AN ABSTRACT OF THE THESIS OF

DONALD JAMES PARKER for the DOCTOR OF PHILOSOPHY
(Name) (Degree)

in GEOLOGY presented on April 5, 1974
(Major) (Date)

Title: PETROLOGY OF SELECTED VOLCANIC ROCKS OF THE HARNEY BASIN, OREGON

Redacted for Privacy

Abstract approved: ______________________
Dr. Harold E. Enlows

The volcanic rocks of the Harney Basin comprise a bimodal assemblage of rhyolites (SiO_2 greater than 72%) and basalts (SiO_2 less than 52%). Tholeiitic basalts account for 15 rocks analyzed and alkalic basalts for three. Most basalts contain phenocrysts of olivine and plagioclase. Pyroxene phenocrysts were not found. Rhyolite flows are peraluminous and contain phenocrysts of hornblende, biotite, plagioclase, quartz, and sanidine. Rhyolite ash-flows are subaluminous and contain phenocrysts of quartz, alkali-spar, clinopyroxene, and magnetite.

Volcanism was apparently episodic with basalt and rhyolite erupted contemporaneously. Age dates of basalts are 2.6, 2.8, 7.0, and 8.9 m.y. and one andesite flow, 5.8 m.y. Rhyolite ages are 2.7, 5.6, 6.6, 8.2, 8.4, and 8.6 m.y. Basaltic volcanism has occurred during historic time.

Strontium isotope initial ratios of rhyolites (0.7035 and 0.7038) are similar to basalts (0.7033 and 0.7036) and both are as low as island arc rocks and distinctly higher than unaltered oceanic basalt. Strontium isotope initial ratios, Rb, K, and Sr data indicate the magmas were derived from a depleted mantle and perhaps contaminated (less than 15%) by crustal material.

The correlation of the Rattlesnake Ignimbrite Tongue over 50,000 km^2 in eastern Oregon is firmly established and the ash flow volume, excluding the airfall component, is estimated to be 930 km^3 magmatic volume. The Rattlesnake Ignimbrite Tongue is 6.6 ± 0.2 m.y. old and issued from fissure type vents in the Buzzard Creek-Alkali Lake area. The top of the magma chamber is estimated to be 6 km in depth and the eruption did not produce a caldera. The Rattlesnake Ignimbrite Tongue is a multiple flow simple cooling unit which is composed of at least two and possibly four flow units. Laminar flow occurred where thick accumulations of hot plastic ash-flow material were faulted soon after the eruption.

The various colors of shards and pumice of the Rattlesnake Ignimbrite Tongue and the ash-flow tuff of Devine Canyon are chemically distinct and the result of contamination which took place when basalt magma was introduced into the rhyolite magma chamber. This basalt "intrusion" produced boiling and eruption of the rhyolite magma.

Petrology of Selected Volcanic Rocks of the Harney Basin, Oregon

by

Donald James Parker

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

June 1974

Approved:

Redacted for Privacy

Professor of Geology

in charge of major

Redacted for Privacy

Chairman of Department of Geology

Redacted for Privacy

Dean of Graduate School

Date thesis is presented April 5, 1974

Typed by Clover Redfern for Donald James Parker

ACKNOWLEDGMENTS

The author would like to acknowledge the guidance of Harold E. Enlows in the pursuit of the thesis problem. His encouragement and flexibility allowed the author to explore all areas of interest as the thesis progressed.

Financial support for this study was provided by a Geological Society of America Penrose Bequest Research Grant, a Grant-in-Aid from the Research Committee of the American Association of Petroleum Geologists, and a Grant-in-Aid of Research from the Society of Sigma Xi.

The author would like to thank Cyrus W. Field for making possible study at Yale University. Special appreciation is extended to Richard L. Armstrong for his guidance and inspiration while the author studied at Yale University. Yale University deserves special thanks for its hospitality to the author during his stay.

George Walker is thanked for a stimulating discussion with the author just before thesis writing began.

It would not have been possible to complete this study without the financial assistance provided by Mr. and Mrs. Walter J. Parker and their constant encouragement.

The author is most grateful to Carol A. Parker for her assistance in this study.

TABLE OF CONTENTS

	Page
INTRODUCTION	1
PETROLOGIC SETTING	4
Blue Mountains	5
Cascades-High Lava Plateau	4
Idaho-Sierra Nevada Batholith Link	7
STRATIGRAPHY	8
Introduction	8
Ash-Flow Tuff of Devine Canyon	8
Tertiary Basaltic Rocks	11
Ash-Flow Tuff of Prater Creek	13
Rhyolite of Double O Ranch	15
Rattlesnake Ignimbrite Tongue	18
Introduction	18
Zonation	22
Laminar Flow	27
Multiple Flow	30
Petrography	34
Geomagnetic Polarity	38
Age Dating	38
Volume of Eruption	40
Source	40
Rhyolite of Palomino Butte	42
Tertiary Sedimentary Rocks	43
Rhyolite of Iron Mountain	43
Tertiary and Quaternary Basalt	44
Tertiary and Quaternary Sedimentary Rocks	46
Subaqueous Pyroclastic Deposits and Associated Cinder Cones	47
Alluvium	52
GEOCHEMISTRY OF SELECTED VOLCANIC ROCKS	54
Introduction	54
Geochemistry of Selected Basalts of the Harney Basin	54
Geochemistry of Selected Rhyolites of the Harney Basin	56
Strontium Isotope Data	70
Introduction	70
Comparison of Data	74
Isotope Constraints on a Model for the Generation of the Bimodal Chemical Assemblage in Oregon	76

Page

Origin of Basalt Magma Suggested by Strontium Isotope Data 78
Origin of Rhyolite Magma Suggested by Strontium Isotope Data 80
Conclusion from Strontium Isotope Data 82
H_2O Pressure in Rhyolite Magma at the Time of Eruption as an Indicator of Eruption Depth 83
Origin of Hybrid Glass and the Eruption of Ignimbrites in the Harney Basin 91

PETROGENESIS OF THE BIMODAL VOLCANIC SUITE 99

BIBLIOGRAPHY 103

APPENDICES
Appendix I: Whole Rock Major and Minor Element Analyses 112
Appendix II: K-Ar Age Dating--Analytical Techniques 114
Appendix III: Strontium Isotope Ratios--Analytical Techniques 117
Appendix IV: Locaton of Samples not Shown on Plate 1 118

LIST OF FIGURES

Figure		Page
1.	Location map of thesis area.	2
2.	Physiographic divisions of Eastern Oregon.	5
3.	Stratigraphic column showing relationships of major rock units.	9
4.	Nonwelded base of the ash-flow tuff of Devine Canyon.	11
5.	Aerial photograph showing circular trace of folia in rhyolite of Double O Ranch.	16
6.	Isopach map of pre-erosion distribution of the Rattlesnake Ignimbrite Tongue.	20
7.	Complete development of zonation in the Rattlesnake Ignimbrite Tongue as found at Alkali Lake.	23
8.	Partial development of zonation along the Silvies River north of Burns, Oregon.	24
9.	Photomicrograph of a fold in the foliated zone of the Rattlesnake Ignimbrite Tongue.	28
10.	Large scale folding in the Rattlesnake Ignimbrite Tongue as a result of laminar flow.	28a
11.	Multiple flow contact of Rattlesnake Ignimbrite Tongue on the south shore of Harney Lake.	31
12.	Multiple flow unit of Rattlesnake Ignimbrite Tongue.	32
13.	Photomicrograph showing mixed shards, clinopyroxene, and magnetite in Rattlesnake Ignimbrite Tongue.	36
14.	Photomicrograph showing mixed shards and anorthoclase in the Rattlesnake Ignimbrite Tongue.	36
15.	Basalt flow on Dog Mountain which is gradational into laminated scoria.	49

Figure		Page
16.	AMF diagram showing bimodal distribution of rocks in this study.	55
17.	Plot of total alkalis and SiO_2 for basalts of the Harney Basin.	56
18.	Normative compositions computed from chemical analyses of the peraluminous rhyolite flow rocks plotted in the system Q-Or-Ab.	85
19.	Normative compositions computed from chemical analyses of the ash-flow tuff of Prater Creek and related flow rocks plotted in the system Q-Or-Ab.	86
20.	Normative compositions computed from chemical analyses of the Rattlesnake Ignimbrite Tongue plotted in the system Q-Or-Ab.	87
21.	Normative compositions computed from chemical analyses of the ash-flow tuff of Devine Canyon plotted in the system Q-Or-Ab.	88
22.	Photomicrograph of Rattlesnake Ignimbrite Tongue showing light and dark shards.	93
23.	Electron microscope scan of the light and dark shards shown in square in Figure 22.	93

Plate		
1.	Geologic Map of the Harney Basin Area, Harney County, Oregon.	Folder

LIST OF TABLES

Table		Page
1.	Summary of Rattlesnake Ignimbrite Tongue regional correlation.	21
2.	Summary of petrographic data for the Rattlesnake Ignimbrite Tongue.	34
3.	Summary of petrographic data for the basalts.	53
4.	Chemical analyses of the late basalt type.	57
5.	Chemical analyses of the Wright's Point basalt type.	58
6.	Chemical analyses of the early basalt type.	59
7.	Chemical analyses of the alkalic basalt type.	60
8.	Chemical analyses of intermediate flow rocks.	67
9.	Chemical analyses of peraluminous rhyolite flow rocks.	69
10.	Chemical analyses of the ash-flow tuff of Devine Canyon.	71
11.	Chemical analyses of the ash-flow tuff of Prater Creek.	71
12.	Chemical analyses of the Rattlesnake Ignimbrite Tongue pumice.	72
13.	Chemical analyses of the Rattlesnake Ignimbrite Tongue shards and average of glasses.	72
14.	Summary of strontium isotope data.	73
15.	Average composition of glass from the Rattlesnake Ignimbrite Tongue, average tholeiitic basalt of this study, and a model hybrid glass.	92
16.	Average composition of glass from the ash-flow tuff of Devine Canyon, average tholeiitic basalt of this study, and a model hybrid glass.	97

PETROLOGY OF SELECTED VOLCANIC ROCKS OF THE HARNEY BASIN, OREGON

INTRODUCTION

The Harney Basin is located south of the Blue Mountains in Harney County, Oregon. The area studied consists of 2,300 km^2 bounded by longitdue 119'30" and 119' and latitude 43'30" and 43' (Fig. 1).

Episodic volcanism from Middle Pliocene to Holocene in age is represented by the volcanic rocks of the study area. These rocks are basaltic and rhyolitic in composition and are part of the bimodal chemical association common throughout the Basin and Range Province (Scott and others, 1971).

The purpose of this study is twofold; first, to complete regional correlation of the Rattlesnake Ignimbrite Tongue thus permitting its use as a time stratigraphic marker for much of eastern Oregon and second, to investigate the petrology of selected volcanic rocks emphasizing regional tectonics and the nature of the crust and mantle in this area.

This area was originally mapped on a reconnaissance scale by Piper, Robinson, and Park (1939) and more recently by Greene and others (1972). A study of the geology of the Malheur Wildlife Refuge was reported by Walker and Swanson (1968a). Walker has studied the

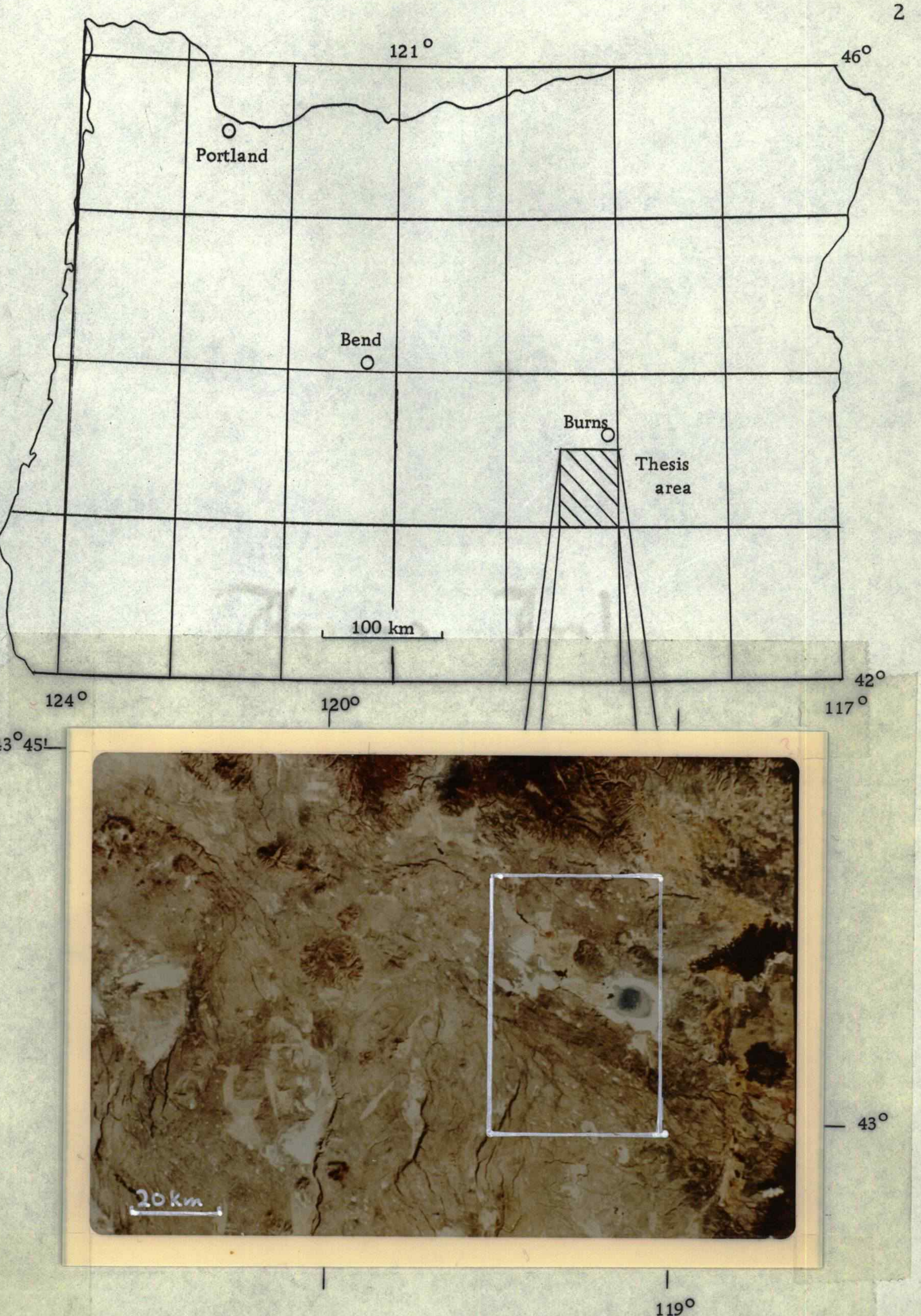

Figure 1. Location map of thesis area (ERTS photo).

Buzzard Creek area in detail (1969c). Niem has described and mapped the Wright's Point area (1974).

Locations of rock units described will be made in reference to sample locations which are shown on the geologic map (Plate 1). Locations of those samples not on Plate 1 are given in Appendix IV. The geologic time scale used is that used by the U.S. Geological Survey in eastern Oregon as outlined by Everden, Savage, Curtis, and James (1964).

PETROLOGIC SETTING

Blue Mountains

The area of study is bounded on the north by the Blue Mountains (Fig. 2). The Blue Mountains are primarily uplifted Pre-Tertiary marine strata, ophiolitic rocks, and granitic intrusions which are lapped upon by Tertiary volcanic rocks.

The Paleozoic rocks in the Blue Mountains range from Devonian to Permian in age. They were deposited in a tectonic environment associated with the margin of a continent or an island arc. Ophiolitic rocks, including the Canyon Mountain Magma Series, are found associated with the unconformity between the Permian and Upper Triassic strata (Thayer and Brown, 1964).

The Mesozoic rocks consist of volcanoclastics, submarine volcanics, argillites, rudites, and biostromal limestone, which also indicate an island arc environment.

Cascades-High Lava Plateau

The area of study is at the eastern extension of the Cascades-High Lava Plateau physiographic province (Fig. 2). The High Lava Plateau is composed of scarcely disected Plio-Pliestocene volcanic rocks of bimodal chemistry; basalt flows and rhyolite domes and ash flows (Waters, 1962).

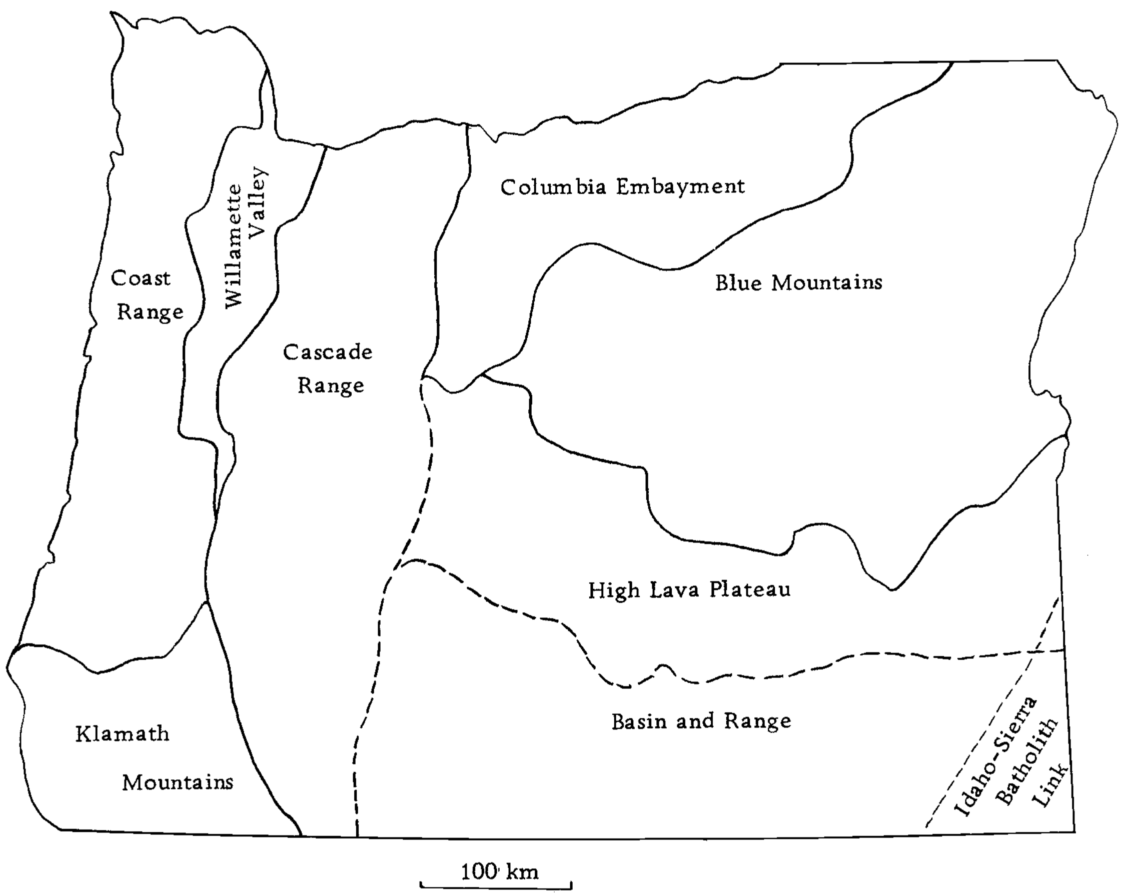

Figure 2. Physiographic divisions of Eastern Oregon. In part, after Baldwin (1964) modified by author.

The plateau merges to the west with the Cascades. The Cascades are composed of at least three chains of volcanoes. The two older chains, represented by the Little Butte, Sardine, and Deschutes formations, are andesitic in character. The third, today's High Cascades, has few andesitic volcanoes. Most of the volcanic peaks in the High Cascades are built of high alumina basalt.

Mt. Mazama, Newberry Crater, and Diamond Craters, all of Holocene age, attest to the continuing volcanic activity in the Cascades-High Lava Plateau.

Basin and Range

The Basin and Range Province lies south of the area of study and continues south into Nevada (Fig. 2). Most Basin and Range igneous rocks in Oregon are Plio-Pliestocene in age and make up a bimodal chemical assemblage.

Miocene age rocks of Steens Basalt that are correlative with the Columbia River Basalt are exposed in uplifted blocks (Walker, 1969a). The Steens Basalt is underlain by the Steens Mountain Volcanics which consist of basalts and andesites. The Steens Mountain Volcanics overlie the Pike Creek Formation of early Miocene age which is composed of dacite and rhyolite flows and ash flows.

Idaho-Sierra Nevada Batholith Link

Based on recent studies by Smith and others (1971) and Taubeneck (1971) the Idaho-Sierra Nevada Batholith link as defined by the quartz diorite line is far to the east of Moore's original line (Fig. 2). Basin and Range faulting in southeastern Oregon has brought to the surface outliers of the batholith along with Permian-Triassic metavolcanic and metasedimentary rocks.

STRATIGRAPHY

Introduction

The stratigraphic sequence is based upon rock units that are distinct and mappable in the field. The primary basis of definition for each unit is its individual field characteristics. Each unit is made up of rocks of generally the same age. K-Ar ages are included for some of the rocks described and more complete data on the age determination technique used and the ages obtained is included in Appendix II. Individual flows discussed will be identified as to chemical types which are defined in the geochemistry section.

The ignimbrites are important regional markers and are mapped and discussed as separate units. The basalt stratigraphy is based upon stratigraphic position and mode of eruption, for example, phreatic versus wide spread mesa basalt flows. A summary of petrographic data for these basalts is presented in Table 3 at the end of this section. A summary of the stratigraphy is diagrammatically shown in Figure 3.

