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AN ABSTRACT OF THE THESIS OF Richard Louis Roche for the Master of Science in Geology presented June 10, 1987.

Title: Stratigraphic and Geochemical Evolution of the Glass Buttes Complex, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Michael L. Lummings, Chairman
Marvin H. Beeson
Ansel G. Johnson

The Glass Buttes complex lies at the northern margin of the Basin and Range province in central Oregon and is cut by the northwest-trending Brothers fault zone. An older acrystalline volcanic sequence of high-silica rhyolites (>75% SiO ) forms a 2 broad platform composed of domes and flows with minor pyroclastic deposits. The high-silica rhyolite sequence is divided on the basis of texture into 1) zoned flows and domes, 2) obsidian flows, 3) felsite flows, and 4) biotite-phyric flows and domes. Stratioraphic relations indicate that high-silica rhyolite units in the western part of the complex overlie those to the east. K/Ar age determinations for the sequence range from 5.03 to 7.7 million years. Geochemical trends within the sequence are characteristic of highly evolved magmas. The majority of the elements analyzed within the Glass Buttes high-silica rhyolite sequence fall into two groups that display similar behavior: 1) Sc, Rb, Cs, Sm, Tb, Yb, Lu, Ta, Th, U, and 2) Mg, Ca, Ti, Fe, Co, Ba, La, Ce, Nd, Eu, and P. Elements within each group generally show positive correlations with each other, but negative correlations with elements of the other group. The variations between the two groups reflects the chemical stratification present within the high-silica rhyolite magma chamber prior to the eruption of the sequence. The presence of biotite phenocrysts within the sequence may indicate that the high-silica rhyolites were erupted from a relatively shallow magma chamber.

The vent locations of a younger volcanic sequence of rhyolites and rhyodacites are strongly controlled by structure. Vents are aligned along the trend of the Brothers fault zone. The petrology and geochemistry of the sequence indicate that it is not genetically related to the high-silica rhyolite sequence of volcanism. The rocks are phyric and contain various proportions of plagioclase (andesine-labradorite), hornblende, quartz, biotite, and ortho- and clinopyroxene phenocrysts. Phenocrysts range up to 40% of the rock volume. There are large variations in the concentrations of Fe, Mg, Ca, Ti, Sc, Co, Cr, and Eu among the different rhyolite and rhyodacite flows, indicating that the different flows represent distinct, but genetically related magma batches.

Basaltic volcanism occurred thoughout the silicic eruptive sequence. Several of the basalt flows erupted within the Glass Buttes complex show petrographic and geochemical evidence of contamination by rocks of the high-silica rhyolite sequence. The intrusion of basaltic magma into the crust is believed to have provided the heat source for the partial melting of crustal materials, leading to the generation of the silicic magmas.

# STRATIGRAPHIC AND GEOCHEMICAL EVOLUTION OF THE GLASS BUTTES COMPLEX, OREGON

ъу

RICHARD LOUIS ROCHE

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

MASTER OF SCIENCE in GEOLOGY

Portland State University

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of Richard Louis Roche presented June 10, 1987.



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#### CHAPTER I

#### INTRODUCTION

The various associations of rock types observed in volcanic terranes often reflect regional tectonism (Atwater, 1970; Stewart and others, 1975; Bacon, 1982, 1985, 1986). The bimodal basaltrhyolite association is indicative of an area which is experiencing regional crustal extension. The rhyolitic magma is generated by the partial melting of crustal material by basaltic magmas which travel to the surface along regional structures (Hildreth, 1981; Bacon and others, 1981; Barker, 1981; Hill and Bailey, 1985).

The High Lava Plains physiographic province of central and southeast Oregon exemplifies the bimodal basalt-rhyolite association. Crustal extension, which dominates the Basin and Range province to the south, is essentially terminated within the High Lava Plains by the northwest-trending Brothers fault zone (Lawrence, 1976). Basalt flows and associated vent deposits predominate, but rhyolitic domes and ash-flow tuffs are abundant (MacLeod and others, 1976). The rhyolitic domes are aligned along a west-northwest trend, subparallel to the Brothers fault zone.

Glass Buttes (Figure 1), a rhyolitic center astride the Brothers fault zone, exhibits a variety of volcanic rock types. The location of the complex at the northern margin of the Basin



Figure 1. Location of the Glass Buttes complex (modified from Baldwin, 1982).

and Range province provides an opportunity to examine volcanic processes along this margin. This study will 1) characterize the stratigraphy, geochemistry, and petrography of the complex, 2) interpret the evolution of the complex and the implications for silicic volcanism in the High Lava Plains, and 3) examine the implications of the petrography and geochemistry for tectonic processes in this region.

#### SCOPE AND METHODS

This study represents the fourth phase of an ongoing study which was initiated in 1980 under the direction of Michael L. Cummings, Portland State University. The scope of the thesis and methods used include:

1) Geologic mapping of the Glass Butte 7 1/2 minute quadrangle. This information was added to a previously existing data base (Berri, 1982; Johnson, 1984a, 1984b; Cummings, 1984) in order to compile a geologic map of the entire Glass Buttes complex (Plate I). Mapping was conducted from August through September, 1985 by the author and M. L. Cummings.

2) Chemical and petrographic characterization of the various stratigraphic units within the Glass Buttes complex. Most of the samples were collected from the Glass Butte quadrangle, but several were collected from the Potato Lake, Tired Horse Butte, and Round Top Butte 7 1/2 minute quadrangles. Major element geochemical analysis of twenty samples by x-ray fluorescence (XRF) was performed under the direction of Dr. Peter Hooper at

Washington State University. Trace and rare earth element (REE) analysis of sixty-two samples by instrumental neutron activation analysis (INAA), and the petrographic study of thin sections were completed by the author at Portland State University. Oxygen isotope analysis of eight rock samples using chlorine trifluoride was completed at the U. S. Geological Survey isotope laboratory under the direction of Dr. Ivan Barnes.

3) Integration of chemical and stratigraphic data collected during this study with data previously reported by Berri (1982), Johnson (1984a), and Cummings (1984). A petrogenetic model for the Glass Buttes complex is based on the interpretation of this data.

4) Interpretation of the tectonic implications of the petrogenetic model with respect to the relationship between regional structural patterns and bimodal volcanism.

#### GEOLOGIC SETTING

The High Lava Plains province of southeastern Oregon, as defined by Dicken (1950), consists of a middle and upper Cenozoic volcanic upland nearly 260 km long extending from the Harney Basin on the east, westward to Newberry Volcano (see Figure 2). The province is contiguous with and gradational into the Basin and Range province to the south, and late Cenozoic volcanic rocks and fault structures are common to both provinces. A comparatively sharp boundary separates the High Lava Plains from the Blue Mountains province to the north, where older Cenozoic and pre-

Cenozoic rocks have been brought to the surface in the Blue Mountains-Ochoco Mountains uplift (Walker and Nolf, 1981).

