1982

The stratigraphic relationships of the Columbia River Basalt Group in the lower Columbia River Gorge of Oregon and Washington

Terry Leo Tolan
Portland State University

AN ABSTRACT OF THE THESIS OF Terry Leo Tolan for the Master of Science in Geology presented May 7, 1982.

Title: The stratigraphic relationships of the Columbia River Basalt Group in the lower Columbia River Gorge of Oregon and Washington.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

[redacted]

Marvin H. Beeson, Chairman

[redacted]

Paul E. Hammond

[redacted]

Robert O. Van Atta

The western end of the lower Columbia River Gorge provides a natural cross section through the western flank of the Cascade Range. The oldest exposed unit in this area is the Oligocene to lower Miocene (?) Skamania Volcanic Series, which consists of basalt, andesite, and dacite flows and associated volcaniclastic material. The Skamania Volcanic Series formed a paleotopographic high in the Crown Point-Latourell, Oregon, area which later Columbia River Basalt Group flows surrounded but failed to cover. Flows of the Miocene Columbia River Basalt Group (CRBG) within this area belong to the

Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt of the Yakima Basalt Subgroup. Thickness of the CRBG in this area ranges from 0 m to greater than 335 m at Multnomah Falls, Oregon. Because of pre-existing topography, regional deformation, and channel and canyon cutting by the ancestral Columbia River no one section contains all 22 CRBG flows that are found in this area. The Grande Ronde Basalt consists of five units recognizable on the basis of chemistry, paleomagnetic polarity, and lithology. These units are, from oldest to youngest, N_1 low MgO unit, R_2 low MgO unit, N_2 low MgO unit, N_2 low MgO Winter Water flow, and N_2 high MgO unit. Few interbeds occur in the Grande Ronde section here along the northern margin of the CRBG, whereas the opposite is true for the southern margin in the Clackamas River area. The Wanapum Basalt consists of the Frenchman Springs and Priest Rapids Members. The Frenchman Springs Member is represented by five plagioclase-phyric to aphyric flows in the western half of this area. The Rosalia chemical type of the Priest Rapids Member is present in this area as an 220-m-thick intracanyon flow which overfilled a northwest-trending ancestral Columbia River channel at Crown Point, Oregon. The lower portion of this intracanyon flow consists of a thick, allogenic, bedded hyaloclastite deposit. The burial of the ancestral Columbia River channel by this intracanyon flow forced the Columbia River to shift northward and re-establish a new channel. Because this new channel, the Bridal Veil channel, of the ancestral Columbia River was only partially filled by an intracanyon flow of the Pomona Member of the Saddle Mountains Basalt, the Columbia River continued to occupy the

Bridal Veil channel in post-Pomona time.

The Troutdale Formation in the thesis area was deposited by the ancestral Columbia River which occupied the Bridal Veil channel. This formation has been found to be divisible into lower and upper members. The lower member of the Troutdale Formation consists of quartzite-bearing, basaltic conglomerates and micaceous, arkosic sandstones which are confined to the Bridal Veil channel. Two Rhododendron lahars are also intercalated with the lower member conglomerates in the Bridal Veil channel. The upper member of the Troutdale Formation consists of vitric/lithic sandstones with minor basaltic conglomerates which contain Boring Lava clasts. Two Boring Lava flows are intercalated with the upper member, and Boring flows also cap the Bridal Veil channel in this area. Continued alluviation and Boring volcanism appear responsible for the final shift of the Columbia River to its present-day position. Field relationships now suggest the lower age of the Troutdale Formation is 12 million years. Circumstantial evidence suggests the upper age of this formation may be less than 2 million years b.p.

The western end of the lower Columbia River Gorge appears to be relatively undeformed, with no major faults or folds discernible. This area has a relatively uniform 2° to 4° southwesterly dip attributable to Cascadian uplift. Stratigraphic evidence suggests that Cascadian uplift and erosion of the present-day gorge in this area may have begun as recently as 2 million years b.p.

THE STRATIGRAPHIC RELATIONSHIPS OF THE COLUMBIA RIVER BASALT GROUP IN THE LOWER COLUMBIA RIVER GORGE OF OREGON AND WASHINGTON

by

TERRY LEO TOLAN

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

MASTER OF SCIENCE
in
GEOLOGY

Portland State University

1982

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of Terry Leo Tolan presented May 7, 1982.

[redacted]

Marvin H. Beeson, Chairman

[redacted]

Paul E. Hammond

[redacted]

Robert O. Van Atta

APPROVED:

[redacted]

Gilbert T. Benson, Head, Department of Earth Sciences

[redacted]

Stanley E. Rauch, Dean of Graduate Studies and Research

ACKNOWLEDGMENTS

I wish to acknowledge and express my gratitude to the following organizations and people for their help and support during the course of this study.

I would like to thank both the Rockwell Hanford Operations and the U.S. Geological Survey who supported portions of the geologic mapping conducted in the thesis area during the summers of 1980 and 1981 as part of the regional geologic studies effort for the Basalt Waste Isolation Project. Rockwell Hanford Operations also provided the major oxide analyses used in this study which were performed by Dr. Peter Hooper of Washington State University.

A grant by the Paul Howell Fund of the Portland State University Earth Sciences Department also aided in the completion of this thesis.

I would like to extend my deepest gratitude to the following people whose counsel, support, and assistance was crucial to the completion of this thesis. First and foremost, I would like to thank Dr. Marvin Beeson, my advisor, whose interest, insight, and advice was invaluable during every phase of this study. I wish to thank Beverly Vogt for her many helpful observations and comments in the field, and also for the time-consuming task of editing this thesis. I also wish to extend a special thanks to James L. Anderson who first kindled my interest in the CRBG and whose instruction, counsel, and encouragement over the past three years has been invaluable to me.

Finally, I wish to dedicate this thesis to my parents, who have always been a constant source of love and encouragement throughout all my endeavors.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

FIGURE PAGE

CHAPTER I

INTRODUCTION

General

The Columbia River Gorge of Oregon and Washington is an area of renowned scenic beauty characterized by numerous waterfalls which plunge over basalt palisades rising precipitously from the valley floor. This area also affords geologists a unique opportunity to study a natural cross section through the Cascade Range of northern Oregon and southern Washington.

Many geologists have investigated this area since the late 1800's, thereby contributing to our present understanding of the individual formations and geologic processes which have shaped this region. Of all the units exposed within the gorge, the Columbia River Basalt Group (CRBG) which forms the steep cliffs was, until recently, one of the least understood units. To the early geologists, the flows of the CRBG were so apparently uniform that it was impossible to separate and trace specific flows over any great distance. In the past 15 years, however, through the concerted efforts of many geologists working on this very problem, techniques have been developed and refined which have made it possible to formally divide Columbia River basalt into formations and members.

The use of these techniques in the lower Columbia River Gorge has revealed unexpected stratigraphic complexity within the CRBG and provided new insights into unresolved questions concerning the history of the ancestral Columbia River in this region.

Previous Work

Since the turn of the century, geologic investigations within the lower Columbia River Gorge have been conducted by Williams (1916), Bretz (1917), Barnes and Butler (1930), Allen (1932), Hodge (1938), Lowry and Baldwin (1952), and Trimble (1963). In their work, these geologists basically recognized six major stratigraphic units: Eocene to early Miocene volcanic rocks (Skamania Volcanic Series), early Miocene Eagle Creek Formation (formerly Warrendale Formation), Miocene Columbia River Basalt (Group), late Miocene to Pliocene Rhododendron Formation, Pliocene Troutdale Formation (formerly Satsop Formation), and Plio-Pleistocene Boring Lava, and High Cascade volcanic rocks ("Cascan" Formation of Hodge (1938)). Of the six units, the CRBG comprises the greatest proportion of exposed geologic section within the lower Columbia River Gorge. Hampered by the apparently uniform nature of the CRBG flows, however, these workers were forced to map it as an undifferentiated unit.

No major structural features (i.e., faults or folds) were mapped by these early workers in the western end of the Columbia River Gorge.

Waters (1973) published the first work identifying specific flows and formations of the CRBG present in the lower Columbia River Gorge. This work established that the CRBG stratigraphy in the lower Columbia River Gorge was not as simple as previously assumed. Part of the complexity lay in a major CRBG intracanyon flow (Priest Rapids

Member of the Wanapum Basalt) which Waters speculated had flowed westward from its source on the Columbia Plateau and entered western Oregon via an ancestral Columbia River channel. Waters' discovery provided the first positive evidence of the existence of an ancestral Columbia River during Miocene time.

Swanson, Anderson, and others (1979) of the U.S. Geological Survey mapped in reconnaissance the CRBG on the Washington side of the lower Columbia River Gorge (Vancouver AMS sheet, scale 1:250,000). Their mapping established the presence of flows of the Grande Ronde Basalt and the Frenchman Springs Member of the Wanapum Basalt in this area.

Continuation of this U.S. Geological Survey project on the Oregon side of the river led to the identification of the Pomona Member of the Saddle Mountains Basalt as an intracanyon flow at Bridal Veil, Oregon (Beeson and Tolan, 1980, unpublished data).

Purpose

The purpose of this study was to produce a detailed geologic map of the CRBG in the western portion of the Columbia River Gorge (fig. 1). The objectives were (1) to identify and delineate the extent of the Priest Rapids Member and Pomona Member intracanyon flows, and (2) to define the relationship of post-CRBG units to the CRBG intracanyon flows.

Geographic Setting

The area examined for this study is located at the western end of the Columbia River Gorge approximately 32 km east of Portland, Oregon, and 16 km southwest of Bonneville Dam (fig. 1). This area is situated on the western margin of the north-south Cascade Range through which the westerly flowing Columbia River has eroded a steep-walled gorge, which in many places exceeds 2.5 km in width. The Columbia River drains an inland area of over 663,000 km^2 and has a mean annual discharge rate of 194,600 cfs, which ranks it second in the United States only to the Mississippi River.

Within the thesis area, the terrain south of the Columbia River generally consists of gentle constructional volcanic slopes and cones of the Boring and High Cascade lavas. The area north of the Columbia River consists predominately of pre-CRBG volcanic terrain which has been eroded into deep ravines and valleys, except where capped by younger CRBG or Boring Lava flows.

Heavy orographic rainfall, exceeding 178 cm/yr, feeds numerous small streams which flow the year around. Waterfalls are a common feature at points where these streams enter the gorge proper.

With the exception of the southeastern corner of the thesis area, all of the study area has been logged off repeatedly during the last 120 years. Land not currently developed or cultivated by man is in various stages of reforestation.

Access

Three major east-west highways cross the length of the thesis area: Washington State Highway 14 (Evergreen Highway), Interstate 84 (formerly Oregon State Highway 30), and the old Columbia River Scenic Highway (also in Oregon). Numerous paved and graveled secondary roads

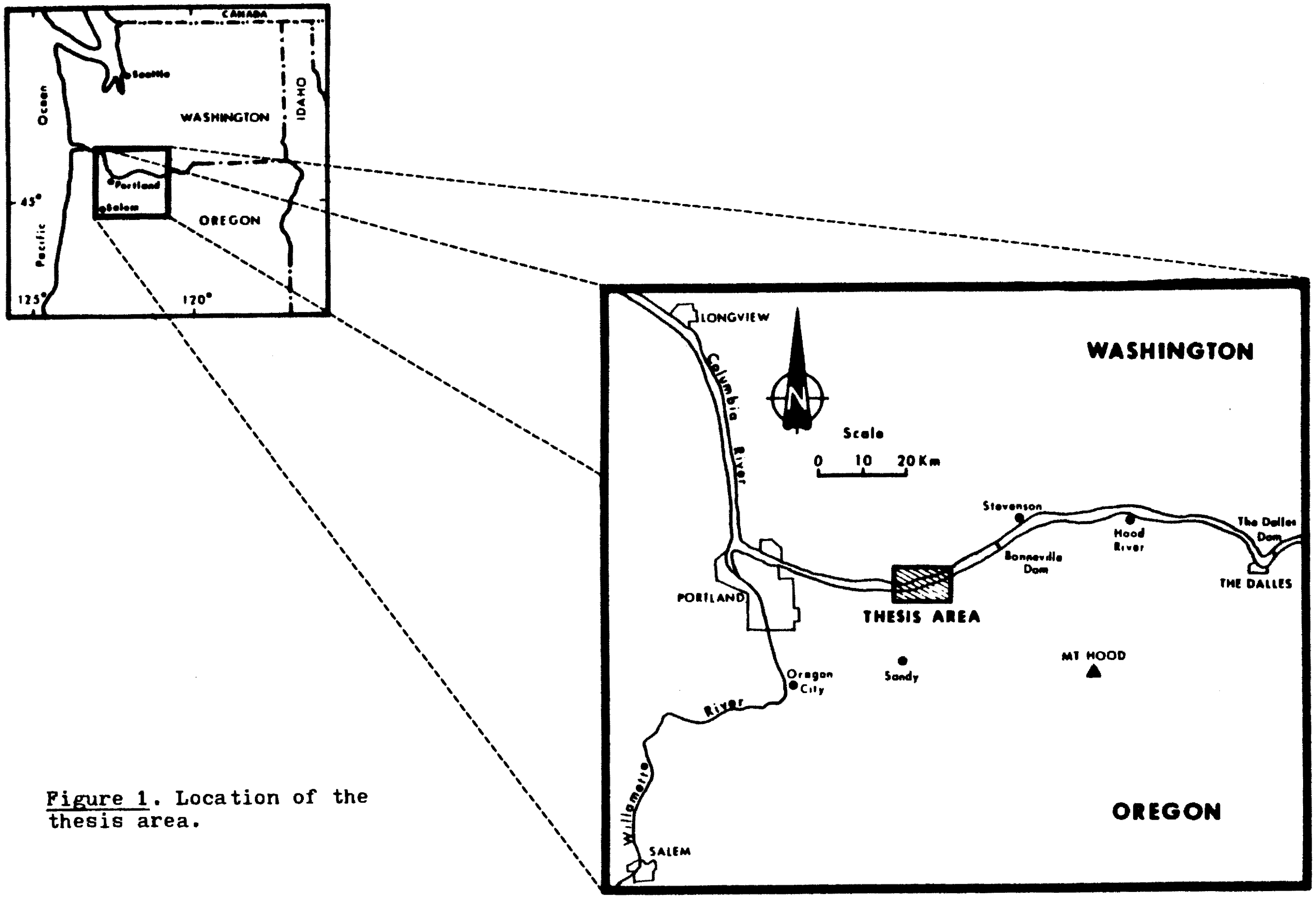


Figure 1. Location of the thesis area.

branching off these main highways provide further access. U.S. Forest Service hiking trails give access to the southeastern portion of the thesis area where few or no roads exist. The U.S. Forest Service has published an excellent map and guide to these trails entitled "Forest Trails of the Columbia River Gorge" which is available for a nominal fee at the District Ranger Station in Springdale, Oregon, or at the Mount Hood National Forest Supervisor Headquarters in Portland, Oregon.

Procedure and Methods of Investigation

This study was conducted in three phases: (1) a preliminary reconnaissance phase during the months of August and September of 1980; (2) a detailed mapping and data collection phase, expanding on the results of the first phase, from October 1980 to March 1981; (3) an analytical and analysis phase consisting of petrographic work, data analysis, map compilation, and field checks.

The first phase of this study was done initially in concert with the CRBG reconnaissance mapping project under the direction of Dr. Marvin Beeson (U.S.G.S. - D.O.E. interagency agreement EY-78-1-06-1078; Dr. Donald Swanson - Principal Investigator). This phase consisted of a road and trail reconnaissance of the thesis area with the primary goals being to establish the distribution and stratigraphy of the CRBG and to identify structural features. Identification of CRBG members was based on lithologic characteristics, superposition, paleomagnetic polarity, and major oxide chemistry. Magnetic polarity of the CRBG flows was determined in the field with a portable fluxgate magnetometer by testing a minimum of at least three samples per flow in each exposure. Samples tested were taken from chilled, nonbrecciated parts of the flow, where possible, because those portions yield the most consistent correct results. Unweathered rock samples were collected for major oxide analysis to confirm tentative field identifications. All major oxide analyses performed for this study are X-ray fluorescence determinations by Dr. Peter R. Hooper of Washington State University, Pullman, Washington.

Phase 2 consisted of expanding and detailing the previous reconnaissance work, including a series of traverses to examine exposures previously not visited. Stratigraphic sections were measured with a Thommen (2000) pocket altimeter and described noting thickness, lithologic character, jointing, contact relationships, flow features, and magnetic polarity of flows. Additional unweathered rock samples from selected flows were collected for major oxide analysis to confirm field identifications. Non-CRBG units were examined in greater detail, noting salient features and stratigraphic relationships.

Petrographic work conducted during the final phase of this study was limited to flows of the Skamania Volcanic Series, the bedded hyaloclastite deposit at the base of the Priest Rapids Member, and the Troutdale Formation. Flows of the CRBG were not studied petrographically because previous petrographic studies have shown this work to be of limited value as a tool for stratigraphic correlation in western Oregon (Beeson and others, 1976; Anderson, 1978; Beeson and Moran, 1979). Map compilation and analysis of geochemical and petrographic data were also conducted during this phase. Field checks were made to resolve any additional problems encountered during the final compilation of the geologic map.

CHAPTER II

REGIONAL GEOLOGY

Introduction

This study, though primarily concerned with the CRBG, has also examined the relationship of the CRBG to both older and younger units. This made necessary a working understanding of the geology of both the non-CRBG and CRBG units in the thesis area (fig. 2). This section provides a foundation for ensuing discussions in later sections.

Skamania Volcanic Series

The oldest rocks exposed within the Columbia River Gorge are altered Eocene to early Miocene basalts, andesites, dacites, and associated volcaniclastic rocks. Felts (1939a,b), who studied this unit, variously referred to it as the "Skamania Series", "Skamania Andesites", and the "Skamania Andesite Series" after its extensive distribution in Skamania County, Washington. Trimble (1963) consolidated these various terms into the name "Skamania Volcanic Series", thereby eliminating the multiplicity of synonymous terms and the ambiguous connotations the names carried when applied to this total sequence of lava flows and volcaniclastic rocks. Trimble's reasoning is valid, and his proposed name "Skamania Volcanic Series" is adopted in this study.

The total thickness of the Skamania Volcanic Series in the lower gorge is unknown but was assumed by Trimble (1963) to exceed

SYSTEM	SERIES	UNIT	LITHOLOGY
QUATERNARY	PLEISTOCENE	HIGH CASCADE LAVAS	ANDESITE FLOWS, LAHARS, AND MINOR AMOUNTS OF PYROCLASTIC MATERIAL.
	PLIOCENE	BORING LAVAS	PLAGIOCLASE-OLIVINE BASALT FLOWS.
		TROUTDALE FORMATION	FLUVIAL QUARTZITE-BEARING CONGLOMERATE AND VITRIC SANDSTONE.
		SANDY RIVER MUDSTONE	LACUSTRINE MUDSTONE, SILTSTONE, AND CLAYSTONE.
		RHODODENDRON FORMATION	ANDESITIC LAHARS AND AGGLOMERATES.
TERTIARY	MIOCENE	COLUMBIA RIVER BASALT GROUP	THOLEIITIC FLOOD-BASALT.
	OLIGOCENE EOCENE	SKAMANIA VOLCANIC SERIES	BASALTIC TO DACITIC FLOWS, MINOR AMOUNTS OF PYROCLASTIC MATERIAL; MINOR TO EXTENSIVE ALTERATION.

Figure 2. Generalized stratigraphy for the lower Columbia River Gorge area of northern Oregon and southern Washington. After Trimble (1963).

many thousands of feet.

Felts (1939a,b) and Trimble (1963) both recognized lower and upper units within the Skamania Volcanic Series. The lower unit is characterized by zeolitized/propylitized, folded basalt and basaltic andesite flows (with subordinate dacite flows) and pyroclastic rocks. The upper unit consists of undeformed and unaltered porphyritic mafic flows with little associated volcaniclastic rock.

No absolute age determinations have been performed on flows of the Skamania Volcanic Series. An age range of late Eocene to early Miocene for the Skamania Volcanic Series was suggested by Trimble (1963) on the basis of fossil flora found between flows and other stratigraphic evidence. R. W. Brown (in Trimble, 1963, p. 13) identified fossil flora from two localities within the lower unit of the Skamania Volcanic Series and determined them to be late Eocene to Oligocene in age. The upper age of early Miocene was established by Trimble on indirect evidence. He reasoned that, since the upper unit of the Skamania Volcanic Series lacks the extensive alteration and deformation of the lower unit and is overlain by unaltered and undeformed flows of the CRBG, the age of the upper unit lies closer to that of the Miocene CRBG flows.

Trimble (1963, p. 14) correlated the Skamania Volcanic Series with both the Keechelus Series and Fifes Peak andesite of Abbott (1955) on the basis of many physical and lithologic similarities. Trimble also suggested that the lower unit of the Skamania Volcanic Series might be correlative with basalt of the Eocene Goble Volcanics of northwestern Oregon and southwestern Washington. Waters (1973) presented evidence that suggests that the Skamania Volcanic Series might be equivalent to the Ohanapecosh Formation of the central Washington Cascade Range. Further, correlations can be made between the Skamania Volcanic Series and the Little Butte Volcanic Series of the northern Oregon Cascade Range (Peck and others, 1964). Similarities in lithology, physical characteristics, age, and overlapping areal distributions suggest that most of these correlations are valid.

Columbia River Basalt Group

The Miocene Columbia River Basalt Group (CRBG) comprises a sequence of subareal tholeiitic flood basalt flows that cover an area of approximately 200,000 km^2 in Oregon, Washington, and western Idaho (fig. 3) with an estimated volume of 200,000 km^3 (Waters, 1962). Flows of the CRBG were erupted during a period from 16.5 to 6 million years b.p. (Watkins and Baksi, 1974; Mckee and others, 1977) from north- to northwest-trending feeder dike systems in southeastern Washington, northeastern Oregon, and western Idaho (Waters, 1961; Taubeneck, 1970; Swanson, Wright, and others, 1979). More than 99 percent by volume of the CRBG was probably erupted during a 3-million-year span centered around 15 million years b.p. (Mckee and others, 1977).

Swanson, Wright, and others (1979) have formalized a revised stratigraphic nomenclature for the CRBG (fig. 4) which has been approved by the U.S. Geological Survey and which is currently in use.

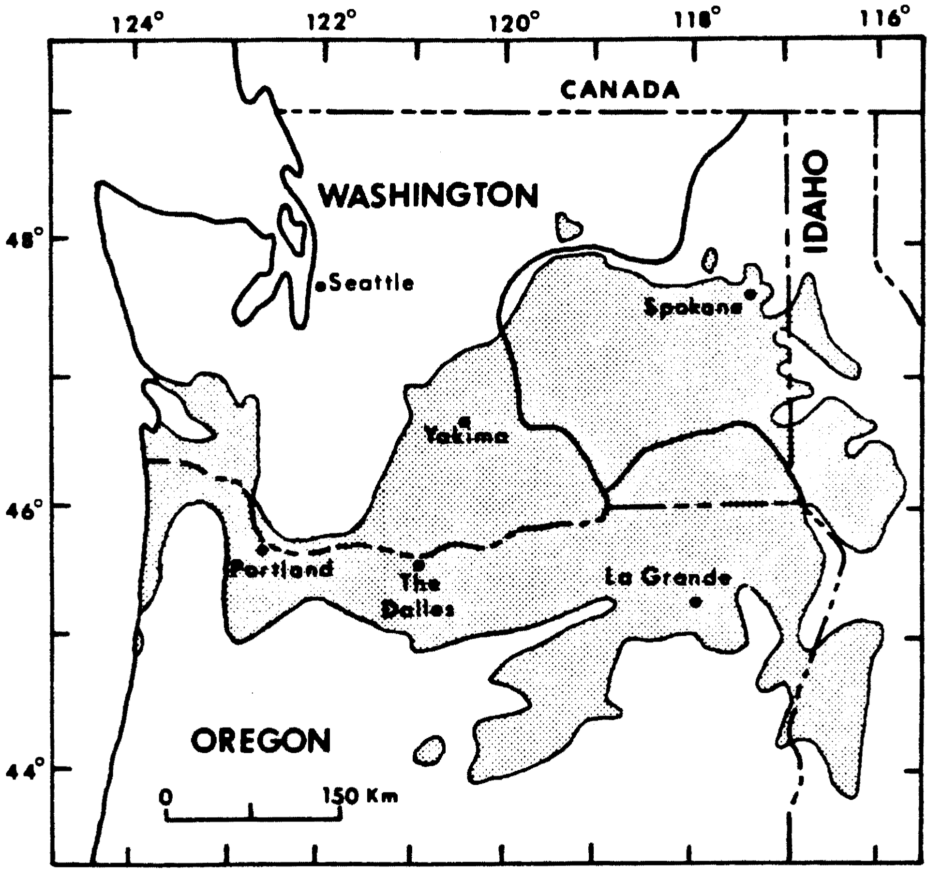


Figure 3. Map showing the distribution of the Columbia River Basalt Group (stippled) in Oregon, Washington, and Idaho. Modified after Snavely and others (1973) and Swanson, Wright, and others (1979).

SERIES	GROUP	SUB-GROUP	FORMATION	MEMBER	K-Ar age (m.y.)	MAGNETIC POLARITY
MIOCENE — UPPER	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	SADDLE MOUNTAINS BASALT	LOWER MONUMENTAL MEMBER	6	N
				Erosional Unconformity		
				ICE HARBOR MEMBER		
				Basalt of Goose Island	8.5	N
				Basalt of Martindale	8.5	R
				Basalt of Basin City	8.5	N
				Erosional Unconformity		
				BUFORD MEMBER		R
				ELEPHANT MOUNTAIN MEMBER	10.5	N,T
MIDDLE				Erosional Unconformity		
				POMONA MEMBER	12	R
				Erosional Unconformity		
				ESQUATZEL MEMBER		N
				Erosional Unconformity		
				WEISSENFELS RIDGE MEMBER		
				Basalt of Slippery Creek		N
				Basalt of Lewiston Orchards		N
				ASOTIN MEMBER		N
				Local Erosional Unconformity		
				WILBER CREEK MEMBER		N
				UMATILLA MEMBER		N
				Local Erosional Unconformity		
			WANAPUM BASALT	PRIEST RAPIDS MEMBER		R_3
				ROZA MEMBER		R_3 T
				FRENCHMAN SPRINGS MEMBER		N
				ECKLER MOUNTAIN MEMBER		
				Basalt of Shumaker Creek		N_2
				Basalt of Dodge		N_2
				Basalt of Robinette Mountain		N_2
LOWER			GRANDE RONDE BASALT		14–16.5	N_2
						R_2
			PICTURE GORGE BASALT	[Basalt of Dayville, Basalt of Monument Mountain, Basalt of Twickenham]*	(14.6–15.8)*	N_1
						R_1
			IMNAHA BASALT			R_1, T, N_0, R_0

*Information in brackets and parentheses refers to Picture Gorge Basalt

Figure 4. Stratigraphic nomenclature, age, and magnetic polarity for units of the Columbia River Basalt Group as revised by Swanson, Wright, and others (1979). N stands for normal polarity and R stands for reversed polarity. Black bar on right side of figure denotes members and units known to be present in western Oregon and Washington.

In this revision, the CRBG is subdivided into the Imnaha Basalt Formation, Picture Gorge Basalt Formation, and the Yakima Basalt Subgroup, which consists of Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt. For a complete treatment of the historical development of the CRBG nomenclature the reader is referred to their paper (Swanson, Wright, and others, 1979).

Flows of only the Yakima Basalt Subgroup are known to occur in the lower Columbia River Gorge and therefore are of principle interest to this study.

Grande Ronde Basalt. The Grande Ronde Basalt constitutes approximately 80 percent (150,000 km^3) by volume of the Yakima Basalt Subgroup (Swanson and Wright, 1978; 1981) and has the most extensive distribution of any formation within the CRBG (fig. 5). Thickness of the Grande Ronde Basalt varies greatly, being largely controlled by pre-Grande Ronde topography. The thickest known section, over 1,000 m, occurs in drill holes in the Pasco Basin of southeastern Washington (Atlantic Richfield Hanford Company, 1976). Stratigraphic sections containing as many as 34 individual flows (830 m in thickness) are also known (Camp and others, 1978).

The Grande Ronde Basalt consists mainly of aphyric tholeiitic basalt flows whose major oxide compositions show only minor variations (Swanson, Wright, and others, 1979; Table I, col. 1-2). Due to the apparently uniform lithologic and chemical nature of the flows, the only formally recognized stratigraphic subdivisions within this formation are based on paleomagnetic polarity of the flows. The

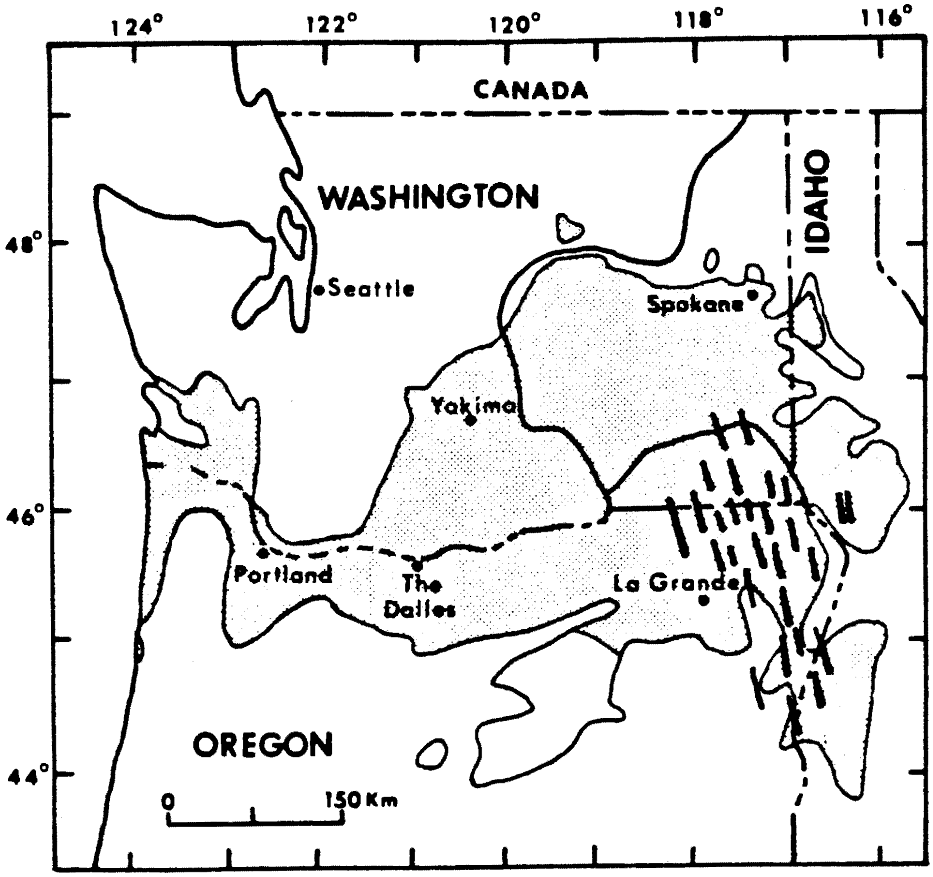


Figure 5. Map showing the distribution of the Grande Ronde Basalt (stippled). Feeder dikes shown schematically. After Snavely and others (1973) and Swanson, Wright, and others (1979).

TABLE I

AVERAGE MAJOR OXIDE CONCENTRATIONS FOR SELECTED CHEMICAL TYPES IN THE COLUMBIA RIVER BASALT GROUP*

Oxide**	Low MgO Grande Ronde	High MgO Grande Ronde	Frenchman Springs	Rosalia Priest Rapids	Lolo Priest Rapids	Pomona
SiO_2	55.94	53.78	52.29	50.27	50.09	51.88
Al_2O_3	14.04	14.45	13.21	13.69	14.31	14.88
FeO	11.77	11.35	14.38	15.04	13.78	10.55
MgO	3.36	5.25	4.04	4.29	5.18	6.96
CaO	6.88	9.07	7.90	8.31	8.88	10.67
Na_2O	3.14	2.83	2.67	2.67	2.57	2.36
K_2O	1.99	1.05	1.41	1.16	1.07	0.64
TiO_2	2.27	1.78	3.17	3.55	3.15	1.62
P_2O_5	0.43	0.28	0.71	0.81	0.78	0.25
MnO	0.19	0.19	0.22	0.21	0.19	0.17

* Source: Swanson, Wright, and others, 1979 - Table 2, pp. 10-11.

** All analyses in weight percent.

magnetostratigraphic units within the Grande Ronde Basalt are, from oldest to youngest, R_1, N_1, R_2, and N_2, where R stands for reversed polarity and N stands for normal polarity (fig. 4). Only the R_1 magnetostratigraphic unit has not been found in western Oregon or Washington to date (Beeson and others, in prep.). Several informal stratigraphic subdivisions within the Grande Ronde Basalt based on lithologic and chemical variations have been recognized and will be discussed in detail in the following chapter.

Wanapum Basalt. The Wanapum Basalt constitutes approximately 15 percent by volume of the Yakima Basalt Subgroup (Swanson and Wright, 1978) and has a far more limited distribution than the Grande Ronde Basalt (fig. 6A). Flows of Wanapum Basalt commonly overlie the Grande Ronde Basalt, with the two formations generally separated by local erosional unconformities or by interbed deposits, both of which have been interpreted to represent a significant hiatus between the end of Grande Ronde volcanism and the onset of Wanapum volcanism. Swanson, Wright, and others (1979) divided the Wanapum Basalt into four members, from oldest to youngest, the Eckler Mountain, Frenchman Springs, Roza, and Priest Rapids Members (fig. 4). Only the Frenchman Springs and Priest Rapids Members have been found in western Oregon and Washington (Kienle, 1971; Waters, 1973; Beeson and Moran, 1979).

Frenchman Springs Member. The Frenchman Springs Member consists of as many as 10 individual flows (totaling 190 m in thickness) east of the Cascade Range (Swanson, Wright, and others, 1979), whereas

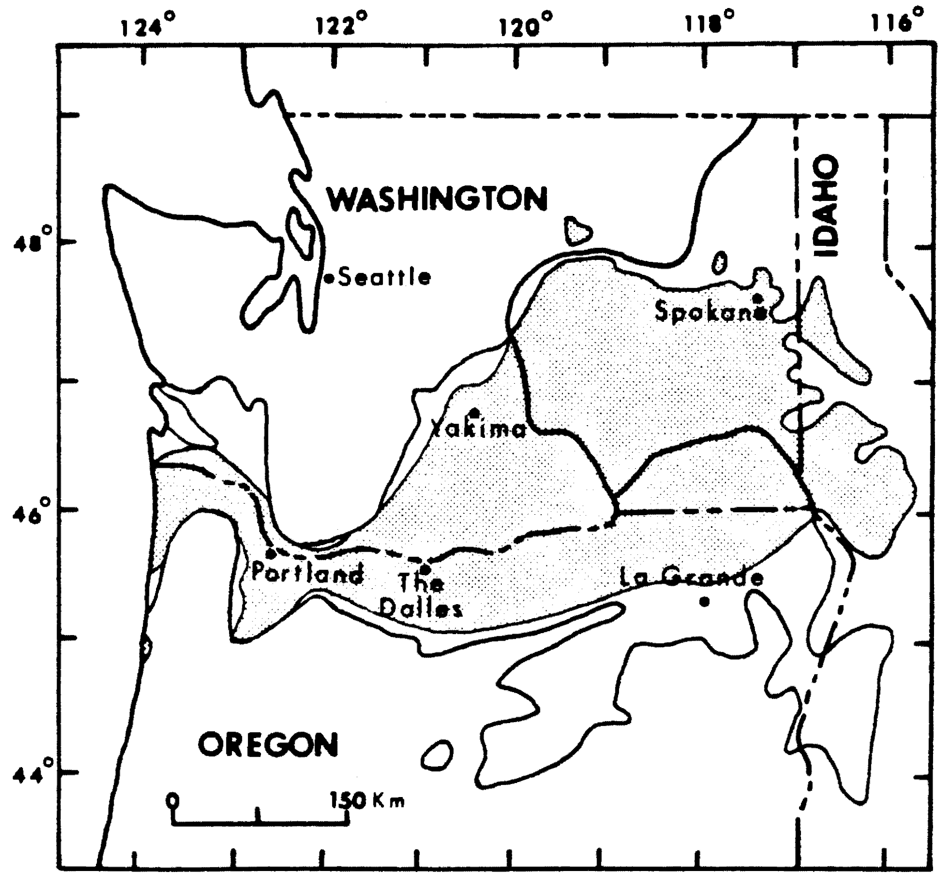


Figure 6A. Map showing the distribution of the Wanapum Basalt (stippled). Modified from Snavely and others (1973) and Swanson, Wright, and others (1979).

west of the Cascade Range only seven individual flows (totaling over 137 m in thickness) have so far been recognized (Beeson and others, in prep.). These flows were erupted from north-northwest-trending dikes located in the Walla Walla area of southern Washington (Swanson and Wright, 1978). The total volume of this member has been estimated by Swanson and Wright (1981) to be 3,000 to 5,000 km^3. Figure 6B shows the regional distribution of the Frenchman Springs Member.