Ash-Flow Tuff of Devine Canyon

The ash-flow tuff of Devine Canyon (Tdv, Plate 1) crops out in Tps. 28 and 29 S., Rs. 29 1/2, 29 1/4, and 30 E. This unit has been described in detail by Greene (1973). The ash-flow tuff of Devine

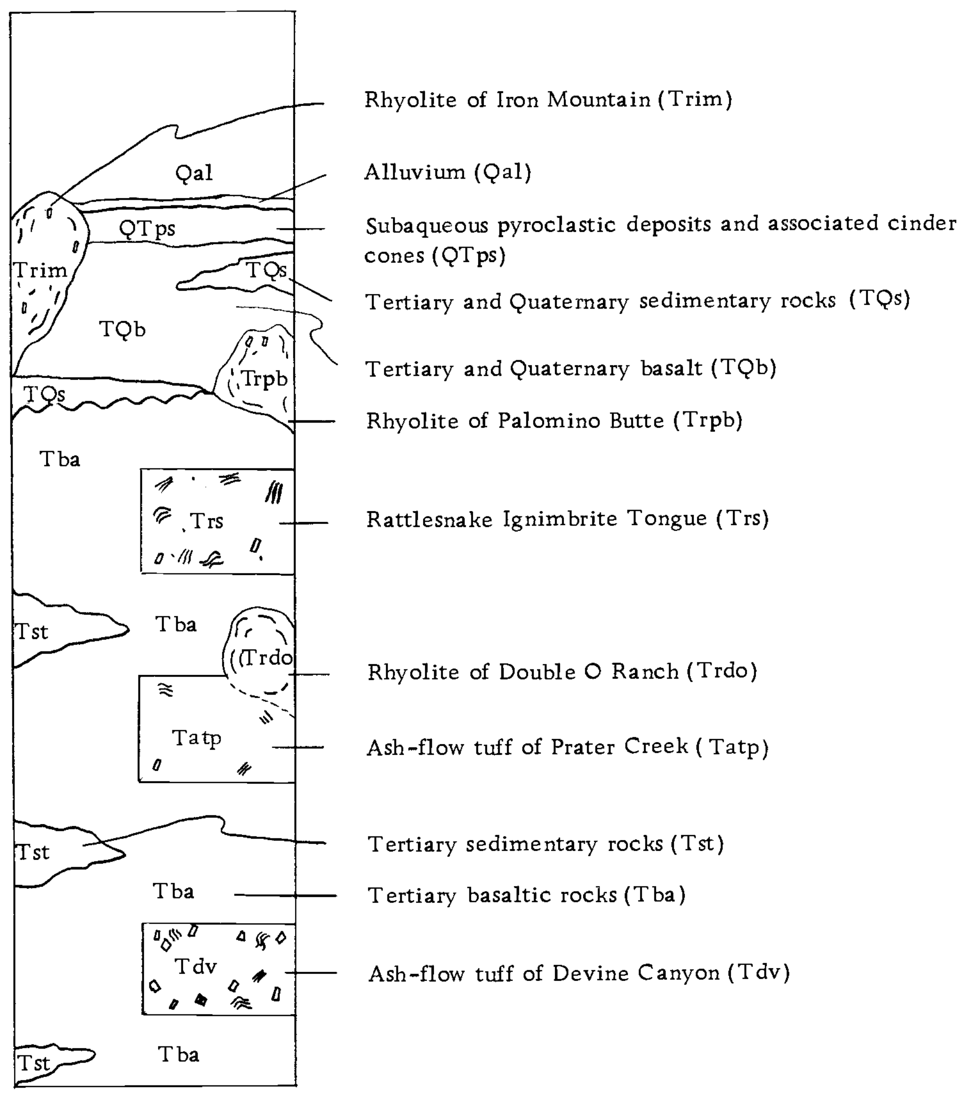

Figure 3. Stratigraphic column showing relationships of major rock units. Not to scale.

Canyon is exposed in an area where landslides have obscured it and mapping is based upon talus except for a small area of Tp. 29 S., R. 30 E., where poorly welded material crops out (DP-245). The tuff is 10 m thick and is overlain by basalt, however the base is not exposed. Small knobs of vitrophyre (protruding through slopewash) were found 1 km to the west (DP-243) of the last described location.

Five age dates for the ash-flow tuff of Devine Canyon were reported by Greene (1973) with an average of 9.2 m.y. An age of 7.1 ± 0.1 m.y. (App. II) was determined for sample DP-243 from an area where many basalt dikes are present and it is suggested that reheating of the flow has resulted in a loss of argon thus resetting the K-Ar clock. The 7.1 m.y. age obtained is close to the age of nearby basalt flows overlying this unit (DP-250). The correlation of the ash-flow tuff of Devine Canyon was based upon stratigraphic position and distinctive mineralogy. This unit was found beneath the ash-flow tuff of Prater Creek. The cognate minerals found were alkali feldspar, quartz, pyroxene and opaque minerals. This assemblage was reported by Greene for the ash-flow tuff of Devine Canyon (1973) and is not found in any of the other major ash-flow sheets in the region.

In the area south of Harney Lake, Devine Canyon, and Diamond Valley, the ash-flow tuff of Devine Canyon contains abundant pumice of different colors in fragments up to 0.6 m in diameter (Fig. 4).

Figure 4. Nonwelded base of the ash-flow tuff of Devine Canyon. Note black and white pumice.

Tertiary Basaltic Rocks

Basaltic rocks found below the Rattlesnake Ignimbrite Tongue, with the exception of one andesite flow make up Tertiary basaltic rocks (Tba, Plate 1). This unit includes basalts of tuffaceous sedimentary rocks, basalt, and welded tuff (Tob) and basalt and andesite

(Tba) of Greene and others (1972). This unit is of limited areal extent croping out just west of Iron Mountain in Tps. 28 and 29 S. and Rs. 29 1/2, 29 3/4 and 30 E. and in T. 26 S. and R. 29 E.

Sample DP-73-4 is from a flow of basalt which underlies the Rattlesnake Ignimbrite Tongue near the mouth of Jackass Creek that was mapped by Greene and others (1972) as basalt and andesite (Tba) and by Piper and others (1939) as Steens Basalt. Sample DP-73-4 is from the top flow in a sequence of three flows totaling 60 m in thickness. A thin section of this flow displayed phenocrysts of plagioclase and olivine in an intergranular groundmass with some pyroxene subophitically enclosing plagioclase.

Sample DP-300 was taken from a flow across Jackass Creek from DP-73-4 and is similar in chemical composition, both are members of the early basalt chemical type (Table 6). Sample DP-300 is 8.8 m.y. old and is the oldest basalt dated (App. II). The age of this flow excludes it from being a flow of the Steens Basalt or of basalt and andesite (Tba) as defined by Greene and others (1972). This flow contained phenocrysts of olivine and plagioclase in an intersertal matrix of plagioclase, clinopyroxene, olivine, opaques, and glass.

Sample DP-278 is from an erosional remnant of basalt lapped upon by the Rattlesnake Ignimbrite Tongue 4 km west of Jackass Creek. This flow contains phenocrysts of plagioclase and olivine in a very finely crystalline matrix of clinopyroxene, plagioclase, opaques, olivine, and glass in an intersertal relationship. Isolated areas of pyroxene subophitically enclosing plagioclase were also found in DP-278.

Included in Tertiary basaltic rocks (Tba) is a flow of andesite which belongs to the intermediate flow rock chemical type that overlies the Rattlesnake Ignimbrite Tongue west of Iron Mountain. It was determined to be 5.8 m.y. old (App. II) which is consistent with its stratigraphic position above the 6.6 m.y. old Rattlesnake Ignimbrite Tongue. This andesite flow contains phenocrysts of plagioclase and olivine in a matrix of granular plagioclase, pyroxene, opaques, and glass.

Ash-Flow Tuff of Prater Creek

Informally named by Greene and others (1972), the ash-flow tuff of Prater Creek (Tatp, Plate 1) is present in three isolated localities in the area of study. Recognition of this unit was based upon its stratigraphic position, K-Ar age, whole rock chemical analysis, and distinctive petrography.

The ash-flow tuff of Prater Creek was placed in the Pliocene epoch by Greene and others (1972) and lies stratigraphically below the Rattlesnake Ignimbrite Tongue and above the ash-flow tuff of Devine Canyon. Whole rock samples from two localities were determined to be 8.2 m.y. old (App. II). Sample DP-311B was taken below the

Rattlesnake Ignimbrite Tongue in the Buzzard Creek area and sample DP-119 was from a prominent scarp near the Double O Ranch mapped as Rattlesnake Ignimbrite Tongue by Walker (Green and others, 1972). Three samples were analyzed for major and minor elements (Table 11) and are correlated with the ash-flow tuff of Prater Creek based upon the similarity of K_2O, Na_2O, TiO_2, and minor element abundances. These analyses resemble those reported by Davenport (1970).

The ash-flow tuff of Prater Creek is a completely devitrified ash-flow with alkali feldspar and quartz phenocrysts and rare pumice fragments (Davenport, 1970; Green and others, 1972). Five thin sections were examined and cognate minerals were not found. Pumice was common but difficult to recognize due to the development of eutaxitic texture and complete devitrification.

The outcrop represented by sample DP-119 is at least 30 m thick because the bottom contact is not exposed. This is the thickest section observed and is more than twice as thick as the 7 to 12 m reported by Greene and others (1972). This outcrop displays lithophysae up to 7 cm in diameter, laminar flow, and eutaxitic texture. It is suggested that the laminar flow, indicative of high fluidity, and large lithophysae are a result of high vapor content and high temperature that would be associated with thick accumulations of ash-flow material close to the source of the flow.

Rhyolite of Double O Ranch

The rhyolite of Double O Ranch (Trdo, Plate 1) crops out in Tps. 26 and 27 S., Rs. 28 and 29 E. and covers approximately 15 km^2 southwest of the Double O Ranch. This unit consists of a cumulo-dome and related flows not part of the dome. All flows display flow banding paralleled by vesicles and fracture surfaces.

Two K-Ar ages were obtained for this unit. Sample DP-316D taken one-half kilometer southwest of the Double O Wildlife Station was determined to be 7.8 m.y. old (App. II). The rhyolite of this location exhibits large scale flow banding which can be traced two miles to the south. Measurements of fracture surfaces parallel to flow folia suggest this flow is a cumulo-dome. The circular trace of the folia in aerial view (Fig. 5) and folia dipping inward at the bottom and dipping outward at the top of the dome attest to its cumulo character.

A flow cropping out 5 km southwest of the Double O Ranch gave an age of 8.4 m.y. (DP-146, App. II) and is overlain by the Rattlesnake Ignimbrite Tongue. This flow and associated flows display flow banding paralleled by fractures and vesicles.

Figure 5. Aerial photograph showing circular trace of folia in rhyolite of Double O Ranch.

Thin sections of three samples of the rhyolite of Double O Ranch were examined. Sample DP-146 is composed of extremely fine crystalline plagioclase and unrecognizable minerals in a flow aligned felty mesh with a glass matrix. Abundant plagioclase and glomero-porphyritic basalt fragments occur in sample DP-145 in a matrix identical to sample DP-146. Crystals in the basalt fragments are embayed and are surrounded by glass darker than the glass of the matrix. The exotic basalt fragments have been partly assimilated. The glass in DP-146 and DP-145 is brown in contrast with the colorless glass of sample DP-316D which contains flow aligned microlites of plagioclase. Sample DP-316D contains abundant "clots" of glomeroporphyritic olivine, clinopyroxene, and plagioclase. Brown glass, observed streaming from crystals of olivine and pyroxene gives a color banded appearance to the rock. Cognate phenocrysts were not found in the three thin sections studied.

The K-Ar age dates of the rhyolite of Double O Ranch are the same as the ash-flow tuff of Prater Creek within the error of the technique and sample variations (App. II). Therefore, it is proposed that the rhyolite of Double O Ranch is a dome and flows associated with the eruptive center of the ash-flow tuff of Prater Creek. This conclusion is strengthened by close resemblance in major and minor elements between chemical analyses of samples DP-146 and DP-316D of the rhyolite of Double O Ranch and samples DP-119 and DP-290 of the ash-flow tuff of Prater Creek (Tables 9 and 11).

The rhyolite of Double O Ranch and the ash-flow tuff of Prater Creek have similar petrographic characteristics in mutual absence of phenocrysts. Their absence suggests that both were at a temperature above the liquidus prior to eruption.

The eruption center located on the southwest edge of the Harney Basin lowland is obscured by Pleistocene and Recent sedimentation. Laminar flow in the ash-flow tuff of Prater Creek (DP-119) on the south shore of Harney Lake near Double O Ranch dips toward the lake. Whether or not this attitude is original or a result of later faulting and tilting could not be determined.

Rattlesnake Ignimbrite Tongue

Introduction

The Rattlesnake Ignimbrite Tongue (Trs, Plate 1) was described and assigned by Merriam (1901) as a member of the Rattlesnake Formation in the John Day Valley. The tongue was first described in the Harney Basin as the tuff breccia member of the Danforth Formation by Piper and others (1939) but they did not recognize the tuff breccia member as correlative to the Rattlesnake Ignimbrite Tongue of the John Day Valley. Campbell and others (1958) first suggested these two units were part of one ash-flow sheet. The same conclusion was reached by Davenport (1970), Beason (1969), and Greene and others (1972). In the Harney Basin this unit was informally named the ash-flow tuff of Double O Ranch by Greene and others (1972) after exposures near the Double O Ranch. Enlows, Parker, and Davenport (1973) suggested that the name Rattlesnake Ignimbrite Tongue be retained throughout its entire extent in keeping with the definition of a formation tongue given in the code of stratigraphic nomenclature (American Commission on Stratigraphic Nomenclature, 1972). The previously informal regional correlation of this ash-flow will be placed on a firm basis.

The Rattlesnake Ignimbrite Tongue as delineated by present outcrops originally covered approximately 50,000 km^2 in eastern Oregon

(Fig. 6). The area outlined includes poorly welded to highly welded tuff and does not include the possible distribution of an airfall component of the eruption. Correlation of this unit throughout much of eastern Oregon was by field mapping, stratigraphic position, field appearance, distinctive petrography, magnetic polarity, K-Ar dating, and major element chemical analyses.

Field mapping by H. E. Enlows (unpublished data) in the John Day Valley, Walker and Repenning (1965), Davenport (1970), Greene (1972), Greene and others (1972), and the author in the Harney Basin and surrounding area to the west and south has revealed almost continuous outcrop. The least control is in the valleys of the Blue Mountains. The author has correlated an ash-flow tuff in the Hart Mountain Antelope Refuge (DP-72-24, App. IV) with the Rattlesnake Ignimbrite Tongue. This unit was part of Walker and Repenning's (1965) tuffaceous sedimentary rocks (Tst) which included many sedimentary rocks and ash-flow tuffs. The western most exposure of the ignimbrite is believed to occur on the east rim of Christmas Lake Valley (DP-72-58, App. IV). East of Harney Lake two outcrops were found (DP-72-77, DP-72-78, App. IV) with the easternmost outcrop 10 km east of Crane. The criteria for the foregoing correlations are summarized in Table 1 and discussed in detail in the following sections.

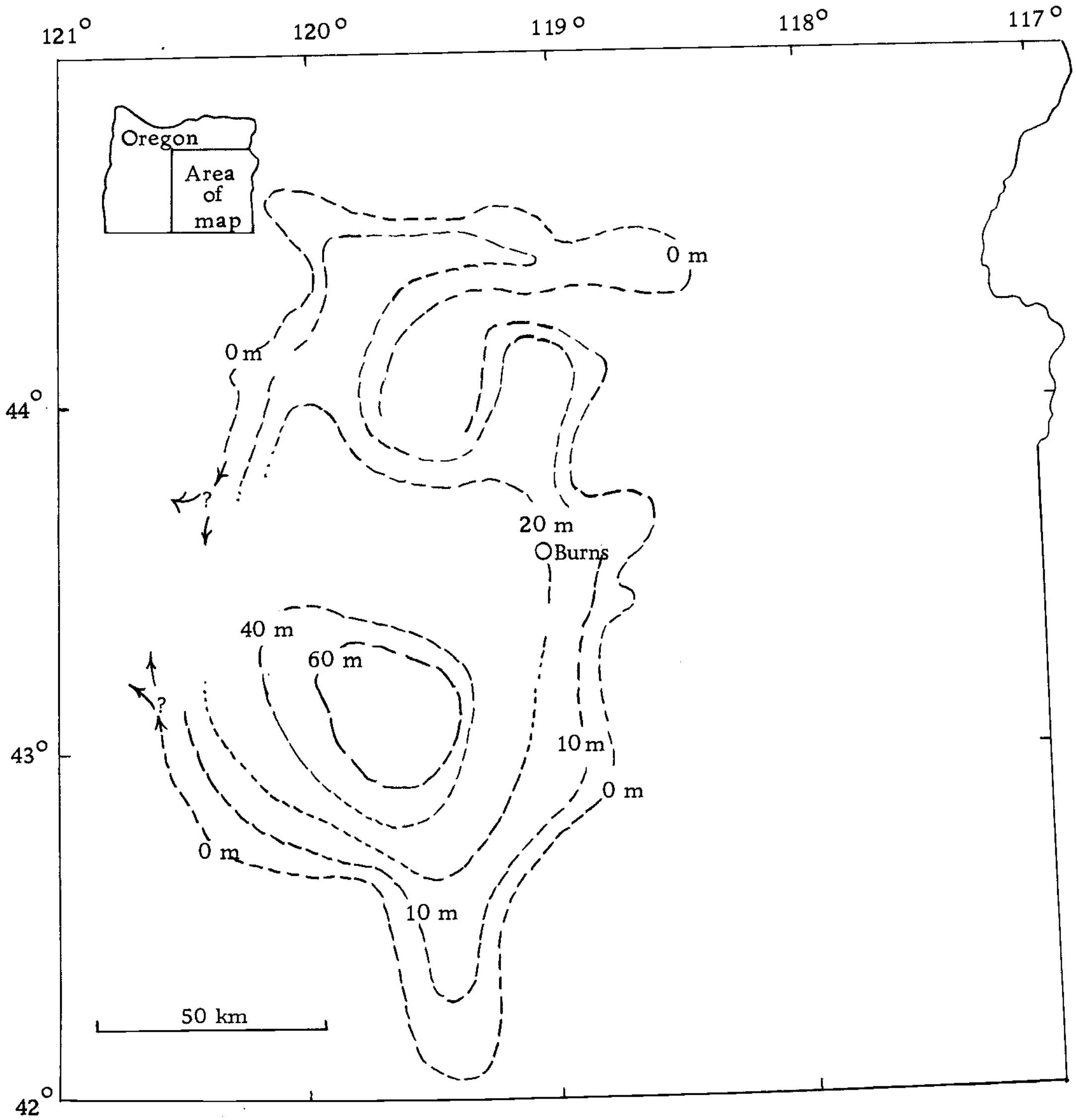

Figure 6. Isopach map of pre-erosion distribution of the Rattlesnake Ignimbrite Tongue.

Table 1. Summary of Rattlesnake Ignimbrite Tongue regional correlation.

Area	Criteria					
	Map Control	Mixed Shards and White Pumice	Mixed Pumice	Cognate Crystals	Polarity	Age (m.y.)
Monument	no	yes	no	yes	reverse	6.4
John Day Valley	yes	yes	no	yes	reverse	6.4
Paulina[1] Basin	yes	yes	yes	yes	reverse	6.5
Burns[2]	yes	yes	yes	yes	reverse	6.8
Buzzard Creek	yes*	yes	yes	yes	reverse	6.6[3]
Alkali Lake	yes*	yes	yes	yes	reverse	n.d.
Hart Mountain	yes*	yes	yes	yes	reverse	n.d.
Christmas Lake	yes*	yes	yes	yes	n.d.	n.d.
Crane	no	yes	no	yes	n.d.	n.d.

[1]Data from Enlows, oral communication.

[2]Data from Davenport, 1970.

[3]Data from Greene and others, 1972.

*A 17 km gap in outcrop occurs across the Harney Basin lowland but all locations indicated by an * are connected by continuous outcrop.

Zonation

The development of zonation as a result of welding and crystallization is discussed in detail by Lund (1966), Davenport (1970), and Walker (1969c). The most complete development of zonation in the Rattlesnake Ignimbrite Tongue is in the Buzzard Creek-Alkali Lake area.

Illustrated in Figure 7 is the character of zonation in this area and is adapted in part from Walker (1969c). The terminology given in Figure 7 will be used in the discussion of zonation in the ignimbrite. The formation of zonation in any section of tuff depends upon original thickness, temperature, volatile content, surface water, and depositional slope. Where the flow is thin or far from the source zonation originates from welding and crystallization zonation is not present. The upper spherulitic zone and the foliated zone are absent in thin sections near the source and in thick sections at intermediate distances from the source. The foliated zone is present only in the thickest sections near the source. Illustrated in Figure 8 is the development of zonation along the Silvies River (DP-10, App. IV) 50 km from the source area of the flow where upper spherulitic and foliated zones are absent.

The air-fall zone is present in the Harney Basin wherever the bottom of the flow is exposed. This zone is composed of white

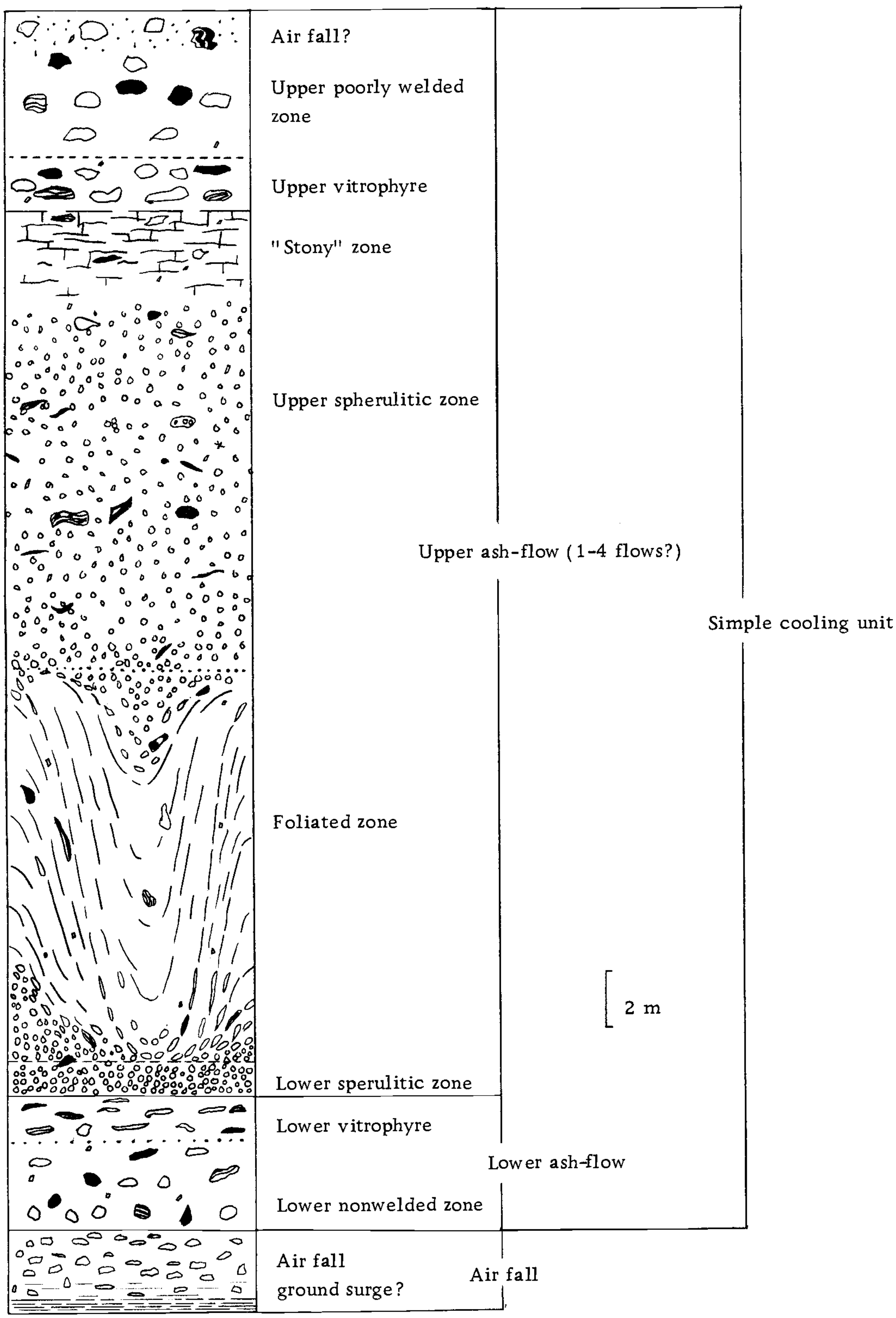

Figure 7. Complete development of zonation in the Rattlesnake Ignimbrite Tongue as found at Alkali Lake.

pumice lapilli which display either crude horizontal bedding or no bedding whatsoever. This zone ranges from 1 to 3 m in thickness.