Reconnaissance mapping of the High Lava Plains, completed by Greene and others (1972), and Walker and others (1967), revealed that the oldest rocks in the province consist of small outcroppings of older Cenozoic volcanic and tuffaceous sedimentary rocks representing parts of the Columbia River Basalt Group and the John Day and Clarno Formations (Walker, 1974). Other than these minor outcrops, the oldest rocks within the province are aphyric and plagioclase phyric basalts and minor andesite flows of middle Miocene age. These flows, referred to as Steens Basalt, were erupted from dike swarms such as those present on the east side of the Steens Mountains. Outcroppings of these flows are exposed at the eastern end of the High Lava Plains province (Walker and Nolf, 1981).

The silicic centers of southeast Oregon occur principally in two broad belts that trend approximately N.75°-80°W. (MacLeod and others, 1976). The northern belt, located in the High Lava Plains and Owyhee Uplands provinces, consists of approximately 100 centers and extends from Newberry Volcano eastward to Duck Butte, southeast of the Harney Basin. The southern belt lies in the Basin and Range province, extending from Yamsey Mountain eastward to Beatys Butte (see Figure 2). Walker (1974) presented 47 potassium-argon radiometric age determinations for crystalline phases from rhyolitic, rhyodacitic, and dacitic domes and associated flows which were sampled during reconnaissance mapping. The dates define a monotonic age progression along the silicic belts from less than one million years in the west to about ten million years in the east (Figure 2) (Walker, 1974; Macleod and others, 1976; Macleod and Sammel, 1982).

Rhyolitic ash-flow tuffs partly cover the Steens Basalt and silicic domes and flows in the eastern portion of the High Lava Plains. There are three major ash-flow tuffs present, ranging in age from approximately 9 to 6.4 million years old (Walker, 1974). The ash-flow tuffs are interpreted to have originated from the Harney Basin (Walker and Nolf, 1981). In the western part of the High Lava Plains, plateau basalts of late Pliocene, Pleistocene, and Holocene age cover most of the middle and upper Cenozoic basalt flows, ash-flow tuffs, silicic domes and flows, and sedimentary rocks.

The volcanic rocks of the High Lava Plains are displaced by numerous en echelon high-angle normal faults of the Brothers fault zone. This zone trends N.60°W. and extends from the Mount Jefferson area southeastward where it is cut by the north-southtrending fault which bounds the Steens and Pueblo Mountains block on the east (Stewart and others, 1975). The Brothers fault zone is interpreted to be the surface expression of a deep-seated right-lateral strike-slip fault (Lawrence, 1976). The distribution of silicic domes and flows in the High Lava Plains province nearly parallels the Brothers fault zone. Lawrence (1976) suggested that the Brothers fault zone and the subparallel Eugene-Denio, Mt. McLoughlin, and Vale fault zones are surface



Figure 2. Younging westward trend of silicic centers in central and southeast Oregon (modified from MacLeod and others, 1976).

expressions of the transition between the tectonic patterns of the Basin and Range province to the south and the Blue Mountains province to the north. Chaplet and others (1986/87) used MSS-Landsat images and paleomagnetism data to model the structural evolution of central and eastern Oregon. The model proposes that a scissors mechanism induced by the subduction of the Farallon plate caused the extension between the Cascade Range and the Olympic-Wallowa lineament during the late Eocene through Recent times. The pole of rotation for the scissors mechanism progressively migrated northwestwards along the Olympic-Wallowa lineament, a paleoplate boundary during pre-Eocene times. Rightlateral strike-slip faults, initially trending east-west, progressively turned N.W.-S.E. due to the basin opening. The migration of the volcanism from east to west within the High Lava Plains province and the clockwise rotation of the Coast Range-Klamath Mountains-Cascade Range block are thought to be results of the spreading basin. North-south-trending faults of the Basin and Range province, an expression of east-west extension, are interpreted by Chaplet and others (1986/87) as being younger than the N.W.-S.E. trending faults.

The structure of the Glass Buttes complex was initially interpreted by Waters (1927a, 1927b) as a faulted anticline. The top of the anticlinal arch had been down-dropped to form a graben that controls a longitudinal valley in the middle of the complex. The rocks within the complex were thought to represent three periods of volcanic activity. The oldest rocks are a series of

basalts consisting of ophitic and intergranular aggregates of labradorite, augite, olivine, and magnetite. Stratigraphically above the basalts is the Glass Buttes series (Waters, 1927a, 1927b), consisting of andesites, dacites, perlite, obsidian, and vitrophyre. These rocks contain various proportions of augite, hypersthene, quartz, and andesine phenocrysts. Waters suggested that the older basalts and the Glass Buttes series correlated with basaltic and acidic rocks exposed within the Steens Mountains to the southeast. The youngest rocks in the complex are a series of basalts erupted from cinder cones located on the surrounding plateau.

Johnson and Ciancanelli (1981, 1983) identified a large andesite flow located on the northwest flank of Glass Butte (Figure 3). The andesite was thought to represent eruptions from the waning stages of silicic volcanism.

The volcanic stratigraphy of Little Glass Butte and eastern Glass Buttes (see Figure 4) was mapped and described by Berri (1982). Included in this study was an investigation of the hydrothermal alteration and mercury mineralization associated with northwest-trending faults. The stratigraphic units were defined as endogenous and exogenous domes and flows of rhyolitic composition overlain by fine-grained plateau basalts. Interfingering obsidian flows (77-78% SiO ) and sparsely-phyric rhyolite (74-75% SiO ) were reported. An obsidian flow dated by Walker (1974) at 4.9  $\pm$ 0.3 million years was interpreted to represent the youngest volcanic unit in the study area. This date



Figure 3. Flows in the middle distance to the left of the valley were classified as andesite by Johnson and Ciancanelli (1983). Photograph looking due west from the top of Glass Butte.

was later recalculated using a new decay constant to 5.03 <u>+</u>0.75 million years (Fieblekorn and others, 1982). A coarsely feldspathic basalt, which was erupted from vents within the complex, also interfingers with rhyolitic rocks, suggesting bimodal volcanism (Berri, 1982).

The stratigraphy of Round Top Butte, located in the southeast portion of the complex (Figure 4), was described by Cummings (1984) as a series of exogenous rhyolitic domes and flows consisting of rhyolitic glass exhibiting varying degrees of vesiculation, and a lesser amount of basalt which was erupted from isolated vents within the butte. Cummings divided the rhyolite sequence into several stages based on observed erosional unconformities. The youngest rhyolite erupted contains sparse phenocrysts of black biotite.

The chemical and mineralogical characteristics of surface and subsurface hydrothermal alteration within the easternmost portion of the complex were investigated by Johnson (1984a). Silicification and mercury mineralization occur in rhyolitic glass along northwest-trending faults (Berri and others, 1983).