Flows of the Frenchman Springs Member disconformably overlie the Grande Ronde Basalt and underlie the Roza Member of the Wanapum Basalt throughout much of the Columbia Plateau. In western Oregon and Washington, the Frenchman Springs Member is generally the youngest CRBG member present and is unconformably overlain by younger non-CRBG units (Beeson and Moran, 1979; Beeson and others, in prep.).

Most of the Frenchman Springs flows contain plagioclase phenocrysts and/or glomerocrysts which range from 1 to 3 cm in size (Swanson, Wright, and others, 1979; Bentley and others, 1980). Frenchman Springs flows also have a distinctive major oxide composition (Table I, col. 3) and normal paleomagnetic polarity.

Priest Rapids Member. The Priest Rapids Member was erupted from dikes in western Idaho (Taubeneck and others, *in* Swanson, Wright, and others, 1979; fig. 6C) approximately 14 million years b.p. (Mckee and others, 1977). This member consists of up to four paleomagnetically reversed flows in some portions of the Columbia Plateau, but more commonly only two flows are found in the western part of

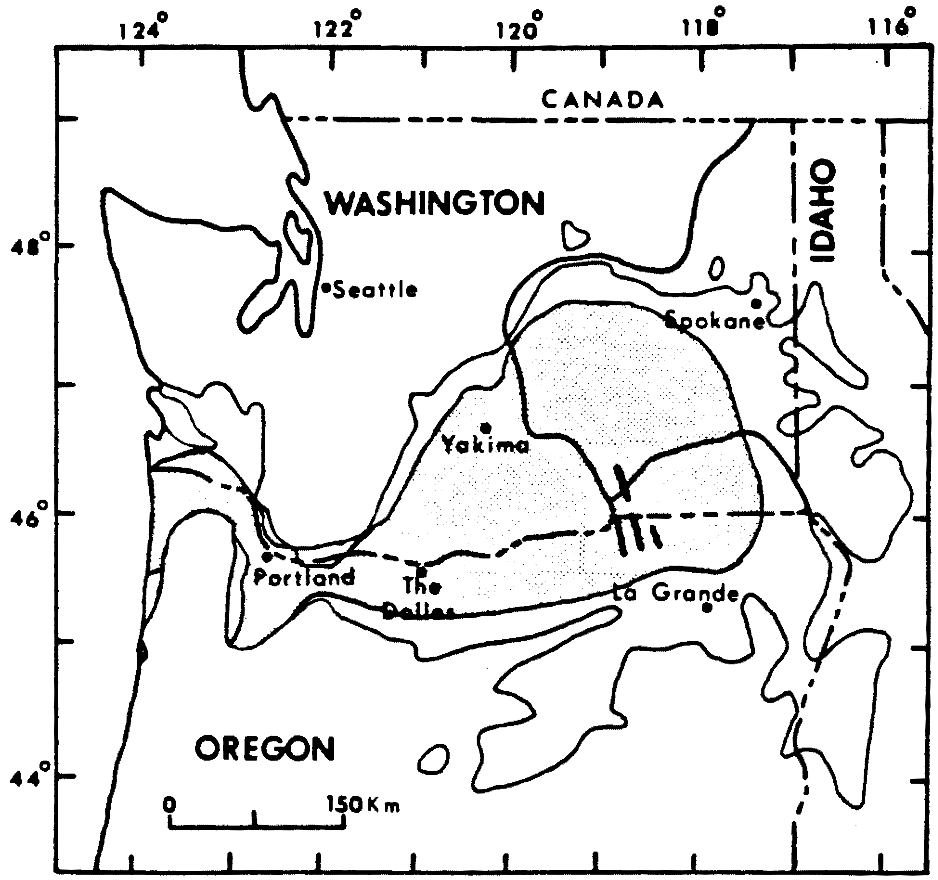


Figure 6B. Map showing the distribution of the Frenchman Springs Member (stippled) of the Wanapum Basalt. Feeder dikes shown schematically. Modified after Snavely and others (1973) and Swanson, Wright, and others (1979).

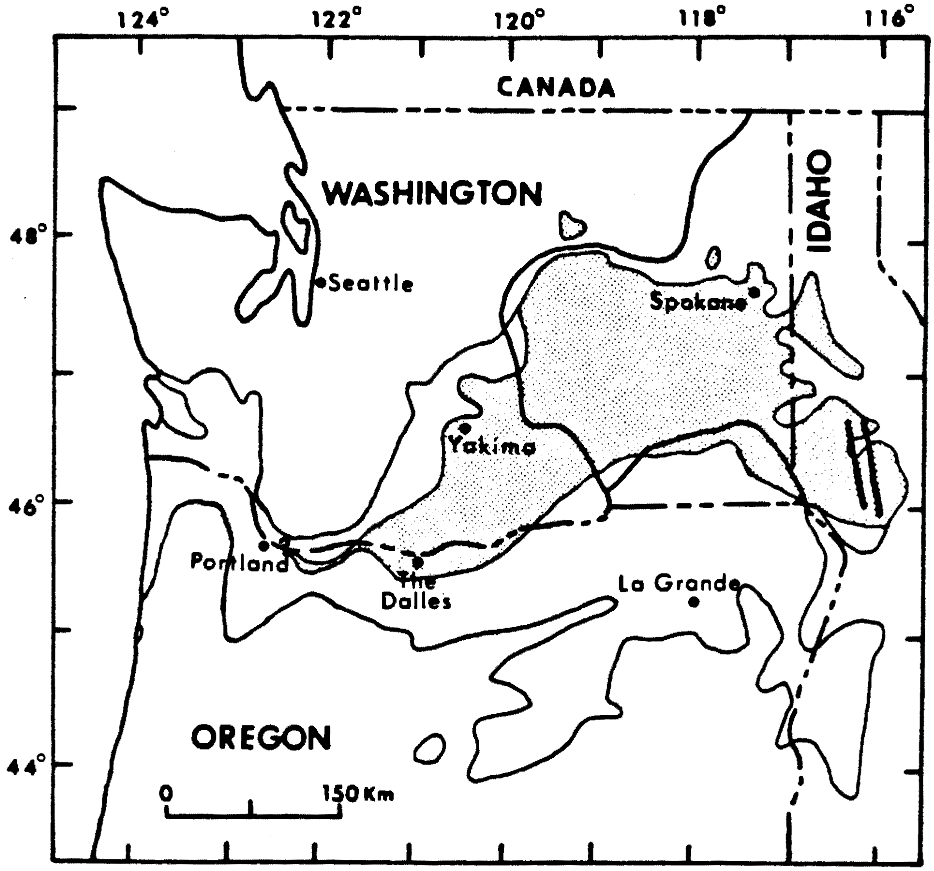


Figure 6C. Map showing the distribution of the Priest Rapids Member (stippled) of the Wanapum Basalt. Feeder dikes shown schematically. After Anderson and Vogt (in prep.).

the Columbia Plateau (Bentley and others, 1980).

Priest Rapids flows can be distinguished from Frenchman Springs flows in that they (1) do not generally contain abundant, large plagioclase phenocrysts and glomerocrysts, (2) have reversed paleomagnetic polarity, and (3) have a distinctive major oxide chemistry. The Priest Rapids Member flows can be subdivided into two different chemical types: a older Rosalia chemical type (Wright and others, 1973) which has higher FeO and TiO_2 (Table I, col. 4), and a younger Lolo chemical type (Griggs, 1976), which has lower FeO and TiO_2 and higher MgO concentrations (Table I, col. 5).

The Priest Rapids Member is represented in western Oregon by a single intracanyon flow (Waters, 1973; Vogt, in Beeson and Moran, 1979).

Saddle Mountains Basalt. The Saddle Mountains Basalt consists of 10 chemically and isotopically diverse members (Swanson, Wright, and others, 1979) and is the youngest formation within the CRBG (fig. 4). Members of this formation were erupted intermittently during the final phase of CRBG volcanism which lasted from approximately 13.5 to 6 million years b.p. (Mckee and others, 1977). The total volume of the Saddle Mountains Basalt erupted has been estimated to be 3,000 km^3 (Swanson and Wright, 1981)-- less than 1 percent of total volume of the entire CRBG.

Distribution of this formation is limited (fig. 7A) with many of its members being confined to structural lows or river canyons through which they moved as intracanyon flows (Swanson, Wright, and

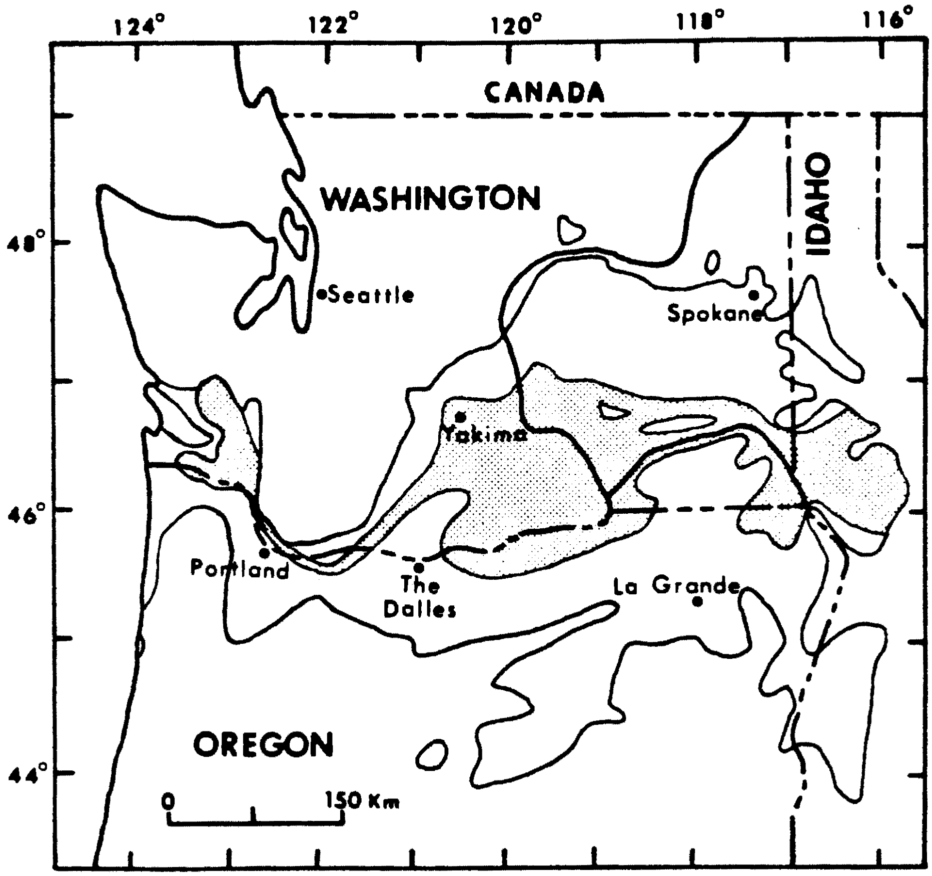


Figure 7A. Map showing the distribution of the Saddle Mountains Basalt (stippled). From Swanson and Wright (1981).

others, 1979; Camp and Hooper, 1980). Only the Pomona Member of the Saddle Mountains Basalt has thus far been found in western Oregon and Washington.

Pomona Member. The Pomona Member consists of a single flow which has been found from western Idaho to southwestern Washington (fig. 7B). This member was erupted from dikes in the Clearwater embayment of western Idaho (Camp, in Swanson, Wright, and others, 1979) about 12 million years ago (Mckee and others, 1977). As the Pomona Member flowed from its source area, it was generally confined to the proto-Clearwater and Snake River canyons (Camp and Hooper, 1980), spreading laterally only in the central portion of the Columbia Plateau. It continued to flow westward along the path of the ancestral Columbia River, finally crossing into western Oregon and Washington (Anderson, in Bentley and others, 1980; Anderson, 1980; Tolan and Beeson, in prep.). The distance from the source area of the Pomona Member to its distal end exceeds 500 km.

The Pomona Member has a highly distinctive lithology in that it contains tabular plagioclase phenocrysts (generally less than 0.5 cm in size) and less commonly clots of olivine and clinopyroxene (Schmincke, 1967; Swanson, Wright, and others, 1979). This combination of phenocrysts, reversed paleomagnetic polarity, and distinctive major oxide composition (Table I, col. 6) makes the Pomona Member one of the best stratigraphic markers within the CRBG (Swanson and Wright, 1981).

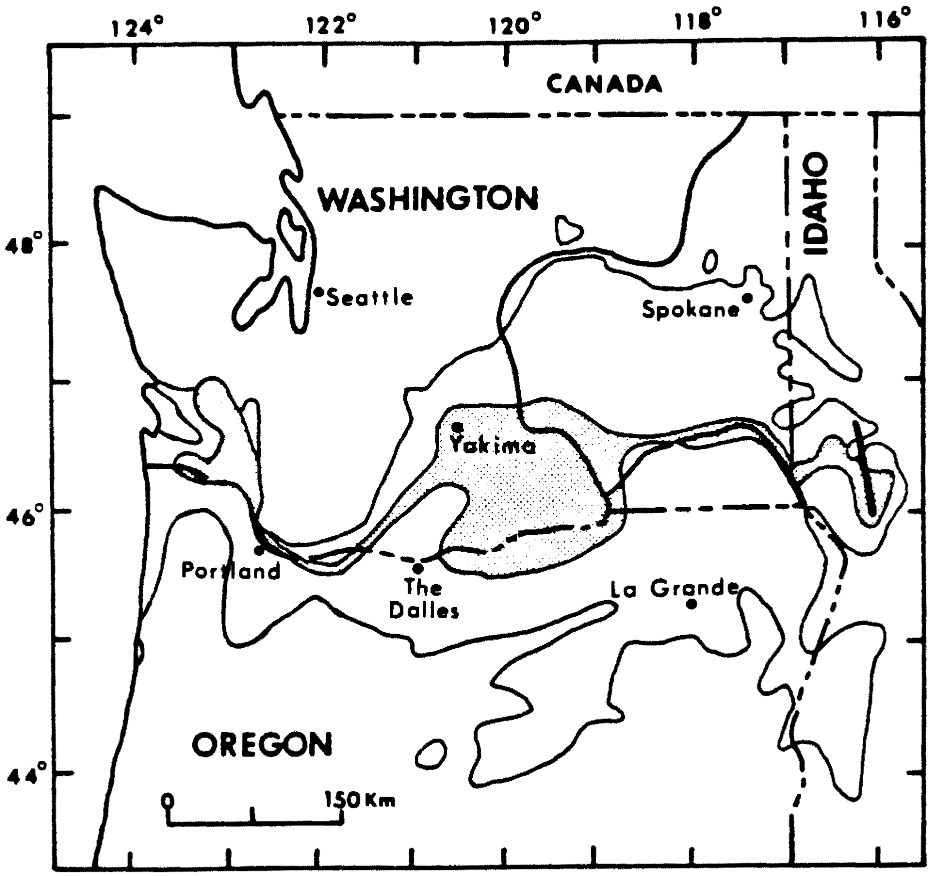


Figure 7B. Map showing the distribution of the Pomona Member (stippled) of the Saddle Mountains Basalt. Feeder dike shown schematically. After Anderson (1980) and Swanson and Wright (1981).

Rhododendron Formation

The Rhododendron Formation consists of late Miocene lahars, agglomerates, pyroclastic flows, and lava flows produced by an episode of explosive andesitic volcanism in the ancestral Cascade Mountains of northern Oregon (Peck and others, 1964; Gannett, 1982).

Barnes and Butler (1930) first described this formation and gave its type locality as Zigzag Mountain on the west flank of Mount Hood. Hodge (1933) applied the name "Rhododendron Formation" to these deposits after the town of Rhododendron, Oregon, which is near Zigzag Mountain. This name was generally used by most subsequent workers, except for Peck and others (1964) who assigned the name "Sardine Formation" to these same deposits.

Deposits of the Rhododendron Formation generally overlie the CRBG surface throughout much of the northern Oregon Cascade Range. However, the Rhododendron Formation has been found to be interbedded with Wanapum Basalt flows of the CRBG in one Old Maid Flat deep drill hole on the western flank of Mount Hood (Gannett, 1982). The Rhododendron Formation is generally overlain by Boring and High Cascade lavas, except locally in the vicinity of the lower Columbia River Gorge, where it is overlain by the Sandy River Mudstone or Troutdale Formation (Trimble, 1963).

The thickness of this formation is highly variable, from less than 10 m to greater than 500 m in some areas of the northern Oregon Cascade Range (Hodge, 1938; Peck and others, 1964).

Troutdale Formation

The upper Miocene to Pliocene nonmarine sandstones and conglomerates of the Troutdale Formation unconformably overlie the Rhododendron Formation throughout much of northern Oregon (Peck and others, 1964), except in the Portland Basin,where they overlie the lacustrine deposits of the Sandy River Mudstone (Trimble, 1963) or in the Columbia River Gorge, where they unconformably overlie the CRBG (Trimble, 1963; Waters, 1973).

The name "Troutdale Formation" was formally proposed by Hodge (1938, p. 873) for what he considered to be a great Pleistocene piedmont fan deposit lying on the west side of the Cascade Range. The name originates from the town of Troutdale, Oregon, which is located at the western end of the Columbia River Gorge adjacent to cliff exposures of this formation along the lower Sandy River.

Prior to 1929, these sandstones and conglomerates were thought to be correlative to the Satsop Formation of northwestern Washington (J. H. Bretz, in Williams, 1916, p. 25). This original correlation was eventually shown to be incorrect by Buwalda and Moore (1927, 1929), who renamed the former Satsop Formation deposits the "Hood River Formation" after exposures in the vicinity of the town of Hood River, Oregon. This name has seen little utilization or acceptance in the literature, even though it has priority over Hodge's later "Troutdale" designation.

The Troutdale Formation, as originally defined by Hodge (1938) and subsequently mapped by others, inherently consists of two separate and distinct lithologic facies. The first facies is characterized by conglomerates which contain foreign clasts (i.e., quartzite, schist, granite, and rhyolite, etc), for which no local sources can be found and for which a distant provenance is suggested. It is commonly thought that this facies of the Troutdale Formation represents deposits of the ancestral Columbia River (Williams, 1916; Lowry and Baldwin, 1952; Trimble, 1963; Waters, 1973). These deposits are generally found in proximity to the modern-day Columbia River and are confined to the northern portion of the Willamette Valley (fig. 8). The section occurring in the type area for the Troutdale Formation along the lower Sandy River, belongs to the ancestral Columbia River facies which contains foreign clasts. The second facies of the Troutdale Formation is characterized by conglomerates which contain only locally derived clasts; it notably lacks the foreign clasts which typify the ancestral Columbia River facies. It is thought that this second facies of the Troutdale Formation represents deposits of local Cascadian streams which drained into The Willamette Valley (Lowry and Baldwin, 1952; Baldwin, 1981). Deposits of this second facies are found along the western flanks of the Cascade Range (fig. 8).

In the study area, deposits of only the ancestral Columbia River facies of the Troutdale Formation are present.

The Troutdale Formation in the Columbia River Gorge and greater Portland area originally included a lower mudstone, siltstone, and sandstone unit as well as the upper, quartzite-bearing, basaltic pebble/cobble conglomerate and pebbly vitric sandstone unit (Lowry

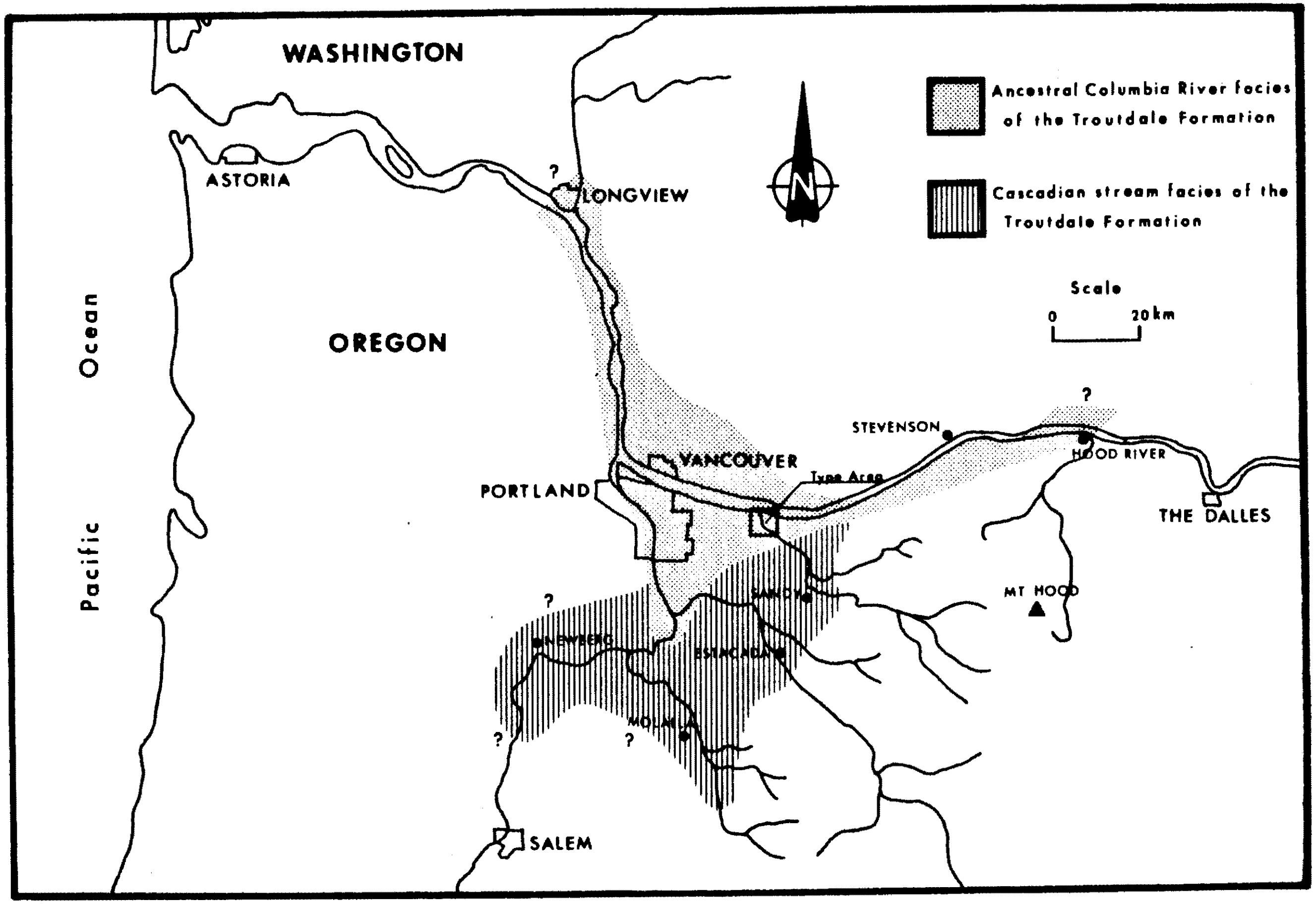


Figure 8. Map showing the distribution of the ancestral Columbia River facies and Cascadian stream facies of the Troutdale Formation. Data for compilation from: Allen (1932), Livingston (1966), Peck and others (1964), Treasher (1942), Trimble (1963), A.C. Waters (1955, unpublished field maps), and Wilkinson and others (1946).

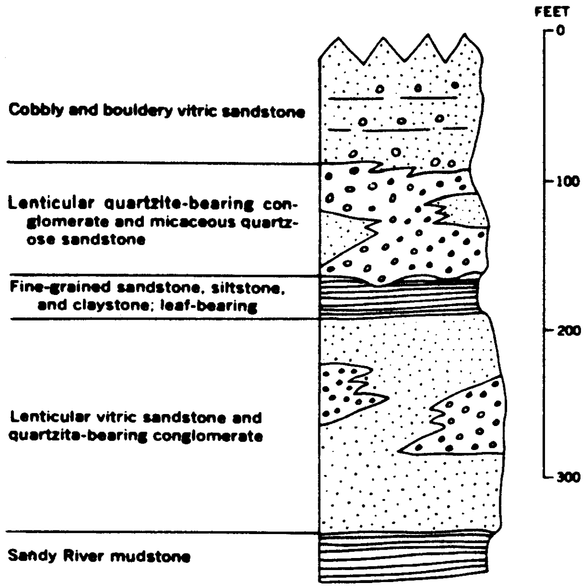
and Baldwin, 1952; Trimble, 1957). Trimble (1963, p. 30) formally proposed restriction of the name "Troutdale Formation" to the fluvial conglomerates and sandstones of the quartzite-bearing upper unit (fig. 9A). The lacustrine mudstones, siltstones, and sandstones of the lower unit were excluded on the basis of differences in lithologic character and genesis. Trimble (1963) assigned the name "Sandy River Mudstone" to these former Troutdale deposits.

The total thickness of the Troutdale Formation in the Portland Basin is not precisely known but is assumed to exceed 300 m (Trimble, 1963). In the Columbia River Gorge the Troutdale Formation, where present, varies in thickness (fig. 9B) from 10 m to greater than 122 m at Bridal Veil, Oregon (Allen, 1932).

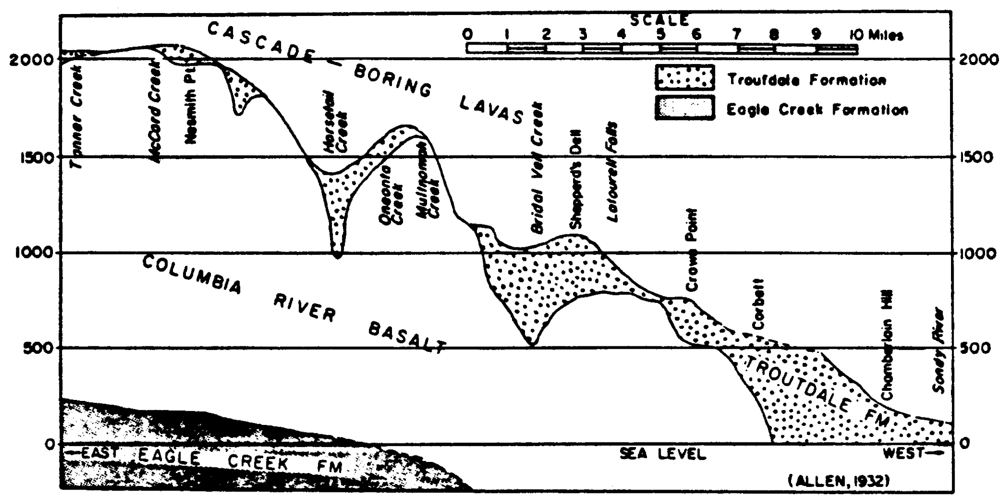
Boring Lavas

The Plio-Pleistocene lavas which commonly overlie the Troutdale Formation in the Portland Basin and lower Columbia River Gorge were named the "Boring Lavas" by Treasher (1942, p. 10) after the type locality in the Boring Hills. This name has never been formally proposed but through repeated usage has gained general acceptance in the literature.

The Boring Lavas have not received much detailed study although over 90 Boring vents are known to exist in the greater Portland area and western foothills of the northern Oregon/southern Washington Cascade Range (Allen, 1975). The most authoritative works to date on the Boring Lavas are by Trimble (1963, pp. 36-42), Peck and others (1964, pp. 36-38), Allen (1975), and Goff (1977).



A.



B.

Figure 9. A. Generalized composite stratigraphic section for the Troutdale Formation in Hodge's type-area along the lower Sandy River, Oregon. From Trimble (1963, p.32 - figure 8).
B. Thickness and distribution of the Troutdale Formation exposed along the south wall of the lower Columbia River Gorge, Oregon. From Allen (1932, p.64 - Plate IV).

It is currently thought that the Boring Lavas resulted from local and discontinuous volcanic activity which produced primarily blocky-jointed, aphyric basalt flows which seldom exceed 10 m in thickness and only minor amounts of associated pyroclastic rocks (Trimble, 1963). Peck and others (1964) informally group the Boring Lavas with flows produced by High Cascade volcanism.

Structural Geology

The study area lies on the boundary between two major physiographic provinces: the Willamette lowlands and the Cascade Range. These provinces represent the results of a very complicated tectonic history, parts of which are only now beginning to be understood. For a overview and synthesis of current knowledge of the tectonic evolution of this region, the reader is referred to a recent paper by Drake (1982).

Within the northern Oregon/southern Washington portion of these two provinces, two major structural trends are chiefly recognized: (1) N40°-60°E-trending thrust-faulted anticlines with broad intervening synclines, and (2) N10°-55°W-trending high-angle wrench faults and aligned folds (Beeson and others, in prep.).

The N40°-60°E-trending thrust faults and folds are thought to be extensions of the Yakima Ridges of the Columbia Plateau, as shown in figure 10 (Beeson and others, in prep.). Typically these anticlinal ridges are asymmetric and dip more steeply on their thrust-faulted sides, with gentler dips (usually less than 15°) on the non-thrusted limb (Bentley, Anderson, and others, 1980; Beeson and others,

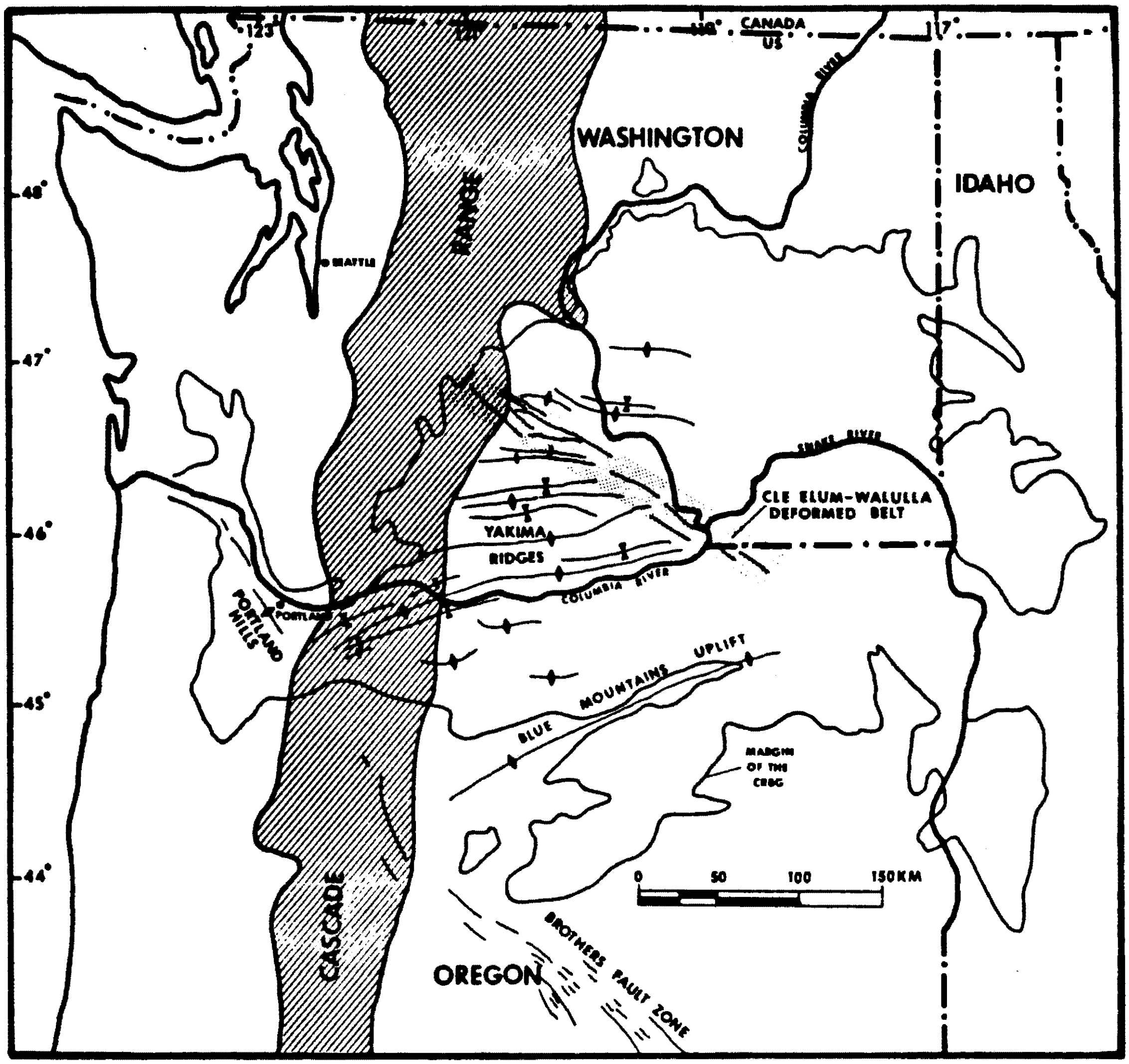


Figure 10. Map showing the Yakima Ridges in relation to other major structural features and the Cascade Range. From Beeson and others (in prep.).

in prep.). Structures of this type have been documented in the Salmon River, Bull Run, Eagle Creek, and Hood River areas (fig. 11). Stratigraphic evidence indicates that uplift along some of these structures began during Grande Ronde time (Bentley, Powell, and others, 1980; Vogt, 1981). Beeson and others (in prep.) attribute these structures to shallow, thin-skinned deformation of the more brittle, competent CRBG in response to north-northwest to south-southeast compression.