Figure 8. Partial development of zonation along the Silvies River north of Burns, Oregon (DP-10, App. IV). Note that the upper spherulitic zone and foliated zone are not present.

Overlying the air-fall component of the ignimbrite is the first ash-flow component which is divided into the lower nonwelded zone and the overlying vitrophyre zone. The lower nonwelded zone is composed of white shards and lapilli sized white pumice fragments that exhibit little compaction. The lower nonwelded zone grades upward into the vitrophyre. The vitrophyre displays eutaxitic texture and collapse of pumice fragments. The white pumice fragments, upon compaction and welding, form dense black striated lenses that provide evidence of their origin. Lithic fragments consist primarily of basalt and are common in the lower ash-flow.

The lower ash-flow unit may be 6.5 m thick with as much as 3 m of ash grading into 3.5 m of vitrophyre. The welding of the upper part of this flow was due in part to reheating and fusion caused by the great thickness of the overlying second ash-flow.

The second ash-flow is divided into six zones. The lower spherulitic zone, as much as 2 m thick, is characterized by abundant spherulites displaying radial structure. This zone is strongly compacted and completely crystallized. The lower spherulitic zone rapidly grades into the overlying foliated zone which is 6 to 30 m thick. It is devitrified and contains lithophysal cavities lined with products of vapor phase crystallization. The high degree of compaction and laminar flow are responsible for the foliation in this unit. Pumice fragments are discoid to thread-like in form and their original color is unrecognizable. Generally the foliation is a result of compaction and minor laminar flow without internal structure. In a few places laminar flow has resulted in complicated structure which involves all zones above the vitrophyre except the top unwelded zone.

The foliated zone grades over a distance of several meters into the upper spherulitic zone which is 3 to 60 m in thickness. The upper spherulitic zone is similar to the lower spherulitic zone in that the dominant feature is abundant spherulites. This zone also contains lithophysae lined with vapor phase minerals. Devitrification has destroyed original textures. Compaction has resulted in flattened pumice fragments but foliation has not been developed. The upper spherulitic zone crops out either as rounded nobs and boulders or as convex slopes devoid of vegetation.

The upper spherulitic zone grades upward into a layer Walker (1969c) named the "stony zone." This zone displays a prominent platy fracture, little compaction, and is devoid of foliation. It has undergone devitrification to a dense grey "stony" rock. The "stony zone" is 1 to 2 m thick.

Overlying the "stony zone" is the upper vitrophyre zone which in turn grades into the upper poorly welded zone. The upper poorly welded zone is not commonly present due to its ease of erosion. The upper vitrophyre zone and upper poorly welded zone are found in the Buzzard Creek area and in downfaulted blocks on the south shore of Harney Lake. The unwelded zone reaches a maximum of 3 m in thickness south of Harney Lake. The maximum thickness of the upper vitrophyre zone is about 1 m and occurs in the Buzzard Creek area.

Important anomalies in zonation occur in the Buzzard Creek area as a result of laminar flow and were discussed by Walker (1969c). They will be discussed in detail and an alternate hypothesis for their origin will be proposed.

Laminar Flow

Laminar flow is well represented in the vicinity of Buzzard Creek (Walker, 1969c). However it is not confined to that area (Plate 1) and is present throughout the area between Harney Lake and Alkali Lake 70 km to the southwest.

Laminar flow is most easily recognized by distortion of pumice fragments. Where compaction is the only force imposed on pumice fragments, they deform to flat disk shaped fragments. These disks become elongated by laminar flow. The elongation of shards and pumice during laminar flow imparts a lineation on the surfaces of foliation. Laminar flow also produces folds on both a microscopic and macroscopic scale. Microscopic folds occur in "shadows" of crystals and other undeformed fragments in the flow (Fig. 9). Macroscopic folds are best developed in the Buzzard Creek area and in the cliff ease of Alkali Lake (Plate 1 and Fig. 10).

Laminar flow and macrofolding occur in small areas of crystallization zones above the vitrophyre zone and below the top unwelded zones. Both laminar flow and folding may have occurred before zonation (Walker, 1969c). However, folding and flow continued after welding and crystallization. Elongation of spherulites and lithophysae into elipsoids with long axis parallel to the lineation and in the plane of the folia indicate flow occurred after the development of zonation.

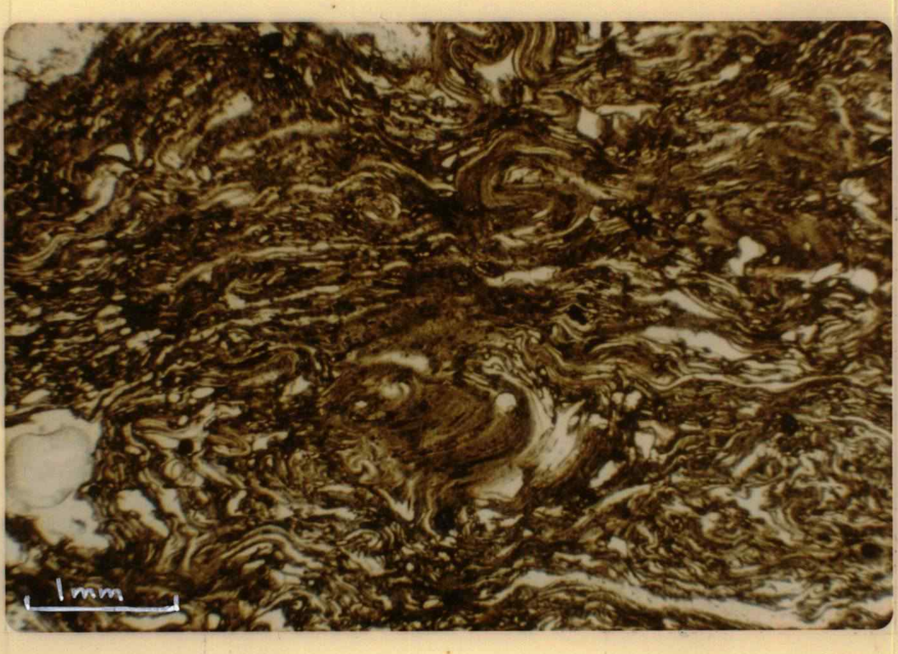

Figure 9. Photomicrograph of a fold in the foliated zone of the Rattlesnake Ignimbrite Tongue.

The amplitudes of folds range from microscopic to 30 m at Buzzard Creek and in excess of 50 m at Alkali Lake. The folds are closed and slightly assymetrical with some fold limbs steepened to become isoclinal. The axis of the major folds parallel northwest faults in the Buzzard Creek area. The fault scarp on the southwest

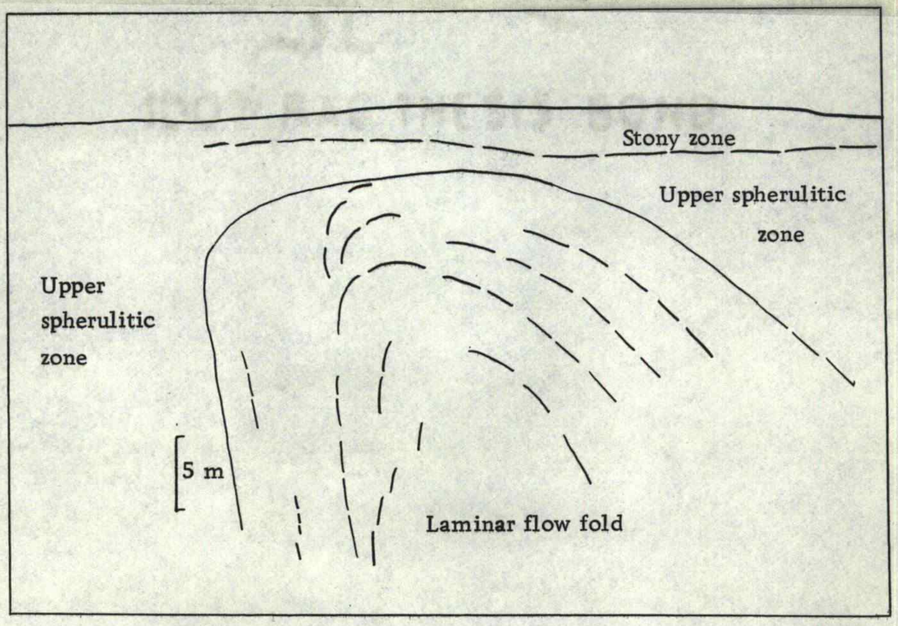

Figure 10. Top: Large scale folding in the Rattlesnake Ignimbrite Tongue as a result of laminar flow.
Bottom: Line drawing of above photo emphasizing fold and zonation relationships.

See Walker (1969c), p. C14, for sketch of same outcrop bank of Buzzard Creek exhibits a limb of a fold for a distance of 3 km. Due to the lack of three dimensional control, few fold orientations could be measured.

From the above data and an exposure on the west wall of the south fork of Buzzard Creek, Walker (1969c) has concluded that these features are a result of fissure eruption. The author investigated the exposure and found it to be consistent with laminar flow within the unit. The sketch of Walker (1969c, Fig. 6) shows lineation approaching the bottom of the unit at a high angle and talus covering the critical point where the foliation was thought to cut the vitrophyre. It is concluded that the break in the vitrophyre at this point is the result of faulting that was contemporaneous with the cooling of the unit. The unit flows in laminar fashion over a small scarp at this point. A basalt flow below the talus area also lies below the tuff a few meters away from the outcrop in question. A similar fault was observed a few kilometers to the east (DP-258). At this locality, offset in the vitrophyre of 3 m caused the horizontal flow lines to change abruptly to vertical flow lines within the spherulitic zone.

The laminar flow features of the Buzzard Creek and Alkali Lake areas are not a result of intrusion or feeder dikes but are related to post-depositional tilting and faulting of still plastic material. Laminar flow and related faulting occur in a restricted area and probably formed by collapse following the withdrawal of the erupted material at depth. Only in the Buzzard Creek area were faults interpreted to be contemporaneous with laminar flow. Thus it is concluded that Buzzard Creek is near the source area.

Multiple Flow

The Rattlesnake Ignimbrite Tongue is a simple cooling unit and compound flow unit composed of at least two and perhaps as many as five flows. The multiple flow characteristic is well exposed in outcrops on the south shore of Harney Lake (DP-64) and west and southwest of the lake extending to Alkali Lake. It is dramatically shown by sharp color breaks in outcrops on the south shore of Harney Lake (DP-64) and near Iron Mountain (DP-165). The break in color is gradational over distances of one to several centimeters (Fig. 11). This gradation may be an imperceptible change in color or sharply outlined wave or flame-shaped protrusions of one color into the other. Joint patterns developed during cooling continue undisturbed through this color break. Some outcrops display a difference in erosional resistance leaving a notch at the color break. The joints continue undisturbed through the notch. A channel of the upper unit in the lower unit was observed (Fig. 12, DP-177). The channel is outlined by a color break and fan joints in the channel itself. The fan joints approach the bottom of the channel perpendicularly and continue through the interface between the two flow units and bend to become perpendicular to the bottom surface of the flow. The upper unit thins and wedges out against a pre-eruption high on the south shore of Harney Lake (DP-79).

Figure 11. Multiple flow contact of Rattlesnake Ignimbrite Tongue on the south shore of Harney Lake (DP-64).

The distribution of shard and pumice types also reflects the compound flow nature of the Rattlesnake Ignimbrite Tongue. At outcrops where the base of the ash-flow sheet is exposed it is

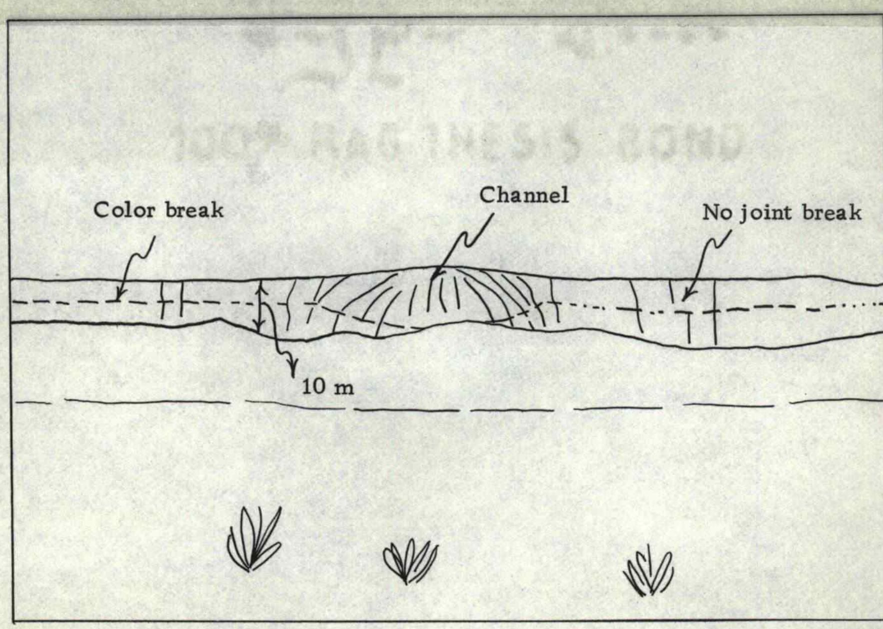

Figure 12. Top: Multiple flow unit of Rattlesnake Ignimbrite Tongue. Note channel of upper flow unit in lower flow unit marked by fan jointing (DP-177).
Bottom: Line drawing of above photo emphasizing flow relationships.

immediately underlain by a bed of laminated or massive white pumice lapilli. This layer is overlain by consolidated ash that grades upward into vitrophyre. This ash contains occasional white pumice lapilli and, including the vitrophyre, varies from 1 to 3 m in thickness. Mixed shards and pumice, to be described later, occur in all zones above the vitrophyre. Davenport (1970) reported mixed shards and pumice in the base of the unit in the Paulina Valley. Where mixed shards and pumice occur throughout the flow it is proposed that the lowest flow unit was not deposited or was completely eroded away by the second or later flows.

Indirect evidence for multiple flows can also be found in the thick devitrified spherulitic and lithophysal zones of the unit. Lithophysal and spherulitic zones up to 100 m thick form as many as six benches upon erosion. These benches which may mark individual flow contacts are present at several localities throughout the Harney Basin area but are best developed southwest of Harney Lake (DP-251 and DP-88). Devitrification and effects of vaporphase activity have obscured or destroyed evidence of the original flow contacts except for the difference in resistance to erosion of flow units. A qualitative difference in pumice abundance and size may be present at some localities but is difficult to quantify because of devitrification effects.

Petrography

The petrography of the Rattlesnake Ignimbrite Tongue has been described by Davenport (1970), Walker (1969c), Oles and Enlows (1972), and Enlows (1973). The author found the same cognate mineral assemblage of anorthoclase, pyroxene, and opaques, comprising less than 1% of the flow (Table 2). Distinct color groups of shards and pumice were first reported by Davenport (1970) and were also found in this study.

Table 2. Summary of petrographic data for the Rattlesnake Ignimbrite Tongue.

Sample	DP-166-5	DP-166-4	DP-166-3	DP-166-2	DP-166-1
Position	Base				Top
Phenocrysts					
Quartz	absent	absent	absent	absent	absent
Anorthoclase	yes	yes	yes	yes	yes
Pyroxene	yes	yes	yes	yes	yes
Magnetite	yes	yes	yes	yes	yes
Shards					
Light	65%	70%	70%	65%	n. d. *
Dark	35%	30%	30%	35%	n. d.
Pumice					
Light	yes	yes	yes	yes	n. d.
Dark	yes	yes	yes	yes	n. d.
Mixed	yes	yes	yes	yes	n. d.

*Not determined.

The anorthoclase phenocrysts are euhedral and range from 0.1 to 0.3 cm in length. Anorthoclase was rimmed by brown glass where it is found to have a coating of glass. Anorthoclase is often found in clusters with pyroxene and opaque minerals resulting in a cumulophyric texture.

The different colors of shards and pumice is a feature unique to the Rattlesnake Ignimbrite Tongue as compared to the other tuffs of eastern Oregon. Shards of the ash-flow tuff of Devine Canyon, ash-flow tuff of Prater Creek, Mascall ignimbrite, and Dinner Creek Welded Tuff are uniform in color. In contrast, shards of the Rattlesnake Ignimbrite Tongue can be divided into light (white) and dark (brown of various shades) groups (Figs. 13 and 14). Dark shards are 1 cm in length and light shards are 3 cm in length based upon the average measured length of ten shards for each type in the 50 thin sections analyzed. The shard sizes may be a result of viscosity differences in a chemically inhomogeneous magma. The chemical inhomogeneity of the shards will be discussed later.

Light colored shards are the exclusive component of airfall bedded ash deposits immediately below the welded ash-flow. They are also the exclusive component of the lower vitrophyre zone at many locations. At Alkali Lake (DP-72-86, App. IV) and Silvies River (DP-10, App. IV) white shards comprise the entire lower vitrophyre zone, the spherulitic zones, foliated zone, stony zone, and upper poorly welded zone.

Figure 13. Photomicrograph showing mixed shards, clinopyroxene, and magnetite in Rattlesnake Ignimbrite Tongue. Note rim of brown glass coating the crystals (plain light).

Figure 14. Photomicrograph showing mixed shards and anorthoclase in the Rattlesnake Ignimbrite Tongue (plain light).

Chemical analyses of the light and dark colored shards (Table 13) show them to be chemically distinct in both major oxide and minor element abundances. Analyses of light and dark pumice show them to be compositionally similar to the light and dark groups of shards (Table 12). The light pumice is found beneath the base of the tuff unit as a lapilli tuff that is interpreted to be part of the sequence of deposition of the ash-flow. Light pumice is found throughout the vitrophyre zone and is the only pumice component in the Rattlesnake Ignimbrite Tongue in the John Day Valley (Enlows, 1974, oral communication). Light, dark, and banded pumice are found in the Paulina Basin (Davenport, 1970), and throughout the Harney Basin and the areas to the south and west.

The pumice varies in size within individual outcrops and throughout the flow. It is concluded that the size of the pumice increases as the Harney Basin is approached from all directions. Pumice was most abundant and largest south of Harney Lake in the Buzzard Creek area. Quantitative measurement of pumice size and abundance was not practical because eutaxitic texture, laminar flow, and devitrification make recognition of pumice difficult. The following estimates of pumice size and abundance are the result of qualitative field observations. In the Buzzard Creek area most pumice in the zones of the Rattlesnake Ignimbrite Tongue affected by laminar flow is in excess of 10 cm in length and occasionally in excess of 60 cm in length. The largest observed pumice fragment was a banded piece 1.5 m in length and 0.5 m in diameter. Pumice increases in size and abundance from the base to the top of the flow. Distinction of pumice types is impossible in the crystallized and vitrophyre zones. Thus, variation in abundance of pumice types could not be determined.

Geomagnetic Polarity

The geomagnetic polarity of several oriented samples of the Rattlesnake Ignimbrite Tongue was measured in the laboratory with a model 70 flux-gate magnometer. Samples larger than 10 kg were used for all determinations. In all samples of the Rattlesnake Ignimbrite Tongue the polarity is reversed (Table 1). The ash-flow tuff of Devine Canyon, ash-flow tuff of Prater Creek, and Mascall ignimbrite are normally polarized (Davenport, 1970). The author found the Dinner Creek Welded Tuff northeast of Buchanan to be normally polarized. The samples of Rattlesnake Ignimbrite Tongue measured were from Buzzard Creek (DP-330), Alkali Lake (DP-72-86, App. IV), Hart Mountain National Antelope Refuge (DP-72-24, App. IV), and Burns, Oregon (DP-331, App. IV).

Age Dating

Five samples thought to be the Rattlesnake Ignimbrite Tongue were dated by the K-Ar method to establish the age and strengthen the basis for regional correlation. Sample descriptions, analytical procedures, and analytical data are given in Appendix II. Previous dating of the Rattlesnake Ignimbrite Tongue has yielded varied results as reviewed by Davenport (1970). Davenport ruled out "anomalous" dates and arrived at an average age of 6.1 m.y. for the Rattlesnake Ignimbrite Tongue.

A sample from Cottonwood Creek (DP-Cottonwood, App. IV) taken near the type section of the Rattlesnake Formation was previously dated by H.E. Enlows and reported by Davenport to be anomalous. This anorthoclase separate was reananlyzed after exclusion of composite grains containing magnetite and suspect off color grains, and a 45 second etch in hydrofluoric acid at 80°C. The age of this sample is 6.4 ± 0.1 m.y. which is identical within analytical error to the other samples of the Rattlesnake Ignimbrite Tongue.

Sample DP-E-84-67 from Murderers Creek (App. IV) and DP-E-6-70 from Dry Creek near Monument, Oregon (App. IV) yielded age dates of 6.7 ± 0.2 m.y. and 6.4 ± 0.2 m.y. respectively. Samples DP-311-G and DP-330 are from the Buzzard Creek area and yielded ages of 6.6 ± 0.2 and 6.7 ± 0.4 m.y. respectively. DP-331-G is from the vitrophyre zone and sample DP-330 is from a highly folded foliated zone. All samples analyzed are identical in age within the limits of the K-Ar technique. The age of the Rattlesnake Ignimbrite Tongue is 6.6 ± 0.2 m.y. based upon the remarkable agreement between analyses of anorthoclase crystal separates and whole rock glass.

Volume of Eruption

The thickness of the Rattlesnake Ignimbrite Tongue is dependent upon pre-eruption topography, compaction, postdepositional erosion, and nearness to the eruptive center. Figure 6 is an isopach map of the Rattlesnake Ignimbrite Tongue based upon present day outcrop thickness. Much of the unit south of Harney Lake is not dissected by erosion and thus the bottom is seldom exposed making thickness estimates speculative.