Figure 4. View of the central and eastern portions of the Glass Buttes complex. This photograph, taken from the top of Glass Butte, is looking to the east. The large peak to the right of center of the photograph is Little Glass Butte. In the middle distance, and, to the left of Little Glass Butte, the white areas are the exploration pits and mines within the mercury mineralized area at the eastern end of the complex. In the middle distance to the right of Little Glass Butte.

#### CHAPTER II

#### STRATIGRAPHY

Four stratigraphic sequences are identified within the Glass Buttes complex. These include 1) high-silica rhyolites, 2) rhyolites and rhyodacites, 3) internal basalts, and 4) plateau basalts (Table I). Pyroclastic units are a minor constituent of the high-silica rhyolite sequence and volcaniclastic sediments crop out locally. The study of the Glass Butte stratigraphy was focused on 1) locating vent areas and describing their eruptive products, and 2) the interpretation of the eruptive history of the complex.

#### HIGH-SILICA RHYOLITE SEQUENCE

The high-silica rhyolite sequence contains units that exhibit an overall glassy appearance, variable degrees of vesiculation, and up to four cooling zones. The rocks of this sequence are dominantly aphyric and acrystalline, but a minor percentage of phenocrysts including biotite, plagioclase, and quartz is present in some units. The largest volume of rocks within the Glass Buttes complex belong to the high-silica rhyolite sequence, which has a minimum thickness of 600 meters (Johnson, 1984a). The distribution of vents for the high-silica rhyolite sequence lacks discernible structural control. Vent areas are

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# STRATURARY OF THE QASS BUTTES CORREX

bloanic thit	Geographic Lonation	Records	Grandness	Texture	Relative Age	Atsolute Age
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Ayolite Floue (Tr6)	1) Glæs Arte 2) Little Glæs Arte	1-66 plagioclæsa, <u>+</u> þynovere, <u>+</u> græq.ø	11% plagicclass, 56% glass	week to strongly faidad, black in color with red oxinized zones	yorgar then high- sillica rhyolita sequence	N.A.
iigh-Sillica Aryolite Seq.erce Pyroclastic Unit (Tr5)	1) Glæss Artte 2) æstem Glæss Artæ	acu	ash natrix	dtsidian, punica, and felsite clasts, 	locally alder then blottle-phyric, decision and falsite	N.R.
Biotite-Ayric flows and Dones (1	rd)1)1805 neter park in the Glass Butte quedrangle	1-21 biotite, + quertz, <u>+</u> plagicclass, <u>+</u> senidine	glæss, lıcally perlitically fræctured	c) m to 0.6 m. punktors glass, veskistes comprise 25-40% of rock,	flows and drives locally younger then zoned flows and drives	N.A.
	2) Little Glass Bute 3) Rorrd Top Bute	ł		ghenlitic zones concritocally		

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Valcanic Unit	Geographic Location	Renarysts	Groundness	lexture	Aelative Age	Absolute Age
felsite flnus (Tr3)	1) Glass Arte 2) Little Glass Arte 3) Rourd Top Arte	80	devitrified glæs	vesicles conprise less tran 54 of rock, flaw barding pourly developed deeper in flaw	locally yourger then cored flaws and dones	N.A.
(Josidian Flous (Tr2)	1) Glass Arte 2) Little Glass Arte	8001	sælg	romesiaular, massive mifarm to strongly faldad	locally younger then zoned flows and domes	.03 <u>+</u> 0.75 m.y. Little Glass Acte)
Zoned Flaus and Danes (Tr1)	1) Glass Artes Comlax	ē	sector	caratece brencia, punice, cosidian, end felsite zones	Iccally older then biotite- phyric, felsite, erd otsidian flues and dones	7.7 $\pm$ 0.4 mV. (eestern Glass Battes) (1.11 $\pm$ 0.3 mV. (1.11 $\pm$ 0.3 mV. (1.11 $\pm$ 0.3 mV. (1.12 $\pm$ 0.3 mV.
Internal Basalt Saquerce (Ibi)	1) Glæs Artæ Coplæ	planicchase, a.gite, <u>+</u> alivine	plagioclase, aujite, iron ovide, quartz, horruterte, glass, wernlitts	ethyric to coersely dyric, several flous evidence of silicic contanination	yanger then sillicic units	х.я.
Plateeu Besalt Sequrce (1b2)	unter plater	plajioclæe, angite, <u>-</u> olivine	plagioclase, a.gite, irm oxide, glass	ethric to coursely phyric	flous erpted creval with silicic volcario locally interlayered with volcariclastic sedinents	ч.ч. М.
N.A. = no analysis						

identified based on 1) the geometry of flows and domes, 2) areas of strongly folded, steeply-dipping flow banding, and 3) resistant outcrops of felsite. The high-silica rhyolite sequence is divided into 1) zoned flows and domes, 2) obsidian flows, 3) felsite flows, and 4) biotite-phyric flows and domes. The obsidian flows, felsite flows, and the biotite-phyric flows and domes locally overlie the zoned flows and domes (Roche and Cummings, 1987b).

#### Zoned Flows and Domes

Erosion exposes four textural zones within many of the flow and dome units. Zones include felsite core, obsidian, pumice, and carapace breccia (Roche and Cummings, 1986). Zoned flows predominate in the Glass Butte and Little Glass Butte areas, while domes dominate on Round Top Butte and eastern Glass Buttes. The domes are differentiated from the flows by their radial distribution from a central source. Four K/Ar age determinations for zoned flows and domes range from  $5.5 \pm 0.3$  to  $7.7 \pm 0.4$ million years (Johnson, 1984a)

1) <u>Felsite Zone:</u> The felsite zone is characterized by devitrified gray glass which shows weak to moderate vesiculation. The vesicles are aligned parallel to moderate to strongly developed flow banding. This flow banding occurs on the millimeter to centimeter scale, and may be strongly folded. Lithophysae, spherulitic zones, and perlitic fracturing occur locally.

2) Obsidian Zone: Black, red, brown, mahogany, and colorless

obsidian occur in the obsidian zone (Figure 5). Textures are nonvesicular, ranging from massive uniform to strongly flow banded. Obsidian breccia clasts in an obsidian matrix occur locally. The thickness of the zone is estimated at one meter and the contact with the underlying felsite zone is presumed to be sharp. The presence of the obsidian zone is recognized by patches of obsidian float which have an average diameter of 50 centimeters. The lateral continuity of the obsidian zone has not been defined.



Figure 5. Various obsidian colors and textures (from Berri, 1982).

3) <u>Pumice Zone:</u> Coarsely vesicular pumice, commonly perlitically fractured, occurs stratigraphically above the obsidian zone. Weathered surfaces are tan and fresh surfaces are light to dark gray. Vesicles, which generally compose more than 50% of the volume of this rock, are ovoid to highly elongate and range from less than one millimeter to a few centimeters in diameter. Black, subrounded marekanite nodules ("apache teardrops") are often present near the contact between this zone and the underlying obsidian zone. Interlayered pumice and obsidian bands mark the contact between the two zones. The pumice zone, believed to be continuous across flow and dome units, has a maximum exposed thickness of 2 meters.