The northwest-trending faults and folds are the most pervasive structural trend within this region (fig. 11). The faults have vertical to near-vertical fault planes, may or may not have significant stratigraphic offsets, and commonly have breccia zones which contain horizontal to subhorizontal striae indicating late-stage strike-slip movement of unknown magnitude (Bentley, Anderson, and others, 1980; Beeson and others, in prep.). A major en echelon zone of N20°-40°W-trending faults occurring in the upper Clackamas River area (fig. 11) is considered to be the northwest extension of the Brothers fault zone of central Oregon (Anderson, 1978; Beeson and others, in prep.). Northwest-trending faults are known to offset the northeast-trending thrust faults (Bentley, Powell, and others, 1980; Bentley, Anderson, and others, 1980; Beeson and others, in prep.), suggesting that some of the northwest-trending faults are younger than the northeast-trending structures. Stratigraphic evidence along the Portland Hills anticline (the northwest extension of the Clackamas River-Brothers fault zone) suggests this area was undergoing deformation in early Wanapum time, approximately 14 to 15

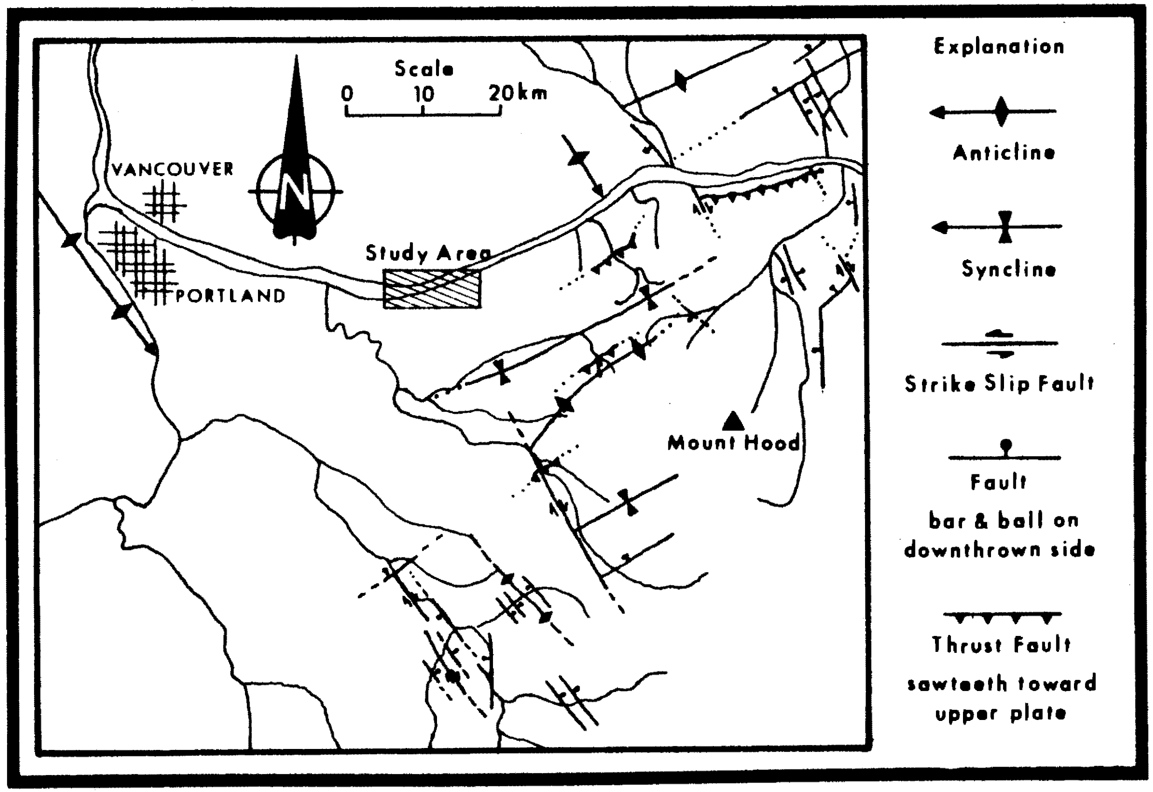


Figure 11. Map showing major folds and faults in the vicinity of the lower Columbia River Gorge of Oregon and Washington. After Swanson, Anderson, and others (1979) and Beeson and others (in prep.).

million years b.p. (Beeson and others, 1976; Beeson and Tolan, 1980, unpublished data).

For an authoritative discussion of the various tectonic and kinematic models for the origin of these structural trends, the reader is referred to a paper by Davis (1981).

A third structural element in this region is the broad uparching of the Cascade Range which presumably occurred during periods of active subduction under this area. In the Columbia River Gorge area, it is thought that the major episode of uplift began in mid to late Pliocene time (Lowry and Baldwin, 1952; Allen, 1979).

CHAPTER III

AREA STRATIGRAPHY

Introduction

This chapter presents the results of new work conducted in the lower Columbia River Gorge area by the author for this study.

Skamania Volcanic Series

The oldest rocks exposed in the thesis area are flows of the Eocene-lower Miocene Skamania Volcanic Series. This unit has been inferred to underlie the CRBG throughout the lower Columbia River Gorge (Trimble, 1963); up until now, however, it was thought to crop out only on the Washington side north and east of the thesis area (Trimble, 1963; Waters, 1973).

In this study, however, the Skamania Volcanic Series has been found to be exposed on the Oregon side of the lower Columbia River Gorge, where it formed a paleotopographic high that may have been a volcanic center east of Crown Point, Oregon, which the Miocene CRBG flows did not cover (plate 1). At this location the younger sands and gravels of the Troutdale Formation and flows of the Boring Lavas directly overlie the rocks of the Skamania Volcanic Series. Deeply weathered and altered rocks of the Skamania Volcanic Series are poorly exposed northeast of Mt. Zion on the Washington side of the thesis area.

Trimble (1963, p. 12) informally divided the Skamania Volcanic

Series into a lower altered/deformed sequence and a upper unaltered/undeformed sequence. The newly found rocks of the Skamania Volcanic Series exposed in the Crown Point-Latourell area (plate 1) appear to be correlative with Trimble's upper sequence because they display only minor alteration and deformation in comparison to the rocks of the lower sequence Skamania Volcanic Series which are exposed northeast of Mt. Zion and in the Washougal River valley and which show signs of extensive alteration and deformation. The lack of extensive alteration/deformation of the Skamania Volcanic Series flows exposed in the Crown Point-Latourell area is probably one of the main reasons why these flows have been consistently mistaken for Columbia River basalt in the past.

Where exposed, the thickness of the Skamania Volcanic Series in the Crown Point-Latourell area varies from less than 10 m west of Sheppard's Dell Park to greater than 274 m between Crown Point and Latourell Creek. The Skamania lava flows seldom exceed 10 m in individual thickness and are generally poorly exposed, with only isolated, resistant portions of the flows protruding above the thick soil cover in this area. Less resistant portions of the flows (i.e., vesiculated or scoriaceous flow tops and pillow complexes) and interflow volcaniclastic material are commonly so deeply weathered that, if present, they can only be recognized by remanent textures. The weathering of this less resistant material has produced a clay-rich soil in this area which on steep slopes gives rise to soil creep and minor earth flows.

Chemically, the Skamania lava flows in the Crown Point-

Latourell area range from basaltic to dacitic in composition as shown in Table II. In all cases, these flows are distinguishable from the younger CRBG flows in that they have higher Al_2O_3 and lower FeO concentrations (fig. 12).

Many of the Skamania lava flows present in the Crown Point-Latourell area superficially resemble some CRBG members in hand sample but with care can be distinguished from them. Skamania basalts generally display crude blocky jointing (fig. 13A). In hand sample they are commonly dark gray on a weathered surface, greenish gray to dark gray on a fresh surface, fine- to medium-grained, and aphyric to rarely phyric, with clear to milky-white tabular plagioclase phenocrysts that rarely exceed 0.4 cm in length. Petrographically, the basalts have pilotaxitic to intersertal textures (fig. 14A), with plagioclase, pyroxene, olivine, magnetite, and glass comprising the groundmass (Table III). The phenocrysts (fig. 14A) are mainly of labradorite (An_{54-60}), with minor amounts of augite.

Skamania andesites commonly display hackly to "dish" jointing (fig. 13B). In hand sample they are commonly gray in color on a weathered surface, light gray to black on a fresh surface, fine to medium grained, and phyric, with blocky plagioclase phenocrysts which range from 0.3 to 1 cm in size. Less common are pyroxene phenocrysts which commonly are less than 0.4 cm in size. Petrographically, the andesites have felted to pilotaxitic textures (fig. 14B), with plagioclase, pyroxene, and magnetite generally comprising the groundmass (Table III). The phenocrysts are mainly

TABLE II

MAJOR OXIDE COMPOSITION OF SELECTED SKAMANIA VOLCANIC SERIES LAVA FLOWS IN THE CROWN POINT-LATOURELL AREA

Sample Number	CG-52	CG-10	CG-46	CG-53	CG-75	CG-45	CG-18
Oxide**							
SiO_2	53.19	53.38	53.76	53.81	55.52	57.45	66.06
Al_2O_3	18.73	18.06	18.43	18.02	18.33	18.19	16.98
FeO*	8.96	8.23	8.49	8.77	8.01	7.12	4.45
MgO	5.21	5.62	5.58	5.40	5.00	4.34	1.35
CaO	9.04	9.31	9.01	9.20	8.56	7.98	2.87
Na_2O	1.92	3.01	2.54	2.55	2.20	2.01	4.18
K_2O	0.44	0.57	0.46	0.46	0.78	1.35	2.58
TiO_2	1.98	1.20	1.20	1.25	1.11	0.99	0.88
P_2O_5	0.16	0.22	0.17	0.18	0.17	0.20	0.24
MnO	0.15	0.20	0.16	0.15	0.13	0.19	0.22

* FeO + 0.9 Fe_2O_3

** All analyses in weight percent.

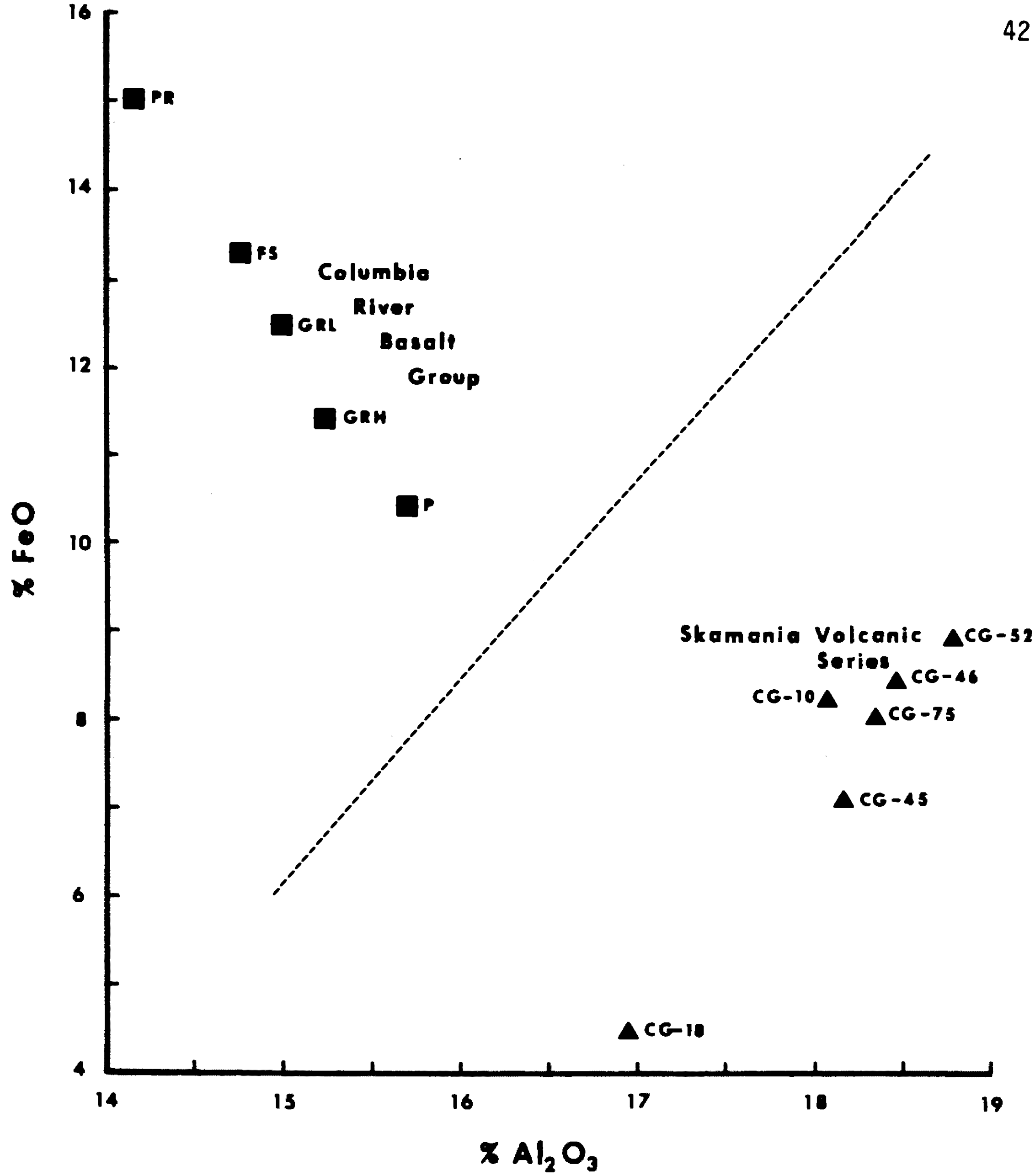


Figure 12. Plot of FeO versus Al_2O_3 differentiating Skamania Volcanic Series flows from Columbia River Basalt Group members found in the lower Columbia River Gorge. Average concentrations for the Columbia River Basalt Group members were plotted, with letter designations: P - Pomona Member, PR - Priest Rapids Member, FS - Frenchman Springs Member, GRH - high MgO Grande Ronde Basalt, and GRL - low MgO Grande Ronde Basalt. Skamania sample numbers correspond to those listed in Table II.

A. B.

<u>Figure 13</u>. <u>A</u>. Blocky- to crudely columnar-jointed Skamania Basalt flow (CG-10) exposed along the Old Scenic Highway west of the town of Latourell, Oregon (SW¼ SW¼ sec. 29, T1N, R5E).
<u>B</u>. Dish- to blocky-jointed Skamania andesite flow (CG-75) exposed along the Old Scenic Highway east of Barr Road junction (NE¼ SE¼ sec. 29, T1N, R5E). Note the fresh appearance of this flow.

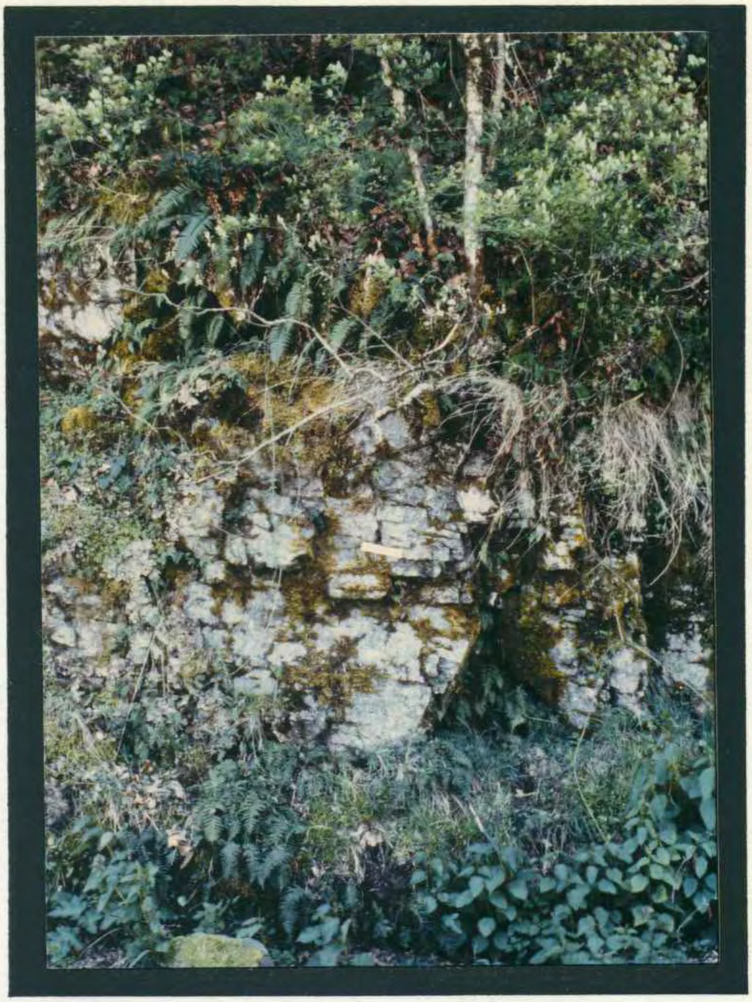


Figure 13C. Platy-jointed Skamania dacite flow. (CG-18) exposed along Latourell Creek below lower Latourell Falls (center sec. 29, T1N, R5E).

A.

B.

Figure 14. A Photomicrograph of a typical Skamania basalt (CG-10) under crossed nicols. Phenocrysts consist dominantly of plagioclase (PC) and pyroxene (PX) with occasional phenocrysts of olivine (Olv) or magnetite (MT).
B. Photomicrograph of a typical Skamania andesite (CG-45) under crossed nicols. Note the corroded and broken outlines and sieve textures displayed by the plagioclase (PC) phenocrysts.

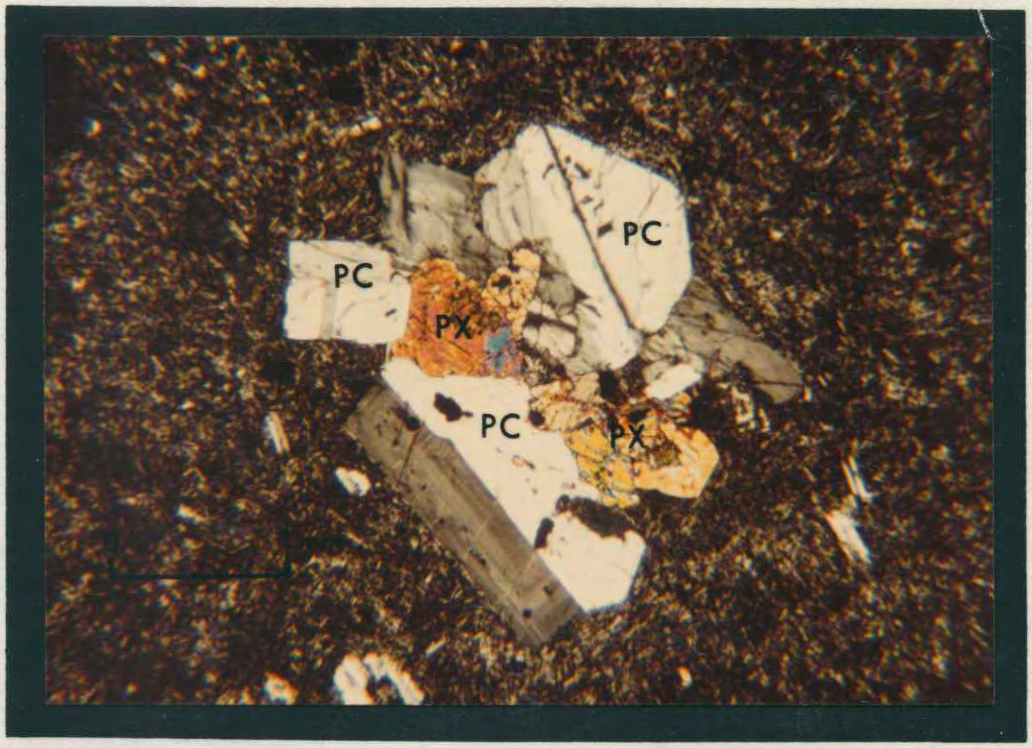


Figure 14C. Photomicrograph of a Skamania dacite glomerocryst under crossed nicols. The glomerocryst is composed of subhedral plagioclase (PC) and anhedral pyroxene (PX) crystals. The glomerocryst is set in a hyalopilitic matrix.

TABLE III

MODAL COMPOSITION OF SELECTED SKAMANIA BASALT, ANDESITE, AND DACITE FLOWS FROM THE CROWN POINT-LATOURELL AREA, OREGON*

	Basalt (CG-10)	Andesite (CG-45)	Dacite (CG-18)
Phenocrysts			
Plagioclase	58.4	28.4	6.4
Augite	24.8	4.2	2.0
Hypersthene	0.0	1.6	0.0
Olivine	3.0	0.0	0.0
Opaque minerals	3.8	1.2	1.2
Quartz	0.0	0.0	0.8
Groundmass			
Plagioclase	4.5	32.1	0.0
Augite	3.7	20.8	0.0
Hypersthene	0.0	5.7	0.0
Olivine	0.8	0.0	0.0
Opaque minerals	Tr**	2.9	0.0
Apatite	Tr**	0.0	0.0
Alteration minerals	Tr**	3.1	0.0
Glass	1.0	0.0	89.6

* 500 points counted per thin section.

** Trace - less than 0.05%.

of andesine (An_{35-47}) and display corroded or broken outlines and sieve textures (fig. 14B).

The single Skamania dacite flow found along lower Latourell Creek displays blocky/platy jointing (fig. 13C). In hand sample it is grayish black to black on a weathered surface and black on a fresh surface. The closely spaced jointing surfaces which pervade this flow often permit the formation of a black resinous coating which makes collecting a fresh sample very difficult. This dacite is glassy to fine grained and microphyric, with plagioclase glomerocrysts that are usually less than 0.3 cm in size. Petrographically, the dacite has a hyalopilitic texture (fig. 14C), with plagioclase, pyroxene, quartz, and magnetite microlites in a glassy matrix (Table III). The glomerocrysts are composed of zoned labradorite (An_{52-58}) crystals and augite crystals (fig. 14C).

Columbia River Basalt Group

Introduction. The lower Columbia River Gorge is situated along the northwestern margin of the CRBG where pre-existing topography and canyon cutting by the ancestral Columbia River have resulted in lateral and vertical variability in the CRBG stratigraphy and the presence of CRBG intracanyon flows. Because of this, no one section contains all CRBG members and units found within the thesis area. A generalized CRBG stratigraphy for the thesis area, including both formal and informal members and units, is presented in figure 15. The total thickness of the composite CRBG section, excluding the

SERIES		GROUP	SUB-GROUP	FORMATION	MEMBER	NUMBER OF FLOWS	MAGNETIC POLARITY
MIOCENE	MIDDLE	COLUMBIA RIVER BASALT GROUP	YAKIMA BASALT SUBGROUP	SADDLE MOUNTAINS BASALT	POMONA MEMBER	1	R
					Erosional unconformity		
				WANAPUM BASALT	PRIEST RAPIDS MEMBER	1	R
					Erosional unconformity		
					FRENCHMAN SPRINGS MEMBER	5	N
					Local erosional unconformity		
				GRANDE RONDE BASALT	HIGH MgO CHEMICAL TYPE*	3	N_2
	LOWER				WINTER WATER*	1	
					LOW MgO CHEMICAL TYPE*	11	N_2 / R_2 / N_1

Figure 15. Stratigraphy of the Columbia River Basalt Group in the lower Columbia River Gorge of Oregon and Washington. '*' denotes informal member or unit.

Priest Rapids Member and the Pomona Member intracanyon flows, exceeds 520 m.

The ensuing discussions employ terminology that quantifies the average abundance of phenocrysts observable on a fresh basalt surface 1 m^2 in size. These terms are abundantly phyric, phyric, sparsely phyric, rarely phyric, and aphyric. These terms and their various permutations are used with great informality among CRBG workers and have somewhat nebulous definitions. Since the abundance of phenocrysts is often a crucial factor in field identification of individual CRBG members, the above terms were defined for this study as follows:

Abundantly Phyric:	an average of greater than 20 phenocrysts/m^2
Phyric:	an average of 10 to 20 phenocrysts/m^2
Sparsely Phyric:	an average of 1 to 10 phenocrysts/m^2
Rarely Phyric:	an average of less than 1 phenocryst/m^2
Aphyric:	no observable phenocrysts

The term "sporadically phyric" is occasionally used to indicate a great variance in the abundance of phenocrysts within a single flow (i.e., ranging from rarely phyric to abundantly phyric). This phenomenon is most prevalent in certain flows of the Frenchman Springs Member.

The term "phenocryst" is applied only to conspicuous crystals which readily stand out from the groundmass and are larger than 0.3 cm in size. Crystals which stand out from the groundmass and are less than 0.3 cm in size are termed "microphenocrysts".

<u>Grande Ronde Basalt</u>. The Grande Ronde Basalt section in the thesis area consists of up to 15 flows that attain a collective thickness of over 426 m. Variations in major oxide chemistry, paleomagnetic polarity, and lithology permit the Grande Ronde Basalt to be divided into five units within the thesis area. These units are, from youngest to oldest, N_2 high MgO chemical type, the Winter Water flow, N_2 low MgO chemical type, R_2 low MgO chemical type, and N_1 low MgO chemical type (fig. 15, plate 1).

<u>N_2 high MgO chemical type</u>. Based on the relative concentration of magnesium oxide, the Grande Ronde Basalt can be informally subdivided into high and low MgO chemical types. This chemical division was first reported by Wright and others (1973). Subsequent work, with notable contributions made by Nathan and Fruchter (1974), Taylor (1976), Atlantic Richfield Co. (1976), and Bentley, Anderson, and others (1980), has shown that the high MgO Grande Ronde flows regularly occur at the top of the N_2 Grande Ronde section and systematically overlie low MgO Grande Ronde flows, thereby producing a useful stratigraphic marker on the Columbia Plateau. Work in western Oregon by Beeson and others (1976), Anderson (1978), Beeson and Moran (1979), Vogt (1981), and Hoffman (1981) also confirms this same relationship.

The reliability of the N_2 high MgO/low MgO Grande Ronde stratigraphic horizon has been questioned by Swanson and Byerly (<u>in</u> Swanson, Wright, and others, 1979), since they have found a low MgO flow intercalated in the N_2 high MgO section in the Wenatchee area of central Washington. This situation however has never been found in western Oregon (Beeson and Moran, 1979; Beeson and others, in prep.). High MgO Grande Ronde flows have been found to occur deep in the low MgO Grande Ronde section in the Columbia River Gorge at both Tanner Creek, Oregon (Tolan and Beeson, 1980, unpublished data), and at Dog Mountain, Washington (J. L. Anderson, 1981, personal communication). Neither case invalidates the reliability of the N_2 high MgO/low MgO break, since the errant high MgO flows have been found to occur far below the N_2 paleomagnetic horizon.

In the thesis area, three flows which comprise the upper 91 m of the N_2 Grande Ronde section are of the high MgO chemical type. Table IV presents the average major oxide compositions of both N_2 high MgO and low MgO flows from the thesis area. Two of the 10 oxides, MgO and CaO, are considered diagnostic in distinguishing the two chemical types, as shown in figure 16. The other major oxide values collectively define the Grande Ronde chemical type (Wright and others, 1973; Swanson, Wright, and others, 1979) but have overlapping concentration ranges which severely diminish their effectiveness in separating the two chemical types. No consistent systematic chemical differences between the three N_2 high MgO flows exist, making it impossible to distinguish individual N_2 high MgO flows on the basis of major oxide chemistry.

The N_2 high MgO flows outwardly appear to have a very uniform lithologic character. In hand samples they are gray to black in color on a fresh surface and fine to medium grained. Fresh samples

TABLE IV

COMPARISON OF AVERAGE MAJOR OXIDE CONCENTRATIONS FOR THE LOW MgO AND HIGH MgO GRANDE RONDE CHEMICAL TYPES IN THE LOWER COLUMBIA RIVER GORGE TO AVERAGE CONCENTRATIONS REPORTED IN OTHER WORKS

Oxide**	This work, 1982		Anderson, 1980 (Col. R. Gorge)		Anderson, 1978 (Clackamas R.)		Hoffman, 1981 (Salem Hills)		Bentley and others, 1980	
	low MgO	high MgO	low MgO	high MgO	low MgO	high MgO	low MgO	high MgO	low MgO	high MgO
SiO_2	55.04	53.81	55.50	53.89	55.11	52.51	56.19	53.82	55.42	53.92
Al_2O_3	14.97	15.24	14.89	15.13	14.56	15.28	15.19	14.84	14.98	15.21
FeO*	12.44	11.46	12.21	11.64	11.99	11.45	11.05	11.85	11.76	11.53
MgO	3.76	4.90	3.63	4.86	3.75	5.34	3.36	4.63	3.60	4.68
CaO	7.21	8.47	7.28	8.35	7.29	9.16	6.90	8.23	7.28	8.69
Na_2O	2.09	2.32	2.83	2.62	2.83	2.72	2.79	2.58	2.44	2.32
K_2O	1.66	1.24	1.79	1.15	1.69	1.01	1.71	1.33	1.75	1.22
TiO_2	2.11	1.87	2.03	1.82	2.02	1.85	2.15	2.01	2.05	1.83
P_2O_5	0.33	0.29	0.32	0.29	0.34	0.29	0.34	0.32	0.32	0.30
MnO	0.21	0.21	0.20	0.21	0.22	0.22	0.21	0.22	0.20	0.21

* FeO + 0.9 Fe_2O_3

** All analyses in weight percent.

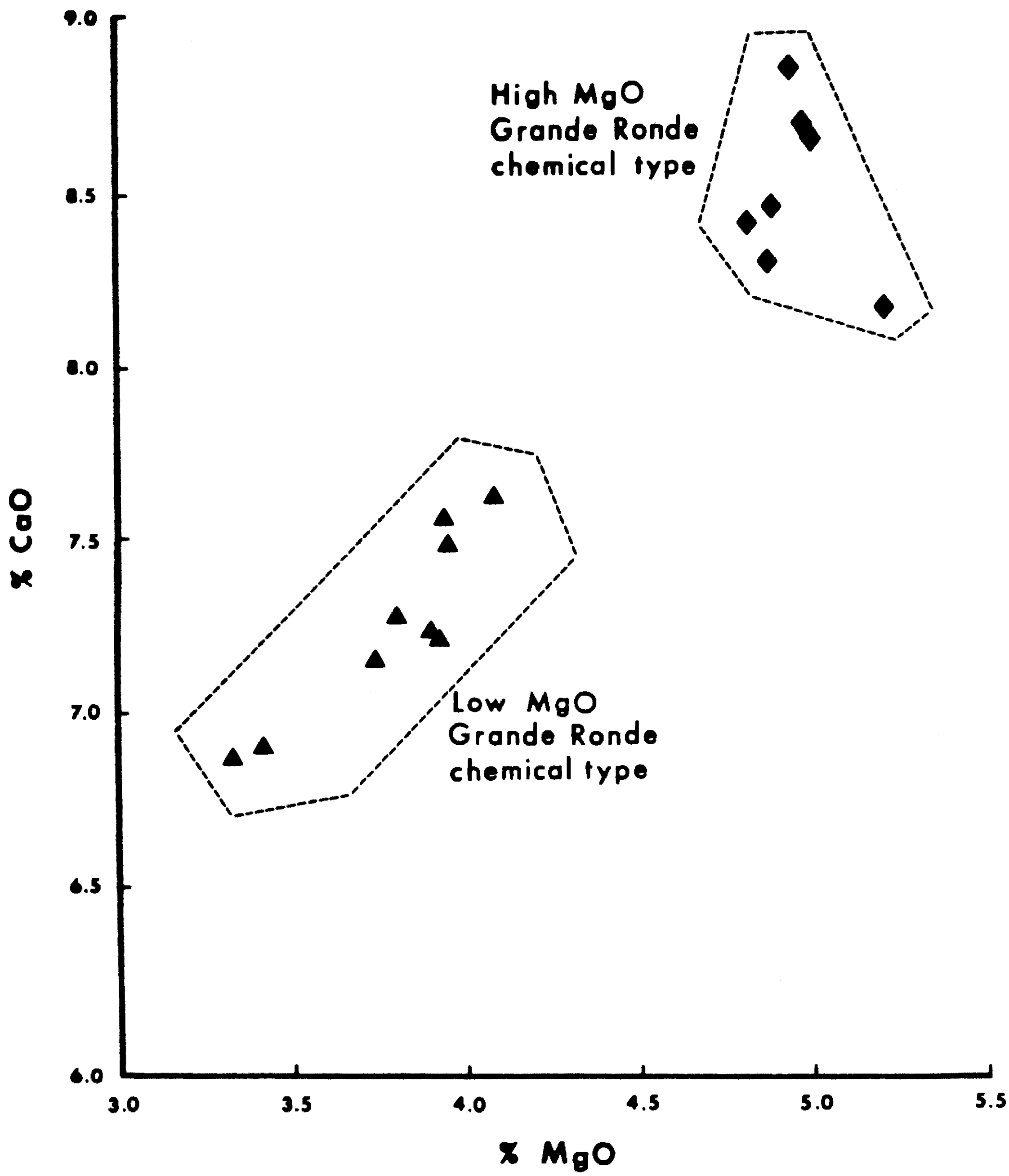
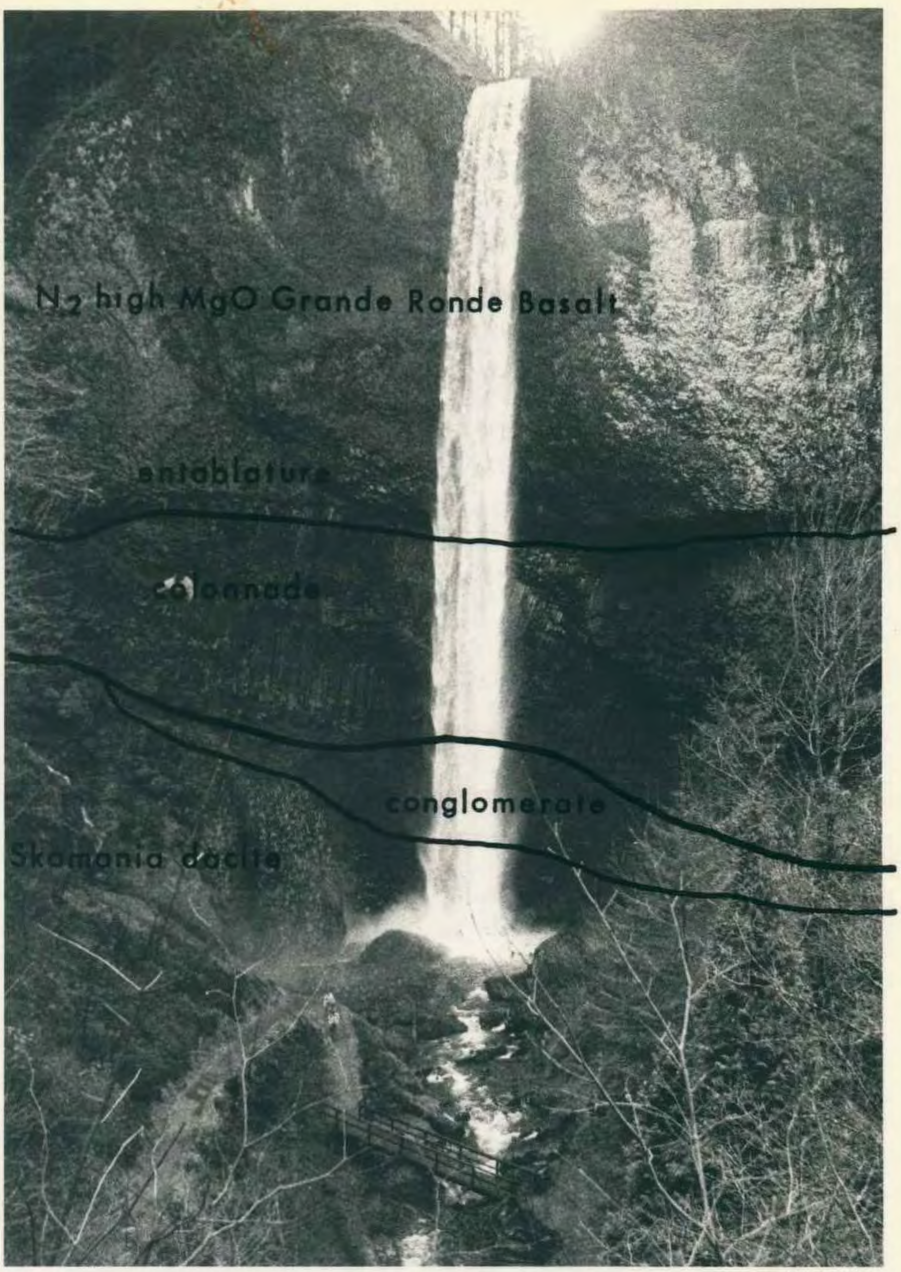


Figure 16. Plot of CaO versus MgO differentiating low MgO and high MgO Grande Ronde chemical types.

from the entablature part of the flow are commonly darker in color and finer grained than fresh samples from the blocky or colonnade part of the flow. All three N_2 high MgO flows contain clear to milky-white tabular/equant plagioclase phenocrysts which range from 0.5 to 1.5 cm in size. Both the lower and upper N_2 high MgO flows are rarely phyric, while the middle N_2 high MgO flow is sparsely phyric. The upper N_2 high MgO flow commonly has a diktytaxitic texture.