The volume of erupted material is estimated to be 1,500 km^3. This estimate is based upon present outcrop thicknesses and excludes probable eroded ash and a distant airfall component. An average thickness of 30 m and a density of 1.5 gm/cm^3 was assumed for the above estimate. The equivalent magmatic volume, assuming a density for the magma of 2.5 gm/cm^3, would be 930 km^3.

Source

Walker (oral communication, July 1973) proposed a source area for the Rattlesnake Ignimbrite Tongue immediately south of the Narrows between Harney and Malheur Lakes. It is based upon a magnetic low of about 250 gammas 13 to 20 km in diameter. Outcrops of the tuff near the western edge of this anomaly are 3 m thick (DP-60), and to the east, one outcrop was found 2 km east of Crane (DP-72-78, App. IV) which is a 5 m thick section of poorly welded ash. It is suggested that thicker accumulations of material would occur near the source.

It is proposed that the source of the Rattlesnake Ignimbrite Tongue is the Buzzard Creek area. The thickest accumulation of material and the best developed zonation occurs in this area as do the largest and most abundant pumice fragments. It has been previously noted that faulting in the Buzzard Creek area occurred while the flow was still plastic. This faulting was perhaps due to crustal readjustment after the emptying of the underlying magma chamber. The flow channel discussed earlier was found a few kilometers from Buzzard Creek. Discrete flows of material could not have traveled far from their source. The area between Harney Lake and Alkali Lake, in which Buzzard Creek is centrally located, includes the only positively identified multiple flow units.

In conclusion, the eruption of the Rattlesnake Ignimbrite Tongue took place in the Buzzard Creek area from fissures in several pulses. The eruption was followed by the subsidence of an elongate area of the Brothers fault zone while the flow was still plastic and a caldera was not formed.

Rhyolite of Palomino Butte

The rhyolite of Palomino Butte (Trpb, Plate 1) protrudes through the Tertiary and Quaternary basalt in T. 24 S. R. 28 E. This dome covers approximately 10 km^2, rises 150 m above the surrounding volcanic plain, and is composed of rhyolite flows which display flow banding formed by mineral orientation, color variation, and streaks of pumice. Two small outcrops of rhyolite northwest of the dome are considered part of the same unit.

A biotite mineral separate yielded an age of 6.4 m.y. (DP-214, App. II). A whole rock age date was 5.6 m.y. The difference in ages is due to the poor Ar retention of volcanic glass. This discordancy is common in the Great Basin ignimbrites where it was concluded that the biotite age represents a more reliable estimate of the true age of the unit (Scott and others, 1971).

Two thin sections of the rhyolite of Palomino Butte were examined. Sample DP-215 contained phenocrysts of hornblende and plagioclase phenocrysts which exhibit oscillatory zoning. The large plagioclase phenocrysts in DP-215 show absorption while the smaller phenocrysts of plagioclase do not. Sample DP-215 contains partially absorbed plagioclase and quartz phenocrysts. It also contains phenocrysts of hornblende, biotite, and sanidine.

Tertiary Sedimentary Rocks

Sedimentary rocks found stratigraphically below the Rattlesnake Ignimbrite Tongue are grouped as Tertiary sedimentary rocks (Tst, Plate 1). They are probably of Pliocene age but may be older. Absolute age dating of confining units was not possible. These sedimentary rocks include sedimentary units of the Danforth Formation of Piper, Robinson, and Park (1939) and tuffaceous sedimentary rocks (Tst) of Greene and others (1972).

Rhyolite of Iron Mountain

The rhyolite of Iron Mountain (Trim, Plate 1) is a dome located in Tps. 26 and 27 S., R. 27 E. 10 km west of Double O Ranch. A K-Ar age date of 2.7 ± 0.2 m.y. was obtained on a biotite mineral separate from a whole rock sample that yielded an age of 2.1 ± 0.2 m.y. (App. II).

The rhyolite flows were found to be in contact with the Rattlesnake Ignimbrite Tongue. A block of the Rattlesnake Ignimbrite Tongue is found on the northeast flank of Iron Mountain 70 m higher in elevation than nearby outcrops. It is also overlain by a flow of rhyolite which forms a prominent scarp on the east side of the mountain. The block of Rattlesnake Ignimbrite Tongue reached its present position by uplift associated with the early intrusive stages of dome development.

One thin section of the rhyolite of Iron Mountain was examined (DP-158). This sample displayed vitrophyric texture, phenocrysts of biotite, amphibole, plagioclase, and opaque minerals, comprised less than 5% of the rock. The matrix is clear glass and contains microlites of plagioclase, hornblende, and biotite, less than 0.01 mm in length.

Plagioclase, the most abundant phenocryst, occurred as subhedral to euhedral laths, and exhibited oscillatory zoning. The phenocrysts range from 0.1 to 1.0 mm in length, and a few displayed corroded interiors. Hornblende and biotite phenocrysts are present in about equal abundance. They range in size from 0.1 to 1.0 mm. Opaque minerals are iron oxides and are least abundant.

Tertiary and Quaternary Basalt

The Tertiary and Quaternary basalt (TQb, Plate 1) map unit includes the Wrights Point capping basalt flows and all basalt flows which overlie them. They belong to the sedimentary rock and basalts (QTsb) of Green and others (1972). The Tertiary and Quaternary basalt is composed primarily of diktytaxitic flows 1 to 12 m thick and in the case of the Wrights Point capping flow, up to 30 km in length.

Wrights Point and late basalt chemical types are represented in this map unit. Sample DP-14 is from the top flow on Wrights Point and was found to be 2.6 m.y. old. Sample DP-52 is thought to be from a stratigraphically equivalent flow north of Freeman Butte. These samples display phenocrysts of olivine and zoned plagioclase in a groundmass of clinopyroxene, plagioclase, olivine, opaque minerals, and rare glass. The plagioclase phenocrysts exhibit absorption features in their cores.

Sample DP-212 is from a basalt flow which overlies the flow represented by DP-52 8 km south of Palomino Butte. Faults which cut DP-52 do not effect the flow from which sample DP-212 came. Sample DP-212 contains olivine and plagioclase phenocrysts in an intersertal groundmass of plagioclase, clinopyroxene, opaque minerals, glass, and very abundant olivine.

Sample DP-181 is from an extensive area of flat lying basalt south of Silver Lake. This basalt flow is not in contact with any other unit or flow except recent playa deposits. However, it is not far from flows stratigraphically equivalent to the Wrights Point capping flows. This flow has no counterpart in the older sequence of rocks to its south and it is therefore placed in the Tertiary and Quaternary basalt map unit. Sample DP-181 belongs to the late basalt chemical type as does sample DP-212. A thin section of DP-181 displays phenocrysts of olivine and plagioclase in a finely crystalline matrix of plagioclase, clinopyroxene, and olivine in an ophitic relationship.

Sample DP-159 is a basalt flow of the alkalic basalt chemical type which crops out north of Iron Mountain and was included in the

Tertiary and Quaternary basalt (TQb) map unit. Because of its chemical type and location on a fault scarp which along trend intersects an area of subsqueous pyroclastic deposits and associated cinder cones it may be a local flow and not part of the plateau forming flows that make up the Tertiary and Quaternary basalt map unit. A thin section of this unit displays the same type of corroded phenocrysts of plagioclase found in the alkalic basalts of the subaqueous pyroclastic deposits and associated cinder cones. The felty matrix of plagioclase, skeletal opaque minerals, clinopyroxene, olivine, and brown glass is also similar to the other alkalic rocks.

Tertiary and Quaternary Sedimentary Rocks

Sedimentary rocks above and below the Wrights Point capping basalt have been included in Tertiary and Quaternary sedimentary rocks (TQs, Plate 1). This unit includes the sedimentary rocks of the Harney Formation described by Piper and others (1939) and Neim (1974), and in part tuffaceous sedimentary rocks (Tst) of Greene and others (1972). It is important to note that subaqueous pyroclastic rocks intimately associated with an eruptive center are not included in this unit although it includes rocks that are the result of subaqueous pyroclastic deposition from yet unrecognized sources. Parts of this unit are time equivalent to the Tertiary and Quaternary basalts, subaqueous pyroclastic deposits and associated cinder cones.

Subaqueous Pyroclastic Deposits and Associated Cinder Cones

Subaqueous pyroclastic deposits and associated cinder cones (QTps, Plate 1) consists of palagonitized basaltic ejecta that makes up tuff and breccia cones and maars. Included are basalt flows of the Tertiary and Quaternary basalt unit over which the pyroclastic material has been deposited and flows and dikes that are genetically related to the phreatic eruptive centers. Wrights Point, late basalt, and alkali basalt chemical types are represented in this Late Pliocene to Recent age unit. Those rocks mapped as subaqueous pyroclastic deposits by Greene and others (1972) are correlative with the subaqueous pyroclastic deposits and associated cinder cones. This unit is located north of Harney Lake with the exception of a small occurrence west of Silver Lake just off the map area (DP-185).

Dog Mountain, the most prominent palagonite breccia complex in the area of study, is located in T. 25 S. and Rs. 30 and 31 E., and covers approximately 45 km^2. The breccia cone overlies the Wrights Point capping basalt flow. Dog Mountain has a central depression 3 km wide that has been breached in the southwest corner. The walls of the cone consist of 100 to 200 m of base surge deposits. Exotic blocks of basalt, rhyolite, and Rattlesnake Ignimbrite Tongue are common in the breccia deposits.

Samples DP-40 and DP-206 from flows associated with the Dog

Mountain eruptive event are of the Wrights Point chemical type. These samples are from the dense cores of flows that are gradational vertically and laterally into laminated deposits of scoria, basalt fragments, and sedimentary fragments. These flows are 2 to 3 m thick and may be isolated parts of the same flow. They are found at the same elevation 0.5 km apart in flat lying strata. The gradational character of one of these flows is pictured in Figure 15. Samples DP-40 and DP-206 contain phenocrysts of olivine and plagioclase in a groundmass of extremely fine crystalline plagioclase, pyroxene, and olivine. The gradational character of these flows and their finely crystalline groundmass suggest an ash-flow origin. The phreatic eruptive products of Dog Mountain overlie the Wrights Point capping flow on its western flank and are younger than the Wrights Point capping flow.

Southwest of Dog Mountain and north of Harney Lake is an elongate fault controlled eruptive center of tuff rings and cinder cones trending in a NW-SE direction. Basaltic material of the Wrights Point and late basalt chemical types are erupted in this area. Sample DP-44 and DP-199 are from isolated remnants of basalt flows not associated with the eruption creating this volcanic center and are thought to belong to the Tertiary and Quaternary basalt map unit. Sample DP-41 is from a flow associated with two adjoining cinder cones in the center of this eruptive complex. This sample was dated at 2.8 m.y. old and is not in contact with the Tertiary and Quaternary basalt map unit but is built upon sediments lithologically similar to those which underlie the Tertiary and Quaternary basalts. Sample DP-41 contains phenocrysts of plagioclase and olivine in a pilotaxitic and subophitic groundmass, which contains plagioclase, clinopyroxene, opaques, olivine, and glass.

Figure 15. Basalt flow on Dog Mountain which is gradational into laminated scoria.

Four kilometers northwest of the above cinder cones is a depression 3 km in diameter surrounded by base surge deposits which overlie the Tertiary and Quaternary sedimentary rocks.

The subaqueous deposits in the area north of Harney Lake are deeply dissected with the exception of two cinder cones represented by sample DP-41. The difference in erosion may be a manifestation of the type of materials deposited or deposition of the cinder cones under later subareal conditions.

Freeman Butte, 3 km west of the North Harney Lake eruption center is a shield shaped volcanic center. This center is composed of basalt flows, scoria deposits, and base surge beds deposited in a subareal environment. Samples DP-193 and DP-194 are from spatter accumulations. Both basalt samples contain phenocrysts of plagioclase and olivine. In sample DP-193 the phenocrysts are enclosed in an ophitic and subophitic matrix of plagioclase, pyroxene, and olivine. In DP-194 the phenocrysts are in a matrix of very fine crystalline plagioclase, pyroxene, and olivine with clots of material similar to the matrix of DP-193. Freeman Butte is built upon the Tertiary and Quaternary basalts and Tertiary and Quaternary sedimentary rocks. It was not possible to date rocks from this volcano because of the altered state of the basalts and abundant secondary minerals.

Included in this unit are two spatter cones and a tuff ring found

5 km west of Silver Lake adjacent to the map area in T. 25 and 26 S. and R. 27 E. These eruption centers occur in a NW-SE trend along a fault scarp in the Tertiary and Quaternary basalts. Samples DP-184 and DP-185, which belong to the alkalic basalt chemical type, are from this area. Sample DP-185 is from the oldest eruption, a maar-like feature with laminated tuffaceous deposits surrounding a central depression. Abundant float of the Rattlesnake Ignimbrite Tongue is present in the depression. The bombs associated with the maar are cored with sediment, basalt, rhyolite, and Rattlesnake Ignimbrite Tongue. Sample DP-184 is from a small spatter cone on the southeast flank of the maar and overlays it. This sample is from one of several spatter cones which are up to 2 m in height and several meters across. Cinders, spatter, and bombs cover the ground and define the unit. A small spatter accumulation occurs 0.5 km southeast of the last described spatter cone.

Two thin sections were examined, one from the spatter cones (DP-184), and one from a bomb associated with the maar (DP-185). Both displayed phenocrysts of oscillatory zoned plagioclase, embayed and spotted due to absorption and a felty groundmass of plagioclase microlites. Sample DP-185 contained exotic grains of quartz rimmed by fibrous brown material that was not identifiable.

Alluvium

Alluvium (Qal. Plate 1) includes Pliestocene and Recent deposits that are partially consolidated to unconsolidated fluvial gravel, sand, and silt. Also included is talus, slope wash, playa deposits, and wind blown sand.

Table 3. Summary of petrographic data for the basalts.

Sample	Basalt Type (age)	Phenocryst Assemblage			Olivine in
		Plagioclase	Olivine	Pyroxene	Groundmass
DP-184	Alkalic	rare	absent	absent	absent
DP-185	Alkalic	common	absent	absent	?
DP-159	Alkalic	common	absent	absent	common
DP-194	Late	common	common	absent	common
DP-193	Late	rare	rare	absent	common
DP-212	Late	rare	common	absent	abundant
DP-181	Late	rare	common	absent	common
DP-41	Late (2.8 m.y.)	common	common	absent	common
DP-40	Wrights Point	rare	rare	absent	?
DP-44	Wrights Point	common	rare	absent	?
DP-52	Wrights Point	common	rare	absent	common
DP-14	Wrights Point (2.6 m.y.)	common	common	absent	
DP-206	Wrights Point	rare	common	absent	?
DP-199	Wrights Point	absent	common	rare (1)	common
DP-58	Early	common	common	absent	rare
DP-250	Early (7.9 m.y.)	rare	common	absent	rare
DP-300	Early (8.8 m.y.)	common	common	absent	common
DP-73-4	Early	absent	rare (1)	absent	common
DP-278	Early	common	common	absent	common
DP197	Andesite	common(1)	common(1)	absent	?
DP-160	Andesite (5.8 m.y.)	common	rare	absent	?

? - matrix extremely fine grained.
(1) exotic?

GEOCHEMISTRY OF SELECTED VOLCANIC ROCKS

Introduction

Major and minor element analyses of forty selected volcanic rocks show them to be of bimodal chemical character (Fig. 16). These analyses can be divided into basalt with silica content less than 53% and rhyolites with a silica content greater than 72%. Two intermediate silica rocks are included at the end of the discussion of basalts. Analyses plotted on silica variation diagrams fall in two isolated concentrations of points. A "silica gap" of nearly 20% is present which makes use of variation diagrams based on silica of minimal value.

Geochemistry of Selected Basalts of the Harney Basin

The basalts have been divided into two categories based upon their major element chemistry; alkalic and tholeiitic. The analyses of basaltic rocks are plotted on a total alkali-silica diagram in Figure 17 and the individual chemical analyses are given in Tables 4, 5, 6, and 7.

Silica in the basaltic rocks ranges from 48.6 to 52.6% and the average is 50.0%. The silica content does not correlate with either stratigraphic or space groupings. Because the analytical error is at least 1%, it precludes the use of silica data as a definite chemical factor (App. I). Samples DP-160 and DP-197 have 57.6 and 63.7%

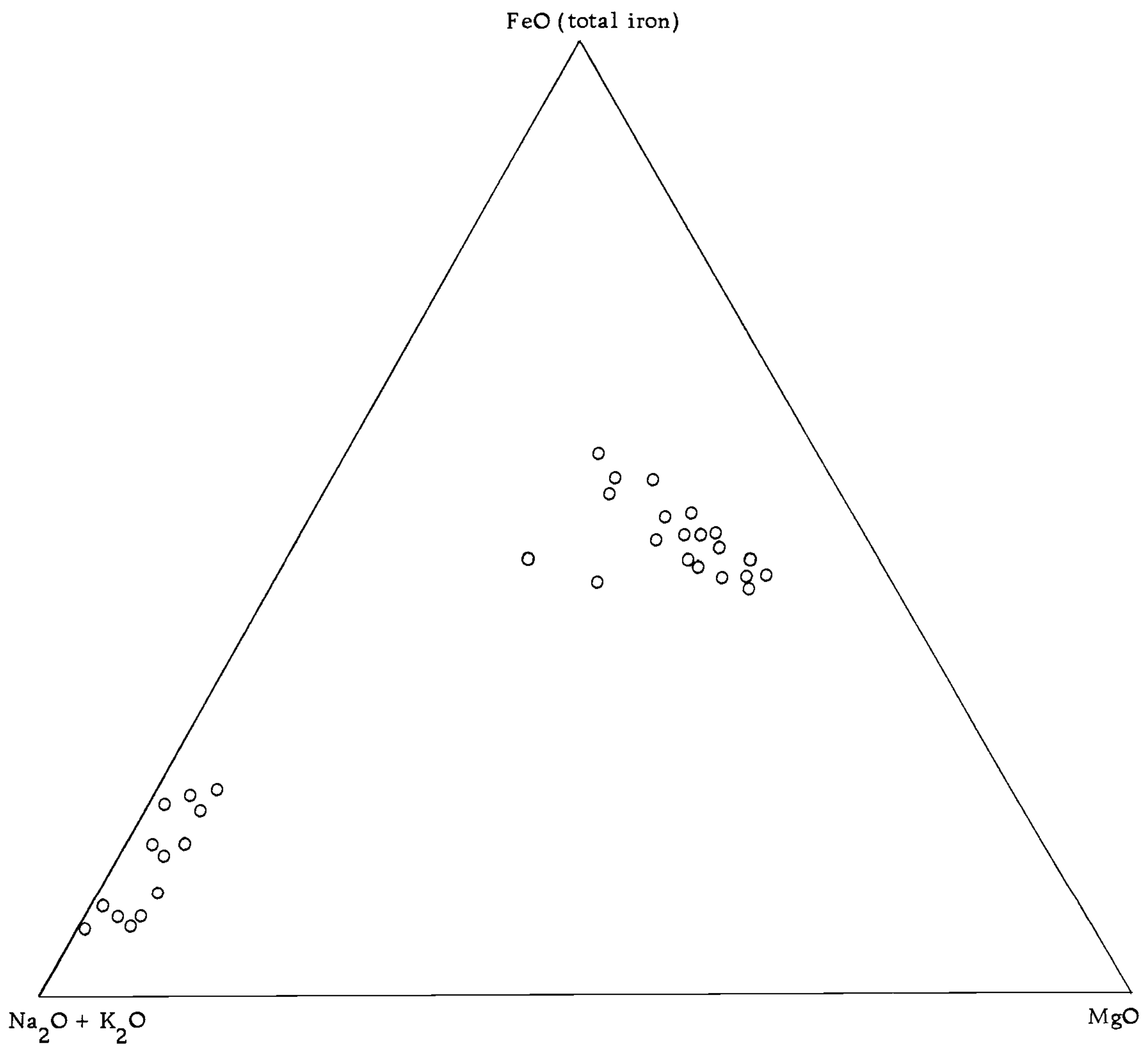

Figure 16. AMF diagram showing bimodal distribution of rocks in this study.

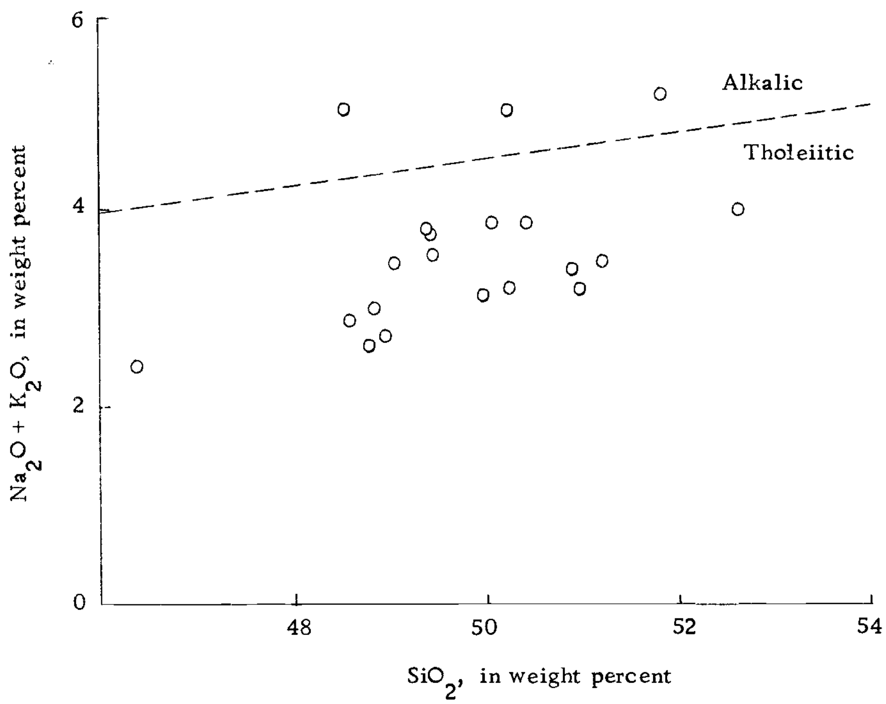

Figure 17. Plot of total alkalis and SiO_2 for basalts of the Harney Basin. Dashed line is boundary between alkalic and tholeiitic basalts of Hawaii (Macdonald and Katsura, 1964). Analyses are from Tables 4, 5, 6, and 7.

Table 4. Chemical analyses of the late basalt type.

