55 above Otter Creek, looking down along N. 10° W.-trending lineation (dashed line) along Bull Run River and Blazed Alder Creek. This trend, visible on SLAR imagery, is the result of numerous N. 10-20° W.-trending fractures.
has been observed locally along this linear zone, no vertical or horizontal offset has been measured along it.

Dikes with Boring-type chemistry (Beeson, 1978, personal communication) and with this same N. 10° W. trend occur on the west side of Falls Creek (Figure 53) and in Blazed Alder Creek (Figure 54), suggesting that east-west extension provided pathways for ascending magma during Boring volcanic episodes.

Another dominant fracture trend is the N. 55° W. trend found also throughout the watershed but most frequently near the thrust fault. Upstream from the thrust fault, N. 20-55° W.-trending fractures often contain breccia zones. These fractures are quite common near the thrust fault (Figure 55) and decrease in frequency with distance from the fault.

The N. 10° W.-trending Boring dike in Blazed Alder Creek (sample 18) cuts a N. 55° W.-trending breccia zone, demonstrating that there, at least, the N. 10° W. trend is younger.

Other fracture trends are north-south, N. 20° E., and N. 80° W. Fractures frequently affect patterns of mass wasting and erosion. For example, at the base of the falls at Falls Creek, in the Log Creek drainage, and along S10 on the east side of Falls Creek, failure of large blocks of Columbia River basalt has occurred along N. 15° W. fractures (Figure 56). Springs and other surface expressions of ground water also follow the major fracture patterns throughout the watershed (Manning, 1981, personal communication).

Fractures often control the direction in which streams in Bull Run flow. For example, along the boundaries of secs. 23 and 24,
Figure 53. Dashed lines outline Boring-type dike on west side of Falls Creek on S10. This N. 10⁰ W.-trending dike cuts Frenchman Springs Member of Wanapum Basalt and is indicative of east-west extension that accompanied north-south compression of this region.
Figure 54. Boring-type dike in R₂ low Mg section in Blazed Alder Creek. Here dike trends N. 10⁰ W. and cuts a N. 55⁰ W. fracture zone. Dike crops out at various places along this stream, with its strike ranging from N. 10-20⁰ W. until it disappears in unnamed stream that drains from the southwest into Blazed Alder Creek.
Figure 55. Breccia zone trending N. 40° W. in Boulder Creek above the thrust fault. Breccia zones and fractures trending N. 10-55° W. are common close to thrust fault but decrease in frequency with distance from the thrust.
Figure 56. Arrow points to large N. 10° W. fracture that cuts Frenchman Springs and Grande Ronde Members at biggest falls on Log Creek.
T. 1 S., R. 7 E., Blazed Alder Creek flows first along a very obvious N. 20° W. fracture and then makes an abrupt turn and flows along an equally obvious N. 55° W. fracture (Figure 57). Stretches of North Fork flow through N. 10° W. fractures (Figure 58). These fractures seem to be most influential in controlling stream directions when the streams are cutting across the regional anticline-syncline structures.

REGIONAL COLUMBIA RIVER BASALT GROUP STRUCTURE

The northwest-trending folds and thrust fault, fracture patterns, strike-slip fault and slickensides, and orientation of the Boring dikes are all consistent with the regional model of north-south compression and east-west extension presented by numerous workers including Beeson and Moran (1979b) and Beeson and others (in press).

The folds in Bull Run are similar in orientation and style to the generally easterly-trending, locally faulted or thrust-faulted, long, narrow anticlines and broad, flat-floored synclines found in the western portion of the Columbia Plateau and described by Kienle and others (1978). Indeed, the Bull Run folds are on strike with--and probably were continuous with--the Mosier syncline and the Columbia Hills anticline in the State of Washington before they were broken by north-northwest-trending faults in the Hood River Valley (Beeson and others, in press). Kienle and others (1978) believe that these folds "emerge" from the Cascades with N. 40-60° E. trends; this study has proved that similar structures with the same trend and style of folding and faulting are found as far west as Bull Run.
Figure 57. Portion of Blazed Alder Creek upstream from thrust fault and confluence with Boulder Creek. This portion of stream is controlled by fractures. Stream enters from left after flowing along N. 20° W. fracture and turns and follows a pronounced N. 55° W. fracture.
Figure 58. Portion of North Fork controlled by N. 10° W.-trending fracture. At this point, stream is flowing through high Mg section of Grande Ronde Basalt.
South of Bull Run, a N. 30° W.-trending fault located near the Salmon River separates the Bull Run-style of northeast-trending folds from the northwest-trending structures of the Clackamas River area to the south and the Portland area to the west (Beeson and others, in press).