All three high MgO flows in the thesis area predominantly display entablature/colonnade jointing patterns and only occasionally have blocky jointing. A spectacular example of this entablature/colonnade type of jointing in a N_2 high MgO flow can be seen at lower Latourell Falls, Oregon (fig. 17). Here the lowermost N_2 high MgO flow fills a stream valley eroded into Skamania Volcanic Series flows, achieving a thickness of over 61 m. The upper 40 m of this flow forms a resistant, hackly entablature, while the lower 21 m consists of a prismatic colonnade. The individual columns average 0.5 m in diameter and overlie a boulder/cobble conglomerate. As shown in figure 17, the prismatic columns are curved, forming a fan-like pattern. This style of entablature/colonnade jointing is displayed by all three high MgO flows in the quarry northeast of Mt. Zion, Washington (NE¼ SE¼ sec. 9, T1N,R5E).

The entablature/colonnade jointing pattern prevalent in the N_2 high MgO flows in the thesis area in no way typifies the jointing style of N_2 high MgO flows elsewhere in western Oregon and in the western portion of the Columbia Plateau. In these other areas, N_2 high MgO flows commonly have tiered, blocky to columnar jointing,



<u>Figure 17</u>. Lower Latourell Falls, Oregon. The cliff is a single N_2 high MgO Grande Ronde Basalt flow (lowest of the three flows present in the thesis area) which filled a valley eroded into Skamania Volcanic Series rocks. Note the curved columns in the colonnade at the base of the flow which overlie a boulder conglomerate.

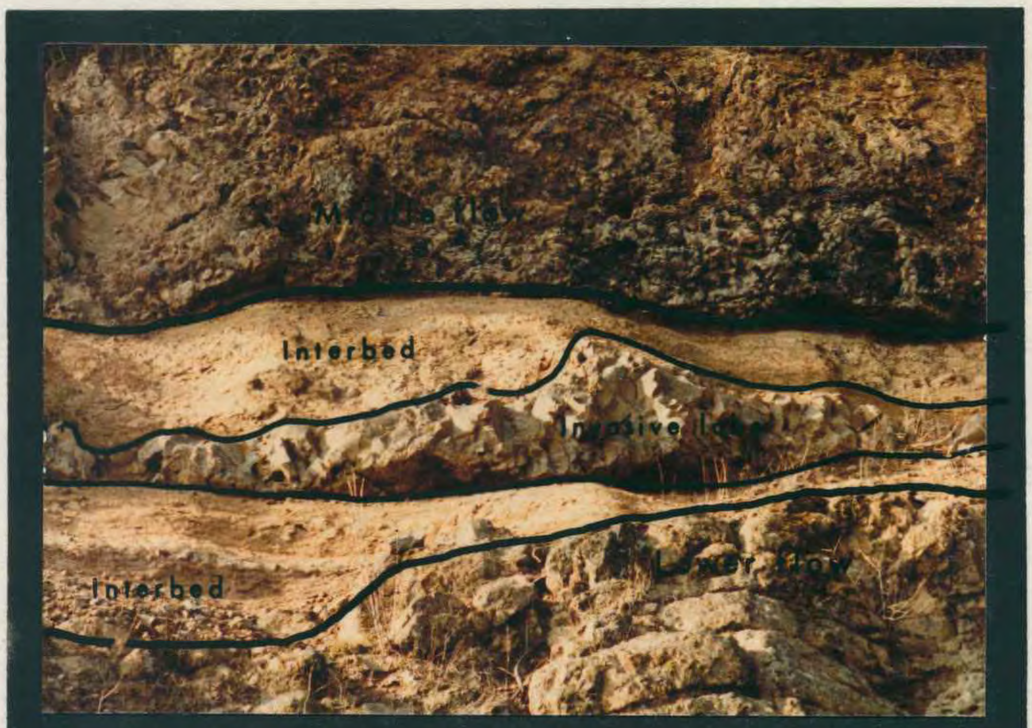
while only low MgO Grande Ronde flows commonly display an entablature/colonnade style of jointing (Anderson, 1978; Powell, 1978; Beeson and Moran, 1979; Bentley, Anderson, and others, 1980). This dichotomy in jointing character is locally reliable enough to be used as a criterion for distinguishing N_2 high MgO flows from low MgO flows in the field (Beeson and Moran, 1979; Bentley, Anderson, and others, 1980).

The entablature/colonnade jointing found in N_2 high MgO flows in the thesis area may be directly attributable to paleotopographic considerations. It has been noted by other workers (J. L. Anderson, 1979, personal communication; Bentley, Anderson, and others, 1980), for reasons not totally understood, that normally blocky-jointed CRBG flows sometimes become entablature dominated when they are channelized as intracanyon flows or located near the margin of the flow. Since both these conditions did prevail in the thesis area during high MgO time, this may possibly explain why the N_2 high MgO flows have a propensity to form entablatures.

All three N_2 high MgO flows commonly have basal pillow-palagonite complexes which vary from 0.5 to 3 m in thickness. This feature is best exposed at the base of the middle N_2 high MgO flow in the quarry northeast of Mt. Zion, Washington. Here the basal complex is composed of palagonitic debris which surrounds apparently isolated pillows (fig. 18). Underlying the pillow-palagonite complex is a 0.3- to 1-m-thick, micaceous sandstone interbed into which lobes of the N_2 high MgO lava have burrowed (fig. 18).

The thesis area is unusual in the fact that three N_2 high MgO

A.



B.

Figure 18. A. Arkosic sandstone interbed between the lower and middle N_2 high MgO Grande Ronde Basalt flows exposed in a slump block east of Mt. Zion, Washington along Highway 14 (SW¼ NE¼ sec. 9, T1N, R5E). Note that the vesicular flow top of the lowest N_2 high MgO flow is blocky-jointed.
B. Close-up view of the arkosic sandstone interbed showing a non-vesicular lobe from the middle N_2 high MgO flow which has invaded the sediment.

flows occur there whereas a maximum of only two N_2 high MgO flows have been so far reported in most other places in western Oregon (Anderson, 1978; Beeson and Moran, 1979; Hoffman, 1981). Based on phenocryst abundance and groundmass characteristics, the middle and upper N_2 high MgO flows in the thesis area appear to be correlative with the two N_2 high MgO flows found elsewhere in western Oregon. The lower N_2 high MgO flow in the thesis area appears to have no identifiable counterpart in the Willamette Valley.

N_2 low MgO Winter Water flow. On the basis of plagioclase phenocryst abundance, stratigraphic position, and paleomagnetic polarity, the uppermost N_2 low MgO Grande Ronde flow in the thesis area appears to be correlative to the Winter Water flow of Powell (1978, pp. 37-38).

Powell's plagioclase-phyric Winter Water flow forms a recognizable unit at the top of the N_2 low MgO magnetostratigraphic unit throughout much of the western Columbia Plateau (Bentley, Anderson, and others, 1980, p. 9; J. L. Anderson, 1980, personal communication). Up to three individual Winter Water flows occur in some areas of north-central Oregon (J. L. Anderson, 1980, personal communication). In western Oregon, two plagioclase-phyric N_2 low MgO flows which occur at the top of the N_2 low MgO section are thought to be correlative with the Winter Water flows of the western Columbia Plateau (Beeson, 1980, unpublished data).

Only a single N_2 low MgO Grande Ronde flow displays the same lithologic characteristics attributed to the Winter Water flow within the thesis area. The Winter Water flow has a fairly broad distribution (Plate 1) but has been found only on the Washington side in the vicinity of Mt. Zion. The Winter Water flow varies in thickness from less than 6 m thick east of Latourell Creek and northeast of Mt. Zion to greater than 36 m east of Multnomah Falls, Oregon (Plate 1).

The Winter Water flow commonly displays a hackly jointed entablature, with a short, basal blocky or columnar jointed zone and/or pillow-palagonite complex. The flow itself is phyric to abundantly phyric, with clear to milky-white plagioclase phenocrysts, glomerocrysts, and microphenocrysts set in a black, glassy to fine-grained groundmass. The phenocrysts and glomerocrysts generally range in size from 0.3 to 0.7 cm, and only rarely will plagioclase phenocrysts or glomerocrysts exceed 1 cm in size. Individual phenocrysts have blocky to tabular shapes, with a tendency to cluster together forming radial, spoke-shaped glomerocrysts. The ratio of phenocrysts to glomerocrysts runs approximately 2:1.

An interesting dichotomy exists in the abundance of phenocrysts/ glomerocrysts found in the entablature versus those found in the colonnade. In the blocky to columnar jointed portion of the flow, phenocrysts/glomerocrysts are often difficult to find, whereas the opposite is true for the entablature portion of the flow. The phenocrysts/glomerocrysts are large enough that the change from the glassy groundmass of the entablature to the fine-grained groundmass of the blocky to columnar part of the flow does not simply camouflage or obscure the crystals from view. This distribution of phenocrysts/

glomerocrysts suggests that the segregation may have originated by some mechanical process during cooling (e.g., crystal floatation). Regardless of how this segregation originated, the net effect is that the Winter Water flow may not be recognized if only the blocky or columnar part of the flow is examined.

N_2 low MgO Grande Ronde Basalt. The N_2 low MgO Grande Ronde Basalt is represented by up to five flows (including the Winter Water flow) in the thesis area and collectively exceeds 166 m in thickness at Multnomah Falls, Oregon (fig. 44, p. 143). The N_2 low MgO unit has the greatest areal extent of all Grande Ronde units, being present throughout the eastern half of the thesis area (Plate 1). The N_2 low MgO section decreases in both thickness and number of flows north and west from the Multnomah Falls area. Only the upper N_2 low MgO flows are found near the margin of this unit, suggesting a progressive on-lap situation during N_2 time.

All N_2 low MgO flows display thick, hackly jointed entablatures which commonly comprise at least 60% (rarely 100%) of the total thickness of the flow. These hackly entablatures often display resistant cornice-like features which have formed because the basal blocky or columnar jointed portion of the flow which overlies less resistant pillow-palagonite or flow top weathers back more rapidly as blocks or columns break away (fig. 19). Many of the N_2 low MgO flows also have 1- to 3-m-thick basal pillow-palagonite complexes.

The N_2 low MgO flows (excluding Winter Water) are usually black in color on a fresh surface, glassy to fine grained, and aphyric to

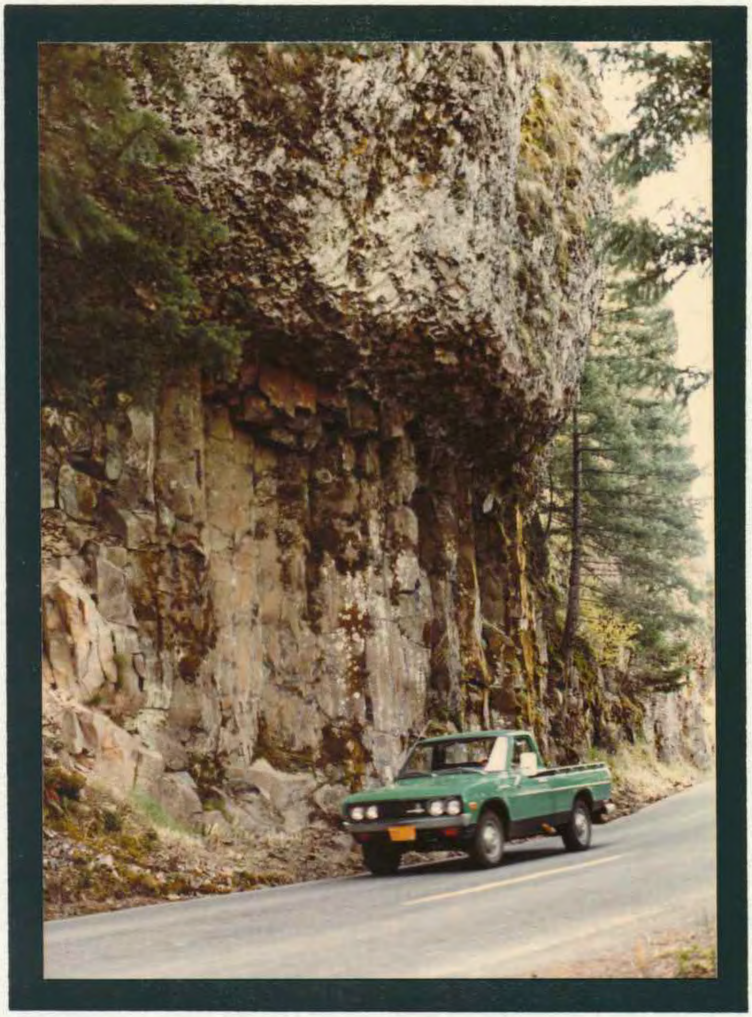


Figure 19. Typical low MgO Grande Ronde entablature/colonnade jointing pattern exposed along the Old Scenic Highway at Sheppard's Dell State Park.

rarely phyric, with acicular to tabular plagioclase microphenocrysts. Occasionally these flows contain rare plagioclase phenocrysts which are less than 0.5 cm in size. None of the five N_2 low MgO flows vary in their individual chemistry in a way that would enable them to be told apart. Major oxide analyses of these flows are presented in Appendix A.

R_2 low MgO Grande Ronde Basalt. The R_2 low MgO Grande Ronde Basalt is represented by up to five flows which achieve a collective thickness of 158 m at Multnomah Falls, Oregon (fig. 44, p.143). This unit has a slightly less extensive distribution than the N_2 low MgO Grande Ronde Basalt (Plate 1). As with the N_2 low MgO section, the R_2 low MgO section decreases in both thickness and number of flows north and west of the Multnomah Falls area (Plate 1).

R_2 low MgO flows have the same entablature/colonnade jointing style as the N_2 low MgO flows. The uppermost R_2 low MgO flow has an unusually thick basal pillow-palagonite complex which often exceeds 14 m in thickness. This pillow-palagonite complex is well exposed at Multnomah Falls (fig. 44, p. 143) and at Coopey Falls (fig. 20), east of the town of Bridal Veil, Oregon.

Flows of the R_2 low MgO Grande Ronde Basalt are glassy to fine grained and range from aphyric to phyric, with acicular plagioclase microphenocrysts. Three of the five R_2 low MgO flows exposed in the thesis area are microphyric. In these phyric flows, the acicular plagioclase microphenocrysts are readily visible in the glassy groundmass of the entablature but are commonly obscured in

Figure 20. R_2 low MgO Grande Ronde Basalt pillow complex exposed at the base of Coopey Falls, Oregon, east of the town of Bridal Veil (SW¼ SW¼ sec. 14, T1N, R5E). This pillow complex can be traced throughout the eastern half of the study area where it often exceeds 14 m in thickness.

the basal blocky or columnar part of the flow because of the increased coarseness of the groundmass.

The three microphyric R_2 low MgO flows also show a 0.2 to 0.3% higher TiO_2 concentration than other low MgO Grande Ronde flows found in this area (Appendix A). A similar relationship has been noted in the upper Columbia River Gorge by J. L. Anderson (1981, personal communication). In the thesis area, the uppermost R_2 low MgO flow displays these characteristics, which helped facilitate the mapping of the N_2/R_2 contact. It is not known whether or not this microphyric R_2 low MgO flow regularly occurs at the N_2/R_2 horizon throughout the rest of the Columbia River Gorge. However if it does, then it may prove to be a useful stratigraphic marker.

<u>N_1 low MgO Grande Ronde Basalt</u>. The oldest Grande Ronde Basalt exposed in the thesis area consists of two N_1 low MgO flows which are found only east of Multnomah Falls (Plate 1). These two flows are collectively less than 45 m thick and display the typical low MgO entablature/colonnade jointing style.

The N_1 low MgO flows are glassy to fine grained and rarely to sparsely microphyric, with acicular plagioclase microphenocrysts. Chemically, the N_1 low MgO flows show no distinctive variations that would separate them from other low MgO Grande Ronde flows (Appendix A). The N_1 flows are distinguishable from other low MgO Grande Ronde flows only on the basis of stratigraphic position and paleomagnetic polarity.

Wanapum Basalt

Frenchman Springs Member. The Frenchman Springs Member in the thesis area consists of up to five flows which collectively exceed 105 m in thickness. This member, which has an irregular distribution pattern (Plate 1), is generally confined to the western half of the thesis area. This member overlies N_2 high MgO Grande Ronde Basalt and is in turn overlain by the Troutdale Formation west of Chanticleer Point (Plate 1). East of Chanticleer Point, the Frenchman Springs Member is overlain by the Priest Rapids Member of the Wanapum Basalt (Plate 1). West of Chanticleer Point, both the N_2 high MgO Grande Ronde/Frenchman Springs Member contact and the Frenchman Springs Member/Troutdale Formation contact are marked by prominent topographic benches.

The stratigraphy of the Frenchman Springs Member in the thesis area is made complex by unconformable relationships within the Frenchman Springs section. Many of the flows fill irregularities and/or channels eroded into underlying flows. This results in laterally discontinuous stratigraphic sections which vary not only in thickness from place to place but also in the number and type of Frenchman Springs flows present.

This difficulty has been overcome by employing a Frenchman Springs flow classification system developed by Beeson and Tolan (1980, unpublished data). This system divides the Frenchman Springs Member in western Oregon into five categories based on chemical, lithologic, and stratigraphic criteria. These criteria, which define each category, are briefly summarized in Table V. Table V also tentatively correlates the categories of this system with the informal Frenchman Springs flow nomenclature used in the western Columbia Plateau (Bentley, 1977; Bentley, Anderson, and others, 1980).

A composite Frenchman Springs section (fig. 21) has been compiled for the thesis area, using the criteria and categories presented in Table V. On this basis, Frenchman Springs flows present in the thesis area belong to categories II, III, and V, with no flows present from categories I and IV.

Three of the five Frenchman Springs flows present in the thesis area belong to category II (fig. 21) and are the oldest group of Frenchman Springs flows present in the thesis area. Together these three flows have the most extensive distribution pattern (fig. 22). Although no one section contains all three flows, good exposures of the lower and middle flows can be found along Corbett Road above Corbett Station (NW¼ sec. 26, T1N, R4E), and a excellent exposure of the middle and upper flows can be seen at the 228-m elevation on the east side of the Latourell Creek valley just below upper Latourell Falls (NW¼ SW¼ sec. 29, T2N, R5E). These three flows have a composite thickness of approximately 61 m.

The lowermost category II flow is commonly hackly jointed, which gives it the outward appearance of a Grande Ronde flow (fig. 23A). In hand sample it is commonly black in color on a fresh surface and has a glassy to very fine-grained groundmass which is

TABLE V

CRITERIA FOR THE CLASSIFICATION OF FRENCHMAN SPRINGS MEMBER FLOWS BY CATEGORIES

CATEGORY	I	II	III	IV	V
No. of Flows	2	3	5	3	2
AVERAGE MAJOR OXIDE COMPOSITION	(22)	(21)	(21)	(24)	(5)
SiO_2	51.55	52.06	51.71	51.86	52.32
Al_2O_3	14.63	14.76	14.61	14.57	14.60
FeO	13.67	13.56	14.05	13.75	13.67
MgO	4.13	4.32	4.15	4.28	3.71
CaO	8.11	8.30	8.14	8.19	7.93
Na_2O	2.11	1.99	2.29	2.30	2.32
K_2O	1.17	1.15	1.17	1.29	1.44
TiO_2	3.04	2.94	3.00	2.86	3.00
P_2O_5	0.58	0.49	0.54	0.49	0.58
MnO	0.23	0.22	0.23	0.23	0.24
LITHOLOGY	Phyric to abundantly phyric with plagioclase phenocrysts /glomerocrysts. Groundmass is fine- to medium-grained and microphyric with tabular plagioclase micro-phenocrysts.	Sparsely phyric to abundantly phyric with plagioclase phenocrysts. Some flows are sporadically phyric. Ground-mass medium- to coarse-grained and rarely to sparsely microphyric with tabular and acicular plagioclase micropheno-crysts.	Rarely phyric to abundantly phyric with plagioclase phenocrysts/glomerocrysts. Groundmass fine- to medium-grained and microphyric with equant and tabular plagioclase microphenocrysts.	Sparsely phyric with plagioclase phenocrysts/ glomerocrysts. Groundmass fine- to coarse-grained and sparsely microphyric to microphyric with tabular plagioclase microphenocrysts.	Aphyric to rarely phyric with plagioclase pheno-crysts. Groundmass fine- to medium-grained and sparsely microphyric to abundantly microphyric with acicular and equant plagioclase microphenocrysts.
MAGNETIC POLARITY	Excursional	Normal	Normal	Normal	Normal
PLATEAU EQUIVALENT	GINKGO	KELLEY HOLLOW & SAND HOLLOW	KELLEY HOLLOW & UNION GAP	UNION GAP (?)	UNION GAP

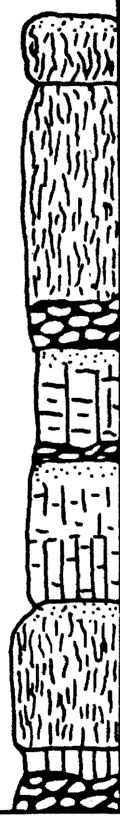
MEMBER	CATEGORY	THICK. (meters)	PROFILE	DESCRIPTION
FRENCHMAN SPRINGS	V	8		Hackly-jointed, dark gray to black on fresh surface, fine-grained, microphyric with white, acicular plagioclase phenocrysts.
	III	36		Hackly-jointed, black on fresh surface, glassy to fine-grained, sparsely phyric with reddish-yellow plagioclase glomerocrysts. Found only in area west of Corbett Station.
	II	15		Blocky- to columnar-jointed, dark gray on fresh surface, medium- to coarse-grained with a dikytaxitic texture, and phyric with clear to yellow plagioclase phenocrysts which range from 0.5 to 3.5 cm in size.
		18		Massive to blocky-jointed, dark gray on fresh surface, medium- to coarse-grained, and sparsely phyric with tabular, yellow-brown plagioclase phenocrysts. Phenocrysts tend to cluster together in loose groups.
		28		Hackly jointed, black on fresh surface, glassy to fine-grained, sparsely microphyric with equant/tabular plagioclase microphenocrysts, and sparsely phyric with clear to reddish-yellow plagioclase phenocrysts and glomerocrysts which range from 0.3 to 2.0 cm in size.

Figure 21. Composite Frenchman Springs Member section for the lower Columbia River Gorge area.

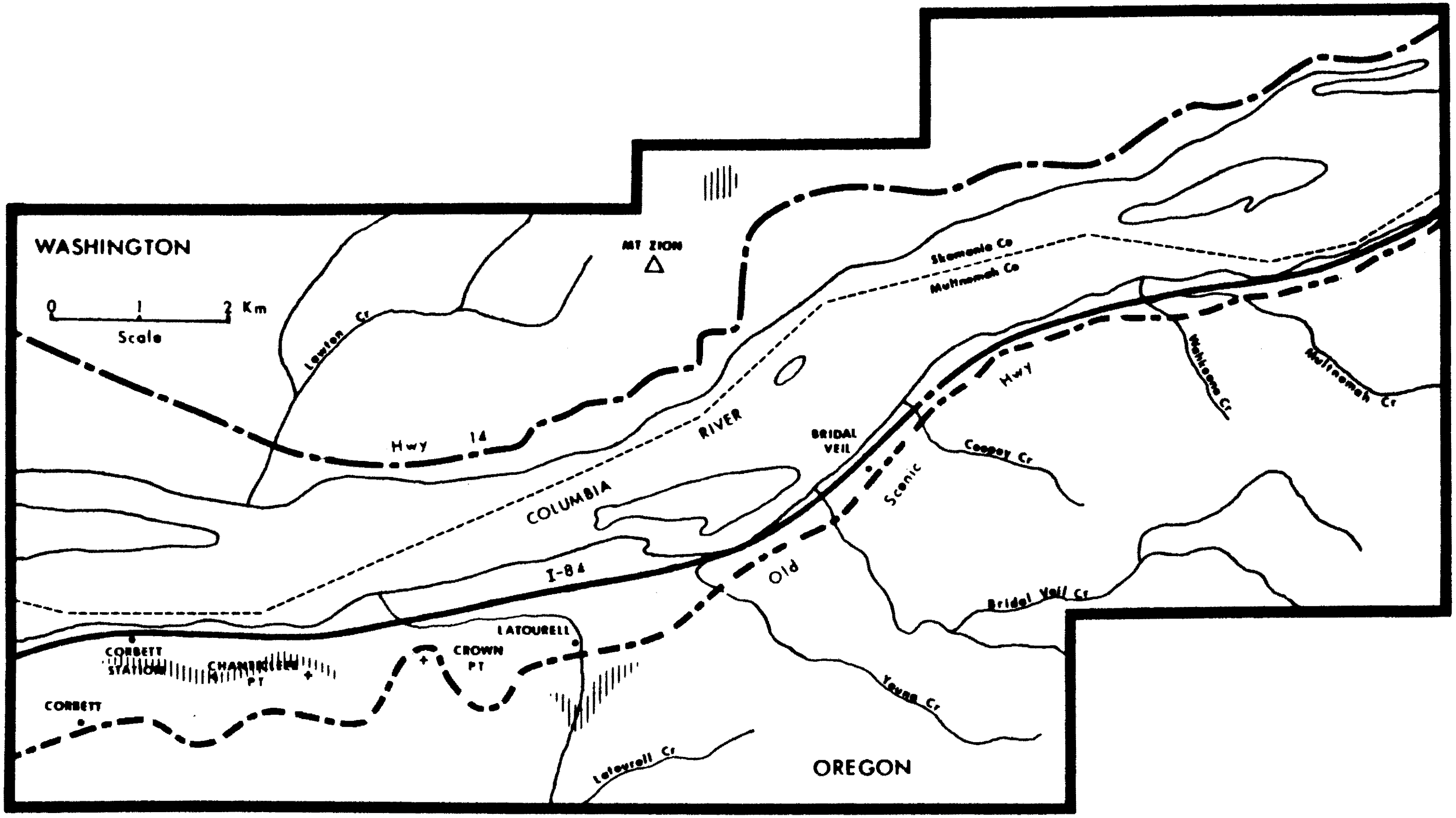
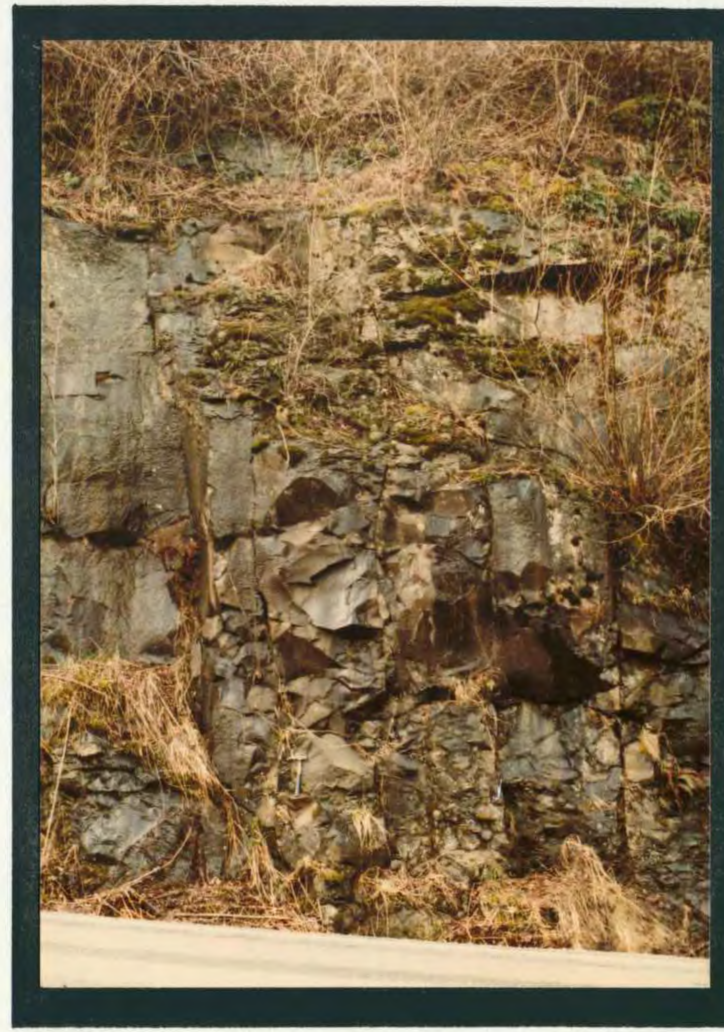


Figure 22. Map showing the location and distribution of category II Frenchman Springs exposures (hachured) in the thesis area.

A.



B.

Figure 23. A. Hackly jointed category II Frenchman Springs Member flow exposed along Reed Road below the town of Corbett, Oregon (NE¼ SW¼ sec. 26, T1N, R4E). This jointing style is typical of the oldest category II flow in this area.
B. Massive to blocky-jointed category II Frenchman Springs Member flow exposed along Corbett Road at the 45-m elevation.

sparsely microphyric with equant plagioclase microphenocrysts. This flow is also sparsely phyric with clear to reddish-yellow, tabular to lath-like plagioclase phenocrysts which range from 0.3 to 1.4 cm in size. Less common are plagioclase glomerocrysts which range from 0.5 to 2 cm in diameter.

The middle category II flow is massive to blocky jointed (fig. 23B). In hand sample it is commonly gray to dark gray in color on a fresh surface and has a medium- to coarse-grained groundmass that has a "sugary" texture. This flow is sparsely phyric, with yellowish-brown tabular plagioclase phenocrysts which range from 0.5 to 1.8 cm in size. These phenocrysts are often unequally distributed throughout the flow, with clusters of three to 10 individual phenocrysts commonly occurring together.

The uppermost category II flow is also blocky to columnar jointed. In hand sample it is gray in color on a fresh surface and coarse grained with a diktytaxitic texture. This flow is phyric with clear to yellow, blocky to equant plagioclase phenocrysts which commonly range from 0.5 to 2 cm in size. An occasional phenocryst may exceed 3.5 cm in size. This flow rarely contains plagioclase glomerocrysts. Major oxide compositions for category II flows are given in Table VI.

Category III is represented in the thesis area by a single flow which fills a 20-m-deep channel cut down through Frenchman Springs (II) and N_2 high MgO Grande Ronde flows. As a result, this flow has a very limited distribution, being found only in the vicinity of Corbett Station (fig. 24). The best exposure of this flow is in the

TABLE VI

MAJOR OXIDE CONCENTRATIONS FOR FLOWS OF THE FRENCHMAN SPRINGS MEMBER BY CATEGORIES

	Category II				
Oxide**	lower flow	middle flow	upper flow	Category III	Category V
SiO_2	51.93	51.71	52.44	52.93	51.62
Al_2O_3	14.53	14.48	15.25	14.92	14.45
FeO*	13.75	14.08	11.82	12.78	14.15
MgO	4.42	4.46	4.37	4.04	4.02
CaO	8.12	8.03	8.37	8.12	7.74
Na_2O	2.18	2.35	2.56	2.67	2.58
K_2O	1.32	1.14	1.46	0.78	1.54
TiO_2	2.84	2.82	2.79	2.82	2.90
P_2O_5	0.49	0.50	0.51	0.53	0.57
MnO	0.23	0.23	0.24	0.22	0.22

* FeO + 0.9 Fe_2O_3

** All analyses in weight percent.

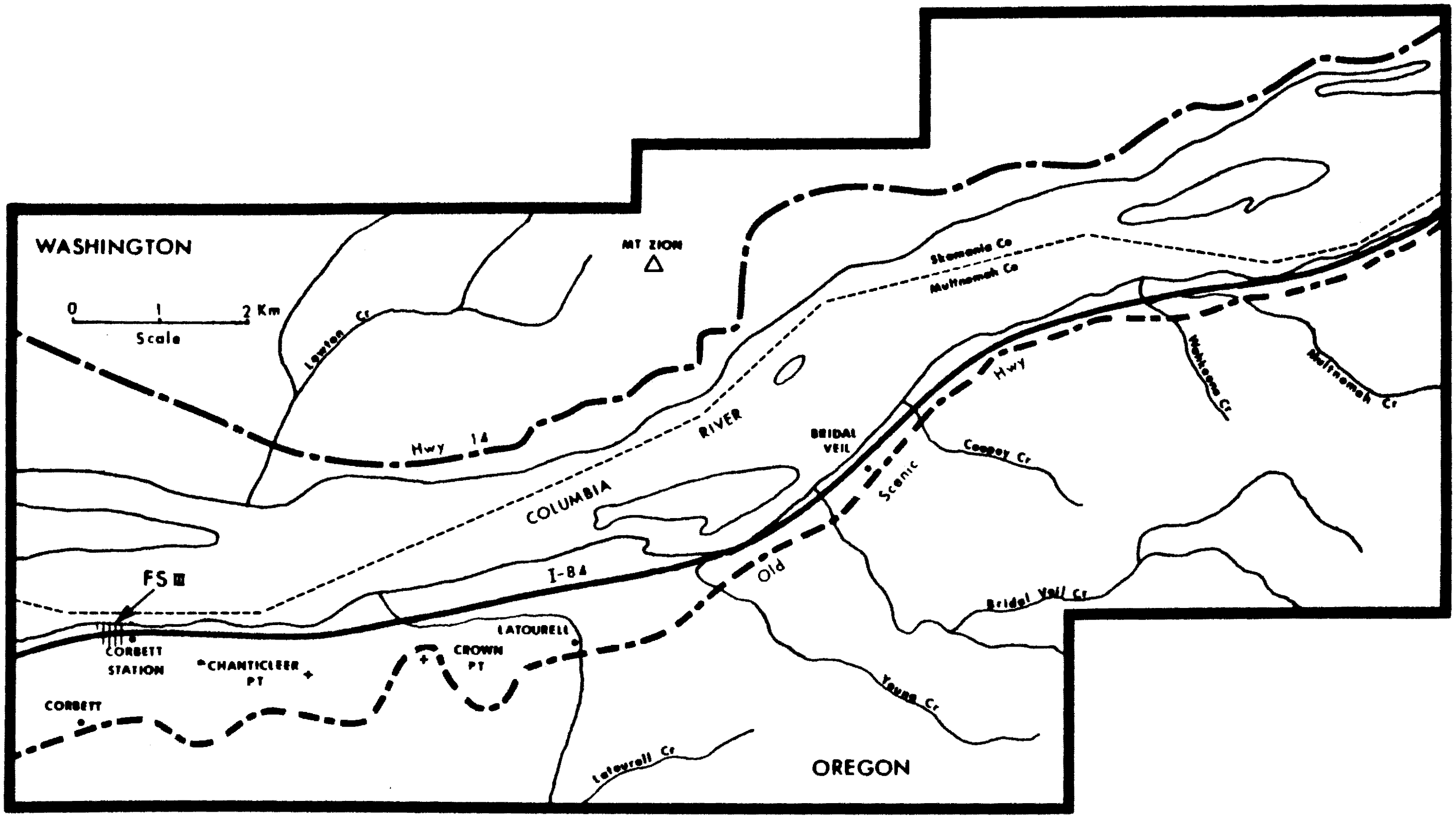


Figure 24. Map showing the location and distribution of category III Frenchman Springs exposures (hachured) in the thesis area.