4) <u>Carapace Breccia Zone:</u> Brecciated pumice zones associated with flows and domes are most often poorly sorted, black to gray to brown pumice clasts within an unaltered pumice matrix of gray to brown color. The clasts are angular, ranging from pebble to boulder size. The clast size and amount of cementation decreases outward, with the outer-most portion believed to be non-cemented pumice clasts. The contact between this zone and the underlying pumice zone is gradational. The best exposures of the carapace breccia zone are located on Round Top Butte (see Plate I), where clasts of stretched pumice up to 2.5 meters in diameter and 0.3 meters in thickness exist near the contact between the carapace breccia zone and the pumice zone (M. Cummings, personal communication, March, 1987).

#### Obsidian Flows

Obsidian flows are differentiated from the obsidian zone of zoned flows and domes by the lack of related cooling zones. The flows contain partings of gray to pink to brown pumice between layers of black obsidian. A black obsidian flow near Musser Draw

(see Plate I), located to the south of Glass Butte, has a length of one kilometer and a maximium width of 0.25 kilometers. The minimum thickness of the flow exposure is 15 meters. Two large obsidian flows erupted from Little Glass Butte, each with exposure areas of 5 to 8 square kilometers, represent the greatest volume of obsidian within the complex (Berri, 1982). An age of 5.03  $\pm$  0.75 million years was reported by Walker (1974) for the obsidian flow on the north side of Little Glass Butte.

#### Felsite Flows

Cooling zones, as described in the zoned flows and domes section, have not been found in association with felsite flows. The felsite flows are devitrified, gray to light purple in color, and tend to break parallel to flow banding. The flows break in a plate-like manner, leading to the formation of scree slopes. The flow banding, which is on the millimeter scale, is poorly developed deeper in the flow unit. Vesicles, which compose less than 5% of the rock by volume, tend to be elongated parallel to flow banding. Felsite flows crop out on the south slope of Glass Butte and on Round Top Butte (M. Cummings, personal communication, March, 1987).

#### Biotite-Phyric Flows And Domes

Biotite-phyric flows and domes contain 1-2% biotite, <u>+</u> quartz, <u>+</u> plagioclase, and <u>+</u> sanidine phenocrysts. The groundmass of the flows and domes is pumiceous, gray to brown in color, and locally perlitically fractured. Vesicles are

elongate, comprising 25-40% of the rock by volume. Spherulitic zones and plagioclase microlites occur locally. The biotite phenocrysts are less than two millimeters in diameter, black in color, and aligned parallel to flow banding.

Outcrops of biotite-phyric flows and domes are found in the southeast corner of the Glass Butte quadrangle and on the crest of Round Top Butte. The former are part of a flow erupted from Little Glass Butte, and the latter a dome erupted from Round Top Butte. Biotite-phyric rocks also form a domal plug on the top of the 1,805 meter peak located in sections 23 and 26 of township 23 south, range 22 east in the Glass Butte quadrangle (see Plate I). In addition to biotite, these rocks contain quartz, plagioclase, and sanidine phenocrysts ranging from 1 to 4 millimeters in size. The modal percentage of phenocryst and groundmass constituents of a sample from this domal plug are included in Table II.

#### TABLE II

#### MODAL ANALYSIS OF A BIOTITE-PHYRIC THIN SECTION

Sample #:	GB-1 31	Volume %
Phenocrysts:	Quartz Plagioclase Sanidine Biotite	6.7% 4.3% 1.7% 1.0%
Groundmass:	Glass Spherulites Plagioclase Microlites	53.6% 26.4% <u>6.3</u> %
		100.0%
(Based on a	total of 1000 points cou	nted.)

#### RHYOLITE AND RHYODACITE SEQUENCE

The rhyolite and rhyodacite sequence stratigraphically overlies the high-silica rhyolite sequence and is characterized by rocks which contain 10-40% phenocrysts in a groundmass of glass and plagioclase microlites. The phenocryst phases and percentages for rhyolite and rhyodacite samples are given in Table III. The rocks are black to gray in color and contain red oxidized zones. Rhyolites and rhyodacites occur as low-volume flows, domes, and spines. An intrusive rhyodacite crops out on the southern end of Glass Butte (see Plate I). Rocks of this sequence exhibit moderate to strong flow banding and may form north and northwesttrending spines, parallel to faults.

Petrographically, rhyolites are distinguished from rhyodacites by a plagioclase content of less than 10% and a lack of hornblende phenocrysts. Rhyolite flows crop out on the northern slope of Glass Butte and the northern and western slopes of Little Glass Butte. The flow on Glass Butte contains approximately 8 percent plagioclase phenocrysts ranging in length from 0.25 to 1 centimeters. The rhyolite flow on Little Glass Butte contains 1 to 3 percent plagioclase phenocrysts with an average length less than 3 millimeters.

Rhyodacite flows, domes, and spines occur exclusively on Glass Butte with one exception, a rhyodacite intrusive plug which crops out on the southeastern side of the 1,805 meter peak located in the Glass Butte quadrangle.

#### TABLE III

MODAL	ANALYSES	OF RHYOLITE	AND RHYODACITE	THIN
	SECTIONS	BASED ON A T	TOTAL OF 1000	
	POINTS	COUNTED ON E	EACH SECTION	

Rocktype	Rhyolite		Rh	yodacite	es	Intrusion	
Sample no.	GB-16		GB-27	GB-28	GB-35	GB-173	
Phenocrysts							
Plagioclase	7.5		9.7	20.0	26.5	23.7	
Hornblende			1.4	2.5	6.4	10.6	
Pyroxene	1.8			0.4		0.2	
Quartz			0.6	0.3		1.0	
Opaque	0.8				0.4	0.9	
Biotite						0.4	
Groundmass							
Plagioclase	33.4		35.6	32.4	22.7	17.6	
Glass	56.5		51.7*	44.4	44.0	45.6	
* part of the	olass has	heen	altered	to a cla	av ohase		

Plagioclase phenocrysts, which are the dominant phase, are up to 1.5 centimeters long, euhedral, and may contain normal or reverse compositional zonation. Phenocrysts commonly contain inclusions of hornblende, biotite, apatite, and colorless glass (Figure 6). Phenocryst compositions, as determined by Michel-Levy's method (Jones and Bloss, 1980), lie between An and An . 41 74 Plagioclase also occurs as the dominant microlite phase, composing up to 36% of the rock by volume. The plagioclase microlite compositions range from An to An . 46 56

Euhedral, brown to green pleochroic hornblende phenocrysts up to two centimeters long occur both as isolated phenocrysts and intergrowths with plagioclase and iron oxide phenocrysts. The long axis of the isolated hornblende phenocrysts define a lineation in most rocks. Pink to light green pleochroic augite phenocrysts up to two millimeters in diameter compose less than 2% of the rocks by volume. The augite may occur as growth rims on hypersthene crystals. Phenocrysts of subhedral quartz, black biotite, and an iron oxide phase compose less than 3% of the total rock volume and are less than two millimeters in size. The biotite flakes, where present, produce a weak foliation.