Southeast of Bull Run, the area around Mount Hood has been downdropped; the top of the basalt section in the Old Maid Flat drillhole is at an elevation of 223 meters (722 feet), whereas 12 kilometers (7.5 miles) to the northwest at the highest exposures on the Bull Run thrust fault, the top of the basalt is at 930 meters (3,100 feet). Part of this offset is undoubtedly due to the effects of the thrust faulting and part of it the result of folding of the basalt. However, as the Old Maid Flat drillhole produced no hyaloclastite characteristic of basalt that flowed into water, it is unlikely that the drillhole is in the axis of a syncline (Beeson and others, in press).
Sometime between 16.5 and 14 million years ago, a series of flows of Columbia River basalt flowed westward from the Columbia Plateau through an east-west-trending structural low into western Oregon and Washington. The underlying rocks are not exposed in the Bull Run Watershed, but rocks similar to the Eagle Creek Formation on the north and the "Beds of Bull Creek" (Hammond and others, 1980) to the south probably formed the gently sloping surface onto which the basalt flowed. The basalt first filled topographic lows and then began to build a relatively flat surface with successive flows. Beeson and others (in press) estimate that one flow entered the area on the average of every 100,000 years. The actual time interval between flows varied considerably.

During or after the time that the low Mg Grande Ronde flows entered the Bull Run area, some sort of structural deformation began, producing the structural high in Blazed Alder Creek either as a fold or as a horst, although poor exposure made it impossible to determine the type of structure that produced the high. The succeeding N2 low Mg flows surrounded, but could not cover, the R2 low Mg high. Eventually, however, high Mg flows entered the area and covered the structural high and the surrounding terrain, as did the succeeding flows of Wanapum Basalt.
During high Mg Grande Ronde time, folding and drainages began to develop, as indicated by the irregular thickness of the lowest high Mg flow, the variably thick interbed between the two high Mg flows, and the pillows found at the base of the uppermost high Mg flow at North Fork and Log Creek. Volcanism occurring at the same time in the Old Maid Flat area to the east produced ash that may have washed into a topographic low to form the tuffaceous interbed found between the two high Mg flows at Reservoir No. 1 and in the core samples from below Dam No. 2.

Between Grande Ronde and Wanapum time, a lull in Columbia River basalt volcanism far to the east occurred. During this period, soil developed on the weathered Grande Ronde surface, trees grew, and more widespread drainages developed. Some gentle folding must have begun by this time, because pillows are found at the base of the lowest Wanapum Basalt flow only in proximity to the present-day syncline.

Following this interval, six flows of Frenchman Springs basalt poured into the area. Pillows were formed at the base of the lowest flow where it poured into water or over wet ground. These flows filled drainages and topographic lows, again completely covering the area.

The north-south compression that was producing the folding continued, leading to the development of structural relief that excluded all younger Columbia River basalt flows, except for a few that invaded the region as intracanyon flows.

At least one deep drainage developed. Priest Rapids basalt
entered the area as an intracanyon flow, overfilling the deep canyon of a westward-flowing river that was probably an ancestor of the much larger, more lengthly present-day Columbia River. Succeeding rivers were undoubtedly forced to develop drainages farther to the north. The Priest Rapids flow undoubtedly backed up into any side streams, leaving basalt in them as well. Because succeeding drainages probably developed to the north, the later Pomona intracanyon flow must have passed farther to the north through one of these later drainages.

As the regional north-south compression continued to affect Bull Run, folds became more pronounced, and the north limb of the anticline failed, with resulting thrusting to the northwest. The thrust produced huge volumes of tectonic breccia, much of which was carried away by erosion, the rest covered by products of succeeding volcanism and the thick Bull Run vegetation.

Continuing structural deformation and erosion produced an irregular post-Columbia River basalt topography onto which the Rhododendron lahars, ash flows, and lava flows poured, unconformably and discontinuously during the late Miocene and early Pleistocene (Schulz, 1980). Deformation probably continued during Rhododendron time (Manning, 1981, personal communication).