Corbett quarry.

This flow is entirely hackly jointed (fig. 25), probably the result of being confined to a channel. One unique feature of this flow is the presence of pillow-palagonite zones interspersed throughout the exposed portion in the Corbett quarry (fig. 25). These pillow zones probably represent a series of flow lobes which interacted with water that was present in this channel.

In hand sample this flow is black in color on a fresh surface, glassy, and abundantly microphyric, with equant and acicular plagioclase microphenocrysts. This flow is also sparsely phyric, with reddish-yellow plagioclase glomerocrysts which range from 0.6 to 1.5 cm in diameter. A representive major oxide analysis of this flow is given in Table VI.

Category V is also represented in the thesis area by a single flow which is found only in the area between Corbett and Chanticleer Point (fig. 26). The most accessible exposure of this flow is found at the 90-m elevation on Corbett Road (NE¼ SW¼ sec. 26, T1N, R4E).

This flow is hackly jointed (fig. 27) and forms a prominent ledge in the Corbett area. In hand sample it is dark gray to black in color on a fresh surface, fine grained, and microphyric, with white, acicular plagioclase microphenocrysts. Chemically this flow is similar to Category I, but it has a lower TiO_2 concentration than Category I flows. A representative major oxide analysis of this flow is presented in Table VI.

Figure 25. Hackly jointed category III Frenchman Springs Member flow exposed in the Corbett Quarry adjacent to Interstate 84. Note the pillow-palagonite zones within this flow.

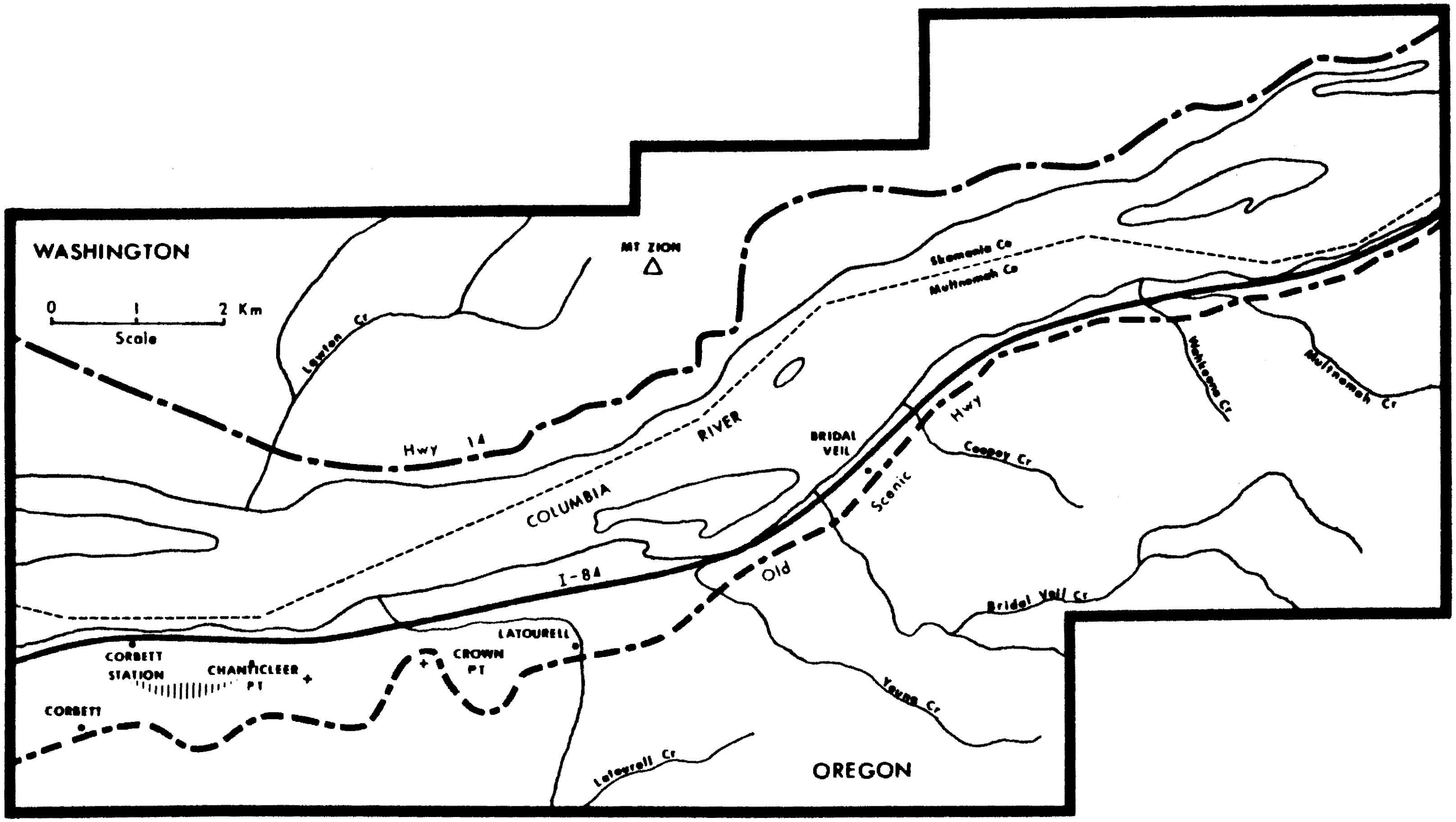


Figure 26. Map showing the location and distribution of category V Frenchman Springs exposures (hachured) in the thesis area.

Figure 27. Hackly jointed category V Frenchman Springs Member flow overlying the blocky-jointed category II flow shown in figure 23B on Corbett Road.

Priest Rapids Member intracanyon flow. In the thesis area the Priest Rapids Member consists of a single intracanyon flow which was first identified in the lower Columbia River Gorge at Crown Point by Waters (1973). This Priest Rapids intracanyon flow has also been found east of Crown Point (fig. 28) in both the Bull Run Watershed (Vogt, 1979; 1981) and in the Hood River Valley-Mosier area (Timm, 1979; Anderson and Vogt, in prep.)

The Priest Rapids Member within the lower Columbia River Gorge (Plate 1) has a wider distribution pattern than previously recognized by Waters (1973). The Priest Rapids Member is found from Chanticleer Point to east of Sheppard's Dell State Park but has not been found on the Washington side of the river. At both Chanticleer Point and Latourell Falls the Priest Rapids Member overtopped the canyon of the ancestral Columbia River. This is responsible for the relatively widespread distribution pattern of the Priest Rapids flow and the relocation of the channel of the ancestral Columbia River in post-Priest Rapids time.

The thickest section of the Priest Rapids Member, over 220 m, is found at Crown Point, which represents the main channel of the intracanyon flow. This section consists of 155 m of Priest Rapids lava which overlies more than 61 m of bedded Priest Rapids hyaloclastic debris. The base of the Priest Rapids intracanyon flow complex is not exposed at Crown Point. The orientation of the paleocanyon here is approximately N45°W. This direction was determined from measuring the orientation of the western margin of the

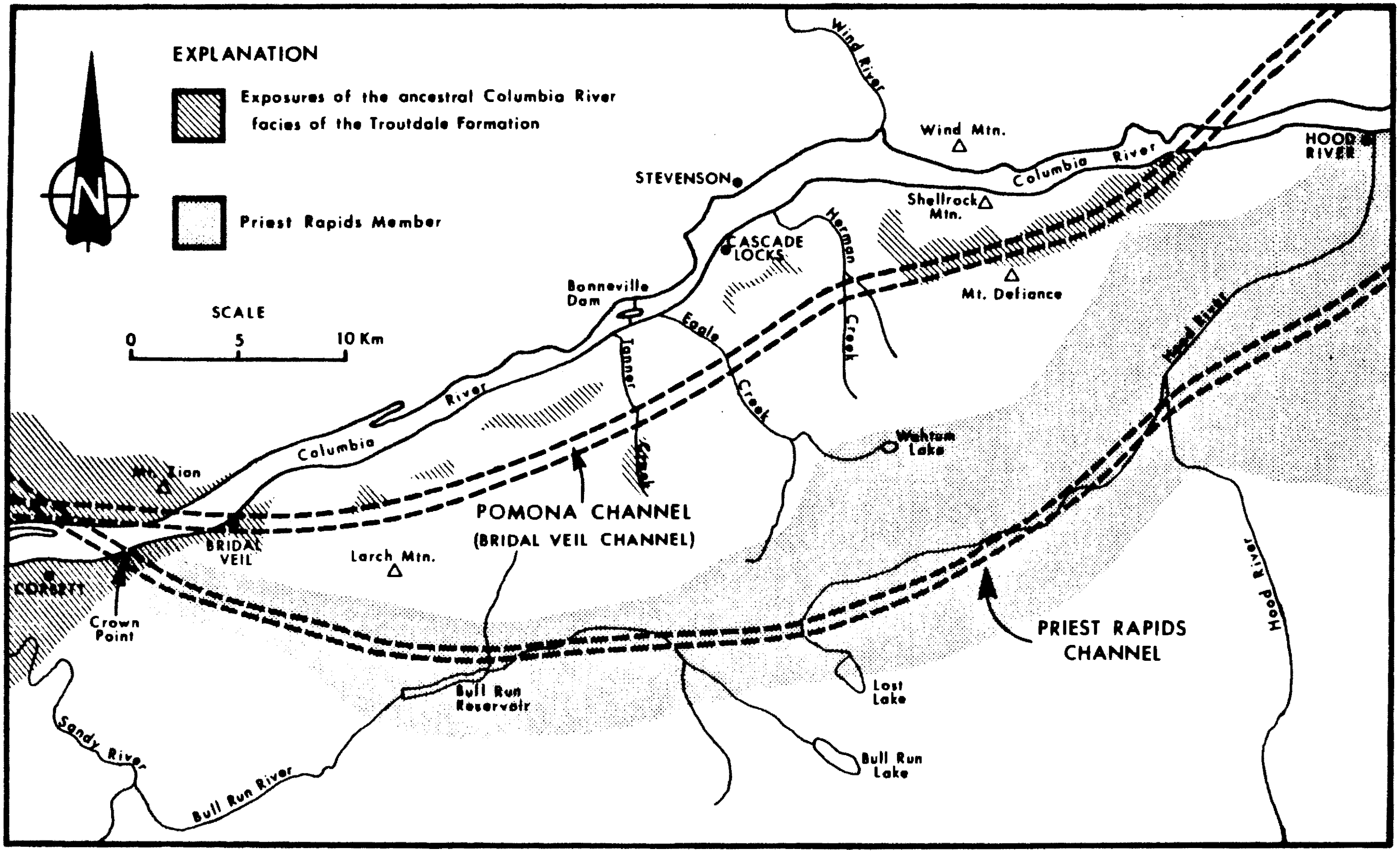


Figure 28. The paths of the Priest Rapids Member and Pomona Member intracanyon flows through the Cascade Range of northern Oregon. Note the correlation between the known exposures of the ancestral Columbia River facies of the Troutdale Formation and the projection of the Bridal Veil channel of the ancestral Columbia River. Data on the location of the Priest Rapids and Pomona intracanyon flows in the Bull Run, Hood River, and Mt. Defiance areas from Anderson and Vogt (in prep.). Data on the Troutdale Formation distribution from: Allen (1932), Hodge (1938), Trimble (1963), Waters and Wilcox (1955, unpublished field maps), Tolan and Beeson (1980, unpublished data), and Anderson (1980).

paleocanyon at Chanticleer Point, the general distribution pattern of the Priest Rapids lava, and paleocurrent directions derived from the orientation of bedding structures within the basal hyaloclastite complex.

Waters (1973, p. 140) stated that the paleocanyon had been incised into flows of the CRBG at Crown Point. This is only partly correct. The western margin of the canyon at Chanticleer Point was cut into flows of the CRBG, but the east side of the paleocanyon at Crown Point was cut into rocks of the previously described Skamania Volcanic Series (Plate 1). The Priest Rapids Member can be observed directly overlying these Skamania Volcanic Series flows at the 198-m elevation on the Old Scenic Highway on the east side of Crown Point (SE¼ SW¼ sec. 30, T1N, R5E).

The jointing style of the Priest Rapids intracanyon flow is in marked contrast to that commonly observed on the Columbia Plateau. There, the Priest Rapids Member is usually blocky to columnar jointed (Mackin, 1961, p. 24), where it occurs as an intracanyon flow; however, it displays a hackly jointed entablature with a basal colonnade which resembles the jointing style of the low MgO Grande Ronde flows (fig. 29). Despite the variability of its jointing style, the Priest Rapids Member can be identified in the field on the basis of stratigraphic position, reversed paleomagnetic polarity, the presence of a thick bedded hyaloclastite deposit, and lithology. In hand sample the Priest Rapids Member is black in color on a fresh surface, glassy to fine grained, and microphyric, with both plagioclase and olivine microphenocrysts. Rare plagioclase phenocrysts may exceed 1 cm in

Figure 29. East side of Crown Point, Oregon showing the contact between the bedded Priest Rapids hyaloclastite deposit and the Priest Rapids lava. Note the similarity of the Priest Rapids entablature/colonnade to that seen in Grande Ronde Basalt flows elsewhere in the thesis area.

length. Chemically, the Priest Rapids is very distinctive having higher TiO_2, FeO, and P_2O_5 and lower SiO_2 concentrations than other CRBG flows within the thesis area (Table VII). Major oxide analyses indicate also that the Priest Rapids intracanyon flow is of the Rosalia chemical type (Swanson, Wright, and others, 1979, p. G37).

An interesting feature which sets the Priest Rapids intracanyon flow apart is the presence of a thick, crudely bedded hyaloclastite deposit, confirmed by major oxide chemistry to also be Rosalia chemical type. Because the deposit is confined within the bounds of the paleocanyon, exposures of it are limited, with the most accessible occurring along the north face of Crown Point.

At Crown Point, the bedded hyaloclastite does not have a uniform thickness; instead it varies from less than 61 m on the west side to greater than 122 m on the east side. Conversely, the Priest Rapids lava is thickest on the west side and thinnest on the east side of Crown Point. The contact between the lava and hyaloclastite is sharp, with only minor local pillowing or brecciation of the overlying lava (fig. 30). The only large amount of pillow lava associated with the Priest Rapids lava occurs well above the hyaloclastite complex exclusively along the flow margins (fig. 31) or in the overflow areas and appears not to be related to, or the source of, the hyaloclastite complex.

Visible on the east side of Crown Point, at the base of Chanticleer Point, and at Sheppard's Dell State Park are large lobes of invasive Priest Rapids lava (fig. 32). These lobes, exceeding 3 m in thickness, disrupt the bedding structure within the surrounding

TABLE VII

COMPARISON OF AVERAGE MAJOR OXIDE CONCENTRATIONS FOR THE ROSALIA CHEMICAL TYPE OF THE PRIEST RAPIDS MEMBER IN THE LOWER COLUMBIA RIVER GORGE TO AVERAGE CONCENTRATIONS REPORTED IN OTHER WORK

Oxide **	This work, 1982 lava	This work, 1982 hyaloclastite	Anderson and Vogt, in prep. (Oregon Cascade Range)	Bentley and others, 1980 (Columbia Plateau)
SiO_2	50.33	50.34	50.29	49.66
Al_2O_3	14.12	14.09	14.01	13.68
FeO*	15.00	14.80	15.13	15.31
MgO	4.31	4.58	4.12	4.51
CaO	8.25	8.36	8.33	8.50
Na_2O	2.23	2.12	2.31	2.53
K_2O	1.19	1.09	1.33	1.20
TiO_2	3.49	3.51	3.52	3.51
P_2O_5	0.67	0.66	0.67	0.65
MnO	0.22	0.26	0.25	0.24

* FeO + 0.9 Fe_2O_3

** All analyses in weight percent.

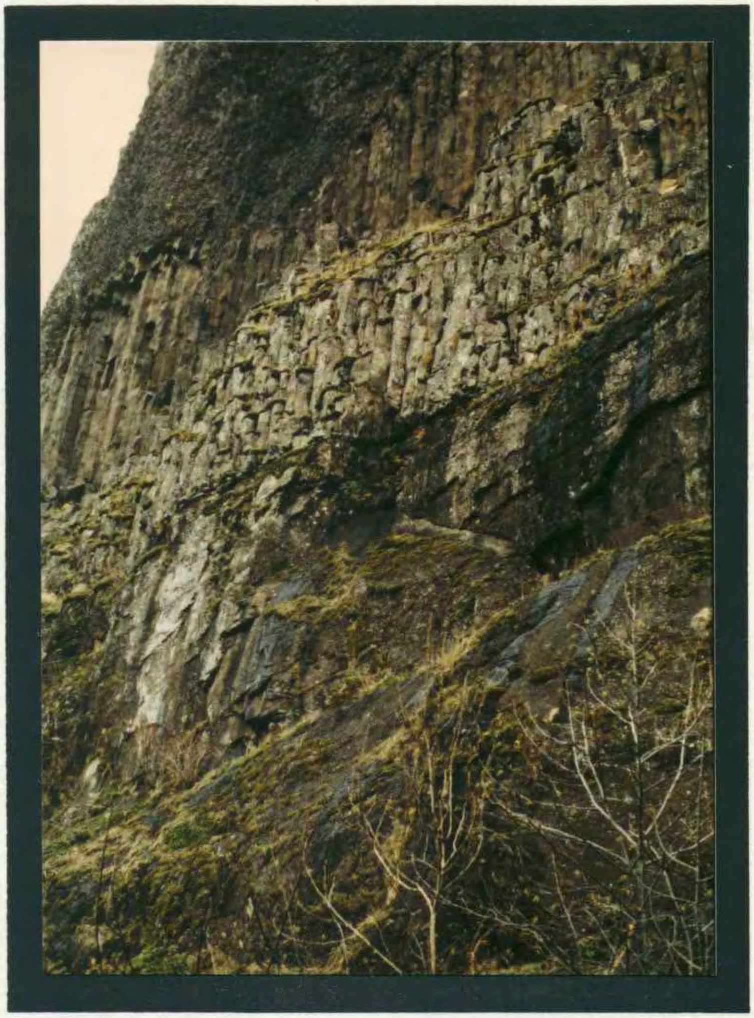


Figure 30. Close-up view of the contact between the Priest Rapids lava and hyaloclastite deposit on the north face of Crown Point, Oregon. Note the lack of pillows and/or brecciation at the contact zone.

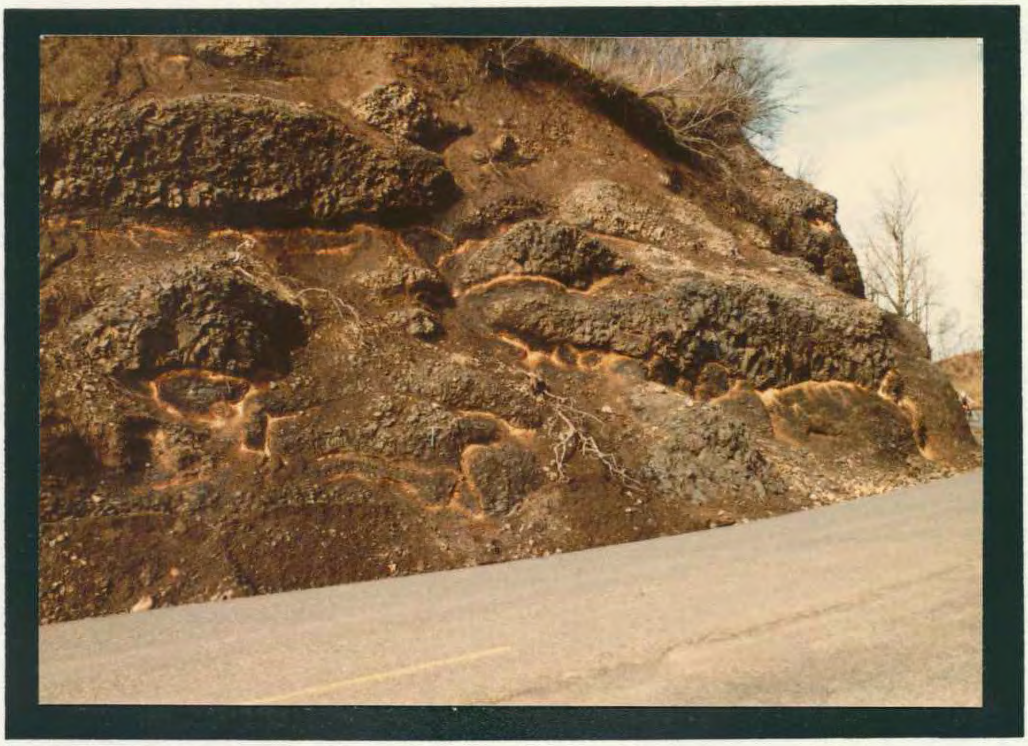


Figure 31. Priest Rapids pillow-palagonite complex exposed on the east side of Crown Point along the Old Scenic Highway at the 213-m elevation. This pillow-palagonite complex formed at the margin of the intracanyon flow and is not related to the basal hyaloclastite deposit.

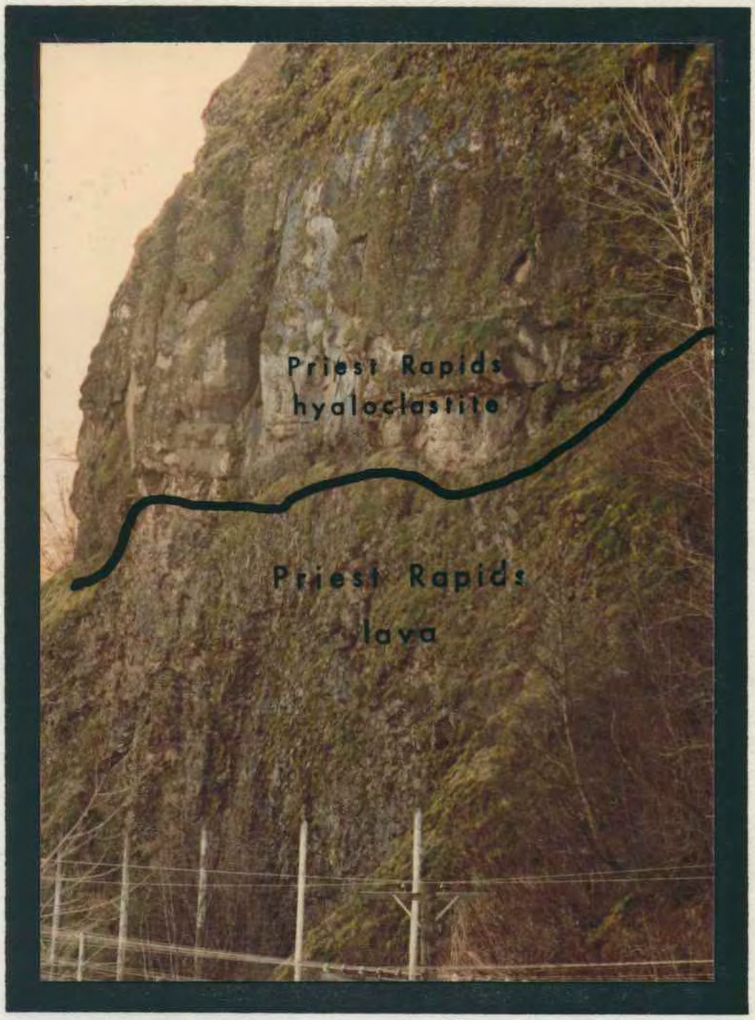


Figure 32. Invasive lobe of Priest Rapids lava exposed at the base of the north face of Chanticleer Point along the Union Pacific railroad tracks (NW¼ SW¼ sec. 25, T1N, R4E).

hyaloclastite, indicating that their emplacement postdates the primary bedding structures within the hyaloclastite. These lobes commonly resemble large pillows in that they have radial jointing and chilled, glassy rims.

The hyaloclastite itself consists of well-indurated, poorly to moderately sorted, subrounded to rounded, sand- to cobble-size hyaloclastic Priest Rapids lava. Most of the hyaloclastic material larger than 2 mm in diameter consists of unaltered glass cores surrounded by jackets of devitrified glass and palagonite which vary in thickness (fig. 33). Sand-size hyaloclastic material in most all cases has been totally converted to palagonite and serves as a cementing agent along with minor amounts of calcite.

The bedding within the hyaloclastite dominantly consists of parallel layers of well indurated, poorly sorted, sand- to pebble-size Priest Rapids hyaloclastic debris and moderately indurated and sorted pebble/cobble Priest Rapids hyaloclastic conglomerate. The poorly sorted sand- to pebble-size beds range from 5 cm to greater than 3 m in thickness, with the thinner beds (less than 30 cm in thickness) having a higher degree of sorting than thicker beds. Less commonly these thinner beds of sand- to pebble-size hyaloclastic debris may also show grading. The moderately sorted pebble/cobble hyaloclastic conglomerate beds generally range from 10 cm to 2 m in thickness but commonly are less than 0.5 m thick. The Priest Rapids hyaloclastic pebbles and cobbles form framework conglomerate with hyaloclastic sand serving as the matrix. Variation in the degree of induration of the conglomerate beds results in the better indurated

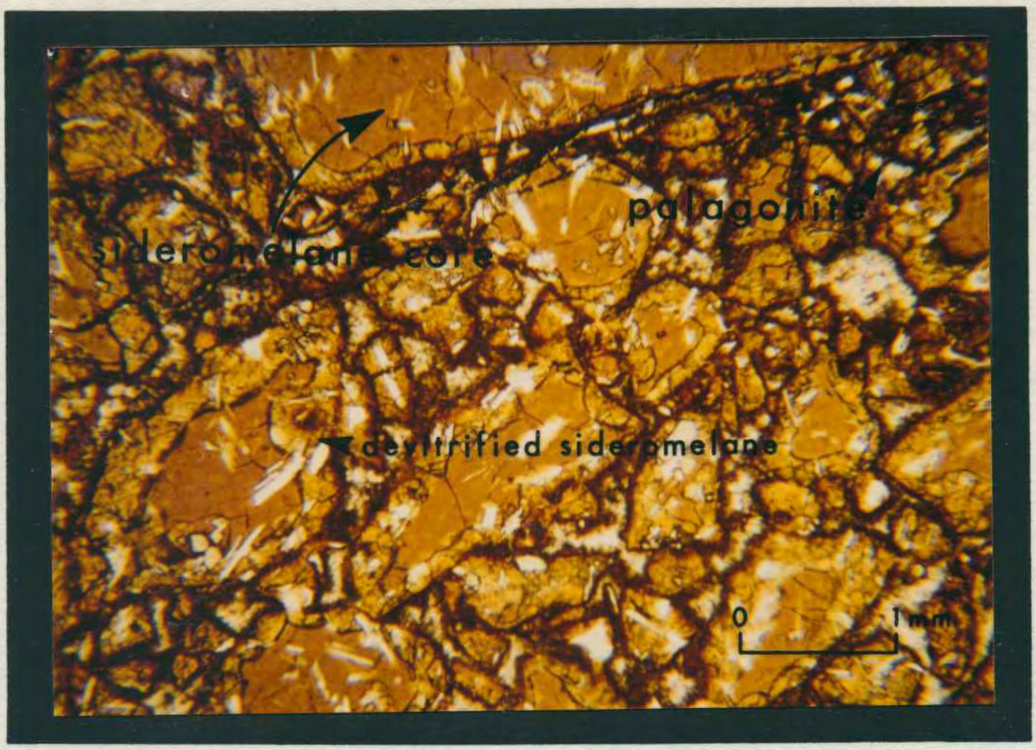


Figure 33. Photomicrograph of Priest Rapids hyaloclastite (PPL) collected from the base of the north face of Crown Point, Oregon. The sand-size hyaloclastite grains commonly have an outer layer of palagonite (opaque) which surrounds a layer of devitrified sideromelane (brownish-yellow) that varies in thickness. Most grains have a core of unaltered sideromelane (brown).

beds standing out in relief, producing the horizontal ridges shown in figure 34. The pebble/cobble conglomerate only rarely displays imbricated structure but when present yields paleocurrent directions between N35° to 50°W.

Much less common in the hyaloclastite deposit are foreset beds, also shown in figure 34. These beds yield paleocurrent directions which average N45°W.

Near the base of the Crown Point exposure is a boulder conglomerate (fig. 34) composed of subangular to subrounded "foreign clasts" of Skamania Volcanic Series, Grande Ronde Basalt, and Frenchman Springs Member lithologies. These foreign clasts lie in a matrix of Priest Rapids hyaloclastite. Scattered foreign cobbles and boulders are found in decreasing numbers above the boulder conglomerate. The local availability of the rock types comprising the foreign clasts, their generally poor degree of rounding, and their relatively large size in comparison to the Priest Rapids hyaloclastic material suggest they were derived locally from the sides of the ancestral Columbia River canyon and not transported very far.

The documented presence of this same type of hyaloclastite deposit underlying the Priest Rapids intracanyon flow in the Bull Run Watershed (Vogt, 1981) and in the Hood River Valley (Anderson and Vogt, in prep.) strongly suggests that the point of generation of the hyaloclastic debris lies far to the east of Crown Point. The high degree of rounding of the hyaloclastic material, bedding structures, and lack of any major source of hyaloclastic debris production in the Crown Point area further support this argument.

Figure 34. North face of Crown Point showing features of the Priest Rapids hyaloclastite deposit. (A) foreset-bedded hyaloclastite. (B) parallel-bedded hyaloclastite. Differences in size of clastic debris, sorting, and degree of induration result in differential resistance to weathering which produces the ridge. (C) scattered foreign boulders. (D) boulder conglomerate.

Pomona Member of the Saddle Mountains Basalt. The Saddle Mountains Basalt is represented in the thesis area solely by the Pomona Member intracanyon flow. Approximately 5.5 km northeast of the main channel of the Priest Rapids intracanyon flow at Crown Point, the present-day Columbia River has dissected a path oblique to the axis of the Pomona Member intracanyon flow at Bridal Veil, Oregon (Plate 1). Here the pre-Pomona ancestral Columbia River re-established itself in post-Priest Rapids time and incised a N75° to 85°W-trending canyon more than 244 m deep and 2.4 km wide into Grande Ronde Basalt. This ancestral Columbia River channel will henceforth be referred to as the "Bridal Veil channel". The subsequent Pomona Member intracanyon flow underfilled the canyon and thus did not displace the ancestral Columbia River. This is evidenced by over 213 m of fluvial conglomerates and sandstones of the Troutdale Formation (Allen, 1932) which directly overlie the Pomona Member and laterally thin away from the axis of the Bridal Veil channel (Plate 1). The Pomona Member can be traced laterally from Bridal Veil Creek eastward to Coopey Creek (Plate 1), except for a 0.32-km gap centered about an unnamed stream valley south of the town of Bridal Veil. Only the Troutdale Formation is exposed in this area, suggesting that the Pomona Member deposited within this portion of the channel was removed by post-Pomona stream erosion.

The thickness of the Pomona Member varies greatly, ranging from less than 6 m at the margins of the flow to greater than 122 m east of Bridal Veil Creek. True maximum thickness of this flow is difficult to ascertain because the base of the pre-Pomona canyon is poorly exposed and the top of the Pomona Member flow has undergone fluvial scouring.

The best exposure of the base of the Pomona Member occurs in a borrow pit behind the Bridal Veil Lumber Company buildings adjacent to Bridal Veil Creek and immediately south of Interstate 84. Here columnar- to fan-jointed basalt of the Pomona Member unconformably overlies the R_2 Grande Ronde Basalt entablature into which the pre-Pomona bedrock channel was incised. The Pomona/R_2 Grande Ronde Basalt unconformable contact at this location is very sharp, with only a 10- to 20-cm-thick zone of clay and carbonized wood fragments separating the two units. The basal part of the Pomona Member exposed here shows no evidence of interaction with water. Other excellent exposures of the Pomona Member can be found along the lower portion of Coopey Creek, which roughly parallels the northern margin of the Pomona Member intracanyon flow. Exposures in this area display a wide range of jointing styles, from blocky to curved, columnar jointing (fig. 35A).

The northern margin of the Pomona Member intracanyon flow has also been located on the Washington side of the lower Columbia River Gorge along the Burlington Northern railroad grade, south of Mt. Zion (Plate 1). The Pomona Member, which is exposed in an abandoned railroad quarry, displays crude columnar jointing pattern consisting of poorly developed, curved prismatic columns varying from 5 to 60 cm in diameter (fig. 35B). The jointing style seen in figure 35B is the jointing style normally associated with the Pomona Member in the

A.

B.

Figure 35. A. Horizontal Pomona Member columns exposed at the 130-m elevation along Angel's Rest trail west of Coopey Creek. B. Entablature-like jointing pattern displayed by the Pomona Member exposed in the old railroad quarry west of Cape Horn, Washington (SW¼ SE¼ sec. 17, T1N, R5E). Note the Troutdale lower member conglomerates overlying the scoured top of the Pomona Member.

western part of the Columbia Plateau (Bentley, Anderson, and others, 1980). Also clearly seen in figure 35B is the Troutdale Formation, which directly overlies the scoured top of the Pomona Member.

Pomona Member lithology is very distinctive and can be easily distinguished from other CRBG flows in the thesis area. The Pomona Member is porphyritic, with both equant and tabular, clear plagioclase phenocrysts which range from 0.3 to 1.3 cm in length. Rare plagioclase phenocrysts may exceed 3 cm in size. Visual counts of these phenocrysts yield an average of 450 phenocrysts/m^2. The Pomona Member also contains scattered clots of olivine that range from 0.3 to 1 cm in size. The groundmass is generally medium to coarse grained in appearance. The coarseness of the groundmass and the uncharacteristic abundance of plagioclase phenocrysts are probably the chief reasons why the Pomona Member intracanyon flow was not previously recognized in this area.

Major oxide chemistry can also distinguish the Pomona Member from other CRBG flows (Table VIII). The Pomona Member is higher in CaO and MgO and lower in TiO_2, P_2O_5, FeO, and K_2O than other CRBG flows found in the thesis area. In addition, the Pomona Member also has reversed paleomagnetic polarity.

The discovery of the Pomona Member intracanyon flow by Anderson (1980) in the upper Columbia River Gorge, now coupled with its identification in the lower Columbia River Gorge, provides firm evidence that the Pomona Member did flow westward from the Columbia Plateau into western Oregon and Washington. This would seem to resolve the question raised by Snavely and others (1973) concerning

TABLE VIII

COMPARISON OF AVERAGE MAJOR OXIDE CONCENTRATIONS FOR THE POMONA MEMBER IN THE LOWER COLUMBIA RIVER GORGE TO AVERAGE CONCENTRATIONS REPORTED IN OTHER WORK

Oxide**	This work, 1982	Anderson, 1980		Bentley and others, 1980
		Cascades	Plateau	
SiO_2	52.37	51.60	51.88	51.91
Al_2O_3	15.70	15.39	14.88	15.20
FeO*	10.45	10.77	10.55	10.66
MgO	6.79	6.81	6.96	6.58
CaO	10.36	10.47	10.67	10.63
Na_2O	1.51	2.27	2.36	2.20
K_2O	0.57	0.65	0.64	0.58
TiO_2	1.63	1.63	1.62	1.64
P_2O_5	0.23	0.24	0.25	0.24
MnO	0.18	0.19	0.17	0.18

* FeO + 0.9 Fe_2O_3

** All analyses in weight percent.

the origin of the Pomona-like Basalt of Pack Sack Lookout in the southwestern Washington area. On the basis of current evidence it would seem certain that the Basalt of Pack Sack Lookout is indeed the Pomona Member, since it is highly improbable, given the nature and volume of the Pomona Member intracanyon flow, that it failed to reach the Kelso/Cathlamet area of southwestern Washington only 80 km to the northwest of Bridal Veil. Future detailed mapping westward from Bridal Veil will no doubt find additional exposures of the Pomona Member.