Sample	DP-194	DP-193	DP-212	DP-181	DP-41
Oxide					
SiO_2	48.6	50.8	49.5	49.1	50.1
TiO_2	0.87	1.14	1.45	1.60	1.70
Al_2O_3	16.9	14.9	14.8	15.4	15.0
FeO (total Fe)	9.0	10.5	11.0	9.4	11.0
MgO	9.1	7.9	7.9	7.5	7.1
CaO	12.2	12.3	10.9	10.9	10.6
Na_2O	2.6	3.1	3.5	3.2	3.0
K_2O	0.29	0.20	0.32	0.32	0.80
Element (ppm)					
Co	30	25	45	50	40
Cr	40	35	40	30	40
Cu	150	110	40	35	105
Ni	125	105	160	125	135
Pb	20	20	10	20	20
V	280	315	310	300	240
Zn	75	70	90	90	100
Cr/Ni	0.32	0.33	0.25	0.24	0.30
Total	99.62	100.90	99.43	99.48	99.36

Table 5. Chemical analyses of the Wright's Point basalt type.

Sample	DP-40	DP-44	DP-52	DP-14	DP-206	DP-199
Oxide						
SiO_2	48.7	51.0	50.0	48.7	51.2	50.4
TiO_2	1.97	0.83	1.36	1.43	1.17	1.52
Al_2O_3	16.3	15.6	15.6	17.4	14.4	14.7
FeO (total Fe)	9.7	9.2	10.3	10.2	9.8	11.0
MgO	8.9	8.5	10.0	8.4	8.2	8.0
CaO	12.0	12.5	10.2	11.2	11.8	11.5
Na_2O	2.4	3.0	2.8	2.8	3.0	3.4
K_2O	0.26	0.19	0.34	0.29	0.53	0.35
Element (ppm)						
Co	35	45	50	40	35	40
Cr	5	5	15	15	15	15
Cu	105	100	45	65	95	95
Ni	125	125	145	135	145	130
Pb	30	30	20	20	30	20
V	260	240	240	300	290	315
Zn	85	80	85	75	80	90
Cr/Ni	0.04	0.04	0.10	0.11	0.10	0.12
Total	99.29	100.88	99.66	100.48	100.16	100.93

Table 6. Chemical analyses of the early basalt type.

Sample	DP-58	DP-250	DP-300	DP-73-4	DP-278
Oxide					
SiO_2	48.9	50.2	49.5	49.5	52.6
TiO_2	1.47	1.38	1.72	1.93	1.07
Al_2O_3	14.0	17.1	15.4	15.5	15.5
FeO (total Fe)	10.8	10.4	12.0	12.0	10.0
MgO	11.0	8.2	8.2	6.5	6.8
CaO	10.3	11.2	10.5	11.0	10.6
Na_2O	2.3	2.7	3.1	3.4	3.2
K_2O	0.38	0.35	0.42	0.32	0.82
Element (ppm)					
Co	30	40	45	35	40
Cr	70	20	65	70	65
Cu	100	55	125	105	120
Ni	205	140	145	110	145
Pb	20	20	20	20	20
V	280	300	320	390	275
Zn	80	80	60	105	100
Cr/Ni	0.34	0.14	0.45	0.64	0.45
Total	99.21	101.59	100.90	100.21	100.65

Table 7. Chemical analyses of the alkalic basalt type.

Sample	DP-159	DP-185	DP-184
Oxide			
SiO_2	48.5	51.7	50.2
TiO_2	3.51	2.82	3.27
Al_2O_3	12.6	13.6	13.1
FeO (total Fe)	13.4	12.6	13.7
MgO	6.2	5.6	5.5
CaO	9.7	8.5	9.0
Na_2O	3.8	3.8	3.9
K_2O	1.15	1.28	1.04
Element (ppm)			
Co	30	5	10
Cu	30	40	25
Cr	40	130	35
Ni	50	35	30
Pb	10	10	10
V	320	270	240
Zn	125	80	90
Cr/Ni	0.80	3.72	1.16
Total	98.92	99.96	99.87

silica respectively and are included at the end of this discussion as intermediate flow rocks.

Titanium is reported as TiO_2 and ranges from 0.75 to 3.51%. The TiO_2 values for the tholeiitic basalts range from 0.83 to 1.97% with an average of 1.4%. The alkalic basalts have values of 3.51, 2.85, and 3.27% for TiO_2. The TiO_2 values for the tholeiitic basalts fall within Chayes (1965) range (less than 1.75%) for circumpacfic basalts.

The Al_2O_3 contents of the tholeiitic rocks range from 14.0 to 17.4% and average 15.5%. This range (14.0 to 17.4%) is within that given by Manson (1967) for continental tholeiites (15.1 to 18.0%, average 16.3%) and above that given for oceanic tholeiite (14.4 to 14.9%, average 14.6%). The alkalic basalts have Al_2O_3 values of 12.6, 13.6, and 13.1% which are within the range given by Manson (1967) for olivine alkalic basalts.

All basalts have Na_2O/K_2O ratios greater than 1.0 which is a result of low K_2O values. The K_2O values of the tholeiitic basalts range from 0.19 to 0.82% and average 0.39% which is a major distinction from the alkalic basalts which contain an average of 1.15% K_2O. A total alkalic vs silica diagram with Macdonald and Katsura's (1964) Hawaiian alkalic and tholeiitic fields shows a clear distinction between the two basalt types found (Fig. 17). Tholeiite sample DP-58 (Table 6), has a MgO/CaO ratio of greater than 1.0, which is the result of olivine accumulation as evidenced by abundant olivine phenocrysts. The abundance of CaO and MgO cannot be systematically related to any major oxide or minor element. This lack of interdependence of element abundances indicates the volcanic rocks analyzed are not members of a fractional crystallization series.

Minor element abundances of the tholeiitic basalts permit further subdivision which coincide with age groups. The tholeiitic basalts were subdivided on the basis of Cr/Ni ratios. The nearly uniform abundance of Ni makes this subdivision largely dependent upon Cr abundance. Similar Cr/Ni ratios are the basis of groups which are stratigraphically equivalent. The Cr/Ni value is not affected by fractional crystallization (Turekian, 1963) thus it is probably a fingerprint of the area of magma origin. According to Prinz (1967), chromium can be strongly fractionated by pyroxene crystallization. However, pyroxene was not found as a phenocryst phase. Because the Ni content of the tholeiitic basalts is not a function of MgO it indicates that olivine fractionation has had little compositional effect on the rock.

The tholeiitic basalts were divided into three groups on the basis of their Cr/Ni values. The first group, the late basalt type, has Cr/Ni value of 0.25 to 0.35 (Table 4). Samples DP-193 and DP-194 are from Freeman Butte which overlies the Wrights Point capping flows as do all basalts of this group. Sample DP-40, 2.8 m.y. old, is from a flow associated with a phreatic eruption center which deposited tuff breccia that overlies the Wrights Point capping flows. Sample DP-212 is also found overlying the Wrights Point capping flow. Sample DP-181 had no stratigraphic relationship to any other unit and was placed in this unit exclusively on the basis of its Cr/Ni ratio.

A second group of tholeiitic basalts, the Wrights Point chemical type, has Cr/Ni values of less than 0.12 (Table 5). They lie stratigraphically below the late basalt type. Samples DP-14 and DP-52 are from the Wrights Point capping flow and display very similar major and minor element chemistry (Table 5). Samples DP-40, DP-206, DP-199, and DP-44 are from the phreatic eruption centers overlying sediments lithologically similar to those below the Wrights Point capping flow and overlain by a flow of the late basalt type. Thus they are stratigraphic equivalents to the Wrights Point capping flow.

The third group, the early basalt type, is composed of basalts stratigraphically below the Rattlesnake Ignimbrite Tongue and with the exception of DP-250 have Cr/Ni ratios greater than 0.33 (Table 6). These groups of basalts represent distinct batches of magma generated in localized areas in the mantle during discrete episodes of volcanism.

Nickel is depleted in the alkalic basalts as compared to the tholeiitic basalts. A similar relationship characterizes MgO, which indicates olivine may have played a role in the generation of the alkalic basalts from a tholeiitic magma.

Copper is variable in abundance (25 to 150 ppm) but does not correlate with stratigraphic groups. It is significantly more abundant in the tholeiitic basalts than the alkalic basalts, which was also reported by Prinz (1967). It has been reported to range widely in volcanic suites and possibly represents a lateral inhomogenity in the mantle (Prinz, 1967).

Lead and Zn show little variation within the tholeiitic basalt group but Pb is distinctly less abundant in the alkalic basalts. This depletion of Pb in the alkalic basalts is consistent with derivation of alkalic basalt from a tholeiitic magma by feldspar removal. Lead is similar in character to K in the crystal fractionation process. However, K_2O is enriched in the alkalic basalt while Pb is depleted. Zinc shows little variation between the tholeiitic and alkalic groups.

Vanadium generally is covarient with the total iron content of a sample. In tholeiites the V ranges from 240 to 390 ppm which includes the value (250 ppm) reported by Turekian and Wedepohl (1961). The alkalic basalts have about as much V (240-320 ppm) as do the tholeiites.

The tholeiitic basalts are not derivatives of a high alumina basalt parent magma because there are no correlations between Al_2O_3 and TiO_2, MgO, Ni, and CaO which would result were a high alumina basalt magma to fractionate by removal of plagioclase and olivine at shallow depths. The lack of high alumina basalt in the Harney Basin volcanic suite as representative of a parent magma also contradicts a high alumina magma as petrogenetor of the tholeiitic basalts.

It is proposed that the tholeiitic basalts were generated in a "second stage" or "depleted" mantle. They are the product of rapidly rising discrete batches of magma facilitated by extensional tectonics. Portions of the tholeiitic parent magma may have resided in shallow magma chambers for periods of time sufficient to produce alkalic differentiates. Crustal contamination played a minor role in this process as evidenced by Sr isotope data reported in this study.

Alkalic basalts (DP-154, 185, and 184, Table 7) contain significantly more TiO_2 and K_2O and slightly more Na_2O and FeO than do the tholeiitic basalts. They are depleted in Al_2O_3, CaO and MgO compared to the tholeiitic basalts. These enrichments and depletions can be accounted for by the removal of 35% plagioclase (An_{70}) and 10% olivine (Fo_{80}) from the average tholeiitic basalt of this study (Table 12). Olivine removal is also supported by the Ni contents of both basalt types. Assuming an average Ni content in the tholeiitic magma of 130 ppm and Hakli and Wright's (1967) distribution coefficient for Ni between basaltic magma and olivine, Ni should be a factor of three lower in the alkalic liquid, which it is (130 vs. 40 ppm). Chromium is not depleted in the alkalic basalts relative to the tholeiitic basalts therefore pyroxene was unimportant in differentiation.

Greene and Ringwood (1967) characterize shallow depth (less than 15 km) differentiation as dominated by olivine and plagioclase in its early stages. It is suggested that the alkalic basalts were derived from a magma similar to the parent magma of the tholeiitic basalts. The derivation was by differentiation at depths of less than 15 km.

Two samples (DP-160 and DP-197) that have silica contents intermediate between those of basalt and rhyolite are called intermediate flow rocks. The major and minor element analyses of the intermediate flow rocks are given in Table 8 along with an average calc-alkaline andesite from continental margins (McBirney, 1969), the average tholeiite and the average alkalic basalt. The Al_2O_3 content of the intermediate flow rocks (Table 8) is depleted by 3 to 4% Al_2O_3 compared to typical calc-alkaline andesites from continental margins (McBirney, 1969). The Al_2O_3 content falls below the lowest values reported for the andesites of the High Cascades of Oregon (Higgins, 1973; Lidstrom, 1972; Williams, 1942; McBirney, 1968) and the Basin and Range (Harrold, 1973; Tower, 1972; Fuller, 1931) of Oregon. The intermediate flow rocks are depleted in the covarient groups of elements, FeO-V-TiO_2 and MgO-Ni-Co, compared to the average tholeiite. The removal of iron oxide and olivine would account for the depletion. The Al_2O_3, CaO, and Na_2O content of these rocks cannot be readily explained by crystal fractionation.

Table 8. Chemical analyses of intermediate flow rocks.

Sample	Average[a] Tholeiite	Average[b] Alkaline Basalt	DP-160	DP-197	Average[c] Andesite
Oxide					
SiO_2	50.0	50.1	57.6	63.7	59.4
TiO_2	1.4	3.2	1.25	0.75	0.80
Al_2O_3	15.5	13.1	14.7	13.2	17.6
FeO (total Fe)	10.4	13.2	8.6	6.0	6.44
MgO	8.3	5.8	4.2	4.1	3.32
CaO	11.2	9.1	7.0	10.2	6.33
Na_2O	3.0	3.8	4.2	1.9	3.86
K_2O	0.39	1.15	2.0	1.9	2.1
Element (ppm)					
Co	35	15	15	-5[d]	
Cr	35	70	10	15	
Cu	90	30	55	105	
Ni	140	40	35	50	
Pb	20	10	10	20	
V	290	275	180	210	
Zn	90	100	45	45	
Total	100.25	99.51	99.61	101.81	99.85

[a] Average tholeiite of this study.

[b] Average alkalic basalt of this study.

[c] Average calc-alkaline andesites from continental margin (McBirney, 1969). Minor elements not given.

[d] -5, less than 5 ppm.

Sample DP-197 is from a small andesite flow in an area of Plio-Pliestocene phreatic eruptions of tholeiitic lavas and may be a differentiate of them. Sample DP-160 is from an extensive flow that overlies the Rattlesnake Ignimbrite Tongue and may be of true andesite origin.

Geochemistry of Selected Rhyolites of the Harney Basin

The rhyolitic rocks can be divided into two groups based upon alumina, soda, potash, and lime abundances (Shand, 1951). The first group, peraluminous rhyolites, has alumina in excess over that required to form feldspar (Table 9). The rhyolitic rocks included in the peraluminous group are the rhyolite flows of Palomino Butte (DP-214 and DP-215), a rhyolite flow from Iron Mountain (DP-158), and the rhyolite flows of Double O Ranch (DP-146 and DP-316-D). All rhyolite flow rocks studied fall into this category. With the exception of the rhyolite from Double O Ranch these rocks contain amphibole and biotite which substantiate their peraluminous character and indicate hydrous low temperature crystallization. Cognate minerals were not found in the rhyolite of Double O Ranch. The plagioclase, olivine, and pyroxene reported in these rhyolite flows are corroded and in clumps. They may be remnants of basalt fragments. The peraluminous character of the rhyolite of Double O Ranch may have originated by incorporation and assimilation of basaltic fragments.

Table 9. Chemical analyses of peraluminous rhyolite flow rocks.

Sample (age m.y.)	DP-316D (7.5 m.y.)	DP-146	DP-215	DP-214 (6.4 m.y.)	DP-158 (2.7 m.y.)
<u>Oxide</u>					
SiO_2	71.0	73.2	73.9	76.0	72.7
TiO_2	0.40	0.47	0.18	0.08	0.13
Al_2O_3	12.9	13.5	13.6	12.9	14.5
FeO (total Fe)	2.4	2.65	1.7	0.75	1.0
MgO	0.6	0.6	0.5	0.4	0.5
CaO	1.45	1.41	1.90	1.6	1.9
Na_2O	4.2	3.9	3.4	3.4	3.05
K_2O	4.90	4.71	4.58	4.88	4.50
<u>Element (ppm)</u>					
Co	-5[a]	-5	n.d.[b]	-5	-5
Cr	15	10	n.d.	10	10
Cu	25	10	n.d.	-5	10
Ni	10	10	n.d.	5	10
Pb	-10	-10	n.d.	10	10
V	20	30	n.d.	60	30
Zn	10	35	n.d.	10	10
Total	97.85	100.44	99.76	99.93	98.38

[a] -5, less than 5 ppm; -10, less than 10 ppm.

[b] n.d.--not determined.

The second group, subaluminous rhyolitic rocks, is composed entirely of ash-flows. These rocks have little or no excess of alumina over that required for feldspar formation (Tables 10, 11, 12, and 13). The Rattlesnake Ignimbrite Tongue and the ash-flow of Devine Canyon contain pyroxene, anorthoclase, and quartz. According to Davenport (1970) the ash-flow tuff of Prater Creek contains alkali-spar and quartz. These minerals reflect the subaluminous character of the ash-flows.

If these rocks are compared to rhyolitic rocks surrounding the Harney Basin, such as those of Newberry Crater which are derived by fractional crystallization of high-alumina basalts (Higgins, 1973), it can be seen that their major element chemistry is different. The Newberry rhyolites contain, on the average, more Al_2O_3 than those of the Harney Basin, and Na_2O, in all samples is more abundant than K_2O. The reverse is true in the Harney Basin. These differences clearly suggest that different volcanic provinces exist on the high lava plateau of central Oregon.

Strontium Isotope Data

Introduction

The measured and initial Sr^{87}/Sr^{86} values of Rb and Sr contents of five volcanic rocks are given in Table 14. Analytical procedures

Table 10. Chemical analyses of the ash-flow tuff of Devine Canyon.

Sample	DP-245L	DP-245D	G-149-5[a]	B-4-21-2[b]
Oxide				
SiO_2	75.0	71.3	75.3	73.05
TiO_2	0.20	0.35	0.24	0.27
Al_2O_3	11.8	13.4	12.0	13.23
FeO (total Fe)	2.7	4.5	0.76	1.04
MgO	0.15	0.41	0.10	0.08
CaO	0.6	1.9	0.31	0.29
Na_2O	3.12	3.85	3.7	3.05
K_2O	6.3	6.0	4.9	5.04
Total	99.87	101.71		

[a]G-149-5 after Greene, 1973.

[b]B-4-21-2 after Beeson, 1969.

Table 11. Chemical analyses of the ash-flow tuff of Prater Creek.

Sample	DP-290	DP-311B	DP-119	B-0-20-2[a]
Oxide				
SiO_2	76.4	74.2	73.8	74.27
TiO_2	0.13	0.15	0.13	0.18
Al_2O_3	11.7	12.1	11.7	13.73
FeO (total Fe)	2.7	3.0	3.0	0.30
MgO	0.7	0.24	0.15	0.16
CaO	0.35	0.43	1.2	0.14
Na_2O	4.4	4.6	4.45	4.02
K_2O	4.28	4.41	4.5	4.37
Total	100.66	99.13	97.93	

[a]B-0-20-2 after Beeson, 1969.

Table 12. Chemical analyses of the Rattlesnake Ignimbrite Tongue pumice.*

Sample	DP-64-2DP	DP-66-1DP	DP-66-4DP	DP-130DP	DP-66-2LP	DP-130LP
Oxide						
SiO_2	77.1	76.1	76.4	70.0	77.7	75.8
TiO_2	0.12	0.14	0.14	0.75	0.12	0.12
Al_2O_3	11.6	11.9	12.5	13.0	12.4	11.2
FeO (total Fe)	0.95	1.6	1.6	4.8	0.7	0.9
MgO	0.1	0.4	0.2	0.1	0.3	0.5
CaO	0.5	0.82	1.6	2.90	0.7	1.40
Na_2O	3.45	3.0	3.1	3.1	3.25	2.7
K_2O	5.22	5.5	5.1	4.5	5.05	6.11
Total	99.04	99.46	100.64	99.15	100.22	98.73

*DP--dark pumice, LP--light pumice.

Table 13. Chemical analyses of the Rattlesnake Ignimbrite Tongue shards* and average of glasses.

Sample	DP-64-3DS	DP-64-3LS	Average of Dark Shards and Pumice	Average of Light Shards and Pumice
Oxide				
SiO_2	76.7	76.7	74.8	76.7
TiO_2	0.12	0.12	0.28	0.12
Al_2O_3	11.9	11.9	12.3	11.8
FeO (total Fe)	0.80	0.70	2.2	0.8
MgO	0.3	0.05	0.25	0.28
CaO	0.80	0.5	1.5	0.87
Na_2O	3.5	3.8	3.2	3.3
K_2O	5.28	5.25	5.1	5.5
Total	99.58	99.02	99.63	99.37

*DS--dark shards, LS--light shards.

Table 14. Summary of strontium isotope data.*

Sample	Sr^{87}/Sr^{86} (observed)	Rb (ppm)	Sr (ppm)	Rb/Sr	K (%)	K/Rb	K-Ar (m.y.)	Sr^{87}/Sr^{86} (initial)
Wrights Point capping basalt flow DP-14	--	5.34	214	0.025	0.29	543	2.6	0.7033
Rhyolite of Iron Mountain DP-158	0.7039	121	222	0.545	4.5	372	2.7	0.7038
Rattlesnake Ignimbrite Tongue								
DP-64-3LS	0.7077	111	8.29	13.6	5.25	473	6.6	0.7041
DP-64-3DS	0.7063	112	14.3	7.85	5.28	471	6.6	0.7042
DP-Cottonwood	--	18.6	148	0.128	3.76	2022	6.6	0.7035
Early basalt DP-250	--	8.11	282	0.029	0.35	432	7.9	0.7036
Rattlesnake Ignimbrite exotic fragment DP-233	--	144	(1)	118	4.5	312	-	--

*Strontium isotope analytical techniques given in Appendix III.

(1) Less than 1 ppm Sr.

are given in Appendix I. Initial Sr^{87}/Sr^{86} ratios of basalts were 0.7033 (DP-14) and 0.7036 (DP-250). A rhyolite flow associated with an exogenous dome had an initial Sr isotope ratio of 0.7038 (CP-158) and the Rattlesnake Ignimbrite Tongue yielded an initial ratio of 0.7035 (Cottonwood) for anorthoclase phenocrysts, 0.7042 for dark shards (DP-64-3-DS) and 0.7041 (DP-64-3-LS) for light shards. With the exception of the ratios for the glass shards from the Rattlesnake Ignimbrite Tongue, the ratios are identical within the analytical uncertainty, ± 0.0002.

The uniform ratios, except those for the glass shards, are consistent with a model in which rhyolite lavas are a product of fractional crystallization of a basaltic parent magma. This model has been proposed by Nobel for rocks of the Basin and Range bimodal suite (1968). A model equally consistent with these isotopic data is partial melting of an isotopically uniform source, such as the mantle, to produce mafic and silicic magmas which may have been contaminated. The isotopic disequilibrium between anorthoclase phenocrysts and glass shards from the same volcanic unit suggests that contamination occurred after crystallization of the phenocrysts and possibly during magma transport.

Comparison of Data

Strontium isotope ratios similar to those found have been reported by Hedge and others (1970) for the Picture Gorge Basalt (0.7033 to 0.7038) and the Sardine Formation and Quaternary volcanic rocks of Oregon and Washington (0.7032 to 0.7037). Church and Tilton (1973) reported similar isotopic ratios for the High Cascade Range (0.7027 to 0.7048). These rocks are the product of magma rising through continental margin crust. Similar Sr isotopic ratios (0.7035 to 0.7045) have been reported from oceanic islands of the circumpacific area where the magma passed only through oceanic crust (Peterman and Heming, In press; Peterman, Lowder, and Charmichael, 1970). The Sr isotope ratios reported in this study are distinctly higher than those of young unaltered oceanic ridge basalts. These oceanic ridge basalts have a Sr isotope initial ratio of 0.7026 (Tatsumoto and others, 1965; Hedge and Peterman, 1970; Subbaro, 1972; Hart, 1972; Dasch and others, 1973).