Figure 6. Compositionally zoned plagioclase phenocryst from a rhyodacite flow. The plagioclase composition on the outer rim of the phenocryst is  $An_{74}$ . Two hornblende inclusions are found in the center of the plagioclase. The photomicrograph is approximately two millimeters wide.

#### PYROCLASTIC UNIT

Well-indurated ash-flow tuff containing clasts of black
obsidian, pumiceous glass, and flow-banded felsite crops out on the south side of Glass Butte. Clasts compose up to 45% of the rock by volume, are subangular to subrounded, poorly sorted, and range in diameter from one millimeter to 0.6 meters. Clasts are supported in a white to pink colored ash matrix and broad crossbedding of cobble-size clasts occurs locally. The pyroclastic unit overlies a zoned high-silica rhyolite flow.

A bedded ash-flow tuff which crops out on the south side of Cascade Ridge (see Plate I) contains angular clasts of felsite, pumice, and black obsidian within a white, ashy, glass matrix. Clasts are poorly sorted and range in diameter from less than one millimeter up to 0.5 meters. Planar bedding varies from massive to laminar and broad, sweeping festoon-type cross bedding occurs locally. The tuff is overlain by a pumiceous breccia on the east, and an obsidian flow on the west (Johnson, 1984a).

### VOLCANICLASTIC SEDIMENT UNIT

Weakly to moderately consolidated volcaniclastic sediments, exposed along the southeastern margin of the Glass Buttes quadrangle (see Plate I), lie stratigraphically above a zoned high-silica rhyolite flow and below an internal basalt flow. Lithic clasts compose 60-75% of the rock by volume, are subrounded, 1-3 millimeters in size, and occur in beds which range in thickness from 1-10 millimeters. Obsidian, felsite, pumiceous glass, and biotite-phyric pumiceous glass clasts are cemented by silica. Many of the clasts are stained by iron oxide. The

consolidated volcaniclastic sediments are differentiated from the ash-flow tuff by the lack of an ash matrix in the former, and the lack of silica cement and iron staining in the latter.

Volcaniclastic sediments up to three meters in thickness are also exposed along a fault scarp located in the southeast corner of the Potato Lake quadrangle (see Plate I). The sediments occur stratigraphically between two plateau basalt flows. Lithic clasts of the high-silica rhyolite sequence are subrounded, 0.5 to 3 millimeters in diameter, and occur in poorly-sorted beds.

# INTERNAL BASALT SEQUENCE

Basalt flows that originate from vents located within the silicic complex are herein referred to as "the internal basalt sequence". They are interpreted to be time equivalent to flows erupted from vents on the surrounding plateau. Basalt flows are phyric to microphyric, vary in degrees of vesiculation, and average 3 to 5 meters in thickness. Flow tops are thin, indistinct, and are locally marked by pahoehoe surfaces that may be overlain by basaltic hyaloclastites. Nearly all of the basalt flows are porphyritic, containing plagioclase phenocrysts which range in length from 1 to 4 centimeters. The plagioclase is honey brown to colorless and aligned parallel to the direction of flow banding. The groundmass contains various proportions of plagioclase, augite, opaques, olivine, and glass. Quartz crystals and silicic xenolith intergrowths, evidence of contamination by silicic glass, occur locally in the lowest basalt flows (Figure 7). Modal analyses of



<u>Figure 7</u>. Symplectite intergrowth of quartz and feldspar in a contaminated basalt flow. Photomicrograph is approximately two millimeters wide.

basalt flows and a hyaloclastite unit are given in Table IV.

The largest volume of internal basalt, erupted from the southwest side of Glass Butte, may contain from 30 to 40 flows with a combined exposed thickness of approximately 210 meters. The internal basalts lie stratigraphically above the high-silica rhyolite sequence. A volcaniclastic unit containing clasts of high-silica rhyolite locally separates the two sequences. The stratigraphic relationship between the internal basalt and the rhyolite and rhyodacite sequence has not been defined due to the lack of field contacts.

#### TABLE IV

## MODAL ANALYSES OF BASALT AND HYALOCLASTITE THIN SECTIONS BASED ON A TOTAL OF 1000 POINTS COUNTED ON EACH SECTION

	Rocktype Sample no.	Internal Basalt GB-4B	Internal Basalt GB-4C	Plateau Basalt **	*Basaltic Hyaloclastite GB-5	
	Phenocrysts Plagioclase Augite Olivine	55.2 29.5	11.0 3.4 	24.1 20.7 8.1	18.0 1.4 8.6	
Grou	undmass Plagioclase Augite Iron Oxide Quartz Hornblende Xenoliths Glass Vesicles	7.9  7.4 ++	31.4 10.4 0.6 0.3 0.1 1.4 41.4 ++	17.4 4.9 4.6  7.1 13.1	   71.6+ ++	
	* Based on 500 ** Completed by + 11.6% of the ++ Vesicles not	points co Berri (19 glass is counted.	ounted. 984): sampl altered to	e no. unk smectite	nown. clay.	

# PLATEAU BASALT SEQUENCE

Plateau basalt flows were erupted from vents located on the surrounding plateau. Phyric flows containing plagioclase, augite, opaque and olivine phenocrysts, within a groundmass of glass, plagioclase, pyroxene, and olivine microlites dominate, but aphyric flows also occur. A modal analysis for a plateau basalt flow is given in Table IV.

The plateau basalts are best exposed along northwest-

trending fault scarps of the Brothers fault zone (Figure 8). The stratigraphic sequence exposed along a fault scarp in section 30 of the Potato Lake quadrangle includes: 1) a plagioclase-phyric basalt flow with a minimum thickness of nine meters, underlain by 2) volcaniclastic sediments up to six meters in thickness, and 3) five to six meters of aphyric olivine basalt.



Figure 8. Photograph taken from the top of Glass Butte looking northwest. Spine in the foreground to the right of center is a rhyodacite unit. Plateau basalts, in the middle distance, are cut by northwest-trending faults of the Brothers fault zone. In the far distance lies the Hampton Butte volcanic complex.

The internal basalts overlie the plateau basalts along the northwest corner of the complex. Interlayered high-silica rhyolite and plateau basalt flows have been reported within Phillips stratigraphic hole 4 (see Plate I) (Johnson, 1984a).

#### STRATIGRAPHIC SUMMARY

The stratigraphy of the Glass Buttes complex, summarized in Table I, consists of high-silica rhyolite, rhyolite and rhyodacite, and basalt sequences.