Troutdale Formation

The fluvial sandstones and conglomerates of the Troutdale Formation are found throughout most of the thesis area, except northeast of Cape Horn, Washington (Plate 1).

Allen (1932, p. 59), in mapping the Troutdale Formation through the lower Columbia River Gorge, recognized that the thickest exposed section of this formation occurs at Bridal Veil, Oregon. Here the Troutdale Formation unconformably overlies the Pomona Member intracanyon flow and attains a thickness in excess of 335 m. Excellent exposures of this formation can be found along Palmer Mill Road, which parallels Bridal Veil Creek, and in the unnamed stream valley south of the town of Bridal Veil (SW¼ NE¼ sec. 28, T1N, R5E).

At Bridal Veil, as well as throughout the rest of the thesis area, the Troutdale Formation has been found to be divisible on the basis of lithology into two members: (1) a lower member consisting of chiefly quartzite-bearing basaltic conglomerates and micaceous arkosic sandstone beds, and (2) an upper member composed dominantly of pebbly to cobbly vitric sandstones, with basaltic conglomerate interbeds which contain Boring Lava clasts and only occasional quartzite pebbles. These informal divisions of the Troutdale Formation are used in this thesis to facilitate discussion and to promote their consideration for future formal adoption.

Lower member of the Troutdale Formation. The lower member of the Troutdale Formation at Bridal Veil exceeds 260 m in thickness, which comprises over 70% of the total Troutdale section exposed here. Despite comprising such a large percentage at this location, lower member gravels and sands have a limited spatial distribution in the lower Columbia River Gorge, occurring only within the strict confines of the Bridal Veil channel (Plate 1). The lower member unconformably overlies the Pomona Member and grades into the upper member.

The lower member is composed of poorly to moderately indurated, pebble/cobble conglomerate (fig. 36A). Pebble counts of this conglomerate (Table IX, col. 1-4) shows that Columbia River basalt clasts dominate, with all clasts of other lithologic compositions together comprising less than 40% of the total. The presence of quartzitic, granitic, and rhyolitic clasts is important, because none of these clasts could have been derived locally, suggesting a distant source possibly in northern Washington or British Columbia (Williams, 1916, p. 15; Lowry and Baldwin, 1952, p. 22; Trimble, 1963, p. 36).

Less common in the lower member are cross-bedded sandstone

<u>Figure 36</u>. <u>A</u>. Typical appearance of a conglomerate of the lower member of the Troutdale Formation. <u>B</u>. Lower member arkosic sandstone.

TABLE IX

BULK CLAST COMPOSITION(in %) OF CONGLOMERATES FROM THE TROUTDALE FORMATION AS DETERMINED BY PEBBLE COUNTS

Sample Number	1	2	3	4	5	6	7	8	9
Constituents									
Columbia River basalt	55.8	76.4	67.7	14.8	64.8	75.7	31.8	30.9	9.5
Basalt	14.1	10.6	8.0	6.0	12.0	8.1	68.2	65.5	88.6
Andesite	6.1	3.3	9.0	9.3	6.8	2.0	0.0	0.0	0.0
Dacite	0.0	0.0	0.0	65.4	0.0	0.0	.0.0	0.0	0.0
Rhyolite	1.8	0.8	0.6	0.0	1.8	0.7	0.0	0.0	0.0
Granitic	0.7	0.0	1.6	0.0	1.3	0.0	0.0	0.0	0.0
Quartzite	9.2	5.6	7.7	3.9	7.6	8.8	0.0	0.0	0.0
Cryptocrystalline quartz	8.0	3.3	5.0	0.6	5.7	4.7	0.0	3.6	1.9
Other	4.3	0.0	0.3	0.0	0.0	0.0	0.0	0.0	0.0

Sample	No. clasts counted	Member	Location
1	163	lower	Collected at the 61 m elevation in unnamed stream valley south of Bridal Veil, Oregon(SW¼ NE¼ sec. 22, T1N, R5E).
2	123	lower	Collected at the 152 m elevation in unnamed stream valley south of Bridal Veil, Oregon(SW¼ NE¼ sec. 22, T1N, R5E).
3	313	lower	Collected at the 240 m elevation on Palmer Mill Road.
4	182	lower (lahar)	Collected at the 137 m elevation in unnamed stream valley south of Bridal Veil, Oregon(SW¼ NE¼ sec. 22, T1N, R5E).
5	159	upper (transitional)	Collected at the 195 m elevation on Highway 14 west of Cape Horn, Washington (NW¼ SW¼ sec. 17, T1N, R5E).
6	148	upper (transitional)	Collected at the 213 m elevation on the east side of Crown Point, Oregon along the Old Scenic Highway(NE¼ SW¼ sec. 30, T1N, R5E).
7	66	upper	Collected at the 213 m elevation on the west side of Crown Point, Oregon along the Old Scenic Highway(NW¼ SW¼ sec. 30, T1N, R5E). Underlies Boring Lava flow.
8	55	upper	Collected at the 213 m elevation on the west side of Crown Point, Oregon along the Old Scenic Highway(NW¼ SW¼ sec. 30, T1N, R5E). Foreset-bedded conglomerate.
9	105	upper	Collected at the 329 m elevation on Palmer Mill Road.

lenses and beds that range from 0.5 to 4 m in thickness (fig. 36B). These sandstones are generally poorly to moderately indurated and tan to gray in color and have a fresh, unweathered appearance. Conspicuous small flecks of muscovite mica are present in these sandstones. Commonly the muscovite flakes in the sand matrix of the lower member conglomerates will adhere and mantle the surfaces of the pebbles and cobbles.

Three representative lower member sandstone samples were collected, and bulk mineral composition was determined for each (Table X, col. 1-3). The sand samples were first prepared by impregnating them with epoxy. Each sample billet was lapped flat, cemented to a glass slide and ground to the proper thickness. The sandstone thin sections were then examined under a petrographic microscope to identify the mineral constituents of the sand. After this, each slide was etched and stained for potassium and sodium feldspar, and subsequently point counted. On the basis of the normalized percentages of quartz, feldspar, and lithic fragments, the lower member sandstone is classified as arkosic arenite using Pettijohn's (1975, p. 211) classification system for terrigeneous sandstones (fig. 37A). Lower member sandstone appears to be distinct from modern-day Columbia River sediment (fig. 37A; Table X, col. 9-11) from below the Bonneville Dam, the Bonneville reservoir, and The Dalles Dam reservoir (Whetten and others, 1969, p. 1160 - Table 1).

The lower member of the Troutdale Formation at Bridal Veil, Oregon, contains two lahar units, each of which have distinctive lithologies.

TABLE X

BULK MINERAL COMPOSITION(in %) OF SANDSTONES FROM THE TROUTDALE FORMATION AS DETERMINED BY PETROGRAPHIC POINT-COUNTS OF THIN-SECTIONS*

Sample Number	1	2	3	4	5	6	7	8	9**	10**	11**
Constituent											
Quartz	12.2	16.4	15.6	0.6	0.4	0.0	2.8	6.0	13	29	29
Plagioclase	32.8	30.4	26.2	0.8	0.6	0.0	16.8	5.0	20	18	17
K - feldspar	22.6	20.2	12.0	0.0	0.0	0.0	2.0	5.4	7	10	13
Lithic fragments	16.6	14.8	23.0	97.2	96.4	99.0	66.4	71.6	56	35	32
Opaque minerals	1.0	2.0	4.2	0.6	0.0	0.0	2.0	1.8	1	4	5
Mafic minerals	10.2	12.4	16.2	0.4	2.4	0.8	8.4	8.6	4	5	4
Mica	4.6	3.8	2.8	0.4	0.2	0.2	1.6	1.6	-	-	-

* 500 grains counted per sample.

** Modern-day Columbia River bottom sediment provide for comparison. From Whetten and others (1969). Location of samples: 9 - below Bonneville Dam; 10 - from Bonneville reservior; 11 - from The Dalles reservior. Bulk mineral compositions for these samples is based on 250 grains counted per sample.

Sample Number	Member	Location
1	lower	Collected at the 61 m elevation in the unnamed stream valley south of the town of Bridal Veil, Oregon(SW¼ NE¼ sec. 22, T1N, R5E).
2	lower	Collected at the 240 m elevation on Palmer Mill Road.
3	lower	Collected at the 95 m elevation below Highway 14 west of Cape Horn, Washington(NW¼ SW¼ sec. 17, T1N, R5E).
4	upper (vitric)	Collected at the 329 m elevation on Palmer Mill Road.
5	upper (vitric)	Collected at the 366 m elevation on Multnomah Creek Trail (Trail No. 441; SE¼ NE¼ sec. 18, T1N, R6E).
6	upper (vitric)	Collected at the 183 m elevation on Chanticleer Point Road (NW¼ SW¼ sec. 25, T1N, R4E).
7	upper (lithic)	Collected at the 329 m elevation on Palmer Mill Road.
8	upper (lithic)	Collected at the 18 m elevation at the Stark Street Bridge, lower Sandy River, Oregon(SW¼ NE¼ sec. 6, T1S, R4E).

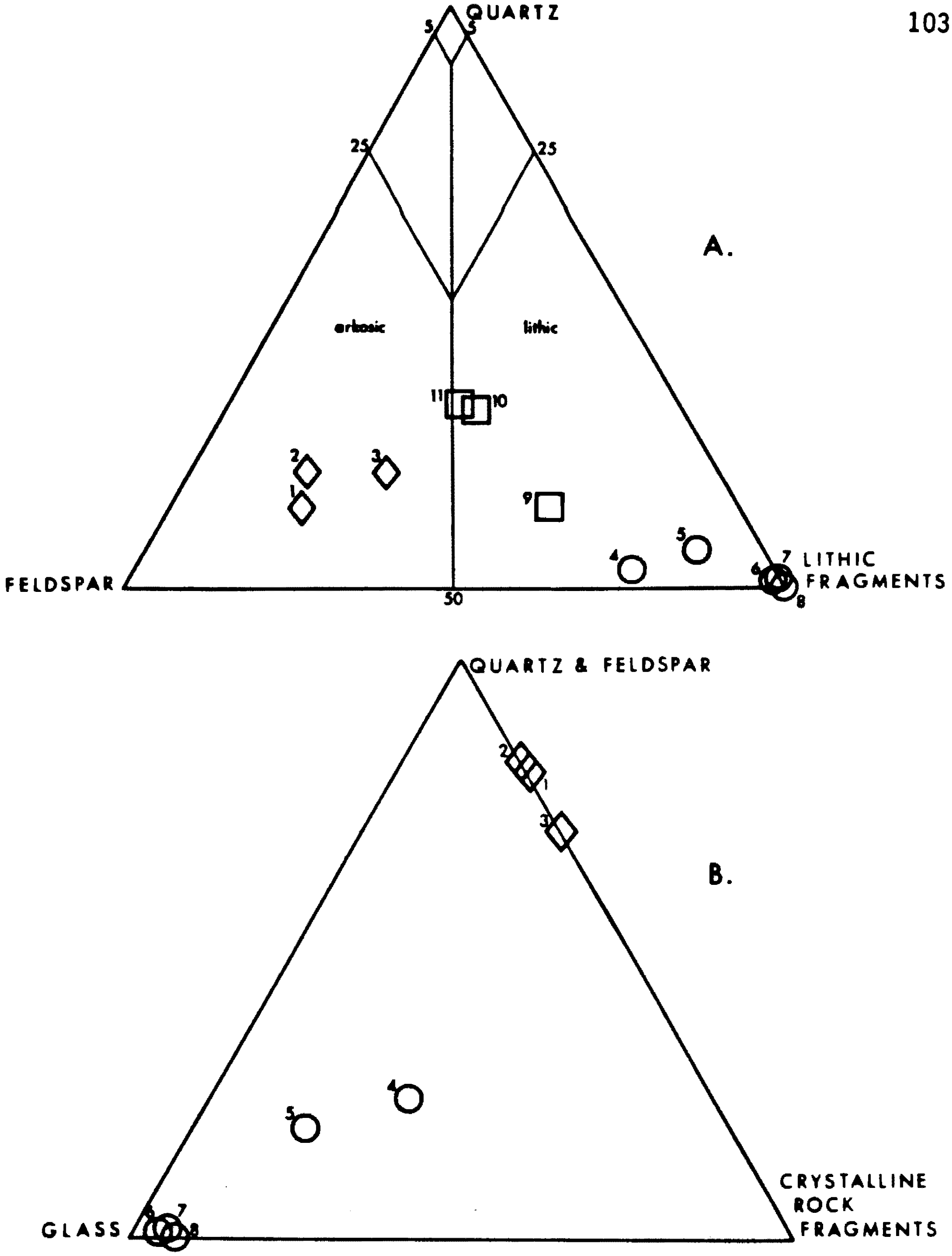


Figure 37. A. Classification of Troutdale member sandstones after Pettijohn (1975, p.211). Symbols: ◇ lower member; ○ upper member; □ modern-day Columbia River sediment. Numbers beside symbols correspond to sample numbers listed in Table X.
B. Division of lithic component of figure 37A into glass and crystalline rock fragments components. This modification serves to differentiate upper member vitric and lithic sandstones (see text).

The lower lahar is approximately 30 m thick and has a limited areal extent, being found only in the western half of the Bridal Veil channel (Plate 1). A pebble count of this unit (Table IX, col. 4) shows it to be dominately composed of rounded, light-gray hornblende dacite clasts. Columbia River basalt and quartzite clasts comprise less than 20% of the total percentage, probably representing lower member gravels incorporated into this lahar as it moved along the Bridal Veil channel. Also scattered throughout this lower lahar, especially near the top, are large boulders of Columbia River basalt composition (fig. 38A). The clasts of this lower lahar are in a clay matrix which contains fragments of carbonaceous material.

Lower member conglomerates conformably overlie this lower lahar with the upper contact being defined by a 0.3 to 0.5 m thick gradational zone. Lower member conglomerates immediately overlying this zone notably lack the light-gray hornblende dacite clasts which the lahar contains in abundance. This lower lahar unconformably overlies the Pomona Member at the 120-m elevation on Palmer Mill Road and is interbedded with lower member conglomerates in the unnamed stream valley south of the town of Bridal Veil.

The upper lahar is approximately 8 m thick and is exposed between the 180- to 188-m elevation on Palmer Mill Road. This upper lahar is composed of rounded, gray to red andesite clasts. Less than 5% of the clasts are of Columbia River basalt or quartzite composition. This lahar also differs in that the clasts are in a gray, coarse-sand to grit-sized matrix which contains no carbonaceous material.

The upper lahar overlies lower member conglomerates and is

A.

B.

Figure 38. A. Lower Rhododendron lahar intercalated with Troutdale lower member conglomerates exposed at the 160-m elevation in the unnamed stream valley (SW¼ NE¼ sec. 23, T1N, R5E) south of the town of Bridal Veil, Oregon.
B. Upper Rhododendron lahar intercalated with Troutdale lower member conglomerates exposed along Palmer Mill Road at the 180-m elevation south of the town of Bridal Veil, Oregon.

overlain by lower member arkosic sandstones, which notably lack the gray and red andesite clasts common to this upper lahar.

The lithologic character, mode of origin, and relative stratigraphic position strongly suggest that these two lahars found intercalated with the lower member of the Troutdale Formation are correlative with the Rhododendron Formation.

Upper member of the Troutdale Formation. The upper member of the Troutdale Formation consists primarily of cobbly/pebbly vitric-lithic sandstones, with minor basaltic conglomerates which contain Boring Lava clasts. The upper member has a much broader distribution than does the lower member (Plate 1) due to continued alluviation of the Bridal Veil channel which eventually freed the ancestral Columbia River from the strict confines of the Bridal Veil channel. The base of the upper member occurs at approximately the 240-m elevation, which is also the approximate level of the top of the CRBG.

The most unusual aspect of the upper member is the vitric sandstone, which has been called "yellow grit" or "tuffaceous sands" by some early workers in this area (Williams, 1916; Barnes and Butler, 1930; Allen, 1932; Hodge, 1938; Lowry and Baldwin, 1952). Trimble (1963, p. 32-33) noted that the vitric sandstones are composed of sideromelane grains (based on index of refraction studies) and comprise the large percentage of the formation along the lower Sandy River, including the exposures in the vicinity of Troutdale, Oregon. In the thesis area, good exposures of the upper member vitric sandstone are found along Palmer Mill Road above the 240-m elevation, on the west side of Crown Point along the Old Scenic Highway, and at Chanticleer Point.

The vitric sandstones are commonly cross bedded (fig. 39A) and consist predominately of medium- to coarse-grained, subrounded to rounded, palagonitized sideromelane grains (Table X, col. 4-6). The degree of alteration of the sideromelane grains varies throughout the thesis area, from totally converted to palagonite to only thin jackets of palagonite surrounding fresh, black glass cores (fig. 40). The devitrification and alteration of the sideromelane to palagonite impart a distinctive yellow to orange hue to these sandstones and also serves as the principle binding agent within the sandstone.

Less common in the upper member are poorly to moderately indurated, gray, fine- to coarse-grained lithic sandstone beds (fig. 39B) which contain a higher percentage of subrounded, hypocrystalline to holocrystalline basaltic rock grains and mineral grains in proportion to palagonitized sideromelane grains. These lithic sandstone beds are found throughout the upper member.

Both vitric and lithic upper member sandstones are easily distinguished from the arkosic lower member sandstones as shown in fig. 37A. The upper member sandstones also appear to be distinguishable from modern-day Columbia River sediments, as also seen in figure 37A. When the lithic component of figure 37A is divided into glass and crystalline lithic components (fig. 37B), upper member vitric sandstones distinguish themselves by containing greater than 90% glass (sideromelane) grains in comparison to upper member lithic sandstones.

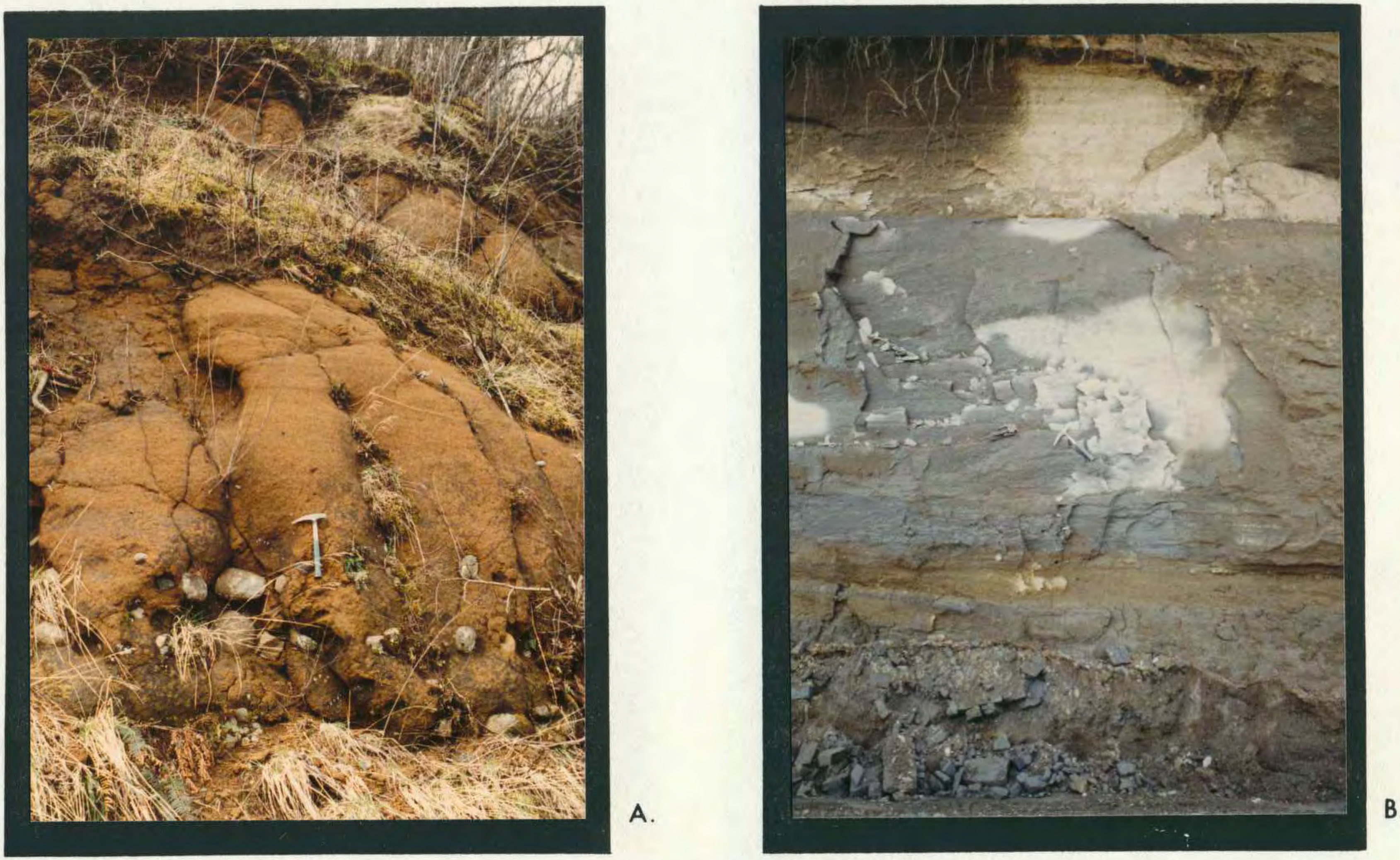


Figure 39. A. Cobbly upper member vitric sandstone exposed along Chanticleer Point Road at the 150-m elevation.
B. Upper member lithic sandstone(gray) intercalated with vitric sandstone at the 330-m elevation on Palmer Mill Road south of Bridal Veil, Oregon.

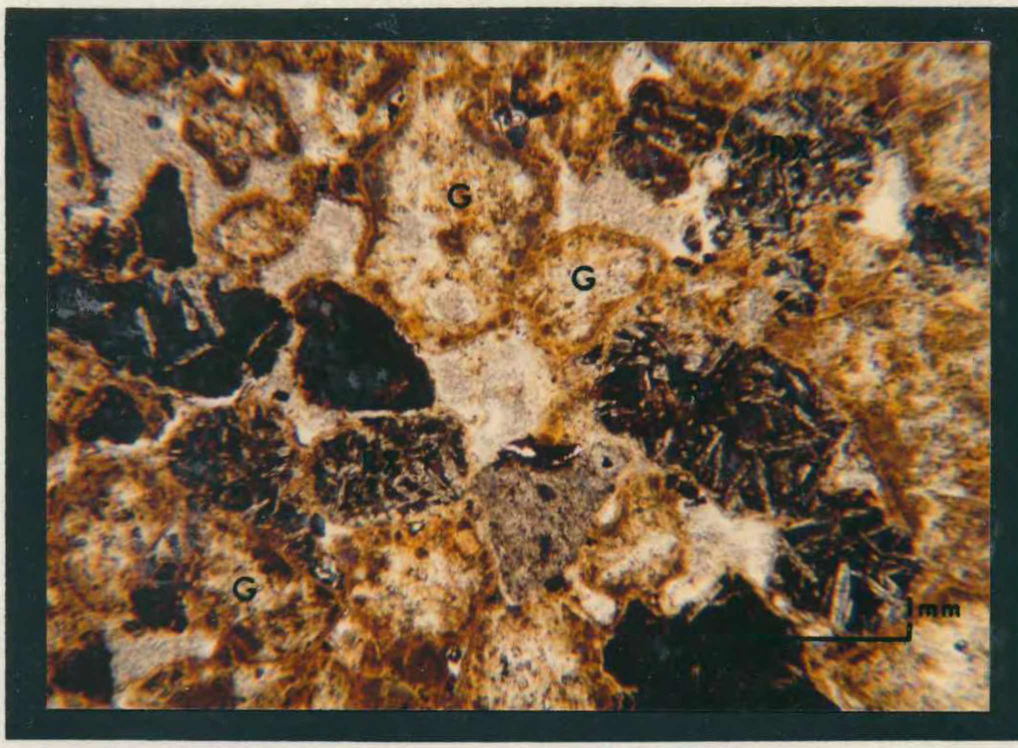


Figure 40. Photomicrograph (crossed nicols) of an upper member vitric sandstone collected from the exposure shown in figure 39A on Chanticleer Point Road. Basaltic rock fragments (RX) can be easily distinguished from the devitrified glass grains (G) on the basis of crystallinity.

Conglomerates within the upper member display a bimodal clast composition consisting of Boring Lava and Columbia River basalt lithologies (Table IX, col. 7-9). The Boring Lava clasts can be readily distinguished from Columbia River basalt clasts by having a light-gray to gray color on a fresh surface and by showing little weathering or alteration even when they have a diktytaxitic or vesicular texture. This contrasts with the Columbia River basalt clasts which commonly are deeply weathered, with only the core of the clast having a black, fresh appearance. Boring clasts are also commonly less rounded than the Columbia River basalt clasts.

Upper member conglomerates are only poorly to moderately sorted and occasionally display westerly dipping "torrential" foreset bedding, as seen west of Crown Point along the Old Scenic Highway (fig. 41).

The contact between the lower and upper members of the Troutdale Formation is not well defined but instead consists of a 5- to 20-m-thick gradational zone which is characterized by the presence of what appears to be interbedded lower and upper member gravels and sands. Close examination of these interbedded "lower member" gravels reveals the presence of Boring Lava clasts which indicate that these conglomerates belong to the upper member despite their apparent similarity to lower member conglomerates (Table IX, col. 6).

With the abundance of Boring material (clasts and vitric sands), it is not unexpected that Boring Lava flows are intercalated with the upper member of the Troutdale Formation. A single Boring flow exposed on the west side of Crown Point along the Old Scenic Highway

Figure 41. Foreset-bedded upper member conglomerate exposed at the 210-m elevation on the west side of Crown Point along the Old Scenic Highway (NW¼ SW¼ sec. 30, T1N, R5E).

east of the Larch Mountain Road junction (NW¼ SW¼ sec. 30, T1N, R5E) was previously recognized as intercalated with the Troutdale Formation by Williams (1916, p. 30) and Lowry and Baldwin (1952, p. 10). This blocky-jointed, olivine basalt flow is approximately 9 m thick and fills a shallow, westerly trending channel which truncates the torrential foreset beds shown in figure 42A. The base of this flow is well exposed along the highway and shows no evidence of interaction with water (fig. 42B). A second flow, previously unknown, is exposed at the 320-m elevation on Palmer Mill Road south of the town of Bridal Veil. This 10-m-thick, blocky-jointed plagioclase basalt flow also fills a shallow, westerly trending channel cut into the upper member. The lower contact of this flow, which is poorly exposed, shows some minor brecciation, suggesting interaction with water.

Origin and Age of the Troutdale Formation

The discovery of the Bridal Veil channel of the ancestral Columbia River and the stratigraphic relationships observed between the Troutdale Formation and both younger and older units necessitate a modification of the accepted model concerning the depositional history and age of the Troutdale Formation.

The currently held model explaining the depositional history of the Troutdale Formation in the lower Columbia River Gorge was proposed by Lowry and Baldwin (1952). Their model contended that the Troutdale Formation was deposited by an aggrading ancestral Columbia River that had always been in its present position, though not in a gorge, since early Pliocene time. The onset of Cascadian

A.

B.

Figure 42. A. Westerly-trending channel in the upper member of the Troutdale Formation exposed along the Old Scenic Highway on the west side of Crown Point (NW$\frac{1}{4}$ SW$\frac{1}{4}$ sec. 30, T1N, R5E). Channel truncates foreset-bedded conglomerates shown in figure 41. A Boring basalt flow is intercalated with the parallel-bedded sediments which fill the channel.
B. Base of the Boring basalt flow shown in figure 42A. Note the lack of pillows or brecciation.

uplift in late Pliocene marked the cessation of Troutdale deposition and the beginning of the incision of the present-day Columbia River Gorge. Lowry and Baldwin cited primarily the distributional pattern of the Troutdale Formation throughout the present-day gorge area as evidence supporting their model. The thick Troutdale deposit at Bridal Veil, Oregon, was explained as backfilling of a tributary valley by the aggrading ancestral Columbia River. Baldwin (1981, p. 62) modified their original model to take into account the presence of an ancestral Columbia River at 14 million years b.p., which was in a different position, as evidenced by the Priest Rapids intracanyon flow.

Evidence gathered in the course of this study, when coupled with data from other recent studies, suggests a scenario which differs from Lowry and Baldwin's model on several key points.

The first point of difference concerns the pathway along which the sands and gravels of the Troutdale Formation were deposited. The evidence produced by this study indicates that the Troutdale sands and gravels were deposited along the Bridal Veil channel of the ancestral Columbia River and not the present-day course of the Columbia River.

Data presented by Anderson (1980; in Bentley, Anderson, and others, 1980) and this study establish that the ancestral Columbia River did incise a new channel in post-Priest Rapids time (14 million years b.p.) which did not coincide with the present-day course of the Columbia River. This relationship between the Troutdale Formation and the Bridal Veil channel is supported by the positive correlation between the projection of the Bridal Veil channel through the Columbia

River Gorge area and the distributional pattern of the Troutdale Formation (fig. 28). Williams (1916), Allen (1932), and Hodge (1938) all noted that no Troutdale deposits could be found east of Cape Horn, Washington, while the Troutdale Formation was present nearly continuously along the Oregon side of the gorge. Allen (1932) and Hodge (1938) both documented an increase in thickness of the Troutdale Formation south of the Columbia River Gorge. Both of these observations are contrary to what would be expected if the Troutdale deposition occurred along the present-day course of the Columbia River, whereas both of these observations are consistent and explainable in terms of deposition along the Bridal Veil channel.

A second point of difference is that present data suggest that Troutdale deposition spanned a much longer period of time than previously believed. The 70-m-thick deposit of pre-Pomona gravels reported in the Mitchell Point-Mt. Defiance area of the Columbia River Gorge (Anderson, 1980) offers direct evidence that the ancestral Columbia River was transporting and depositing gravels in the Bridal Veil channel before 12 million years b.p. The Mitchell Point pre-Pomona gravels, which based on their lithologic composition and stratigraphic context (Anderson, 1980) would be assigned to the lower member of the Troutdale Formation, represent the oldest portion of the Troutdale Formation. The Mitchell Point pre-Pomona gravels are not an isolated occurrence, since similar gravels underlie the Pomona Member in the Kelso-Cathlamet area of southwestern Washington (Snavely and others, 1973, p. 412).

The extension of the lower age limit of the Troutdale Formation to more than 12 million years conflicts with the accepted lower age limit of 4 to 6 million years, which was assigned by R. W. Brown (in Trimble, 1963, p. 35) on the basis of fossil flora collected from two locales. This 6- to 8-million-year discrepancy between the two lower age limits can be resolved by re-examining the stratigraphic positions of both fossil locales in light of the Troutdale member stratigraphy developed in this study.

Brown based his age determination on sets of similar fossil flora collected from two widely separated locations. The first site is found opposite of the town of Troutdale, Oregon, on the east side of the lower Sandy River (NE¼ SE¼ sec. 25, T1N, R3E). The second site lies far to the southwest of the first, east of Park Place, Oregon, and is near Oregon City, Oregon. Both fossil locales lie beyond the boundaries of the thesis area. However, Brown's first locality was examined because of its close proximity to the thesis area. This site, opposite of the town of Troutdale, Oregon, is stratigraphically situated in the basal portion of the upper member of the Troutdale Formation, as evidenced by the interbedding of both upper and lower member lithologies. This places this fossil locality in the upper member of the Troutdale Formation and not near the base of this formation as was previously thought. This suggests that the 4- to 6-million year age determined by Brown is more applicable as an approximate age boundary between the lower and upper members than as a representative lower age limit for the entire Troutdale Formation. In actuality, this 4- to 6-million year age tenatively provides an approximate date for the onset of gorge-area Boring volcanism which contributed to the ancestral Columbia River the copious amounts of both clastic and hyaloclastic debris which now characterize the upper member of the Troutdale Formation.

A tentative upper age limit of less than 2 million years has been assigned to the Troutdale Formation based solely on a single K-Ar date of 1.56 $\pm$ 0.2 million years obtained for the Basalt of Bear Prairie (Paul E. Hammond, 1981, written communication), a Boring Lava flow which overlies the Troutdale Formation 5 km northwest of Mt. Zion, Washington. This upper age limit must remain tentative until further radiometric dates are received for Boring Lava flows which are intercalated with and cap the Troutdale Formation in the Bridal Veil, Oregon, area.

With the above proposed scenario, it is necessary for the ancestral Columbia River to have shifted from the Bridal Veil channel to its present-day position. This final shift probably occurred in late Troutdale time and resulted from (1) continuing alluviation which freed the ancestral Columbia River from the confines of the Bridal Veil channel, and (2) Boring volcanism which eventually capped the Bridal Veil channel, forcing the river to migrate northward. The capping of the Bridal Veil channel by the Boring Lavas is essential to this scenario, since their presence prevented the Columbia River from re-occupying and incising a new canyon in its former position when Cascadian uplift began. Instead, the Columbia River eroded a new channel near where the CRBG flows lap out against older volcanic rocks and sediments.

CHAPTER IV

STRUCTURE

Introduction

Previous mapping in the lower Columbia River Gorge has found virtually no major structures, either folds or faults (Barnes and Butler, 1930; Allen, 1932; Trimble, 1963; Swanson, Anderson, and others, 1979). This structural simplicity also typifies the thesis area.

Regional Dip

Where measurable, flows of the CRBG and beds of the Troutdale Formation generally display a relatively uniform 2° to 4° south-westerly dip in the thesis area (Plate 1). This same regional dip was previously noted in this area by Williams (1916), Bretz (1917), Allen (1932 - Plate III), and Trimble (1963). The regional dip is attributed to Cascadian uplift which may have begun as recently as 2 million years b.p.

Hodge (1938, pp. 851-853), on the basis of his work in the lower Columbia River Gorge, suggested that there was no broad uplift or "arching" of the Cascades in this region. Instead, he suggested a broad monoclinal structure dipping 3½° to 4° S13°E was responsible for the "regional dip" observed in the lower Columbia River Gorge. Hodge contended that previous workers had mistakenly measured the westward apparent dip component of the true dip. Hodge defined this broad monoclinal structure based on (1) north-south differences in the elevation of the base of the CRBG, and (2) "thousands" of measured dips in the lower Columbia River Gorge area.

Hodge (1938, p. 841) believed that flows of the CRBG were essentially conformable with the underlying units in the lower Columbia River Gorge region. He further believed that CRBG flows once extended far north of the present-day gorge area and had been eroded away following the monoclinal folding of this area. It is now known that both of Hodge's assumptions are incorrect, thus invalidating his first line of proof for the existence of a broad monoclinal structural in this area. Hodge (1938, p. 852) apparently confused elevations of the top of the CRBG in the lower gorge area for elevations of the base of the CRBG in the lower gorge area. This mistake was also reflected in his block diagram (p. 852) which illustrated the "deceptive" westerly dip using the base of the CRBG, when in actuality the horizon depicted in this diagram was the top of the CRBG.