The isotopic ratios of the Harney Basin rocks (0.7033 to 0.7042) are distinctly lower than those reported for Quaternary volcanic rocks of New Zealand which have an average Sr^{87}/Sr^{86} value of 0.7042. The andesites and rhyolites of New Zealand are thought to be derived through partial fusion of eugeosynclinal sedimentary rocks and thus they have Sr isotope ratios higher than basalts (Ewart and Stipp, 1968). The average Rb and Sr concentrations of the basalts analyzed are 6.8 ppm and 247 ppm respectively. Jakes and White (1971) reported that island arc basalts contain 5 to 10 ppm Rb and 200 to 250 ppm Sr.

Dasch, Hedge, and Dymond (1973) report 1.11 ppm Rb and 132 ppm Sr as averages for unaltered oceanic tholeiite which agrees closely with results of Hart (1972). Kay and others (1970) report less than 5 ppm Rb in abyssal tholeiite and Jakes and White (1971) report 100-125 ppm Sr in oceanic tholeiites. The Rb and Sr contents of the basalts in this study are much lower than those from oceanic islands reported by Peterman and Heming (In press).

Isotope Constraints on a Model for the Generation of the Bimodal Chemical Assemblage in Oregon

Three mechanisms can be proposed for the generation of bimodal magmas based upon Sr isotope evidence. They are: (1) partial fusion of the mantle, the simplest method; (2) partial fusion of oceanic basalt and seafloor sediments in the subducted oceanic lithosphere as proposed by Armstrong and Cooper (1971) and Armstrong and Hein (1973); (3) anatexis of eugeosynclinal sedimentary rocks.

Partial melting in the mantle and the uncontaminated rise of the resultant magma to the surface is unreasonable because the isotopic ratios reported in this study (0.7033 to 0.7042) are much higher than those of unaltered oceanic basalt (0.7026). This conclusion is based upon the assumption of an isotopically uniform mantle. A mantle derived origin for the parent magmas is possible if either limited contamination by crustal rocks takes place or if the mantle under the continental margin is isotopically more evolved (higher Sr^{87}/Sr^{86} ratio) than oceanic mantle. A contamination model will be developed later to test the feasibility of crustal influence.

The subduction model of oceanic basalt and sea floor sediments undergoing partial fusion is compatible with the Sr isotope ratios of this study. However, the Harney Basin is at least 480 km from any proposed subduction zone and is 240 km east of the High Cascades, perhaps a more obvious product of subduction. Assuming the volcanic rocks in the Harney Basin are related to the bimodal volcanic suites found throughout the Basin and Range Province and Snake River Plain demands a model of magma genesis not directly related to subduction at the continental margein.

Anatexis of eugeosynclinal sediments is the third possible mechanism of generation for the bimodal assemblage. The crust of Eastern Oregon is composed primarily of Mesozoic ocean floor strata, which include island arc derived sedimentary rocks, rocks of apparently ophiolitic character, and granitic intrusions. An isotopic analogy between this crust and the Tyee Formation of western Oregon and the Franciscan Formation of California can be drawn. The Sr ratios of the Tyee Formation rocks average 0.706, the basaltic component has an isotopic ratio of 0.704 and the low melting sedimentary fraction 0.709 (Peterman and others, 1967). Under reasonable physical concitions it is difficult to partially melt this material, even selectively, and yield both basalts and rhyolites with isotopic ratios of 0.7035. The lack of intermediate rock types in sufficient volume to account for generation of rhyolite from basalt by fractional crystallization precludes the simple generation of one parent magma.

Origin of Basalt Magma Suggested by Strontium Isotope Data

Partial melting of mantle material and the contamination of the resultant magma will be evaluated using the Sr isotope contamination model of Pushkar (1966). It is possible for this contamination scheme to assess the feasibility of assimilation of bulk crust as the magma rises to the surface. This scheme excludes the extreme cases of selective Sr or Sr^{87} migration although it includes the possible selective assimilation of a low melting more radiogenic fraction. The fraction of assimilated crustal contaminant can be calculated by Pushkar's equation (1966):

$$\frac{Sr_m}{Sr_m + XSr_c}(Sr^{87}/Sr^{86})_m + \frac{XSr_c}{Sr_m + XSr_c}(Sr^{87}/Sr^{86})_c = (Sr^{87}/Sr^{86})_{cm}$$

where the following definitions are used:

Sr_m = Sr in parent magma,

Sr_c = Sr in contaminant,

$(Sr^{87}/Sr^{86})_m$ = ratio of parent magma,

$(Sr^{87}/Sr^{86})_c$ = ratio of contaminant,

$(Sr^{87}/Sr^{86})_{cm}$ = ratio of contaminated magma,

X = part of contaminant for one part of parent magma.

In this equation the parent magmas are assumed to be isotopically identical to oceanic basalt and rhyolite. For the contamination model of a basaltic parent magma a Sr isotope ratio of 0.7026 and a Sr concentration of 132 ppm is used for the parent magma (Dasch and others, 1973). The isotopic character of the contaminant is approximated by a composite of the Tyee Formation, Jurassic and Cretaceous Franciscan Formation, and Cretaceous Franciscan Formation (Peterman and others, 1967). An average Sr^{87}/Sr^{86} ratio of 0.7060 and 300 ppm Sr is suggested for these units. The Sr^{87}/Sr^{86} of the contaminated magma is estimated from the measured values for basaltic rocks of this study, 0.7035. For this contamination model, X equals 0.1584; which requires that 13.7% of the basaltic volcanic rock of this study consists of bulk crustal contaminant. If it is assumed that the magma selectively assimilated a low melting fraction of sedimentary material the percentage of contaminent becomes less. If a Sr^{87}/Sr^{86} ratio of 0.7090 and 500 ppm Sr is used by analogy with the sedimentary rocks of the Tyee Formation in the equation the percentage of contaminant assimilated drops to 4.5% (X = 0.0472).

To further test these models the concentrations of Sr and Rb in the contaminated magma should coincide approximately with their concentrations in the volcanic rocks. In the first example of contamination of basalt magma with 132 ppm Sr by contaminant with 300 ppm Sr the contaminated magma would have 155 ppm Sr; compared to the 214 ppm Sr in basalt sample DP-14. Assuming 1.11 ppm Rb in the parent magma (Dasch, Hedge, and Dymond, 1973) and 45 ppm Rb in the contaminant (Peterman and others, 1967) the magma resulting from 13.7 percent assimilation would have 7.2 ppm Rb, a value near the average of 7 ppm Rb for the two basalts measured. In the model with the contaminant containing 500 ppm Sr, $Sr^{87}/Sr^{86} = 0.7090$, and a Rb content of 40 ppm the resultant contaminated magma would have 4.6 ppm Rb and 150 ppm Sr compared to the average of the basalts of this study with 247 ppm Sr and 6.8 ppm Rb. These contamination models thus define reasonable limits to the percentage contamination of a parent magma of oceanic basalt isotopic character.

Origin of Rhyolite Magma Suggested by Strontium Isotope Data

The rhyolites have similar Sr^{87}/Sr^{86} ratios and Rb and Sr contents to those found on oceanic islands and island arcs (Peterman and Heming, In press). A rhyolite flow analyzed (DP-158, whole rock analysis) contained 222 ppm Sr which is similar to the value (214 and 282 ppm) for basalts analyzed. This high Sr content does not support a fractional crystallization origin for the rhyolite which would have resulted in a much lower Sr content.

The isotopic disequilibrium between the anorthoclase phenocrysts and glass matrix in the Rattlesnake Ignimbrite Tongue strengthens the possibility of contamination playing a role in the isotopic character of these rocks. This disequilibrium could be the result of exchange of Sr in ground water with the glass matrix or assimilation of radiogenic Sr by the melt at a faster rate than the co-existing anorthoclase could isotopically reequilibrate (Dasch, 1969; Scott and others, 1971). Because oxygen isotope data are unavailable the role of ground water contamination cannot be evaluated. The shard types have retained their distinct Sr contents with the same Sr isotope ratios and therefore it is concluded that Sr exchange with ground water was minimal.

Assuming a Sr distribution coefficient of 4.0 between alkali-feldspar and melt reported by Korringa and Noble (1971) the melt must have been contaminated by Sr-poor material. The anorthoclase contains 148 ppm Sr, the light shards 8.3 ppm Sr, and dark shards 14.3 ppm Sr. If the distribution coefficient of anorthoclase (Korringa and Noble, 1971) is near 7.0 (that of sodic plagioclase) elemental disequilibrium exists. An exotic fragment (DP-233, Table 14) found in the ash-flow, identified as a partially melted sedimentary rock, contains less than 1.0 ppm Sr and is possibly a contaminant.

From the previous discussion it is apparent that the Sr content of the melt at the time of crystallization of the cognate minerals was less than 40 ppm. This low value could have originated by fractional crystallization of a higher Sr basalt although less than 1% crystals were present.

Conclusions from Sr Isotope Data

1. Volcanic rocks have Sr isotope initial ratios near 0.7035 which are as low as those reported for island arc rocks and oceanic island rocks, and they are distinctly higher than unaltered oceanic basalt.
2. The Rb content of these rocks is similar to island arc rocks. The Sr content of the rocks of the Harney Basin is within the range reported for island arc rocks but the rhyolite has as much Sr as the basalt.
3. The isotopic data are consistent with two models: (1) fractional crystallization of a basaltic magma to yield rhyolite, (2) contamination of mantle derived basalt and rhyolite parent magmas by a "primitive" crust.

H_2O Pressure in Rhyolite Magmas at the Time of Eruption as an Indicator of Eruption Depth

Tuttle and Bowen (1958) have shown that the position of the quaternary isobaric minimum in the system $NaAlSi_3O_8$-$KAlSi_3O_8$-SiO_2-H_2O (Ab-Or-Q-water) is dependent upon water pressure. This relationship has been applied to natural silicic magmas to find the depth of eruption and water pressure at the time of eruption (Lipman, 1966). This technique is based upon the normative albite, orthoclase, and quartz content of each rock recalculated to equal 100%. This recalculated normative data is plotted on a ternary diagram of the system Ab-Or-Q with experimentally determined isobars plotted. To determine the magmatic water pressure it is necessary to have a mineral pair which indicates the magma is at a minimum. Quartz and feldspar in equilibrium with a residual liquid whose normative composition is plotted on the diagram meet this criterion. Differentiation trends of related rock series plotted on the diagram will intersect the isobaric minimum and indicate the magmatic water pressure which is represented by the sample at the intersection. This method requires several analyses of a related magma series including the most silicic member.

This technique has several important limitations. It must be assumed that (1) the bulk rock compositions are a result of crystal-liquid equilibrium; and (2) that mechanisms such as assimilation, volatile transfer, and liquid immiscibility have not occurred.

The degree to which the rhyolites match the experimental Ab-Or-Q system is important in applying this method. Noble (1967) criticized Lipman's (1966) application of this technique because small amounts of calcium have a serious effect upon the water pressure data. However, this criticism overlooks the end members of Lipman's rock series which have little if any calcium and no anorthite in the norm. Rocks that best define a trend with low calcium end members are the Rattlesnake Ignimbrite Tongue, ash-flow tuff of Devine Canyon, and the ash-flow tuff of Prater Creek. Rocks with appreciable amounts of calcium (greater than 1%) and normative anorthite do not form trends and do not plot near phase boundaries representing their phenocryst assemblage. Sample DP-214 is an example of an analysis plotting far from the position suggested by its phenocryst composition. It contains plagioclase, quartz, and sanidine and as the norm is plotted (Fig. 18) falls far from the tertiary eutectic. It is concluded that this method remains acceptible for rocks containing less than 1% calcium.

The normative Ab-Or-Q content of the Rattlesnake Ignimbrite Tongue, ash-flow tuff of Devine Canyon, ash-flow tuff of Prater Creek, and the Iron Mountain and Palomino Butte domes are plotted in Figures 18, 19, 20, and 21. The samples plotted from the ash-flow tuff of Devine Canyon are described by Greene (1973) as

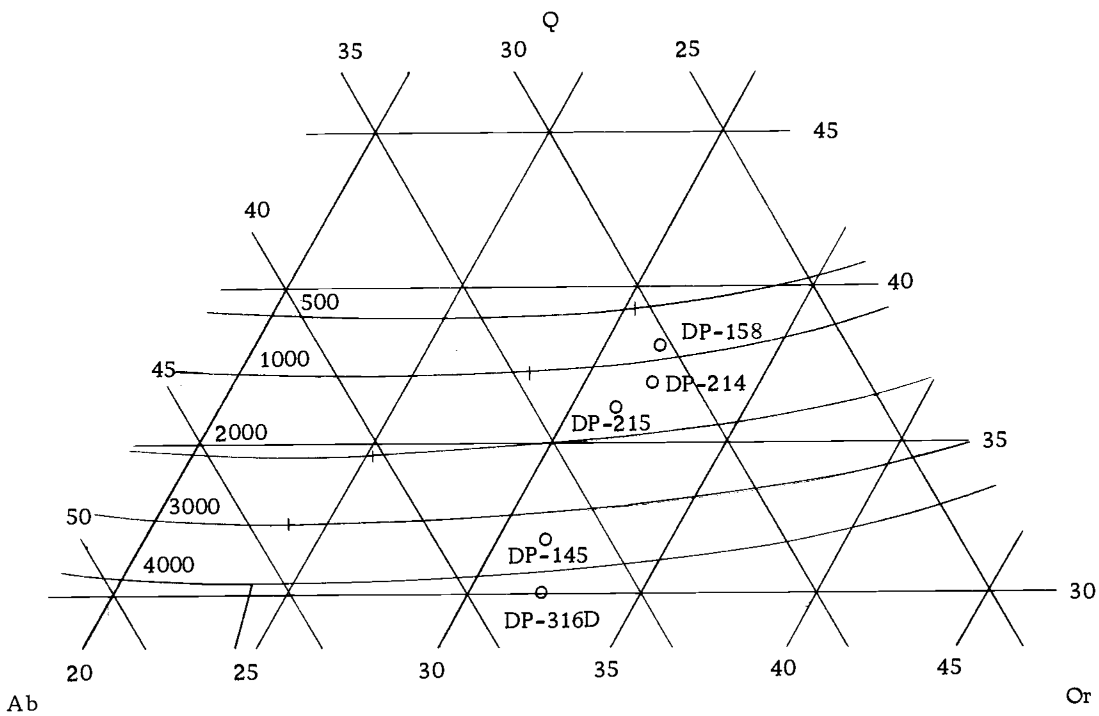

Figure 18. Normative compositions computed from chemical analyses of the peraluminous rhyolite flow rocks plotted in the system Q-Or-Ab. Curved lines are isobaric minima for this system at various water pressures in bars, after Tuttle and Bowen (1958). Thermal minima indicated by dashed or ternary intersection.

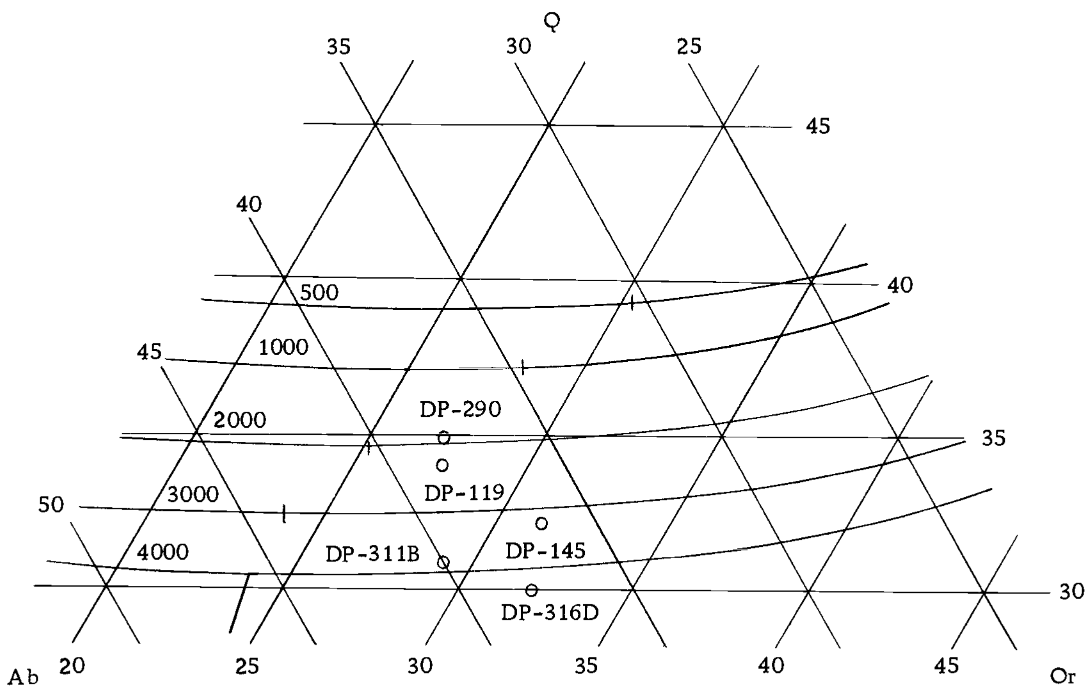

Figure 19. Normative compositions computed from chemical analyses of the ash-flow tuff of Prater Creek and related flow rocks plotted in the system Q-Or-Ab. Curved lines are isobaric minima for this system at various water pressures in bars, after Tuttle and Bowen (1958). Thermal minima indicated by dash or ternary intersection.

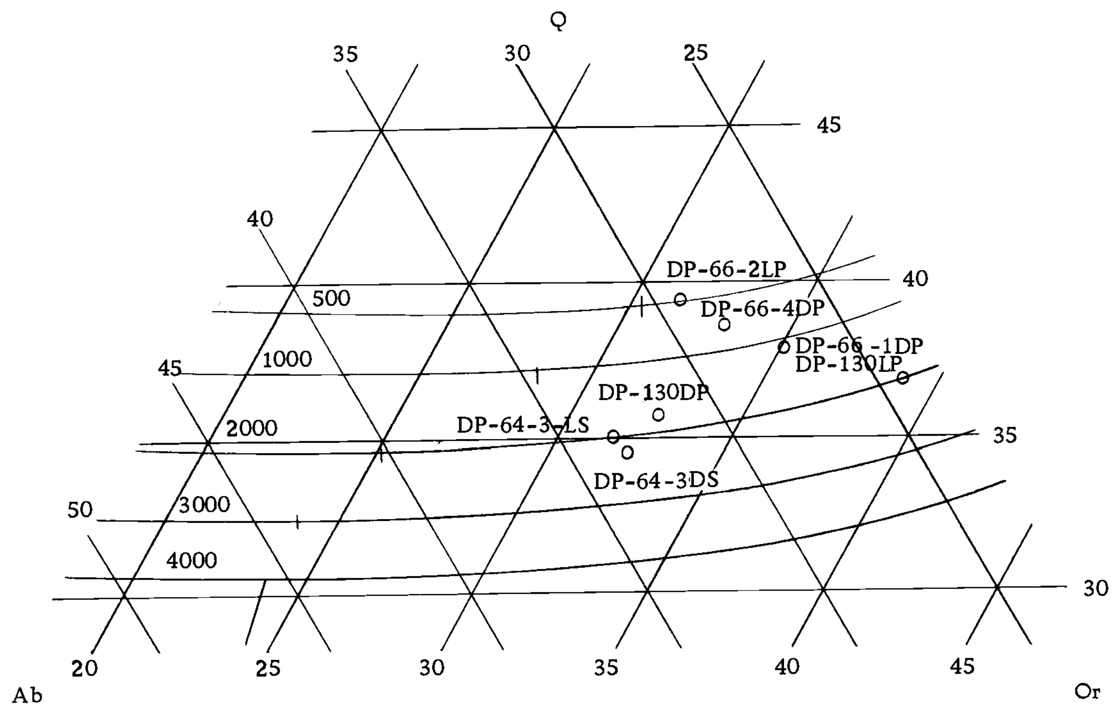

Figure 20. Normative compositions computed from chemical analyses of the Rattlesnake Ignimbrite Tongue plotted in the system Q-Or-Ab. Curved lines are isobaric minima for this system at various water pressure in bars, after Tuttle and Bowen (1958). Thermal minima indicated by dash or ternary intersection.

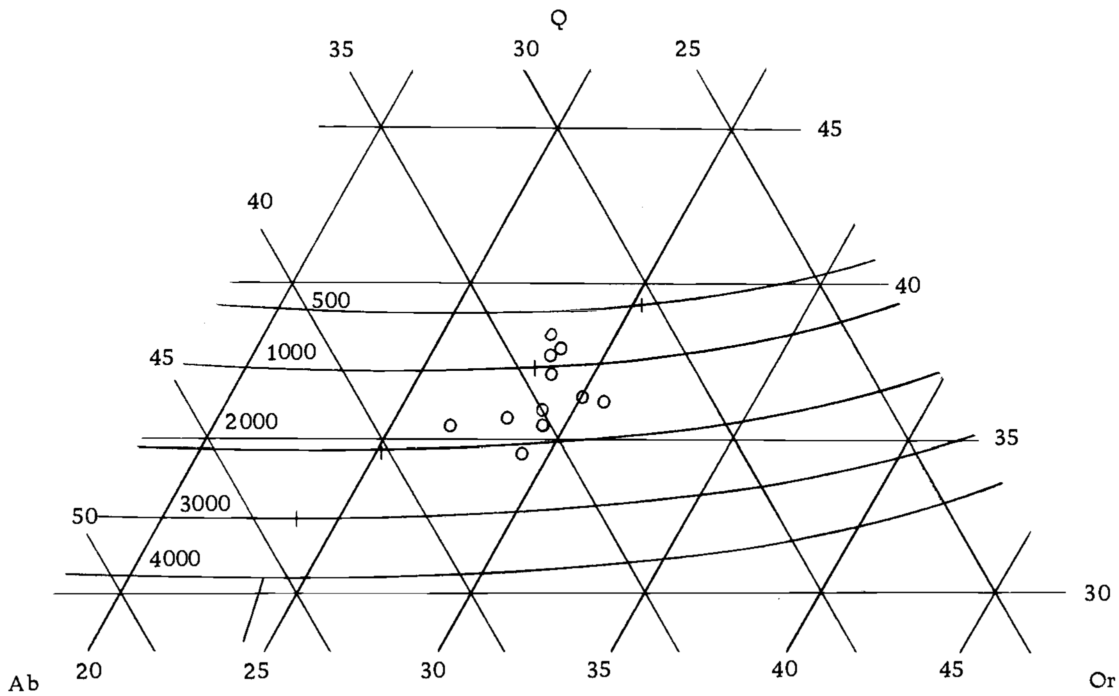

Figure 21. Normative compositions computed from chemical analyses of the ash-flow tuff of Devine Canyon plotted in the system Q-Or-Ab. Curved lines are isobaric minima for this system at various water pressures in bars, after Tuttle and Bowen (1958). Thermal minima indicated by dash or ternary intersection. Analyses (after Greene, 1973) plotted for devitrified samples.

devitrified. Rocks with this texture reflect the original composition better than glass which may be subjected to ground water leaching (Lipman, 1965). Samples DP-145 and DP-316D of the rhyolite of Double O Ranch are vitric and perhaps represent leached compositions. Evidence for the assimilation of basalt was observed in thin section examination of these samples.