The high-silica rhyolite sequence represents the initial phase of volcanic activity within the Glass Buttes complex. Age dates for the sequence range from  $5.03 \pm 0.75$  to  $7.7 \pm 0.4$  million years. Zoned flows and domes, which were erupted from numerous vent areas, represent the largest volume of high-silica rhyolite volcanics (see Plate I). Zoned flows predominate in the Glass Butte and Little Glass Butte areas, whereas small-volume domes dominate on Round Top Butte and eastern Glass Buttes. The zoning is largely the result of differential cooling that formed multiple zones within an individual lava flow (Wilson and Emmons, 1985). Pyroclastic deposits, containing high-silica rhyolite clasts, are locally interfingered with zoned flows and domes. These relationships indicate that the zoned flows and domes and pyroclastic deposits belong to the same stage of volcanic activity.

Obsidian flows, felsite flows, and biotite-phyric flows and domes locally overlie the zoned flows and domes. These flows, units of the high-silica rhyolite sequence, represent the late stage high-silica rhyolite volcanism within the Glass Buttes complex. Outcrops of these units are concentrated on the south side of Glass Butte and in the Little Glass Butte and Round Top Butte areas (see Plate I).

Rhyolitic and rhyodacitic volcanism followed the high-silica rhyolite activity. Vent locations for the rhyolite and rhyodacite sequence are structurally controlled, exhibiting an alignment along the trend of the Brothers fault zone. This sequence crops out on Glass Butte and Little Glass Butte (see Plate I). A rhyolite flow on Little Glass Butte was stratigraphically positioned below an obsidian flow by Berri (1982). Reevaluation of the field relationships on Little Glass Butte along with the observed stratigraphy of the Glass Butte quadrangle has led to a reinterpretation of this relationship; the rhyolite flow lies stratigraphically above the obsidian. The rhyodacitic intrusive, which crops out at several locations within the Glass Butte quadrangle, may represent one of the final pulses of rhyodacitic volcanism.

Field relationships indicate that the internal basalt sequence lies stratigraphically above the high-silica rhyolite sequence. There are no contacts between the internal basalt sequence and the rhyolite and rhyodacite sequence, but it is believed that the internal basalts are younger. The basalts were erupted from numerous vents which generally lie on the perimeter of the complex. The volume of the basaltic eruptions and the number of flows from a vent area is highly variable.

The plateau basalt stratigraphy, which includes interlayers of plagioclase-phyric basalt, aphyric olivine basalt, and volcaniclastic sediments, is poorly understood. Johnson (1984a)

reported interlayered hydrothermally altered high-silica rhyolite and plateau basalt flows within Phillips stratigraphic hole 4 (see Plate I). The internal basalt sequence may be time equivalent to the late erupted plateau basalt flows.

## CHAPTER III

## GEOCHEMISTRY

Geochemical data for high-silica rhyolite, rhyolite, rhyodacite, and basalt samples are presented in the Appendix. On the basis of Shand's classification (1951), all high-silica rhyolite, rhyolite, and rhyodacite samples within the Glass Buttes complex are classified as peraluminous.

The geochemical data were examined in relation to: 1) stratigraphy, and 2) the following geographic divisions of the Glass Buttes complex: the Glass Butte quadrangle, Little Glass Butte, eastern Glass Buttes, and Round Top Butte.

## HIGH-SILICA RHYOLITE SEQUENCE

High-silica rhyolites, as used by Cameron and Cameron (1986), contain more than 75% SiO . Rocks of the high-silica 2 rhyolite sequence at Glass Buttes contain 77-78% SiO , less than 0.13% TiO , 0.011-0.048% P O , less than 0.11% MgO, 0.43-0.91% 2 5 CaO, 0.77-1.54 ppm Ta, 3.6-8.3 ppm Sc, and less than 0.7 ppm Co. Geochemical data for selected elements of zoned flows and domes, obsidian and felsite flows, and biotite phyric flows and domes are presented in Table V.

Variations in the major and trace element geochemistry of the high-silica rhyolite sequence were examined in relation to  different high-silica rhyolite units within a geographic area, and 2) high-silica rhyolite units from different geographic locations within the complex.

The major and trace element concentrations of different high-silica rhyolite units from a given geographic area are within the analytical error of instrumental neutron activation analysis. Thus, within a geographic area the different flow and dome units are not distinguished on the basis of geochemistry (Table VI).

Variations of certain elements in samples from different geographic areas have been identified (Figure 9). Iron, the only major element that displays a linear variation, increases from east to west across the complex. Samples of zoned flows and domes collected from eastern Glass Buttes and Round Top Butte contain 0.72-0.85% FeO, whereas samples from the Glass Butte quadrangle contain 0.87-1.03% FeO. Biotite-phyric flows and domes of Round Top Butte, Little Glass Butte, and the Glass Butte quadrangle exhibit the same systematic variation, containing 0.65-0.74%, 0.83-0.84%, and 0.91% FeO respectively. Obsidian and felsite flows from Little Glass Butte and the Glass Butte quadrangle contain the highest FeO concentrations, varying from 0.84-1.04% and 1.09-1.11% respectively.

The trace element geochemistry defines variations in highsilica rhyolite samples from different geographic areas within the complex. Concentrations of Sc, Rb, Cs, Ta, Th, and U are higher and those of Co and Ba lower in the high-silica rhyolite units of Round Top Butte and eastern Glass Buttes relative to samples from TABLE V

HIGH-SILICA RHYOLITE SEQUENCE GEOCHEMISTRY

 $P_2 0_5 = 0.011 - 0.048$ 5c = 3.6-8.3 ppm Co = 0.0-0.7 ppm = 0.43-0.91% **Oiagnostic Characteristics:** 

<u>RTB-86</u> ..... Top Butte Round <u>RTB-19</u> 78.50 0.09 0.82 0.82 0.45 0.45 0.011 7.26 N.D. 116 850 1.06 12.5 6.0 28.0 0.48 7.3 ARW-2 EGB-1 **Glass Buttes** eastern 0.85 0.35 0.35 0.35 1.54 1.54 1.54 1.21 1.21 1.21 Ta = 0.77-1.54 ppm i <u> 68-44 68-43 68-7</u> --------4.45 0.37 2.9 1420 1.05 7.8 N.0. 34.0 16.9 16.9 0.94 Zoned Flows and Domes 1.07 8.0 8.0 32.0 17.0 292 78.75 71 0.08 0.93 0.93 0.49 0.49 0.024 4.46 0.124 0.128 0.132 0.32 2.6 1280 1280 1.03 8.0 5.5 30.0 0.62 13.9 272 CB-82 CB-67 78.61 7 0.09 0.91 0.91 0.018 0.018 4.45 4.45 4.45 8.46 8.2.8 2.8 1340 1 Glass Butte Quadrangle 1.08 7.9 8.0. 30.0 0.67 15.0 279 GB-111 -----0.91 -----2.7 2.7 2.7 2.7 2.7 320 0.96 32.0 . 32.0 . 32.0 . 269 269 <u>G8-116</u> 1.02 ------------4.23 4.23 4.23 75.6 76 76 1.14 8.1 1.14 8.1 38.0 38.0 358 358 Sample No. CB-152 CB-148 Sample Origin: Unit: Ba/Rb Ba/K<sub>2</sub>( Si02 Ti02 Co30 Sc05 Co Co Co Co Co Co Co Bb La Ba La £