Bridal Veil Fault

A N30°W-trending fault zone has been exposed by new trail construction on the east bank of Bridal Veil Creek below the plunge pool at Bridal Veil Falls (Plate 1). This fault zone is approximately 2 m wide and is composed of several 10- to 15-cm-wide shear zones which have vertical to subvertical planes. The subvertical planes are inclined as much as 30° from vertical and dip to the northeast.

This fault zone is exposed within a microphyric R_2 low MgO Grande Ronde entablature with no vertical stratigraphic offset detectable. The mylonite within the shear zones, however, contains numerous horizontal striae and occasional step structures which indicate the last movement along this fault zone was strike-slip in a right-lateral sense.

Northwest-trending fractures and lineations

Many of the CRBG exposures within the thesis area are cut by vertical to subvertical N10° to 40°W-trending fractures. These fractures have no discernible stratigraphic offset and display virtually no brecciation along the fracture planes. The majority of the observed fractures fall into two distinct trends: (1) a N5° to 15°W-trending set, and (2) a N30° to 40°W-trending set. It is probable that these fractures represent a synthetic response and adjustment to the regional dextral stress.

Also displaying these same trends are prominent aerial-photograph lineations which are shown on Plate 1. Field investigation of these lineations found no detectable vertical stratigraphic offset across them. In a few cases, minor fracture sets were observed to occur along the trend of the lineation.

Yamhill-Bonneville Lineament

The Yamhill-Bonneville lineament (Hammond, 1972; Allen and Beaulieu, 1976) is a N65°E-trending structural zone which is thought to extend from the Oregon coast near the town of Taft to beyond the Bonneville Dam area of northern Oregon and southern Washington. This feature, as defined by Hammond (1972), consists of a broad zone of en echelon, left-lateral strike-slip faults. The width of this zone ranges from less than 3.2 km where it crosses the Oregon Coast Range to greater than 40 km in the lower Columbia River Gorge region (Hammond, 1972, p. 4).

The area of this study lies along the projected path of the Yamhill-Bonneville lineament. However, no northeast-trending faults or fractures have been found in the thesis area within flows of the CRBG that could be attributed to this structural zone. The course of the present-day Columbia River does have a pronounced northeast trend in this area. However, both the Pomona Member intracanyon flow and the N_2/R_2 low MgO Grande Ronde contact project across the trend of the present-day Columbia River with no discernible lateral or vertical displacement. This evidence, combined with the lack of documentable northeast-trending faults, strongly argues against the presence of a major northeast-trending structural zone that has been active in this area since middle Miocene time.

CHAPTER V

GEOLOGIC HISTORY

In Oligocene to early Miocene time, basaltic and andesitic lava flows were erupted from a volcanic center situated along the northwestern margin of a broad, northeast-trending structural low. This volcanic center built an edifice over 244 m high in the vicinity of Crown Point, Oregon, and was likely a member of a larger, north-south belt of volcanic centers in the Western Cascade Mountains of northern Oregon and southern Washington. The Crown Point volcanic center had ceased activity by middle Miocene time, whereas other volcanic centers, 60 km to the southeast along the southern margin of the broad structural low, continued their eruptive activity into middle Miocene time.

The middle to late upper Miocene CRBG flows used the broad structural low as a pathway into western Oregon and Washington, with most of the flows entering this area during a 2-million year period, centered about 15 million years b.p.

The first CRBG flows to enter this area were the low MgO chemical type of the Grande Ronde Basalt. The earliest N_1 low MgO Grande Ronde flows probably filled and smoothed topographic irregularities within the broad low. Subsequent R_2 and N_2 low MgO Grande Ronde flows progressively filled the low and onlapped the northern margin of the low. During this process, low MgO Grande Ronde flows overwhelmed and partially backfilled the lower portions of streams which drained the older highlands to the north. These events led to brief, dynamic interaction between the advancing lava and the streams, producing local pillow-palagonite complexes at the bases of these flows. This action also probably produced temporary, shallow lakes where the undisturbed, upper portion of these streams encountered the margin of the basalt flow. Had these lakes remained for prolonged periods, they would have accumulated sedimentary deposits which would manifest themselves today as interbeds within the Grande Ronde section. However, the paucity of sedimentary interbeds within the Grande Ronde section would suggest these lakes were generally quite ephemeral, with new drainage courses for these streams being re-established with relative rapidity.

The interval between the end of Grande Ronde volcanism and the onset of Wanapum volcanism ("Vantage horizon") is characterized in the thesis area by only minor weathering of the uppermost N_2 high MgO Grande Ronde flow.

The first Frenchman Springs flows to enter western Oregon (Category I, Ginkgo flows) were excluded from this area. However, later flows of the Frenchman Springs Member did reach this area. The irregular distribution, the filling of shallow channels eroded into underlying flows, the lack of sedimentary interbeds, and the presence of pillow-palagonite complexes suggest the continuing presence of small streams, none of which, however, could be considered a fore-runner of the ancestral Columbia River.

At the beginning of Frenchman Springs time, what would properly be called the ancestral Columbia River lay to the south of the present-day gorge area. This ancestral Columbia River followed a southwesterly course through the Clackamas/Molalla River areas, on toward Salem, Oregon, and presumably on westward to the coast. The Ginkgo (Category I) Frenchman Springs flows along with later Frenchman Springs flows filled this ancestral Columbia River channel (Beeson, 1980, unpublished data; Hoffman, 1981). These events led to the re-establishment of a new ancestral Columbia River channel, north of its former position, by 14 million years b.p..

This entire process was aided by the fact that the Roza Member of the Wanapum Basalt failed to enter western Oregon, thereby permitting a longer hiatus which allowed the headward erosion of this new channel to continue unabated. At Crown Point, this northwest-trending channel of the ancestral Columbia River reached a depth of over 190 m and achieved a width of over 1.6 km.

A single Priest Rapids Member flow overfilled this new channel of the ancestral Columbia River approximately 14 million years ago. This event was unusual in that a large volume of Priest Rapids hyaloclastic debris was produced by interaction between the fluid Priest Rapids lava and water.

In the brief time before the arrival of the Priest Rapids lava, the ancestral Columbia River channel experienced mudflow-like surges of hyaloclastic debris, with interim periods where running water probably reworked and redeposited hyaloclastic debris. Up to 122 m of Priest Rapids hyaloclastic debris was eventually deposited in portions of the ancestral Columbia River channel.

The massive amount of Priest Rapids hyaloclastic debris greatly reduced the capacity of the channel, thus permitting the advancing Priest Rapids lava to overtop the channel. The destruction of the ancestral Columbia River channel by the Priest Rapids intracanyon flow forced the river to shift northward and begin again the process of eroding a new channel.

During the two-million year hiatus, the ancestral Columbia River eroded a new channel which in the Bridal Veil area was over 2 km wide and 240 m deep. Foreign clasts within the gravels exposed today at Mitchell Point, Oregon, in the upper Columbia River Gorge indicate that before 12 million years b.p. the Columbia River had extended its provenance beyond the limits of the Columbia Plateau.

At approximately 12 million years b.p., the Pomona Member of the Saddle Mountains Basalt was erupted from vents in western Idaho. The voluminous outpouring of Pomona lava flowed down the ancestral Snake River to the ancestral Columbia River, which provided a pathway into western Oregon and Washington. The Pomona Member intracanyon flow, unlike the Priest Rapids Member intracanyon flow, underfilled the ancestral Columbia River channel, therefore allowing the Columbia River to remain in this channel in post-Pomona time.

After the Pomona Member intracanyon flow, the ancestral Columbia River resumed transporting and depositing quartzite-bearing basaltic gravels and arkosic sands. This regime in the present-day lower gorge area was briefly interrupted sometime between 12 and 10 million years b.p. by a dacitic lahar which probably originated from the flanks of a Rhododendron volcano in the late Miocene Cascade Mountains of northern Oregon.

The onset of Boring volcanism estimated at approximately 4 to 6 million years b.p. changed the character of the sands and gravels that the ancestral Columbia River deposited. Boring volcanism produced tremendous amounts of clastic and hyaloclastic debris which entered the ancestral Columbia River, mixing with and diluting the normal bedload material being transported and deposited. The influx of Boring material probably helped accelerate the aggradation of the lower portion of the ancestral Columbia River channel, which eventually allowed the Columbia River to escape the confines of the channel. Continued Boring volcanism ultimately capped this channel with lava flows, thus preventing the river from re-occupying this channel at a future time.

The onset of Cascadian uplift in northern Oregon and southern Washington, which may have begun as late as 1.5 million years b.p., marked the end of Troutdale deposition and the beginning of the erosion of the present-day Columbia River Gorge.

CHAPTER VI

SUMMARY AND CONCLUSIONS

Oligocene to lower Miocene(?) Skamania Volcanic Series rocks formed a paleotopographic high in the Crown Point-Latourell area on the Oregon side of the lower Columbia River Gorge. Exposures of these rocks consist primarily of basalt and andesite flows, with only a single dacite flow occurring below lower Latourell Falls. Circumstantial evidence suggests that this area may have been a Skamania volcanic center which had ceased activity before the first CRBG flows entered this region. The incursion of the CRBG flows into this area made this Skamania high a kipuka which was later covered by younger sediments of the Troutdale Formation and flows of the Boring Lavas.

The CRBG is represented in the thesis area by three formations belonging to the Yakima Basalt Subgroup, namely the Grande Ronde Basalt, Wanapum Basalt, and Saddle Mountains Basalt. The composite section consists of 22 individual flows which have a collective thickness exceeding 873 m. The thickest stratigraphic section exposed within the thesis area is found at Multnomah Falls, Oregon, and consists of 11 Grande Ronde Basalt flows which have a collective thickness of over 335 m.

The Grande Ronde Basalt can be divided into five recognizable units based on major oxide chemistry, paleomagnetic polarity, and lithology. These units are, from oldest to youngest, N_1 low MgO

Grande Ronde Basalt, R_2 low MgO Grande Ronde Basalt, N_2 low MgO Grande Ronde Basalt, N_2 low MgO Winter Water flow, and N_2 high MgO Grande Ronde Basalt.

Flows of the Grande Ronde Basalt generally have basal pillow-palagonite complexes, indicating they flowed into water that was likely in the form of small streams or shallow lakes. Few sedimentary interbeds occur within the Grande Ronde section, suggesting either that the rate of sediment production and transport was very low in this region or, more likely, that sediment was transported through this area and not deposited. In either case, these conditions are opposite of what was occurring along the southern margin (present-day Clackamas River area) of the broad structural low.

The Grande Ronde section within the thesis area contains three N_2 high MgO flows. The lower most of the three N_2 high MgO flows is generally confined to a shallow stream valley cut into older Skamania lava flows in the Crown Point-Latourell area. This lowermost N_2 high MgO flow has no identifiable counterpart in the Willamette Valley of western Oregon. The upper two N_2 high MgO flows are tentatively considered to be correlative with the N_2 high MgO flows found elsewhere in western Oregon, solely on the basis of plagioclase phenocryst abundance and superposition.

The Frenchman Springs Member of the Wanapum Basalt is represented within the thesis area by five flows which have a collective thickness of approximately 105 m. The five flows occur only in the western half of the thesis area, often filling irregularities or shallow channels in the underlying flows.

The five Frenchman Springs flows can be divided into three categories based on chemical, lithological, and stratigraphic criteria. The three oldest Frenchman Springs flows found in this area belong to Category II, with Categories III and V each represented by a single flow.

The Priest Rapids Member of the Wanapum Basalt is represented by a single intracanyon flow of the Rosalia chemical type. The Priest Rapids intracanyon flow attains a thickness of over 220 m at Crown Point, Oregon, where the former ancestral Columbia River valley once had a width of over 1.6 km and a depth of over 190 m.

The Priest Rapids intracanyon flow is composed of an upper hackly jointed lava and a lower bedded hyaloclastite deposit. This Priest Rapids hyaloclastic debris was generated upstream from Crown Point by interaction between the fluid lava and water. This material was transported downstream and deposited ahead of the lava, reaching thicknesses in the Crown Point area of over 122 m. This tremendous amount of Priest Rapids hyaloclastic debris reduced the capacity of the ancestral Columbia River valley, allowing the advancing lava to overtop the valley, which in turn forced the ancestral Columbia River to re-establish a new channel in post-Priest Rapids time.

The Saddle Mountains Basalt is represented by a 122-m-thick Pomona Member intracanyon flow which underfilled the post-Priest Rapids Columbia River channel. A cross section through this channel is exposed at Bridal Veil, Oregon, where before 12 million years b.p., the ancestral Columbia River had eroded a channel over 2 km wide and over 240 m deep. The ancestral Columbia River continued to remain in this channel in post-Pomona time.

The Troutdale Formation in the lower Columbia River Gorge area was deposited by the ancestral Columbia River which occupied the Bridal Veil channel. Examination of the 335-m section of the Troutdale Formation exposed within the Bridal Veil channel at Bridal Veil, Oregon, suggests that the Troutdale Formation can be divided into lower and upper members based on lithology of the sandstones and conglomerates.

The lower member of the Troutdale Formation consists of quartzite-bearing basaltic conglomerates and arkosic sandstones, while the upper member is characterized by vitric-lithic sandstones and basaltic conglomerates that bear Boring Lava clasts. The lower member has a limited distribution in the lower gorge, being found only within the confines of the Bridal Veil channel. The upper member has a broader distribution, being found nearly throughout the entire area. The wider distribution of the upper member is the result of continuing alluviation of the Bridal Veil channel which allowed the ancestral Columbia River to escape the confines of the channel during upper member time.

The relationship between the Pomona Member intracanyon flow and the Troutdale Formation at both Bridal Veil, Oregon, and at Mitchell Point, Oregon, in the upper Columbia River Gorge necessitates that the lower age of the Troutdale Formation be extended back to at least 12 million years b.p. The formerly accepted lower age boundary of 4 to 6 million years appears to be more applicable as the approximate boundary between the lower and upper members of the

Troutdale Formation as defined in this study. The upper age of the Troutdale Formation is believed to be less than 2 million years.

Two Boring basalt flows are intercalated with the upper member of the Troutdale Formation in the thesis area. Boring Lavas also capped the Bridal Veil channel, thus preventing the Columbia River from re-occupying this channel in the future. Boring volcanism probably also resulted in the Columbia River being shifted to its present-day position before the start of Cascadian uplift.

The onset of Cascadian uplift in northern Oregon and southern Washington may have began less than 2 million years b.p. This tentative date is based on stratigraphic considerations and a single K-Ar date for the Boring Lava in the Bear Prairie area of Washington.

REFERENCES

Abbott, A. T., 1955, Volcanic and sedimentary stratigraphy in the Cascade Range, east of Chinook Pass, Washington (abstract): Geol. Soc. Amer. Bull., vol. 66, no. 12, pt. 2, p. 1641.

Allen, J. E., 1932, Contributions to the structure, stratigraphy, and paleontology of the lower Columbia River Gorge: M. A. thesis (unpublished), Univ. of Oregon, Eugene, 96 p.

Allen, J. E., 1975, Volcanoes of the Portland area, Oregon: Ore Bin, vol. 37, no. 9, pp. 145-157.

Allen, J. E., 1979, The magnificent gateway: Timber Press, Forest Grove, Oregon, 144 p.

Allen, J. E., and Beaulieu, J. D., 1976, Plate tectonic structures in Oregon: Ore Bin, vol. 38, no. 6, pp. 87-96.

Anderson, J. L., 1978, The structure and stratigraphy of the Columbia River basalt in the Clackamas River drainage: M.S. thesis (unpublished), Portland State Univ., Portland, 136 p.

Anderson, J. L., 1980, Pomona Member of the Columbia River Basalt Group: an intracanyon flow in the Columbia River Gorge, Oregon: Oregon Geology, vol. 42, no. 12, pp. 195-199.

Anderson, J. L., and Vogt, B. F., in prep., Intracanyon flows of the Columbia River Basalt Group: evidence of paleodrainage development in the Cascade Range, Oregon and Washington.

Atlantic Richfield Hanford Company, 1976, Preliminary feasibility study of radioactive waste in Columbia River basalts: ERDA Report ARH-ST-137, text 168 p., appendices 264 p.

Baldwin, E. M., 1981, Geology of Oregon: Kendall/Hunt Publishing Company, Dubuque, Iowa, 147 p.

Barnes, F. F., and Butler, W., 1930, The structure and stratigraphy of the Columbia River Gorge and Cascade Mountains in the vicinity of Mount Hood: M.S. thesis (unpublished), Univ. of Oregon, Eugene, 73 p.

Beeson, M. H., Moran, M. R., and Olson, F. L., 1976, Geochemical data on the Columbia River basalt stratigraphy in western Oregon: Geol. Soc. Amer. Abstracts with Programs, vol. 8, no. 3, p. 354.

Beeson, M. H., and Moran, M. R., 1979, Columbia River Basalt Group stratigraphy in western Oregon: Oregon Geology, vol. 41, no. 1, pp. 11-14.

Beeson, M. H., Moran, M. R., Anderson, J. L., and Vogt, B. F., in prep., Stratigraphy and structure of the Columbia River Basalt Group in the Cascade Range, Oregon.

Bentley, R. D., 1977, Stratigraphy of the Yakima Basalts and structural evolution of the Yakima Ridges in the western Columbia Plateau, in Brown, E. H., and Ellis, R. C., eds., Geological excursions in the Pacific Northwest: Bellingham, Western Washington Univ. Press, pp. 339-389.

Bentley, R. D., Anderson, J. L., Campbell, N. P., and Swanson, D. A., 1980, Stratigraphy and structure of the Yakima Indian Reservation, with emphasis on the Columbia River Basalt Group: U.S. Geol. Survey Open-file Report 80-200, 76 p.

Bentley, R. D., Powell, J., Anderson, J. L., and Farooqui, S. M., 1980, Geometry and tectonic evolution of the Columbia Hills anticline, Washington and Oregon: Geol. Soc. Amer. Abstracts with Programs, vol. 12, no. 3, p. 97.

Bretz, J. H., 1917, Satsop formation of Washington and Oregon: Jour. Geol., vol. 25, pp. 446-458.

Buwalda, J. P., and Moore, B. N., 1927, Age of the "Satsop" and Dalles formations of Oregon and Washington: Science, vol. LXVI, p. 236.

Buwalda, J. P., and Moore, B. N., 1929, The Dalles and Hood River formations, and the Columbia River Gorge: Carnegie Inst. Pub., no. 404, pp. 11-26.

Camp, V. E., and Hooper, P. R., 1980, Tectonic evolution of the southern part of the Columbia River Plateau: Geol. Soc. Amer. Abstracts with Programs, vol. 12, no. 3, p. 100.

Camp, V. E., Price, S. S., and Reidel, S. P., 1978, Descriptive summary of the Grande Ronde Basalt type section, Columbia River Basalt Group: Rockwell Hanford Operations Document, RHO-BWI-LD-15, Richland, Washington, 26 p.

Davis, G. A., 1981, Late Cenozoic tectonics of the Pacific Northwest with special reference to the Columbia Plateau: Washington Public Power Supply System Final Safety Analysis Report, draft, preliminary, 44 p.

Drake, E. T., 1982, Tectonic evolution of the Oregon continental margin: Oregon Geology, vol. 44, no. 2, pp. 15-21.

Felts, W. M., 1939a, A granodiorite stock in the Cascade Mountains of south-western Washington: Ohio Jour. Science, vol. 39, no. 6, pp. 297-316.

Felts, W. M., 1939b, Keechelus andesitic lava flows of Washington in southward extension: Pan-Am. Geol., vol. 71, no. 4, pp. 294-296.

Gannett, M., 1982, A geochemical study of the Rhododendron and the Dalles Formations in the area of Mount Hood, Oregon: M.S. thesis (unpublished), Portland State Univ., Portland, Oregon, 70 p.

Goff, F. E., 1977, Vesicle cylinders in vapor-differentiated basalt flows: Ph.D. dissertation (unpublished), Univ. of California, Santa Cruz, 181 p.

Griggs, A. B., 1976, The Columbia River Basalt Group in the Spokane quadrangle, Washington, Idaho, and Montana: U.S. Geol. Survey Bull. 1413, 39 p.

Hammond, P. E., 1972, Plate tectonics and the Yamhill-Bonneville structural zone in northwestern Oregon: Geol. Soc. of the Oregon Country Newsletter, vol. 28, no. 3, pp. 3-5.

Hodge, E. T., 1933, Age of the Columbia River and lower canyon (abstract): Geol. Soc. Amer. Bull., vol. 44, pt. 1, pp. 156-157.

Hodge, E. T., 1938, Geology of the lower Columbia River: Geol. Soc. Amer. Bull., vol. 49, no. 6, pp. 831-930.

Hoffman, C. W., 1981, A stratigraphic and geochemical investigation of ferruginous bauxite deposits in the Salem Hills, Marion County, Oregon: M.S. thesis (unpublished), Portland State Univ., Portland, 130 p.

Lowry, W. D., and Baldwin, E. M., 1952, Late Cenozoic geology of the lower Columbia River Valley, Oregon and Washington: Geol. Soc. Amer. Bull., vol. 63, no. 1, pp. 1-24.

Kienle, C. F., 1971, The Yakima Basalt in western Oregon and Washington: Ph.D. dissertation (unpublished), Univ. of California, Santa Barbara, 171 p.

Mackin, J. H., 1961, A stratigraphic section in the Yakima Basalt and Ellensburg Formation in south-central Washington: Washington Div. of Mines and Geol., Report Inv. 19, 45 p.

Mckee, E. H., Swanson, D. A., and Wright, T. L., 1977, Duration and volume of the Columbia River basalt volcanism, Washington, Oregon, and Idaho: Geol. Soc. Amer. Abstracts with Programs, vol. 9, no. 4, pp. 463-464.

Nathan, S., and Fruchter, J. S., 1974, Geochemical and paleomagnetic stratigraphy of the Picture Gorge and Yakima Basalts (Columbia River Group) in central Oregon: Geol. Soc. Amer. Bull., vol. 85, pp. 63-76.

Peck, D. L., Griggs, A. B., Schlicker, H. G., Wells, F. G., and Dole, H. M., 1964, Geology of the central and northern part of the western Cascade Range in Oregon: U.S. Geol. Survey Prof. Paper 449, 56 p.

Pettijohn, F. J., 1975, Sedimentary rocks, third ed.: Harper and Row, New York, New York, 628 p.

Powell, L. V., 1978, The structure, stratigraphy and correlation of the Grande Ronde Basalt on Tygh Ridge, Wasco County, Oregon: M.S. thesis (unpublished), Univ. of Idaho, 57 p.

Schmincke, H. U., 1967, Stratigraphy and petrography of four upper Yakima Basalt flows in south-central Washington: Geol. Soc. Amer. Bull., vol. 78, pp. 1385-1422.

Snavely, P. D., Jr., MacLeod, N. S., and Wagner, H. C., 1973, Miocene tholeiitic basalts of coastal Oregon and Washington and their relation to coeval basalts of the Columbia Plateau: Geol. Soc. Amer. Bull., vol. 84, no. 2, pp. 387-424.

Swanson, D. A., Anderson, J. L., Bentley, R. D., Byerly, G. R., Camp, V. E., Gardner, J. N., and Wright, T. L., 1979b, Reconnaissance geologic map of the Columbia River Basalt Group in eastern Washington and northern Idaho: U.S. Geol. Survey Open-file Report 79-1363, scale 1:250,000.

Swanson, D. A., Wright, T. L., Hooper, P. R., and Bentley, R. D., 1979a, Revisions in stratigraphic nomenclature of the Columbia River Basalt Group: U.S. Geol. Survey Bull. 1457-G, 59 p.

Swanson, D. A., and Wright, T. L., 1978, Some important facts and inferences concerning the Columbia River Basalt Group: Tectonics and seismicity of the Columbia Plateau workshop, Seattle, Washington.

Swanson, D. A., and Wright, T. L., 1981, Guide to geologic field trips between Lewiston, Idaho and Kimberly, Oregon, emphasizing the Columbia River Basalt Group, _in_ Johnston, D. A., and Donnelly-Nolan, J., eds., 1981, Guides to some volcanic terranes in Washington, Idaho, Oregon, and northern California: U.S. Geol. Survey Circ. 838, 189 p.

Taubeneck, W. H., 1970, Dikes of Columbia River basalt in northeastern Oregon, western Idaho, and southeastern Washington, in Gilmour, E. H., and Stradling, D., eds., Proceedings of the second Columbia River basalt symposium: Cheney, Eastern Washington State College Press, pp. 73-96.

Taylor, T. L., 1976, The basalt stratigraphy and structure of the Saddle Mountains of south-central Washington: M.S. thesis (unpublished), Washington State Univ., Pullman, 116 p.

Timm, S., 1979, The structure and stratigraphy of the Columbia River basalt in the Hood River Valley, Oregon: M.S. thesis (unpublished), Portland State Univ., Portland, 56 p.

Treasher, R. C., 1942, Geologic history of the Portland area: Oregon Dept. Geol. Min. Ind. Short Paper 7, 17 p.

Trimble, D. E., 1957, Geology of the Portland quadrangle, Oregon-Washington: U.S. Geol. Survey Geol. Quad. Map GQ-104.

Trimble, D. E., 1963, Geology of Portland, Oregon and adjacent areas: U.S. Geol. Survey Bull. 1119, 119 p.

Vogt, B. F., 1979, Columbia River Basalt Group stratigraphy and structure in the Bull Run Watershed, western Cascades, northern Oregon (abstract): Proceedings Oregon Acad. Science, vol. 15, no. 5, p. 52.

Vogt, B. F., 1981, The stratigraphy and structure of the Columbia River Basalt Group in the Bull Run Watershed, Oregon: M.S. thesis (unpublished), Portland State Univ., Portland, 151 p.

Waters, A. C., 1961, Stratigraphic and lithologic variations in the Columbia River basalt: Amer. Jour. Science, vol. 259, pp. 583-611.

Waters, A. C., 1962, Basalt magma types and their tectonic association- Pacific Northwest of the United States: Amer. Geophys. Union Mon. 6, pp. 158-170.

Waters, A. C., 1973, The Columbia River Gorge: basalt stratigraphy, ancient lava dams, and landslide dams, in Beaulieu, J. D., field trip chairman, 1973, Geologic field trips in northern Oregon and southern Washington: Oregon Dept. of Geol. Min. Ind. Bull. 77, pp. 133-162.

Watkins, N. D., and Baksi, A. K., 1974, Magnetostratigraphy and oroclinal folding of the Columbia River, Steens, and Owyhee basalts in Oregon, Washington, and Idaho: Amer. Jour. Science, vol. 274, pp. 148-189.

Whetten, J. T., Kelley, J. C., and Hanson, L. G., 1969, Characteristics of Columbia River sediment and sediment transport: Jour. Sed. Petr., vol. 39, no. 3, pp. 1149-1166.

Wilkinson, W. D., Lowry, W. D., and Baldwin, E. M., 1946, Geology of the St. Helens quadrangle, Oregon: Oregon Dept. Geol. Min. Ind. Bull. 31.

Williams, I. A., 1916, The Columbia River Gorge: its geologic history interpreted from the Columbia River Highway, Oregon: Bur. Mines and Geol., Min. Res. of Oregon, vol. 2, no. 3, 130 p.

Wright, T. L., Grolier, M. J., and Swanson, D. A., 1973, Chemical variation related to the stratigraphy of the Columbia River basalt: Geol. Soc. Amer. Bull., vol. 84, no. 2, pp. 371-386.

APPENDIX A

MAJOR OXIDE ANALYSES OF CRBG SAMPLES FROM THE STUDY AREA (VALUES IN %)

Sample Number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
POMONA MEMBER										
CG-23	52.58	15.41	10.50	6.40	10.35	1.94	0.57	1.64	0.22	0.18
CG-33	52.24	16.18	10.25	6.83	10.24	1.41	0.63	1.62	0.22	0.18
CG-40	52.09	15.76	10.57	6.87	10.51	1.41	0.56	1.63	0.23	0.19
CG-41A	52.23	15.62	10.30	7.07	10.27	1.76	0.52	1.61	0.23	0.18
CG-64	52.69	15.55	10.61	6.80	10.45	1.05	0.58	1.63	0.24	0.19
PRIEST RAPIDS MEMBER										
CP-1	50.17	14.32	15.10	4.43	8.23	2.12	1.07	3.45	0.68	0.22
CG-9	50.74	14.24	14.76	4.09	8.25	2.22	1.18	3.49	0.68	0.16
CG-30	50.10	14.06	15.13	4.32	8.28	2.21	1.28	3.50	0.67	0.25
CG-34	50.31	13.86	14.99	4.38	8.24	2.38	1.24	3.50	0.65	0.24
PRIEST RAPIDS HYALOCLASTITE										
CG-57A	50.35	14.15	14.99	4.46	8.31	1.97	1.11	3.55	0.66	0.25
CG-57B	50.65	14.02	14.52	4.39	8.47	2.23	1.07	3.53	0.67	0.25
CG-58A	50.11	14.16	15.06	4.74	8.27	1.96	1.10	3.49	0.65	0.26
CG-58B	50.26	14.03	14.62	4.73	8.38	2.31	1.08	3.47	0.67	0.26

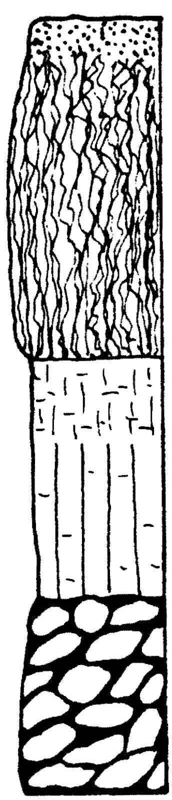
Sample Number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
FRENCHMAN SPRINGS MEMBER										
CATEGORY V										
CG-4	51.62	14.45	14.15	4.02	7.74	2.58	1.54	2.90	0.57	0.22
CATEGORY III										
CG-1	52.93	14.92	12.78	4.04	8.12	2.67	0.78	2.82	0.53	0.22
CATEGORY II										
CG-3	51.71	14.48	14.08	4.46	8.03	2.35	1.14	2.82	0.50	0.23
CG-5	51.66	14.58	13.94	4.64	7.94	2.40	1.18	2.78	0.49	0.20
CG-7	52.44	15.25	11.82	4.37	8.37	2.56	1.46	2.79	0.51	0.24
CG-36	51.80	14.50	14.11	4.08	8.13	2.25	1.31	2.91	0.49	0.23
CG-37	52.21	14.35	13.68	4.15	8.06	2.35	1.41	2.87	0.49	0.22
CG-56A	51.54	14.62	14.13	4.58	8.18	1.82	1.33	2.87	0.49	0.23
CG-56B	51.94	14.34	13.80	4.54	8.10	2.20	1.33	2.84	0.49	0.23
CG-68	52.43	14.79	12.82	4.51	8.33	2.03	1.33	2.78	0.50	0.26
HIGH MgO GRANDE RONDE BASALT										
CG-2	54.16	15.52	9.97	5.00	8.65	2.74	1.37	1.88	0.29	0.22
CG-11	54.06	15.37	11.21	5.02	8.16	2.50	1.28	1.70	0.30	0.22
CG-12	53.46	15.20	11.71	4.89	8.47	2.42	1.27	1.88	0.29	0.22
CG-13	53.40	15.11	11.99	4.87	8.30	2.53	1.21	1.89	0.29	0.21
CG-17	53.92	15.20	11.47	4.67	8.30	2.62	1.28	1.93	0.29	0.12
CG-65	53.43	15.19	11.83	4.93	8.85	1.97	1.14	1.94	0.29	0.23
CG-66	53.68	15.03	11.92	4.97	8.62	1.91	1.21	1.93	0.30	0.22
CG-67	54.35	15.32	11.55	4.81	8.41	1.90	1.18	1.80	0.28	0.20

Sample Number	SiO_2	Al_2O_3	FeO	MgO	CaO	Na_2O	K_2O	TiO_2	P_2O_5	MnO
LOW MgO GRANDE RONDE BASALT										
N_2 WINTER WATER										
CG-47	54.76	15.05	12.84	3.94	7.57	1.61	1.51	2.02	0.29	0.22
CG-49	55.80	14.96	11.52	3.74	7.15	2.23	1.88	1.99	0.32	0.20
CG-62A	54.83	14.97	12.93	3.95	7.48	1.62	1.49	2.03	0.28	0.22
CG-62B	54.32	15.05	12.52	4.07	7.62	2.18	1.51	2.03	0.28	0.22
CG-82	55.81	14.97	12.58	3.60	6.81	1.79	1.63	2.07	0.33	0.20
N_2 LOW MgO										
CG-59A	55.07	15.17	12.29	3.90	7.22	1.86	1.67	2.09	0.33	0.21
CG-59B	55.15	14.91	12.04	3.92	7.21	2.24	1.17	2.07	0.34	0.20
R_2 LOW MgO										
CG-14	54.33	14.83	12.68	3.33	6.86	3.00	1.85	2.33	0.38	0.22
CG-63	55.62	14.57	12.42	3.41	6.89	2.24	1.73	2.34	0.38	0.20
N_1 LOW MgO										
CG-84	54.66	15.23	12.58	3.70	7.26	2.11	1.58	2.15	0.33	0.20

APPENDIX B

STRATIGRAPHIC SECTIONS

Presented in this appendix are the locations and characteristics for five measured stratigraphic sections from the thesis area. Jointing characteristics and flow features are represented in a stylized manner as shown below.



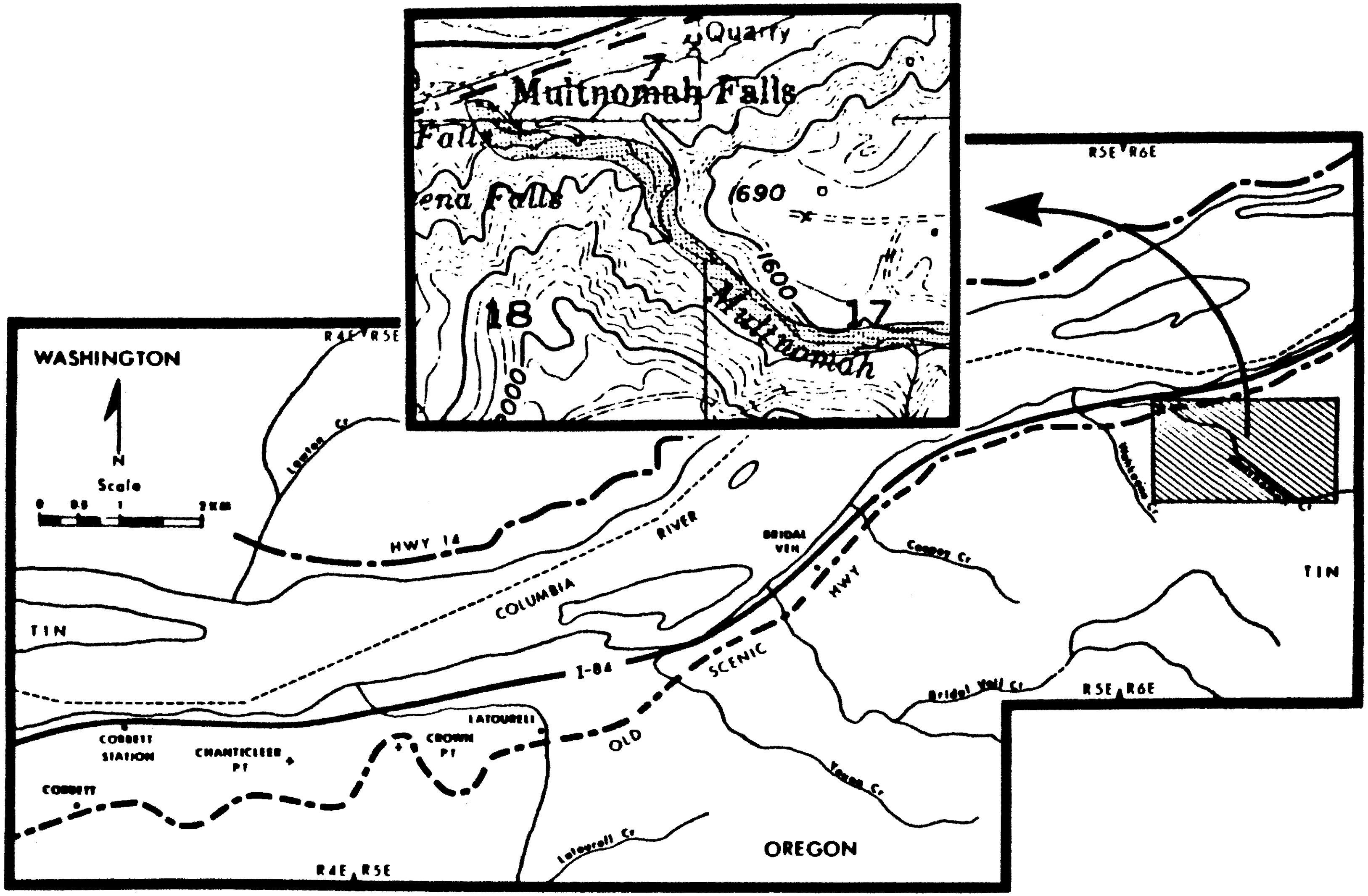


Figure 43. Location map of Multnomah Falls section. Inset shows traverse path (stippled).