Samples of the Rattlesnake Ignimbrite Tongue are glass and therefore were susceptible to leaching; especially the samples of pumice. It will be subsequently shown that the dark shards are most likely the result of basalt contamination and therefore do not represent a fractional crystallization trend. The dark shards contain more calcium than their light counterparts, and in such high amounts, that the normative anorthite content is high and therefore this technique is invalid (Noble, 1967).

The Ab-Or-Q compositions of the ash-flow tuff of Devine Canyon are plotted in Figure 21 and grossly parallel the isobaric minimum and intersect it in the area of 1000 to 700 bars water pressure. Greene (1973) has postulated that phenocrysts are not present as accumulates, but in equilibrium with their groundmass and therefore reflect the state of the magma. It is possible that the range of values of water pressure represents that present in the magma chamber at the time of eruption.

The normative Ab-Or-Q content of the ash-flow tuff of Prater

Creek and related flow rocks define a trend which intersects the isobaric minimum at about 1500 bars of water pressure (Fig. 19). The phenocrysts of alkali-spar and quartz (Davenport, 1970) agree with the mineral phases predicted by the diagram. A water pressure of 1500 bars indicates the top of the magma chamber must have been at least 4.8 km deep. Samples DP-145 and DP-316D are glasses from a rhyolite dome complex related to the ash-flow tuff of Prater Creek and are plotted on Figures 18 and 19. They do not contain cognate crystals and show evidence of assimilation of basaltic material.

The normative Ab-Or-Q compositions of samples of the Rattlesnake Ignimbrite Tongue are plotted in Figure 20 and do not define either a trend or close group. This is attributed to ground water alteration of the glass shards and pumice. Compositions plot in 500-2000 bar area which indicates a minimum depth of magma residence of 1.5 km. If sample DP-64-3-LS is assumed to indicate the unaltered magma composition because of its low Ca, Ti, Fe and high Na and K, the isobaric minimum would be at 2000 bars and the minimum depth to the magma chamber is assumed to be 5.6 km.

It is difficult to assess the validity of shallow depths of magma residence for these units by assumption of water saturated magmas because their calderas have not been identified. Greene (1973) proposes a source area in the Harney Basin lowland for the ash-flow tuff of Devine Canyon on the basis of circumstantial evidence, especially the distribution of crystals. The ash-flow tuff of Prater Creek had its source in the Harney Lake area and the rhyolite of Double O Ranch may be a related resurgent dome. A shallow magma chamber would seem reasonable.

The lack of a collapse feature associated with the source of the Rattlesnake Ignimbrite Tongue and its high pressure of water saturation collectively suggest a deep seated magma chamber. The eruption of a deep magma chamber would produce only slight readjustment detectable as faults at the surface as previously discussed.

The water pressures and depths of the magma chambers calculated are similar to those reported by Lipman (1966) for six rhyolite ash-flow sheets from Southern Nevada and seven analyzed glasses from the Island of Arran, Scotland.

Origin of Hybrid Glass and the Eruption of Ignimbrites in Harney Basin

Major element analyses of shards and pumice from the Rattlesnake Ignimbrite Tongue show a gradation in composition from light to dark glass types. Averages of major oxide values for each glass type given in Table 15 show that the dark shards are enriched in TiO_2, Al_2O_3, FeO (Fig. 22 and 23), and CaO, and are depleted in K_2O. The dark glass also contains less SiO_2 than the light glass but due to the analytical error the true difference is not known. This contrast in

Table 15. Average composition of glass from the Rattlesnake Ignimbrite Tongue, average tholeiitic basalt of this study, and a model hybrid glass.

Sample	Rattlesnake Light Glass (a)	Average Tholeiite (b)	Hybrid (c)	Rattlesnake Dark Glass (d)
Oxide				
SiO_2	76.7	50.0	74.0	74.8
TiO_2	0.12	1.4	0.25	0.28
Al_2O_3	11.8	15.5	12.2	12.3
FeO (total Fe)	0.8	10.4	1.72	2.2
MgO	0.28	8.3	1.1	0.25
CaO	0.87	11.2	1.90	1.5
Na_2O	3.3	3.0	3.27	3.2
K_2O	5.5	0.39	5.0	5.1

[a]Rattlesnake light glass--average of all light shards and light pumice analyses.

[b]Average tholeiite--average of all tholeiite basalts of this study.

[c]Hybrid--10% average tholeiite and 90% Rattlesnake light glass.

[d]Rattlesnake dark glass--average of all dark shards and dark pumice analyses.

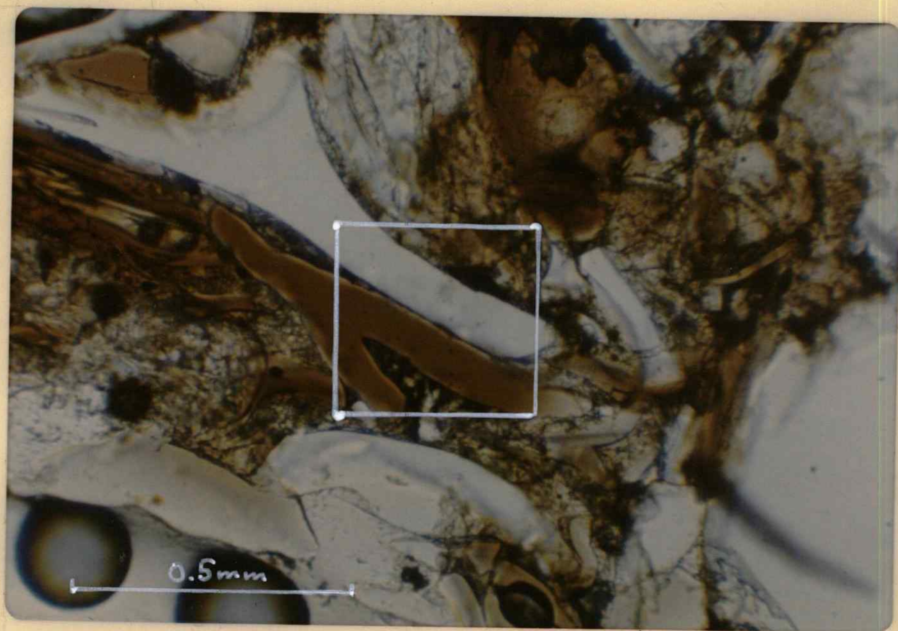

Figure 22. Photomicrograph of Rattlesnake Ignimbrite Tongue showing light and dark shards. Area in square is shown in Figure 23.

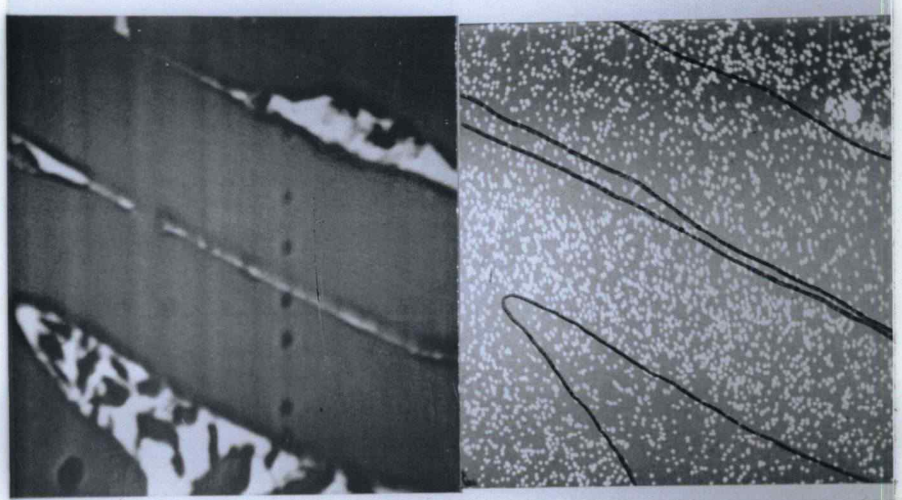

Figure 23. Electron microscope scan of the light and dark shards shown in square in Figure 22. Density of dots in the right hand scan is proportional to total iron content.

chemistry is consistent with the assimilation of basaltic material by a magma with the composition of the light glass. The average composition of the light and dark glasses from the Rattlesnake Ignimbrite Tongue, the average tholeiite basalt of this study, and a hybrid of 10% basalt and 90% light glass is given in Table 15. Oxide values for hybrid glass are comparable to those of the dark glass. Magnesia is much less abundant in the dark glass than suggested by this mixing model and is unexplained. It should be noted that MgO is uniformly low in all shard and pumice analyses (less than 0.4%) and only 0.1% in DP-130-DP which contains 4.8% FeO. The brown glass may be a result of bulk mixing of basaltic and rhyolitic magmas or the assimilation of basaltic wall rock by a rhyolitic magma. Chemical data cannot identify which of these possibilities is valid.

Davenport (1970) reviewed studies of the generation of volcanic rocks containing mixed glass. Most reports of mixed glass volcanic rocks have been from calc-alkalic andesite-dacite-rhyolite suites such as Lassen Peak (Mcdonald and Katsura, 1965), Mount Katmai and Novaupta (Williams, Curtis, and Juhle, 1956), San Juan volcanic field (Lipman, 1973), Crater Lake (Lidstom, 1972), Meseta Central Occidental in Costa Rica (Williams, 1952), and Taupo New Zealand (Ewart, 1963). All are apparently related to subduction tectonics. Yoder has reviewed occurrences of mixed magma throughout the world (1973). Lipman (1973) attributes mixed glass ash-flows, as in the case of the San Juan field to eruption from a zoned magma chamber. This zonation was a result of crystal settling, volatile and element migration, and eruption which produced an upside down counterpart of the magma chamber at the surface. The Rattlesnake Ignimbrite Tongue does not fit this model because no major change in chemistry occurs over its 420 km north-south extent. Crystal settling in the magma did not result in zonation because cognate crystals total less than 1%. Lidstrom (1972) attributed a mixed ash-flow at Crater Lake to magma mixing which triggered the culminating eruptions of the volcano to form ash-flows and the summit collapse caldera.

The above studies and the data of this study suggests that the hybrid glass of the Rattlesnake Ignimbrite Tongue may be the result of bulk magma mixing or assimilation of wall rock. Assimilation of basaltic wall rock by a rhyolitic magma, represented by the light glass, would have resulted in the crystallization of at least an equal part of the light magma. Phenocrysts comprise less than 1% of the ash-flow and nowhere were crystals more abundant. Anorthoclase phenocrysts in the John Day Basin commonly show effects of absorption (Enlows, oral communication, 1974) which would be an indication of an increase in the temperature of the magma.

The eruption of the Rattlesnake Ignimbrite Tongue occurred as follows. A uniform magma with less than 1% crystals was residing in a magma chamber 6 km in depth. This chamber was intruded by basaltic magma which caused an increase in magma temperature and a change in water solubility that resulted in boiling and the initiation of absorption of phenocrysts into the magma. Initial eruption of magma took place from the top of the magma chamber when the vapor phase exceeded confining pressure and resulted in the deposition of the basal ash-flow sheet which went as far as the John Day Basin and contained hybrid shards and white pumice. This partial emptying of the magma chamber introduced more basalt into contact with the rhyolite magma and was followed by a second eruption containing hybrid pumice. It is proposed that hybridation took place across a chemical and physical interface and actual magma mixing was not important.

The ash-flow tuff of Devine Canyon also displays mixed glass types. Two pumice lumps, one light (DP-245LP) and one dark (DP-245DP) were analyzed. The chemical analyses of these glasses and a hybrid of 15% average tholeiitic basalt and 85% light pumice (DP-245LP) is given in Table 16. Comparison of the hybrid and dark pumice (DP-245DP) analyses indicate that simple bulk assimilation of basalt has not occurred. This ash-flow contains from 2 to 40% phenocrysts, primarily of alkali feldspar which may control the amount of CaO, Na_2O, and K_2O present in a sample. Greene (1973) described the pumice fragments of this tuff as "pale brown to colorless glass"

Table 16. Average composition of glass from the ash-flow tuff of Devine Canyon, average tholeiitic basalt of this study, and a model hybrid glass.

Sample	Devine Canyon Light Glass (a)	Average Tholeiite (b)	Hybrid (c)	Devine Canyon Dark Glass (d)
Oxide				
SiO_2	75.0	50.0	71.3	71.3
TiO_2	0.20	1.4	0.38	0.35
Al_2O_3	11.8	15.5	12.4	13.4
FeO (total Fe)	2.7	10.4	3.9	4.5
MgO	0.15	8.3	1.4	0.41
CaO	0.6	11.2	2.2	1.9
Na_2O	3.12	3.0	3.1	3.85
K_2O	6.3	0.39	5.46	6.0

[a] Devine Canyon light glass--one analysis of pumice (DP-245LP).

[b] Average tholeiite--average of all tholeiite basalts of this study.

[c] Hybrid--15% average tholeiite and 85% Devine Canyon light glass.

[d] Devine Canyon dark glass--one analysis of pumice (DP-245DP).

and the shards as "stretched shards (colorless) and uniform, pale-brown glass matrix." Greene (1973) also reported that "the vast majority of phenocrysts show some rounding or embayment. . . and show no apparent relation to position in the section, or to abundance of phenocrysts." The ash-flow tuff of Devine Canyon may have a magmatic history similar to that of the Rattlesnake Ignimbrite Tongue. The major difference was a later introduction of mafic magma, after crystallization had progressed to approximately 20% of the magma.

The ash-flow tuff of Prater Creek does not display either hybrid glass or other features that would relate to it the eruption sequence as outlined above. The rhyolite of Double O Ranch, perhaps related to the eruption center of the ash-flow tuff of Prater Creek, contains "basalt clots" as discussed earlier in this study. Their origin is not known.

PETROGENESIS OF THE BIMODAL VOLCANIC SUITE

Any hypothesis proposed for the origin of the bimodal (basalt-rhyolite) suite of volcanic rocks should take into account its worldwide distribution, the lack of intermediate rock types associated with it, the contemporaneous eruption of both magma types (often from the same vent), and the recurrence of these features throughout geologic time. An earlier discussion listed occurrences of the bimodal magma suite in calc-alkaline volcanic provinces related to subduction. The basalt-rhyolite bimodal association is not analogous to the andesite-dacite calc-alkaline association. Basalt-rhyolite suites have been reported from Iceland (Blake and others, 1965), an oceanic spreading ridge environment devoid of "granitic" crust; from the volcano Tejeda of Gran Canaria (Schmincke, 1967), an oceanic island; and in the Snake River Plain--Yellowstone area (Christiansen, 1973), a trail of a "hot spot" through the continent.

The basalt-rhyolite association is most common to the continents. It has been suggested that rhyolite of the bimodal suite has its origin in heating and melting of the lower crust by crustal thinning and rising basaltic magma (Scott and others, 1971; Christiansen, 1973). It is suggested that bimodal volcanism may be a part of the oceanic ridge volcanic suite. Ophiolitic complexes, perhaps old ocean floor, such as the Canyon Mountain complex of Oregon (Thayer, 1967) and

Thoodos Massif of Cyprus (Gass, 1967) contain albite granite dikes. Thayer (1967) reports these dikes are an important part of the alpine mafic magma stem. These granitic magmas apparently have their origin in the mantle with little influence from crustal material because the continental crust is absent (oceanic environment). Rhyolitic magmas formed as minimum melts from granitic crustal rocks would not have sufficient energy to rise to the surface (Fyfe, 1970). The rhyolite flow rocks of this study have small amounts (less than 1%) of hydrous minerals (biotite-hornblende) in a phenocryst assemblage that comprises less than 5% of the rock. This small amount of hydrous minerals indicates that water saturation occurred late in the magmatic process. Moreover, ash-flow sheets erupted from shallow magma chambers have an anhydrous mineral assemblage (alkali-feldspar and pyroxene) indicating that they were undersaturated at the time of eruption. Therefore, it is suggested that rhyolites of the Harney Basin bimodal suite did not originate as minimum granites, but as anhydrous granitic magmas at temperatures above the liquidus.

Models for the genesis of the bimodal volcanic suite must be consistent with the data for rhyolites obtained in this study which are part of a Basin and Range bimodal suite. The strontium isotope data presented in this study show the Sr^{87}/Sr^{86} ratios of the rhyolites to be less than ratios for the crustal rocks beneath eastern Oregon, and thus renders unlikely an origin by crustal anatexis. The bimodal suite is also found in ocean basins, where crustal anatexis cannot occur. It is therefore necessary to develop an alternative process for the generation of basalt-rhyolite suites.

Differentiation from a basaltic liquid has been proposed as the origin of Basin and Range rhyolite (Noble, 1972). Yoder (1973) has recently proposed partial melting of the mantle as the possible origin of rhyolite magma of the bimodal association. The paucity of phenocrysts in rhyolitic rocks of the Harney Basin does not support Noble's conclusion that rhyolites of the Basin and Range are differentiates of basaltic magma. The ash-flow tuff of Devine Canyon is zoned as to phenocryst content but is uniform in bulk composition, despite crystallization of 40% of the magma (Greene, 1973). From geologic evidence it would be unreasonable to suggest a purge of crystals from a magma prior to eruption as would be the case of the "crystal poor" ash-flow tuff of Prater Creek and the Rattlesnake Ignimbrite Tongue. Moreover, the high Sr content of the Iron Mountain rhyolite (DP-158, Table 14) is inconsistent with Noble's suggestion that the Basin and Range rhyolites are the result of protracted feldspar (alkali-feldspar) crystallization and settling. The fractional crystallization model also implies that intermediate magma is produced in volumes greater than rhyolitic magma. The bimodal distribution of volcanic rocks is still referred to by many authors who have found an insufficient quantity of intermediate rocks to abandon the term bimodal (Noble, 1972).

In conclusion, it is suggested that the bimodal suite of volcanic rocks in the Harney Basin formed as a consequence of partial melting of the mantle which resulted in the generation and rise of basalt and rhyolite magmas to the surface.

BIBLIOGRAPHY

American Commission on Stratigraphic Nomenclature, 1972, Code of Stratigraphic Nomenclature: The Am. Assoc. of Petroleum Geologists, Inc., Tulsa, Oklahoma, 22 p.

Armstrong, R. L., 1970, Geochronology of Tertiary igneous rocks, Eastern Basin and Range Province Western Utah and Eastern Nevada, and vicinity, U.S.A.: Geochim. et Cosmochim. Acta, v. 34, p. 203-232.

Armstrong, R. L. and Cooper, J. A., 1971, Lead isotopes in island arcs: Bull. Volcanol. v. 35, p. 27-63.

Armstrong, R. L. and Hein, S. M., 1973, Computer simulation of Pb and Sr isotope evolution of the earth's crust and upper mantle: Geochim. et Cosmochim. Acta, v. 37, p. 1-18.

Baldwin, E. M., 1964, Geology of Oregon, Eugene, distributed by University of Oregon Cooperative Book Store, 156 p.

Beeson, M.H., 1969, A trace element study of silicic volcanic rocks: Ph. D. thesis, San Diego, University of California. 130 numb. leaves.

Blake, D.H., Elwell, R.W.D., Gibson, I.L., Skelhorn, R.R., and Walker, G.P.L., 1965, Some relationships resulting from the intimate association of acid and basic magmas: Quart. J. Geol. Soc. London, v. 121, p. 31-50.

Campbell, I., Conel, J.E., Rogers, J.J.W., and Whitfield, I.M., 1958, Possible correlations of Rattlesnake and Danforth Formations of Eastern Oregon: (Abstract) Geol. Soc. America, Bull., v. 69, p. 1678.

Chayes, F., 1965, Titania and alumina content of oceanic and circumoceanic basalt: Mineralog. Mag. v. 34, no. 268, p. 126-131.

Christiansen, R.L., 1973, Rhyolitic ash-flows of the Yellowstone Plateau volcanic field--Wyoming, Idaho, Montana--and generation of the rhyolite basalt association (abstract): Geol. Soc. America Abstracts with Programs, v. 1, p. 21-22.

Church, S.E. and Tilton, G.R., 1973, Lead and strontium isotopic studies in the Cascade Mountains: bearing on andesite genesis: Geol. Soc. America Bull., v. 84, p. 431-454.

Dasch, E.J., 1969, Strontium isotope disequilibrium in a porphyritic alkali basalt and its bearing on magmatic processes: Journal of Geophysical Research, v. 78, p. 560-565.

Dasch, E.J., Hedge, C.E., and Dymond, J., 1973, Effect of sea water interaction on strontium isotope composition of deep-sea basalts: Earth and Planetary Science Letters, v. 19, no. 2, p. 177-183.

Davenport, R.E., 1970, Geology of the Rattlesnake and other ignimbrites in the Paulina Basin and adjacent area, Central Oregon, Ph.D. thesis, Corvallis, Oregon State University, 132 numb. leaves.

Dickinson, W.R. and Vigrass, L.W., 1965, Geology of the Suplee-Izee area, Crook, Grant, and Harney Counties, Oregon: Oregon Dept. Geol. Min. Indus. Bull. 58, 109 p.

Enlows, H.E., 1973, Rattlesnake Formation in Geologic field trips in Northern Oregon and Southern Washington: Oregon Dept. of Geol. Min. Inds. Bull., 72, p. 24-27.

Enlows, H.E., Parker, D.J., and Davenport, R.E., 1973, The Rattlesnake Ignimbrite Tongue: (Abstract) Geol. Soc. America Abstracts with Programs, v. 5, no. 1, p. 38.

Evernden, J.F., Savage, D.E., Curtis, G.H., and James, G.T., 1964, Potasium-argon dates and the Cenozoic mammalian chronology of North America: Amer. Jour. Sci., v. 262, no. 2, p. 145-198.

Ewart, A., 1963, Petrology and petrogenesis of the Quaternary pumice ash in the Taupo area, New Zealand: Journal of Petrology, v. 4, p. 392-431.

Ewart, A., Stipp, J.J., 1968, Petrogenesis of the volcanic rocks of the Central North Island, New Zealand, as indicated by a study of Sr^{87}/Sr^{86} ratios, and Sr, Rb, K, U, and Th abundances: Geochim. Cosmochim. Acta, v. 32, p. 699-736.