Unit:	Obsidian	i Flows		Felsite	Flows	Biotite F	hyric fl	ows and I	Domes	
Sample Origin:	Glass Butte Quadrangle	Little But	e Glass tte	Glass ( Quadra	Butte ngle	Glass Butte Quadrangle	Little Butt	Glass e	Round To Butte	d.
Sample No.	GB-151	LGB-1-A	9N FC-14	GB-155	<b>GB-169</b>	G8-131	<u> </u>	G8-878	RT8-70	RTB-82
Sio,	78.43					78.71	77.57	1	1	6 9 6
Tio5	0.08			1 1 1		0,09	0.13	1	1  - 	
fe0 <sup>•</sup>	0.84	1.04	0.99	1.09	1.11	0.91	0.85	0.83	0.74	0.65
MgO	N.D.					N.O.	0.07	1	1	
CaO	0.49		1 - 1 - 1 - 1	1	1	0.48	0.91	•	1	
P,0 <u>,</u>	0.024	# 1 		111		0.028	0.048	1 1 1		1 1
Sc J	4.86	3.56	3.93	4.39	4.29	4.55	3.82	3.95	4.63	3.75
Co	0.38	0.46	0.48	0.42	0.66	0.45	0.50	0.39	N.D.	0.25
Cs	2.5	4.3	4.5	2.5	3.0	3.0	4.6	5.4	7.0	5.8
Rb	73	105	117	73	78	77	121 1	26	145	103
Ba	1190 1	1500 1	1210	1590 1	520	1330	1050 9	160	510	370
Ta	1.22	0.77	1.01	1.0	0.89	1.08	0.95	0.97	1.23	1.19
Ih	6.0	10.3	10.4	9.6	0.0	8.1	9.7	10.3	11.7	9.9
n	N.D.	N.D.	3.0	N.D.	N.D.	7.0	7.0	4.5	9.0	4.2
La	25.0	30.0	35.0	44.0	46.0	29.0	25.D	24.0	21.0	17.0
Eu	0.90	0.75	0.60	1.40	1.30	0.60	0.60	0.80	0.45	0.44
Ba/Rb	16.3	14.3	10.3	21.8	19.5	17.3	8.8	7.6	3.5	3.6
Ba/K <sub>2</sub> O	276	349	193	378	345	246	219 2	53	100	72
SiO, TiO, FeO	1, MgO, CaO, á	and P,O,	given in w	eight per	cent.					
Traĉe element c w O - cot doto	chemistry give	en in <sup>6</sup> ppr								
= not dete	ermined									

TABLE V: CONTINUED

				IINN	S OF DIF	FERENT GEO	GRAPHIC	ORIGIN				
Sample Or	igin:	Glass But Quadrangl	e		ittle Gla Butte	SS	East	ern Glas Buttes	S	Ro	und Top Butte	
Element:	Rb	Сs	٩I	Rb	C s	ЧI	Rb	Сs	ſh	Rb	Cs	۲h
	72-92	2.6-2.9	7.3-8.7			8 8 8 8	116-150	4.3-5.2	12.5-13.2	103-140	5.9-7.1	10.6-11.4
2.	77	3.0	8.1	121-126	4.6-5.4	9.7-10.3	1 1 1			103-145	5.8-7.0	9.9-11.7
3.	73	2.5	6.0	105-117	4.3-4.5	10.3-10.4			* * *	1	1	
••	73-78	2.5-3.0	9.0-9.6	-    -   		* * *	3 8 7 8		•	4 6 8 8		
1. Zoned 2. Biotit 3. Obsidi 4. Felsit All conce	flow an flo t detu ntrat	and dome t ric flows ows ermined. ions given	units and dome: i in ppm.	ŋ								

TRACE ELEMENT CONCENTRATIONS OF HIGH-SILICA RHYOLITE

TABLE VI



Figure 9. Comparison of elemental concentrations for eastern Glass Buttes and Glass Butte obsidian samples. Enrichment factors are based on elemental concentrations for eastern Glass Buttes (EGB-1) divided by concentrations for Glass Butte (GB-152).

the Glass Butte quadrangle. Trace element concentrations in highsilica rhyolite units from Little Glass Butte are chemically intermediate between the concentrations observed in samples from eastern Glass Buttes and Round Top Butte, and those observed in samples of the Glass Butte quadrangle (Figures 10, 11). Highsilica rhyolite samples from Round Top Butte and eastern Glass Buttes are also enriched in heavy rare earth elements (HREE), depleted in light rare earth elements (LREE), and exhibit larger negative Eu anomalies relative to the samples from the Glass Butte quadrangle (Figure 12)(Roche and Cummings, 1987a).

## RHYOLITE AND RHYODACITE SEQUENCE

SiO content (anhydrous basis) is used to differentiate 2 the rhyolite and rhyodacite units: rhyolites contain 72-75%, and rhyodacites 68-72% (Bacon, 1983). Rocks of the rhyolite and rhyodacite sequence contain 70-76% SiO, 0.18-0.38% TiO, 0.04-2 0.11% P O, 0.22-1.34% MgO, 1.37-3.4% CaO, 0.34-0.76 ppm Ta, 5.5-25 15.3 ppm Sc, and 1.9-10.7 ppm Co. Geochemical determinations for selected elements of rhyolite and rhyodacite units are given in Table VII.

Larger variations are observed in the major and trace element concentrations of different rhyolite and rhyodacite units relative to the high-silica rhyolite sequence. The geochemical variations do not show a systematic relationship to variations in phenocryst abundance or type.

The geochemistry of the rhyolite in the Glass Butte



<u>Figure 10</u>. Scatter plot of Ba/K and Ba/Rb ratios of high-silica rhyolite units from different geographic areas.



Figure 11. Scatter plot of Sc and Th concentrations of highsilica rhyolite units from different geographic areas.



Figure 12. REE abundances for high-silica rhyolite samples normalized to concentrations from Ekambaram and others (1984). ARW-2 is a representative sample from eastern Glass Buttes, whereas GB-44A and GB-152 represent samples from the Glass Butte quadrangle.