Pliocene-Pleistocene volcanism was fed by N. 10° W.-trending dikes--evidence of east-west extension accompanying the ongoing north-south compression of the entire region. The products of this volcanism eventually covered most of the watershed to a thickness of at least 600 meters (2,000 feet) (Schulz, 1981).

The Cascade uplift, which produced the southeastward dip of
structures in Bull Run, and the N. 10° W. regional fracturing such as that found along Blazed Alder Creek and the Bull Run River undoubtedly helped the cycle of erosion and accompanying landsliding that began again to expose first the Pliocene-Pleistocene volcanic pile, then the Rhododendron Formation, and finally the Columbia River basalt to view again.

Pleistocene glaciation carved out the upper portions of the watershed, forming cirques in which lakes such as Bull Run Lake lie (Figure 59).
Figure 59. Bull Run Lake, with Mount Hood to the southeast in the background. Contrary to popular local belief, the Bull Run Watershed is not fed by water from Mount Hood; Lolo Pass lies between the watershed and Mount Hood.
The Bull Run Watershed lies in the middle of a trough through which Columbia River basalt poured into western Oregon and Washington. For that reason, detailed study of the basalt exposed by the erosive action of the Bull Run River and its tributaries was essential to the regional Columbia River basalt stratigraphic and structural picture. The relationship between the Bull Run stratigraphic column and those of surrounding areas demonstrates the areal extent of the various flows and the effects of structural development on their distribution.

Structurally, the Bull Run Watershed provided the best look at any thrust fault as yet identified in the Western Cascades of Oregon. Without the exposure of the actual thrust plane, the nature of the fault would have had to have been determined only on the basis of the presence of tectonic breccia and the amount of observed offset. Because the Bull Run thrust fault was well exposed, it was possible to recognize the similarity between the Bull Run and Columbia Plateau type of faulting (see Regional Columbia River Basalt Group Structures in Chapter VII).

Indeed, before this study it was not believed that the Plateau type of faulted, narrow, easterly-trending anticlines and broad synclines had extended west past the Cascades. Because the vegetation,
topography, degree of weathering, and amount of younger volcanism were so different on the wet side of the mountains, the structures had appeared to be different too. This study has proved, however, that the style of folding and faulting found in the Bull Run Watershed is similar to the Columbia Plateau type of folds and faults. The Bull Run anticline and syncline are on strike with and were probably once part of the Mosier syncline and Columbia Hills anticline. The Bull Run Watershed was undoubtedly subjected to the same type of stress that produced the structures of the Columbia Gorge and the Columbia Plateau.

The abbreviated section in the Grande Ronde section in Bull Run suggests that structural development of the region was occurring there during low Mg Grande Ronde time. In fact, the presence of this high and the northeast-trending folds and fault suggest that the east-west-trending trough through which the basalt flowed may have also been, at least in part, structural in origin. This would set the time of onset of structural development even earlier—pre-Grande Ronde Basalt time.

The exclusion of the post-Frenchman Springs flows except for the Priest Rapids intracanyon flow demonstrates the effects of continuing structural growth that barred later basalt flows and led to the development of a deep drainage system south of the course of the Columbia River of today. The overfilling of the Priest Rapids canyon probably forced succeeding rivers to develop channels farther to the north.

The younger strike-slip faults, breccia zones, and dikes of
Bull Run are similar to other regional features. Indeed, the motion of the February 13, 1981, earthquake northwest of Mount St. Helens was also strike-slip (Beaulieu, 1981, personal communication), which is certainly consistent with the type of faulting observed in Bull Run.

Although the limited exposures of Columbia River basalt in Bull Run do not provide a broad enough data base to enable generalizations to be made about the Cenozoic tectonic history of all of western Oregon, Bull Run does fit well into current plate tectonic models of the region. Most current models suggest that the western margin of the North American continent has grown by accretion as the Pacific and North American Plates converged obliquely, with oblique subduction of small oceanic subplates.