Fuller, R.E., 1931, The geomorphology and volcanic sequence of Steens Mountain in Southeastern Oregon: University of Washington Publications in Geology, v. 3, p. 1-30.

Fyfe, W.S., 1970, Some thoughts on granitic magmas: in Mechanism of Igneous Intrusion, Liverpool, England, Gallery Press, p. 201-216.

Gass, I.G., 1967, The ultrabasic volcanic assemblage of the Thoodos Massif, Cyprus: in Ultramafic and Related Rocks: New York, John Wiley and Sons, p. 121-134. (edited by P.J. Wyllie)

Green, D.H. and Ringwood, A.E., 1967, The genesis of basaltic magmas: Contributions to Mineralogy and Petrology, v. 15, p. 103-190.

Greene, R.C., 1972, Generalized geologic map of the Burns and West Myrtle Butte 15-minute quadrangles, Oregon: U.S. Geol. Survey Misc. Geol. Inv. Map I-680.

Greene, R.C., 1973, Petrology of the welded tuff of Devine Canyon, Southeastern Oregon: U.S. Geol. Survey Prof. Paper 797, 25 p.

Greene, R.C., Walker, G.W., and Corcoran, R.E., 1973, Geologic Map of the Burns Quadrangle, Oregon: U.S. Geol. Survey Misc. Geol. Inv. Map I-680.

Hakli, T.A. and Wright, T.L., 1967, The fractionation of nickel between olivine and augite as a geothermometer: Geochim. Cosmochim. Acta, v. 31, p. 877.

Harrold, J.L., 1973, Geology of the North-Central Pueblo Mountains, Harney County, Oregon: Corvallis, Oregon State University. 135 numb. leaves.

Hart, S.R., 1972, Sr isotopic composition of the oceanic crust, in Annual Report of the Director, Department of Terrestrial Magnetism 1971-1972, p. 288-290.

Hedge, C.E., Hildreth, R.A., and Henderson, W.T., 1970, Strontium isotopes in some cenozoic lavas from Oregon and Washington: Earth and Planetary Science. Letters, v. 8, p. 434-438.

Hedge, C.E., and Peterman, Z.E., 1970, The strontium isotope composition of basalts from the Gordo and Juan de Fuca Rises, Northeastern Pacific Ocean: Contributions to Mineralogy and Petrology, v. 27, p. 114-120.

Higgins, M.W., 1973, Petrology of Newberry Volcano, Central Oregon: Geol. Soc. America Bull. v. 84, p. 455-488.

Jakes, P., and White, A.J.R., 1970, K/Rb ratios of rocks from island arcs: Geochim. Cosmochim. Acta, v. 34, p. 849-856.

Korringa, M.K. and Noble, D.C., 1971, Distribution of Sr and Ba between natural feldspar and igneous melt: Earth and Planetary Sci. Letters, v. 11, p. 147-151.

Lidstom, J.W., 1972, A new model for the formation of Crater Lake Caldera, Oregon, Ph.D. thesis, Corvallis, Oregon State University, 85 numb. leaves.

Lipman, P.W., 1965, Chemical comparison of glassy and crystalline volcanic rocks: U.S. Geological Survey Bulletin 1201-D, p. 1-24.

Lipman, P.W., 1966, Water pressures during differentiation and crystallization of some ash-flow magmas from southern Nevada: American Journal of Science, v. 264, p. 810-826.

Lipman, P.W., 1973, Compositionally zoned ash-flow sheets: quenched samples of differentiated batholiths: (Abstract) Geological Society of American Abstracts with Programs, v. 5, no. 1, p. 72.

Lund, E.H., 1966, Zoning in an ash-flow of the Danforth Formation, Harney County, Oregon: The Ore Bin, Oregon Dept. Geol. Min. Indus., v. 28, p. 161-170.

Macdonald, G.A. and Katsura T., 1964, Chemical composition of Hawaiian lavas: Journal of Petrology, v. 5, p. 82-133.

Macdonald, G.A. and Katsura, T., 1965, Eruption of Lassen Peak, Cascade Range, California, in 1915: Example of mixed magmas: Geological Society of America Bulletin, v. 76, p. 475-482.

Manson, V., 1967, Geochemistry of basaltic rocks: major elements, in Basalts (The Poldervaart Treatise on Rocks of Basaltic Composition): New York, John Wiley and Sons, p. 215-270. (Edited by H.H. Hess and A. Poldervaart)

McBirney, A.R., 1969, Andesitic and rhyolitic volcanism of orogenic belts in Geophysical Monograph 13 (The Earth's Crust and Upper Mantle): American Geophysical Union.

McBirney, A.R., 1968, Compositional variations of the climactic eruptions of Mount Mazama: Oregon Department of Geology and Mineral Industries Bulletin 62, p. 53-56.

Merriam, J.C., 1901. A contribution to the geology of the John Day Basin: University of California Publications in Geological Sciences, v. 2, p. 269-314.

Niem, A.R., 1974, Wright's Point, Harney County, Oregon, an example of inverted topography: The Ore Bin, Oregon Dept. Geol. Min. Indus., v. 36, no. 3, p. 33-49.

Noble, D.C., 1967, Calcium contents, Na_2O:K_2O ratios, and water contents of the Paintbrush and Timber Mountain magmas: American Journal of Science, v. , p. 860-864.

Noble, D.C., 1972, Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, Western United States: Earth and Planetary Science Letters, v. 17, p. 142-150.

Oles, K.F. and Enlows, H.E., 1972, Geology of the Mitchell Quadrangle, Wheeler County: Oregon Dept. Geol. Min. Indus. Bull., 72, 62 p.

Peterman, Z.E., Hedge, C.E., Coleman, R., and Snavely, P.D. Jr., 1967, Sr^{87}/Sr^{86} ratios in some eugeosynclinal sedimentary rocks and their bearing of the origin of granitic magma in orogenic belts: Earth and Planetary Science Letters, v. 2, p. 433-439.

Peterman, Z.E. and Heming, R.F., In Press, Sr^{87}/Sr^{86} ratios of calc-alkaline lavas from the Rabaul caldera, Papau, New Guinea: Geol. Soc. America Bull.

Peterman, Z.E., Lowder, G.G., and Carmichael, I.S.E., 1970, Sr^{87}/Sr^{86} ratios of the Talasea Series, New Britian, Territory of New Guinea: Geol. Soc. America Bull., v. 81, p. 39-40.

Piper, A.M., Robinson, T.W., and Park, C.F., 1939, Geology and ground water resources of the Harney Basin, Oregon: U.S. Geol. Survey Paper 841, 189 p.

Prinz, M., 1967, Geochemistry of basaltic rocks: trace elements, in Basalts (The Poldervaart Treatise on Rocks of Basaltic Composition): New York, John Wiley and Sons, p. 271-324. (Edited by H.H. Hess and A. Poldervaart)

Pushkar, P.D., 1966, The isotopic composition of strontium in volcanic rocks from island arcs. Ph.D. thesis, University of California, San Diego.

Schmincke, H.U., 1967. Cone sheet swarm, resurgence of Tejeda Caldera, and the early geologic history of Gran Canaria: Bull. Volcanol. v. 31, p. 153-162.

Scott, R.B., Nesbitt, R.W., Dasch, E. Julius, and Armstrong, R.L., 1971, A strontium isotope evolution model for Cenozoic magma genesis, eastern Great Basin, U.S.A: Bull. Volcanol. Tome XXXV-1, p. 1-26.

Shand, S.J., 1951, Eruptive Rocks: New York, John Wiley and Sons, Inc., 488 p.

Smith, J.G., McKee, E.H., Tatlock, D.B., and Marvin, R.F., 1971, Mesozoic granitic rocks in Northwestern Nevada: a link between the Sierra Nevada and Idaho Batholiths: Geol. Soc. America Bull., v. 82, p. 2933-2944.

Subbarao, K.V., 1972, The strontium isotopic composition of basalts from the East Pacific and Chile rises and abyssal hills in the Eastern Pacific Ocean: Contributions to Mineralogy and Petrology, v. 37, p. 111-120.

Tatsumoto, M., Hedge, C.E., and Engle, A.E.J., 1965, Potassium, rubidium, strontium, thorium, uranium, and the ratio of strontium-87 to strontium-86 in oceanic tholeiitic basalt: Science, v. 150, p. 886-888.

Taubeneck, W.H., 1971, Idaho Batholith and its southern extension: Geol. Soc. America Bull., v. 82, p. 1899-1928.

Thayer, T.P., 1967, Chemical and structural relations of ultramafic and feldspathic rocks in alpine instrusive complexes, in Ultramafic and Related Rocks: New York, John Wiley and Sons, p. 222-239. (edited by P.J. Wyllie)

Thayer, T.P. and Brown, C.E., 1964, Pre-Tertiary orogenic and plutonic intrusive activity in central and Northeastern Oregon: Geol. Soc., America Bull., v. 75, p. 1255-1262.

Tower, D.B., 1972, Geology of Central Pueblo Mountains, Harney County, Oregon: Master's thesis. Corvallis, Oregon State University. 96 numb. leaves.

Turekian, K.K., 1963, The chromium and nickel distribution in basaltic rocks and ecologites: Geochim. Cosmochin. Acta, v. 27, p. 815-846.

Turekian, K.K. and Wedepohl, K.H., 1961, Distribution of elements in some major units of the earth's crust: Geol. Soc. America Bull., v. 73, p. 801-812.

Tuttle, O.F.. and Bowen, N.L., 1958, Origin of Granite in Light of Experimental Studies in the System $NaSlSi_3O_8$-$KAl\ Si_3O_8$-SiO_2-H_2O: Geol. Soc. America Memoir 74, 153 p.

Walker, G.W., 1968, Summary report on the geology and mineral resources of the Harney Lake and Malheur Lake areas of the Malheur National Wildlife Refuge, north-central Harney County, Oregon, U.S.Geol. Survey Bull. 1260-L, p. L1-L17.

________________, 1969a, Some comparisons of basalts of southeast Oregon with those of the Columbia River Group, in Proceedings of the Second Columbia River Basalt Symposium, Cheney, Washington: Cheny, Eastern Washington State College Press, p. 223-237.

________________, 1969b, Geology of the High Lava Plains Province: Oregon Dept. Geol. Min. Indus. Bull. 64, in coop. with U.S. Geol. Survey, p. 77-79.

_______________, 1969c, Possible fissure vent for a Pliocene ash-flow tuff, Buzzard Creek area, Harney County, Oregon: U.S. Geol. Survey Prof. Paper 650-C, p. C8-C17.

_______________, 1970, Cenezoic ash-flow tuffs of Oregon: The Ore Bin, Oregon Dept. Geol. Min. Indus., v. 32, no. 6, p. 97-105.

_______________, 1973, Tectonic map of Oregon: U.S. Geol. Survey Miscellaneous Field Studies Map MF-495, Sheet 2 of 2.

Walker, G.W. and Repenning, C.A., 1965, Reconnaissance Geologic Map of the East Half of the Adel Quadrangle, Lake, Harney, and Malheur Counties, Oregon: U.S. Geol. Survey Misc. Geol. Inv. Map I-446, scale 1:250,000.

Walker, G.W. and Swanson, D.A., 1968a, Summary report on the geology and mineral resources of the Harney Lake and Malheur Lake areas of the Malheur National Wildlife Refuge, north-central Harney County, Oregon: U.S. Geol. Survey Bull. 1260-L, p. L1-L17.

_______________ and Swanson, D.A., 1968b, Laminar flowage in a Pliocene soda rhyolite ash-flow tuff, Lake and Harney Counties, Oregon, in Geological Survey Research, 1968: U.S. Geol. Survey Prof. Paper 600-B, p. B37-B47.

Waters, A.C., 1962, Basalt magma types and their tectonic associations: Pacific Northwest of the United States: Washington, D.C., National Academy of Science-National Research Council, p. 158-170. (Publication 1035. American Geophysical Union, Monograph 6).

Williams, H., 1942, The Geology of Crater Lake National Park, Oregon: Carnegie Institute of Washington. Publication no. 540. p. 1-162.

Williams, H., 1952, Volcanic history of the Meseta Centeral Occidental. Costa Rica: University of California Publications in Geological Sciences, v. 29, p. 145-180.

Williams, H., Curtis, G., and Juhle, W., 1956, Mount Katamai and the Valley of Ten Thousand Smokes, Alaska. (Abstract) In: Proceedings of the Eight Pacific Science Congress, Manilla, 1953, v. 2, Quezon City, National Research Council of the Philippines, 129 p.

Yoder, H.S. Jr., 1973, Contemporaneous basaltic and rhyolitic magmas: American Mineralogist, v. 58, p. 153-171.

APPENDICES

APPENDIX I

Whole Rock Major and Minor Element Analyses

Sample Preparation

All weathered and sawed surfaces were removed from rocks to be analyzed. Rock samples were broken into pieces smaller than 5 cm with a hardened steel hammer or rock crusher. One-half kg of this material, for whole rock major element analysis, was fed through a jaw crusher with hardened steel plates. This material was split and one-half was pulverized by hand in a steel percussion mortar or ceramic mortar. This powder was further pulverized in a ball mill for longer than five minutes. The second half of the sample was sent to the Rocky Mountain Geochemical Corporation where all sample preparation is done with aluminum oxide surfaces.

Shards were separated from samples of the Rattlesnake Ignimbrite Tongue by curshing the sample and passing the 65 to 200 mesh fraction through the Frantz magnetic separator to get maximum color separation. The light colored fraction contained only white shards while the dark fraction contained many shades of shards ranging from dark brown to light brown. Samples of light shards are designated by the initials LS following the sample number and the dark shards by DS. Pumice is discriminated by the initials LP and DP following the sample number.

Si, Al, Fe, Ca, K, and Ti Analysis

Si, Al, Fe (total iron as FeO), Ca, K, and Ti analyses were done by X-ray fluorescence technique. The rock powders were ignited and fused with anhydrous lithium tetraborate flux and cast into buttons. A polished face of this button was analyzed using a Cr target X-ray source with appropriate analyzing crystals and detection systems.

Mg and Na Analyses

Analyses for Mg and Na were done on a model 103 Perkin-Elmer atomic absorption spectrophotometer by Edward M. Taylor.

Minor Element Analyses

Analyses for Cu, Pb, Zn, Ni, Co, V, and Cr were done by atomic absorption by Lawrence R. Reid of Rocky Mountain Geochemical Corporation. Mo was found to be present in detectable amounts in only one sample analyzed colorimetrically by Mr. Reid.

Accuracy of Whole Rock and Minor Element Analyses

Analytical accuracy estimated for replicate analyses on U.S. Geological Survey rock standards and comparison with analyses from other laboratories is given below.

Si:	3% of amount present in rock.
Al:	3% of amount present in rock.
Fe:	3% of amount present in rock.
Ca:	3% of amount present in rock if over 1%, 0.03% Ca if less than 1%.
K:	2% of amount present in rock of over 1%, 0.02% K if less than 1%.
Ti:	2% of amount present in rock if over 1%, 0.02% Ti if less than 1%.
Mg:	2% of amount present in rock if over 5%, 0.1% Mg if less than 5%.
Na:	3% of amount present in rock if over 3%, 0.1% Na if less than 3%.

APPENDIX II

K-Ar Age Dating--Analytical Techniques

Sample Preparation

Mineral separates were recovered from 40 to 100 mesh sieve fractions of crushed rock using a shaking table, rapid and slow magnetic separators, and heavy liquids. All mineral separates were hand picked to remove obvious foreign material and altered or composite grains. The separates were then cleaned with an ultrasonic cleaner. Whole rock samples were crushed to 0.3 to 1.0 cm size for Ar analysis and a fraction of this size was ground further for K analysis.

Anorthoclase separates E-6-70, E-84-67, and Cottonwood were hand picked after mechanical and heavy liquid separation from a glass matrix by Harold E. Enlows. These separates were further hand picked by the author to remove composite grains of anorthoclase and magnetite and off color grains of feldspar. Sample Cottonwood was etched in 80°C hydrofluoric acid for 45 seconds to remove any glass adhering to the crystals.

K Analyses

The K analyses were done with a model 303 Perkin-Elmer atomic absorption spectrophotometer using a Na-Li alkali buffer. The precision of the K analysis is 1% based upon replicate analysis of standards and duplicate analysis of unknowns. Where duplicate analysis differed by more than 2% or 0.02% K for samples containing less than 1% K the analyses were repeated until satisfactory reproducibility was achieved.

Ar Analyses

The Ar analyses was done by typical isotope dilution analysis procedures in the static mode on a modified Nier Type 60° sector mass spectrometer. Ar^{40} and Ar^{36} peaks were measured on the 3V and 10 MV scales respectively, of a Carey vibrating reed electrometer with 1 x 10^{11} ohm input resistor, using a Leeds and Northrup strip chart recorder.

The error for the analyses reported is 1% of the total Ar content (radiogenic plus atmospheric). The precision of K-Ar age dates reported is 1.5 to 2.0 percent (±4 percent for 95% confidence limits) for samples with less than 50% air contamination. At 90% air contamination the uncertainty increases to 10%. Uncertainties reported are for analytical error only and represent one standard deviation, or the standard error for averaged dates.

The dates are computed using the following constants: K^{40} = 0.0119 atom percent; $K_{\lambda_\beta} = 4.72 \times 10^{-10}\ yr^{-1}$, $K_{\lambda_\epsilon} = 0.584 \times 10^{-10} yr^{-1}$.

Laboratory

The Ar and K analyses were done by the author at the Yale University Kline Geology Laboratory and the analytical techniques used are described in greater detail by Armstrong (1970). The geochronometry lab of Yale University is supported by NSF Grant GA 26025.

Table I. Potassium-argon data for the rocks dated.

Sample	% K	Ar^{40} 10-6 cc/m	Ar^{40} %	K-Ar Date (m.y.)
DP-14				
whole rock	0.244, 0.239	0.0280, 0.0229	7, 5	2.6 ± 0.3
DP-41				
whole rock	0.655, 0.669	0.0709, 0.0766	9, 6	2.8 ± 0.2
DP-119				
whole rock	3.78, 3.79	1.26, 1.23	59, 47	8.2 ± 0.12
DP-146				
whole rock	4.26, 4.26	1.41, 1.45	4, 5	8.4 ± 1.3
DP-158				
whole rock	3.75, 3.66	0.307	9	2.1 ± 0.24
biotite	5.35, 5.38	0.569	7	2.7 ± 0.4
DP-160				
whole rock	1.79, 1.74	0.4652, 0.3826	8, 6	5.8 ± 0.8
DP-214				
whole rock	4.07, 4.06	0.907	16	5.6 ± 0.4
biotite	6.82, 6.97	1.755	35	6.4 ± 0.2
DP-243				
sanidine	6.53, 6.51	1.837, 1.845	59, 55	7.1 ± 0.10
DP-250				
whole rock	0.289, 0.293, 0.294	0.0922	8	7.9 ± 0.9
DP-300				
whole rock	0.341, 0.348	0.124, 0.119	4, 5	8.8 ± 1.4
DP-311B				
whole rock	3.73, 3.76	1.26, 1.39	42.8	8.6 ± 0.12
DP-311G				
whole rock	4.09, 409	1.092, 1.083	26, 21	6.6 ± 0.2
DP-316D				
whole rock	4.13, 4.03	1.28	16	7.8 ± 0.5
DP-330				
whole rock	4.04, 403	1.044, 1.106	10, 11	6.7 ± 0.4
E-84-67				
anorthoclase	4.41, 4.43	1.161	29	6.6 ± 0.2
E-6-70				
anorthoclase	3.85, 3.83	0.985	28	6.4 ± 0.2
Cottonwood				
anorthoclase	3.76, 3.75	0.965	56	6.4 ± 0.1

APPENDIX III

Strontium Isotope Ratios--Analytical Techniques

Sample Preparation

Sample material prepared for K analysis and whole rock analysis was further ground for 15 minutes in an agate mortar. This powder was used to make a pellet for X-ray fluorescence analysis for total Tb and Sr. Samples DP-64-3-DS and DP-64-3-LS were prepared as described in whole rock analyses analytical techniques and then ground in the agate mortar.

Rb and Sr Analysis

Rock, glass, and anorthoclase were analyzed for Rb and Sr contents by X-ray fluorescence using U.S. Geological Survey rocks powders AGV, GSP 1, BCR 1, and NBS feldspar 70a as standards.

Sr Isotope Analyses

Sr isotope analyses were done on a twelve inch radius, 60 degree sector, mass spectrometer equipped with an expanded scale recorder. The standard deviation for individual measurements is 0.0002. On this instrument and E and A Sr standard gives $Sr^{87}/Sr^{86} = 0.7080$.

Laboratory

The Rb and Sr analyses and Sr isotope analyses were done at Yale University Kline Geology Laboratory by Richard Lee Armstrong. The geochronometry laboratory at Yale University is supported by NSF Grant Ga 26025.

APPENDIX IV

Location of Samples not Shown on Plate 1

DP-E-84-67	Rattlesnake Ignimbrite Tongue, Murderers Creek, collected by H. E. Enlows, 119°30'00"W, 44°19'00"N, Grant Co., Oregon.
DP-E-6-70	Rattlesnake Ignimbrite Tongue, Dry Creek near Monument, Oregon, collected by H. E. Enlows, 119°27'51"W, 44°46'54"N, Grant Co., Oregon.
DP-Cottonwood	Rattlesnake Ignimbrite Tongue, Cottonwood Creek near type section of Rattlesnake Formation, collected by H. E. Enlows, 119°38'42"W, 44°26'36"N, Grant Co., Oregon.
DP-10	Rattlesnake Ignimbrite Tongue, on Silvies River 2.8 km north of Burns in center of T.22S., R.30E., collected by Donald Parker, 119°04'00"W, 43°37'13"N, Harney Co., Oregon.
DP-331	Rattlesnake Ignimbrite Tongue, in Burns, across from city park, collected by Donald Parker, 119°05'00"W, 43°35'40"N, Harney Co., Oregon.
DP-72-86	Rattlesnake Ignimbrite Tongue, 1.4 km east on Highway 395 north of Alkali Lake, Oregon, collected by Donald Parker, 119°54'00"W, 43°07'00"N, Lake Co., Oregon.
DP-72-78	Rattlesnake Ignimbrite Tongue, 14 km east of Crane on north side of road at intersection of the boundary of T.25S. and T.26S. (R.35E.) with the road, collected by Donald Parker, 118°27'00"W, 43°21'00"N, Harney Co., Oregon.
DP-72-24	Rattlesnake Ignimbrite Tongue, 17 km east of Hart Mountain National Antelope Refuge, collected by Donald Parker, 119°15'00"W, 42°40'00"N, Harney Co., Oregon.

DP-72-58 Rattlesnake Ignimbrite Tongue, East side of Christmas Lake Valley in cliff marked by white ash layer, collected by Donald Parker, 120° 16'00"W, 43° 13'00"N, Lake Co., Oregon.