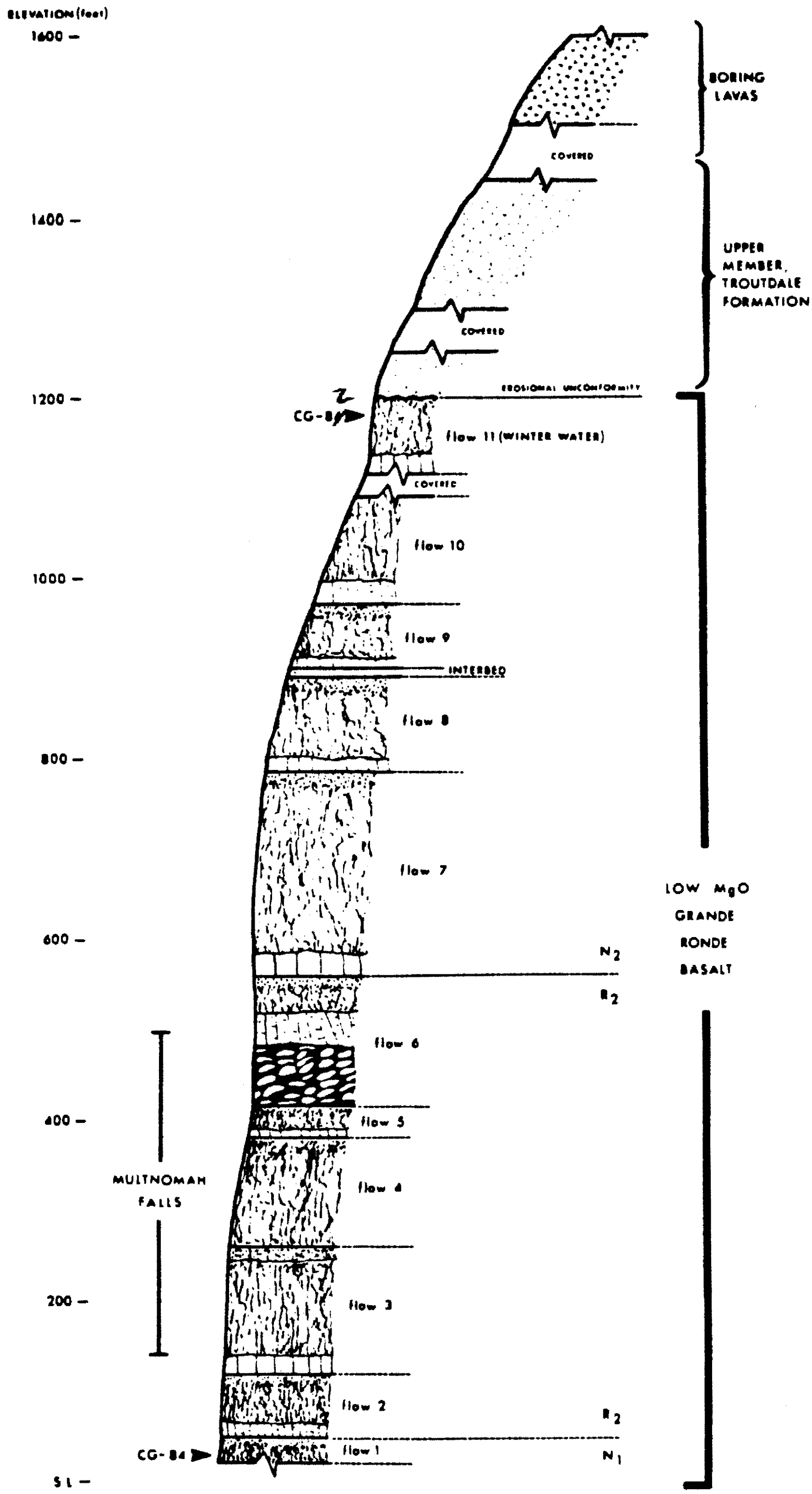


Figure 44. Multnomah Falls section.

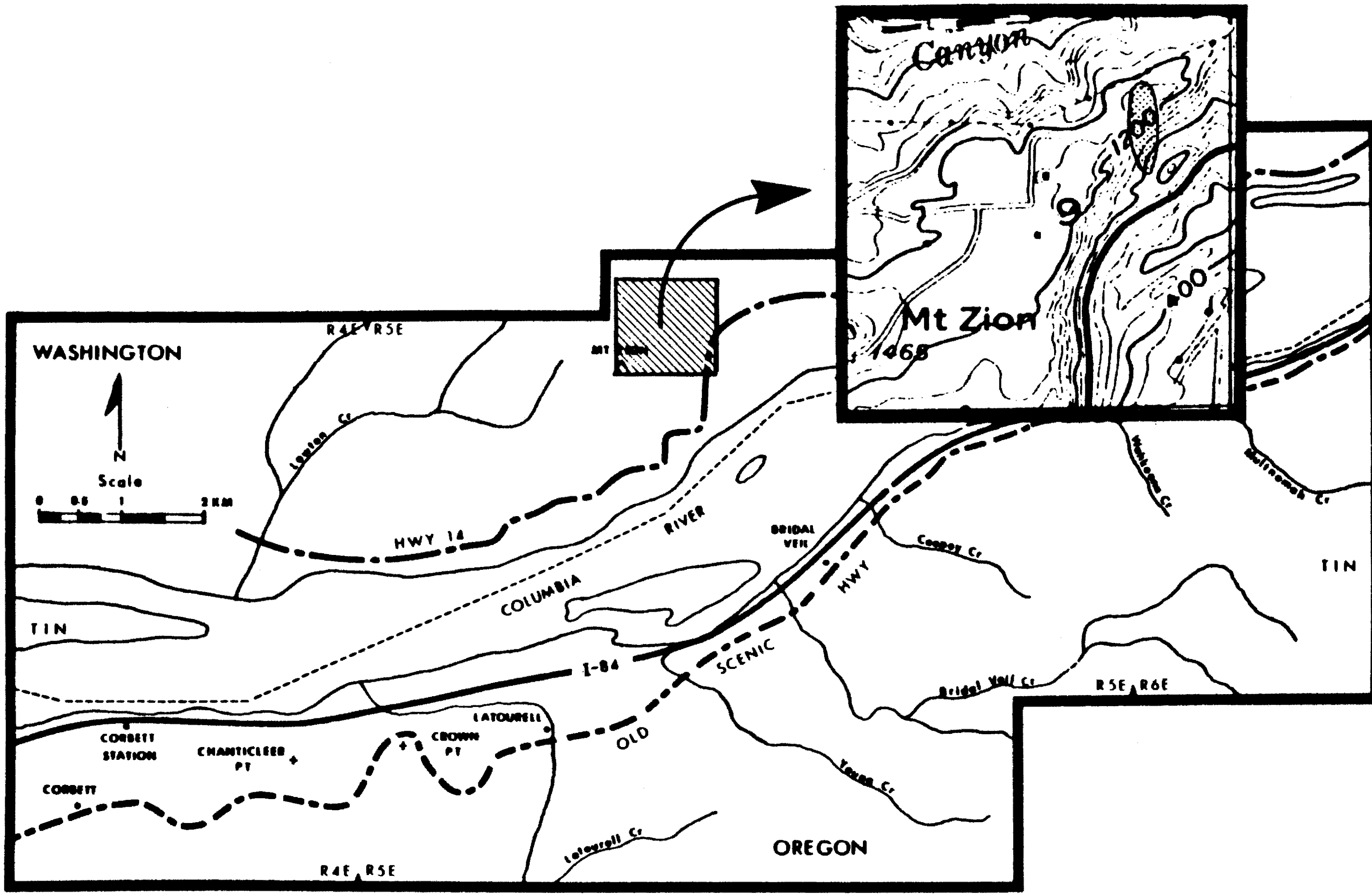


Figure 45. Location map of Mt. Zion quarry section. Inset shows traverse path (stippled)

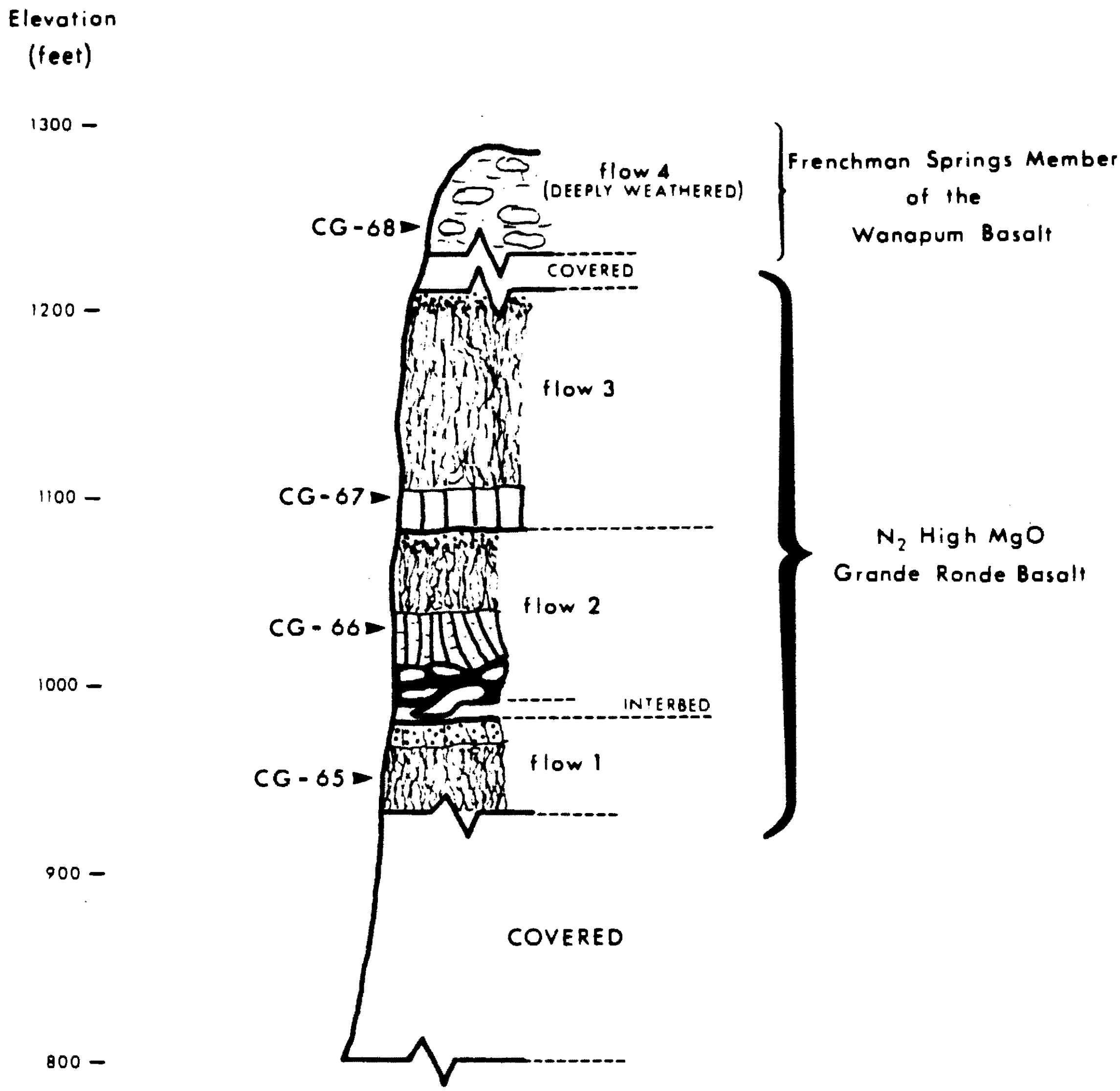


Figure 46. Mt. Zion quarry section.

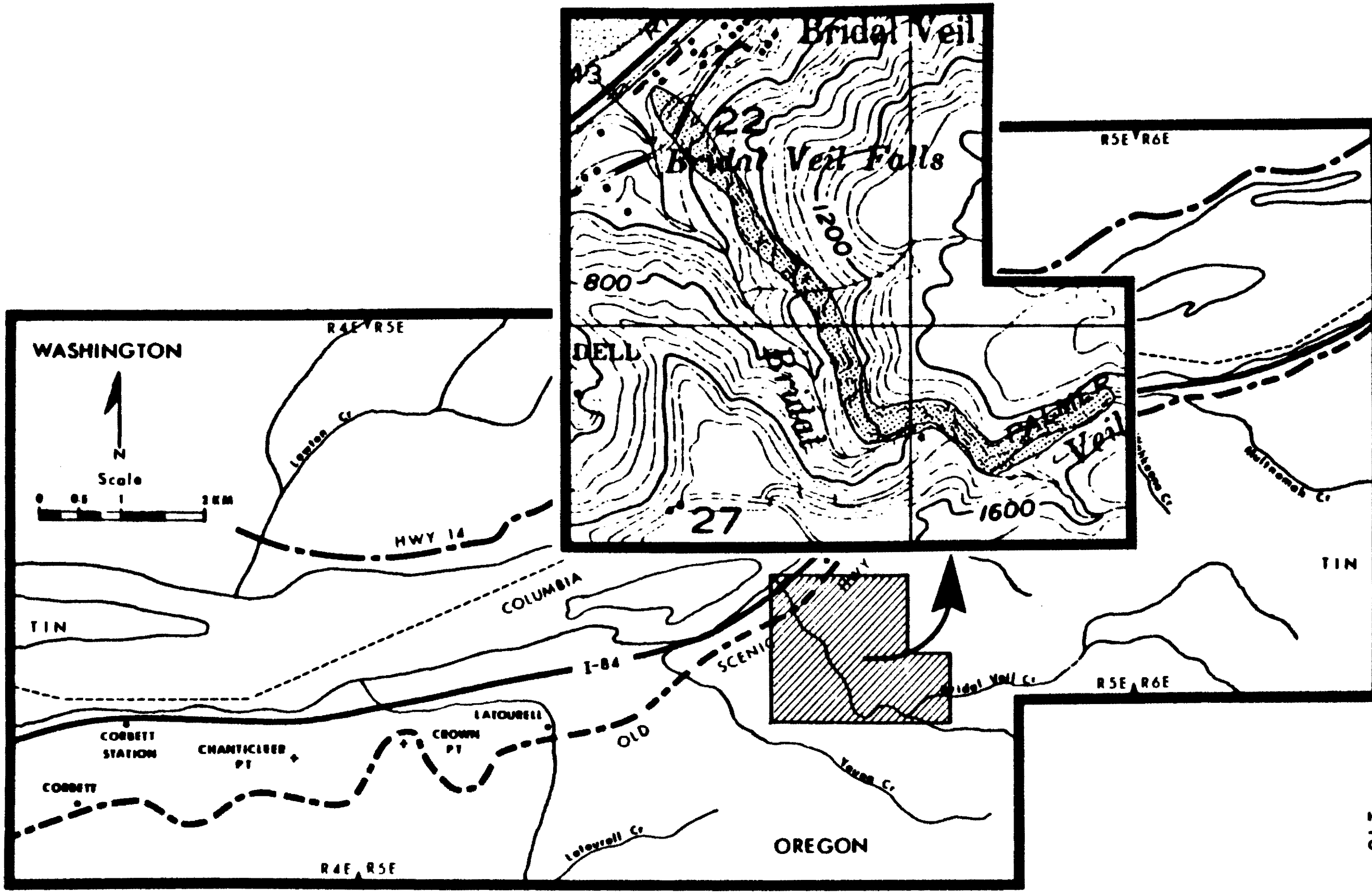


Figure 47. Location map of Palmer Mill Road section. Inset shows traverse path(stippled

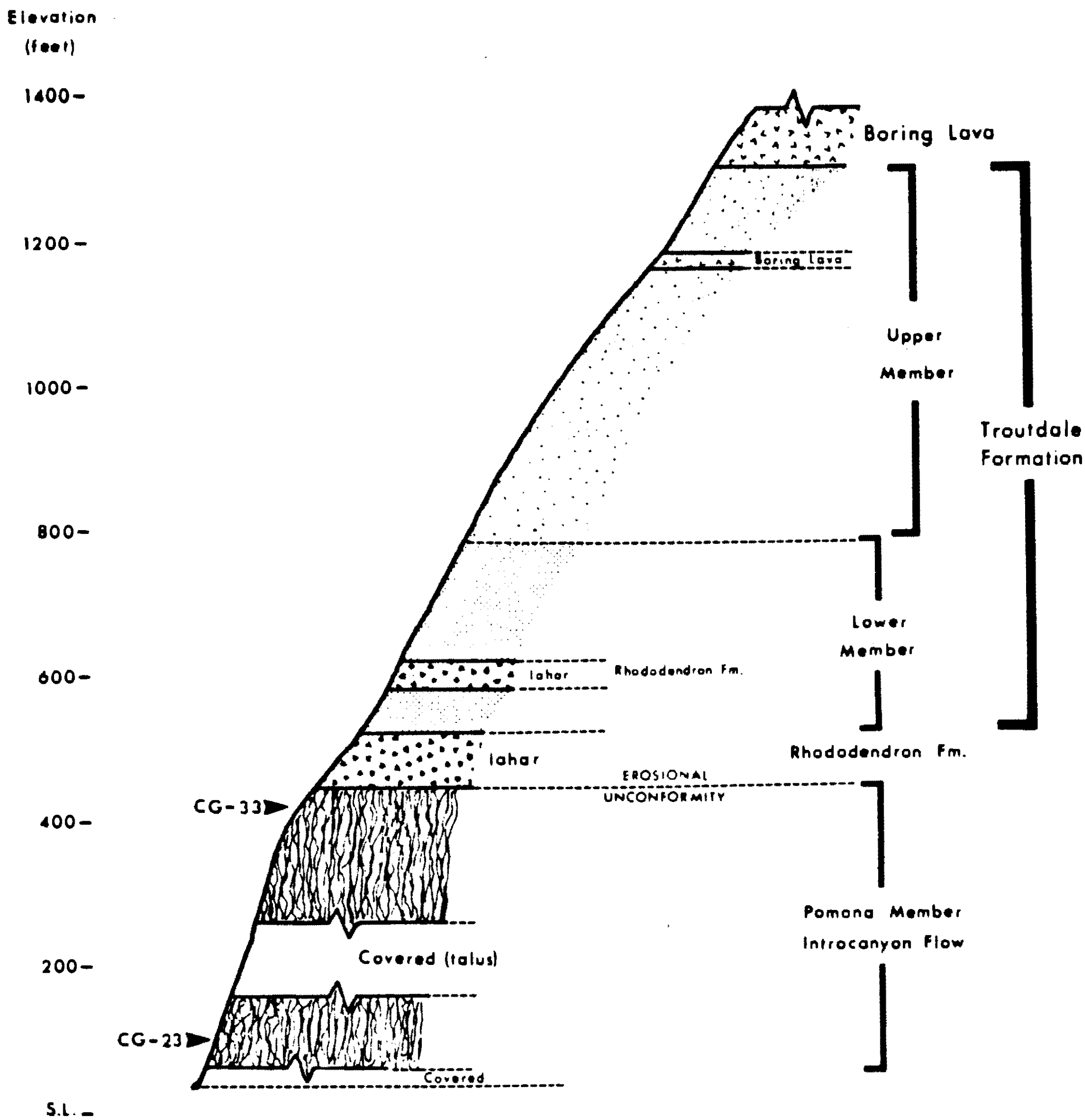


Figure 48. Palmer Mill Road section.

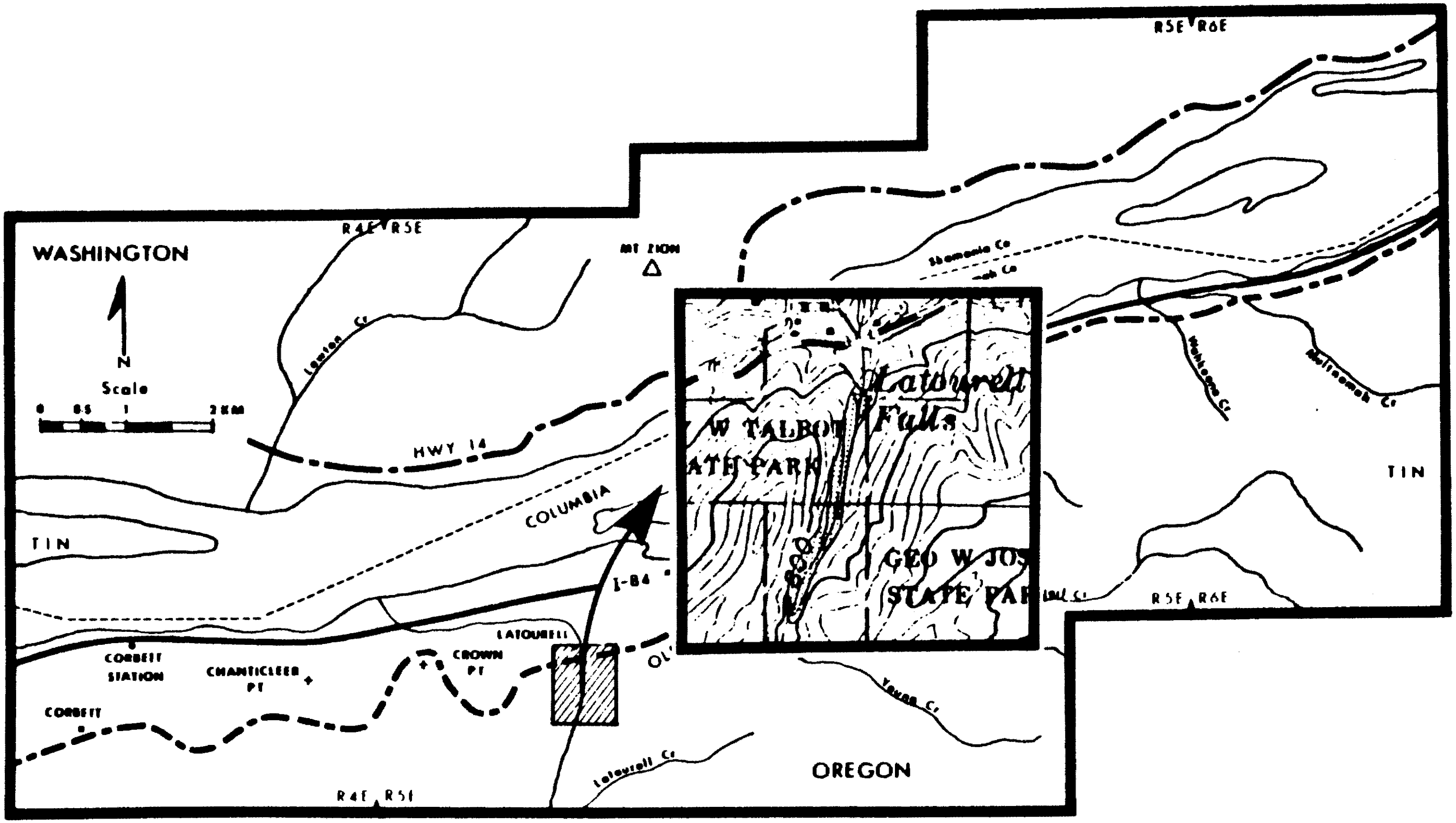


Figure 49. Location map of Latourell Creek section. Inset shows traverse path (stippled).

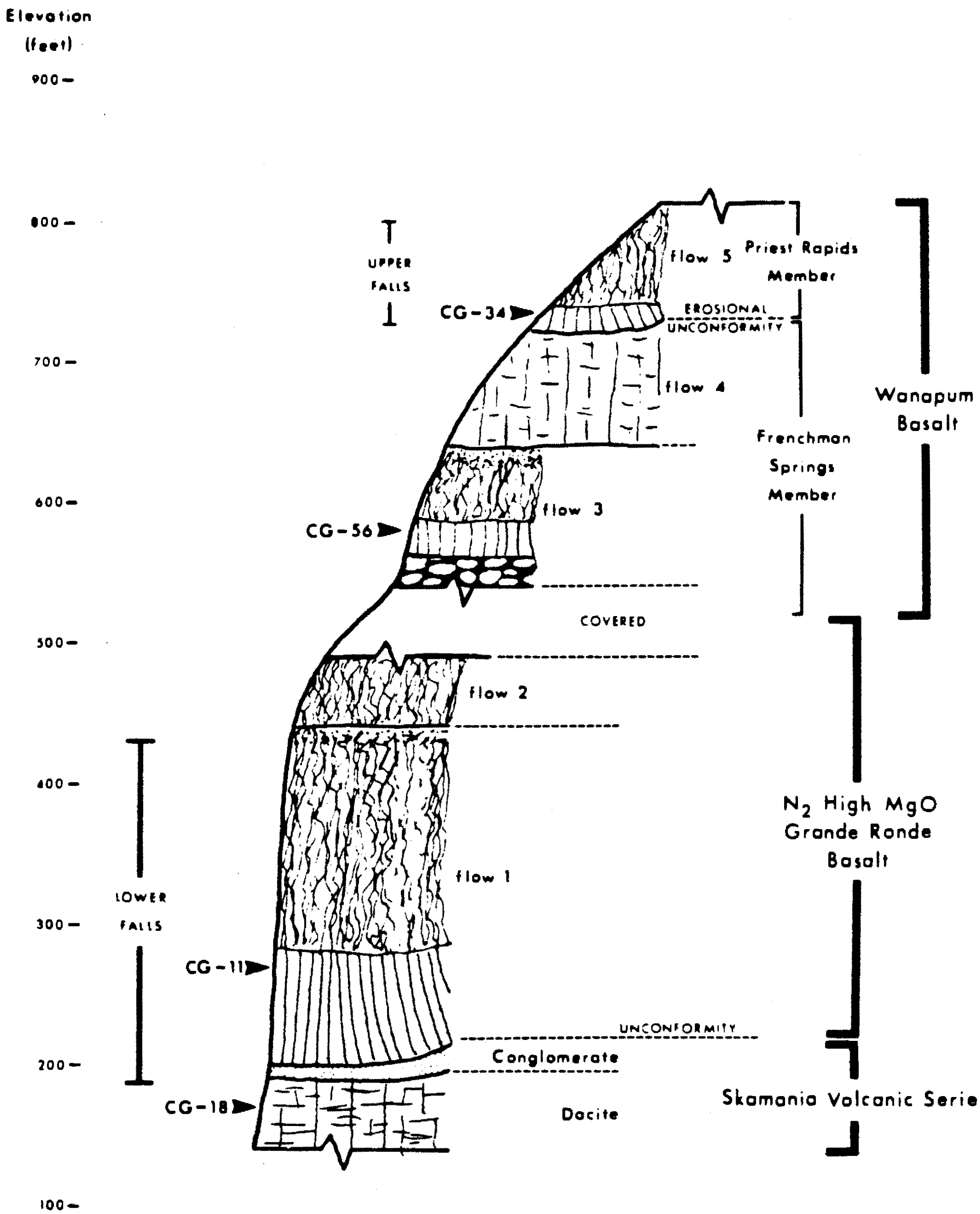


Figure 50. Latourell Creek section.

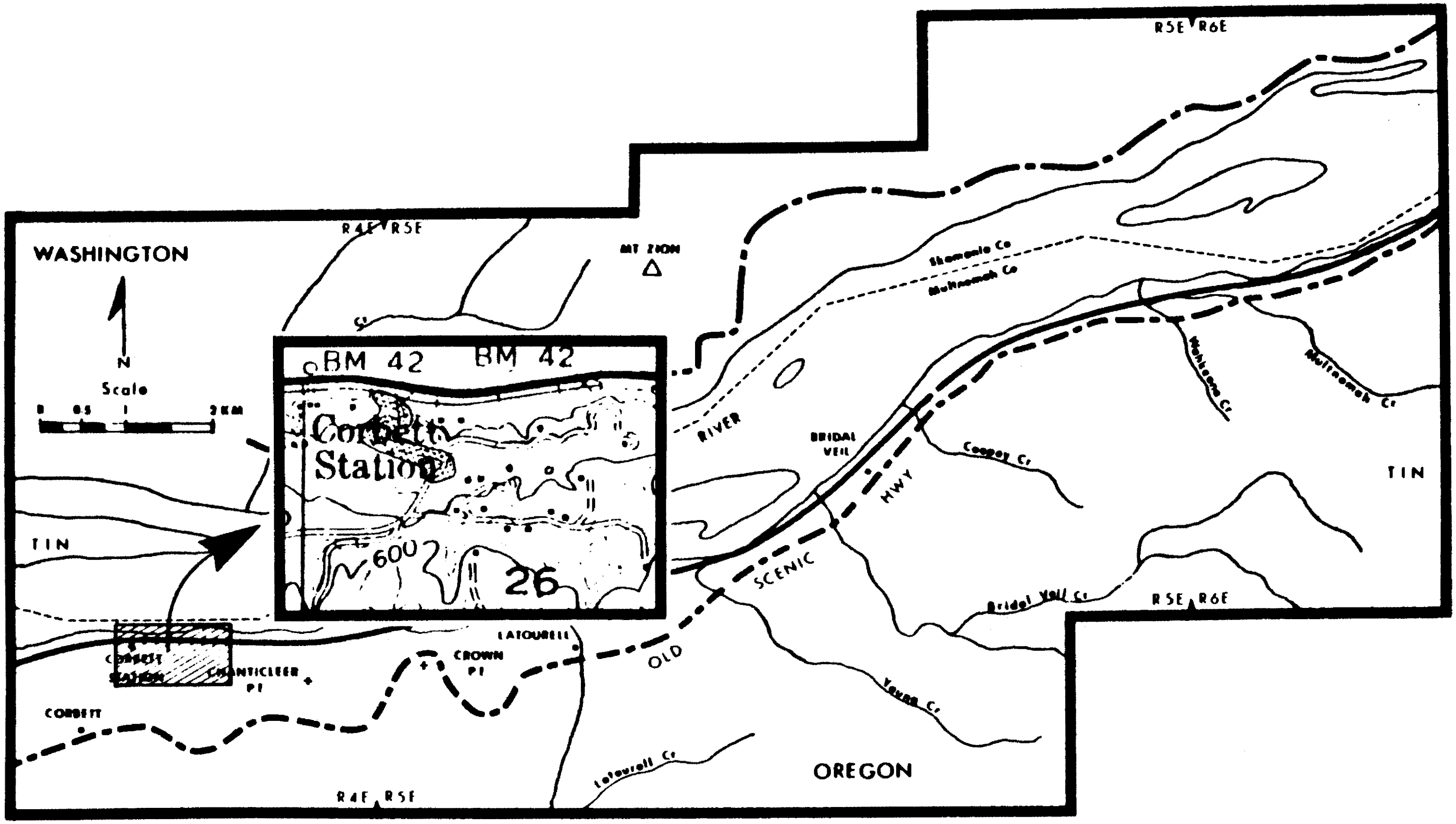


Figure 51. Location map of Corbett Road section. Inset shows traverse path (stippled).

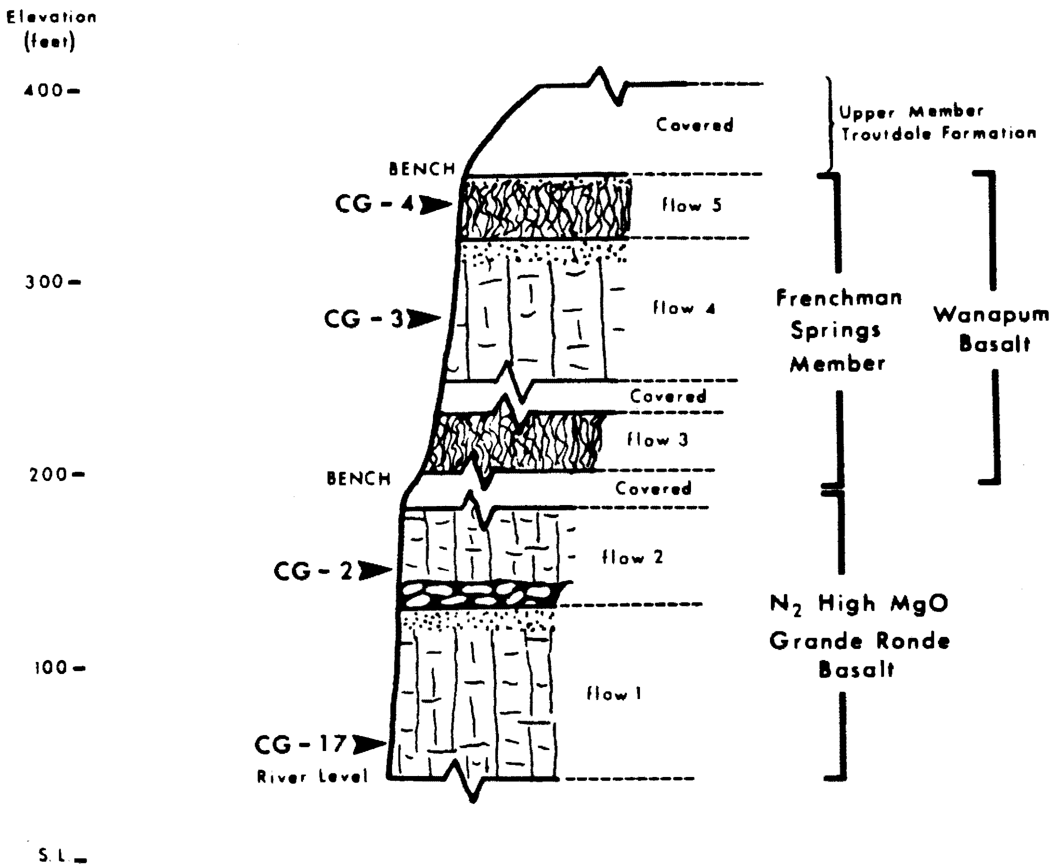


Figure 52. Corbett Road section.