Beeson and others (in press) suggest that the net effect of plate tectonic motion in this region has been a dextral wrench or couple in the western United States, with north-south compression and east-west extension. The pattern of folding and faulting exhibited in Bull Run is consistent with this model. The north-south compression produced the folds; in fact, Beeson and others (in press) suggest that these structures may be only shallow, thin-skinned deformational response of brittle competent basalt to such a regional stress. Because no mineralization or alteration occurs in the northeast-trending thrust fault, it appears it was not deep seated enough for magma or hydrothermal fluids to have ascended through it to the surface.

The structures trending north-northwest appear, however, to be more deep seated, for it is through dikes with these trends that
basaltic magma rose to the surface to produce the Boring volcanoes. The orientation of these dikes is also consistent with a pattern of east-west extension. Strike-slip motion along the north-northwesterly trends is also consistent with north-south compression, for this type of motion would be anticipated in such a stress field.
REFERENCES CITED


Shannon and Wilson, 1958a, Test embankment Bull Run Dam No. 2: Portland, Oreg., unpublished report to the City of Portland, 8 p.


APPENDIX A

NEW ROAD NUMBERS

The following road numbers will replace current road numbers at some time in the future. The old number is listed first, followed by the new number.

S10 = 10
S158 = 1008
S158A = 1008158
S10A = 1010
S10B = 1000101
S10F = 1000151
N130 = 20
S155 = 1015
S154 = 10
S10 between two junctions with S154 = part closed, part 1025
S154A = 1000530
S2020 = 1027
S127 = 1027
S126 = 12
S157 = 1217
S14 = 12
S111 to junction with S126 = 12
S111 from junction with S126 to end = 1211
APPENDIX B

INAA LABORATORY PROCEDURE

Samples included in this thesis were analyzed in five separate experiments (see section on Laboratory Methods in Chapter IV). The samples were broken into small pieces with a hammer. Approximately 20 grams of fresh chips were picked from each sample and crushed in a stainless steel mortar with a stainless steel pestle to 80-mesh powder. This powder was split into smaller portions, and approximately 1 gram of powder from each sample was placed in a clean, scribed polyethylene vial.

Samples and a BCR-1 standard were irradiated at the TRIGA reactor at Reed College, Portland, at a flux of approximately \(2 \times 10^{12}\) neutrons/cm\(^2\)sec (250 kw) for one hour.

Eight days after irradiation, samples and standard were transferred to clean, scribed polyvials for the first count and weighed. Each vial was put into a clean plastic bag and placed into the Ge(Li) detector in geometry 1 position for counting. Samples were counted for 16 minutes; the standard was counted for 32 or 64 minutes. A second count was conducted the same way 62 days after irradiation.

Concentration values for BCR-1 were taken from Flanagan (1973). Data were processed on the Portland State University PDP-11 and Harris 200 computers with existing programs.

INAA data appear in Appendix C. Data are listed in two ways: once in sequence of map numbers, and once by separate experiment
and by separate detector for samples counted at the University of Oregon.

The first number for each element indicates concentration in parts per million except for Na and Fe, which are in percent. The second number is the relative error.
Appendix C

Chemical Data

Tables III through X on the following pages present the instrumental neutron activation analysis data used in preparation of the geologic map for this thesis. Table III presents the data in the order that the samples appear on the geologic map.

Tables IV through X present data as analyzed in different experiments or on different detectors. Table IV presents data analyzed by Beeson and others (1975) as part of the Portland Environmental Project (PEG); Table V contains data analyzed by the author in 1977 and counted on the green detector at the University of Oregon; Table VI contains data analyzed by the author in 1977 and counted on the orange detector at the University of Oregon; Table VII contains data analyzed by the author in 1977 and counted on the red detector at the University of Oregon. Tables VIII, IX, and X contain data counted by Beeson and Moran in 1978 as parts of their experiments 7-7, 7-9, and 7-10, respectively.

Sample number is also map location number. Chemical group abbreviations are as follows: FS = Frenchman Springs; PR = Priest Rapids; HM = high Mg Grande Ronde; LM = low Mg Grande Ronde; Bor. = Boring; Undetr. = undetermined. The first number is concentration in parts per million, except for Na and Fe, which are in percent. Second number is relative error in parts per million, except for Na and Fe, which are in percent.
### Table III

**All DNA Data Used in This Study**

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</table>

**Note:** The tables contain data related to DNA samples and their characteristics, spanning from 1975 datasets. The entries represent various measurements or counts, contributing to the study's analysis.