9 2080722289 1 B R	RHYOLITE AND RHYODACITE SEQUENCE GEOCHEMISTRY	Rhyolite       Rhyodacite         Diagnostic Characteristics:       1. SiO2 = 74-76%       70-73%         2. TiO2 = 0.18-0.38%       0.31-0.36%         3. MgO2 = 0.22-0.54%       0.6-1.34%         4. CaO = 1.37-1.72%       2.9-3.4%	5. P2U = U.U4-U.U3% U.U92-U.I1% 6. S2 <u>5</u> 5.5-8.8 ppm 7.2-15.3 ppm 7. Co = 1.9-3.1 ppm 6.1-10.7 ppm 8. Ta = 0.67-0.69 ppm 0.34-0.76 ppm	yolite Rhyodacite Rhyodacite Intrusion	itte Little Glass Butte Glass Butte Glass Butte Butte	*RB-1 6B-20B 6B-27 6B-39B 6B-56B 6B-93 6B-95 6B-3B 6B-173	74.87 71.92 70.82 73.21 72.51	0.25 0.31 0.36 0.31 0.31	14.38 15.12 15.31 14.36 14.69	2.0 4.8 2.7 3.1 3.3 3.7 2.9 2.8 2.8	0.24 0.91 1.34 0.78 1.04	1.58 3.31 3.45 2.88 2.95	5.4 2.7 2.9 3.4 3.5 2.4 2.9 3.5 3.1	7 0.070 0.096 0.110 0.092 0.101	5.6 15.3 7.2 8.2 8.8 12.5 7.9 7.7 7.2	2.0 7.9 6.7 8.3 8.6 6.1 7.6 6.6 6.2	4.5 N.D. 7.3 6.1 6.8 N.D. 6.2 6.5 5.4	B7 41 65 73 66 50 82 70 87	7.3 4.7 5.8 6.2 6.8 6.0 7.3 6.5 6.4	52 34 22 21 24 34 24 27 23
	RHYOLITE AN	Diagnostic Cha		Rhyolite	Butte Little Glass Butte	16 *RB-1	89 74.87	38 0.25	21 14.38	7 2.0	22 0.24	72 1.58	7 5.4	077 0.070	8 5.6	0 2.0	2 4.5	87	9 7.3	52

" Wajor element chemistry from Berri (1982). SiO<sub>2</sub>, TiO<sub>2</sub>, Al<sub>2</sub>O<sub>3</sub>, FeO, MgO, CaO, K<sub>2</sub>O, and P<sub>2</sub>O<sub>5</sub>, given in weight percent. Trace element chemistry given in ppm. N.D. = not detected. ---- = not determined.

IIV

TABLE VII

quadrangle shows some distinct differences when compared to the rhyolite at Little Glass Butte. These include: 1) higher concentrations of TiO , FeO, and Sc, and 2) lower concentrations 2 of Al O , K O, Rb, Th, and La. 2 3 2

Rhyodacite samples exhibit relatively large geochemical variations between different units. Variations are most apparent for MgO (0.6-1.34%), FeO (2.7-4.8%), Sc (7.2-15.3 ppm), Rb (41-87 ppm), and Eu (0.81-2.34 ppm). Relationships could not be established between variations in elemental concentrations and 1) differences in the elevation of samples or, 2) the geographic origin of samples. A relationship between a time sequence and geochemical variances could not be established due to the lack of contact exposures between the different rhyodacite units. The only contact which has been identified between rhyodacite units occurs between the intrusion and the unit it intrudes, both of which contain similar elemental concentrations.

REE plots of rhyolite and rhyodacite units (Figure 13) exhibit similar HREE depletions relative to the LREE. The rhyolite at Glass Butte has a La/Yb ratio of 5.5, compared to ratios of 8.2 and 7.2 for the rhyolite at Little Glass Butte. Rhyodacite La/Yb ratios range from 4.0 to 8.7.

# INTERNAL AND PLATEAU BASALT SEQUENCES

Major oxide data (Table VIII) indicate that the internal and plateau basalts are classified as high-alumina and olivine tholeiites (Irvine and Baragar, 1971). Geochemical relationships



Figure 13. REE abundances for rhyolite and rhyodacite samples normalized to concentrations from Ekambaram and others (1984). GB-16 and RB-1 represent rhyolite samples, whereas GB-20B, GB-26A, and GB-56B represent rhyodacites.

between internal, contaminated, and plateau basalt samples are shown in Figures 14 and 15. The internal basalt flows are geochemically characterized by rocks which contain 12.3-14.1% FeO, 35-42 ppm Sc, 42-71 ppm Co, and 25-138 ppm Cr. FeO, Na O, Sc, Co, 2 Cr, and Th concentrations for different flows of the internal basalt sequence exhibit similarities. However, the Cr and Co concentrations of sample GB-1868, an aphyric basalt, are distinctly enriched relative to the other basalt flow samples.

Chondrite-normalized REE patterns for the internal basalts are relatively flat, but several of the samples exhibit negative Yb anomalies (Figure 16). La/Yb ratios range from 2.6 to 5.9, reflecting the variation in Yb concentrations.

GB-102A, a plateau basalt from the Potato Lake quadrangle, contains 16.2% FeO, 41 ppm Sc, 54 ppm Co, and 17 ppm Cr. PB-1 and PB-2, also plateau basalts, contain lower concentrations of SiO 2 and Na O and higher concentrations of CaO and MgO relative to the 2 internal basalts (see Table VIII).

# ISOTOPE GEOCHEMISTRY

The results of eight  $\overset{18}{0}$  0 isotopic determinations for high-silica rhyolite, rhyolite, rhyodacite, and basalt samples are

TABLE VIII

INTERNAL, CONTAMINATED, AND PLATEAU BASALT GEOCHEMISTRY

	lasalt	Eastern Glass Buttes	**p8-1 ***p8-2	48.6 49.9	2.25 1.69	16.63 16.83	11.90 10.40	6.63 6.93	9.96 9.15	2.74 3.53	0.54 0.37	9 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8 8	1 1 1 1 1 1	         		
Plateau 49-50% 1.6-2.25% 16.6-16.8% 10.4-16.2% 6.6-6.9% 9.1-10% 41 ppm 17 ppm	Plateau B	Potato Lake Quadrangle	GB-102A		1	t 1 1	16.2	P 9 1	1	4.1	1 5 1	41	54	17	N.D.	
Contaminated 67.4% 1.12% 1.3.9% 6.5-7.8% 1.6% 24-28 ppm 11-19 ppm 11-19 ppm			GB-106A GB-186A	55,80	1.73	16.27	12.3 14.1	3.54	7.58	4.3 4.0	0.404	36 42	42 48	30 27	2.0 2.4	cent.
Internal = 55.8% = 1.73% = 16.3% 12.3~14.1% 3.5% 7.6% 35-42 ppm 42-71 ppm 42-71 ppm	al Basalt		GB-76 GB-98A		0 1 1 1 1 1 1 1 1 1 1 1		12.8 12.3	8 \$ 8 8 8 7 8	8 8 8 7 8 7 8	4.1 4.0		36 35	46 43	25 35	2.3 2.1	en in weight per
ristics: 1. Si02 3. Alg02 5. Ag0 4. Fe0 0 5. Ag0 4. 7. Sc = 4. 8. Co = 4. 8. Cr = 4.	Intern	lass Butte uadrangle	*GB-1868 ·GB-4C		1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	1,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,,	12.8 12.5		1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	3.5 4.0	***	42 36	71 43	138 31	N.D. 2.4	a <sub>2</sub> 0, and P <sub>2</sub> 0 <sub>3</sub> , giv
Diagnostic Characte	ontaminated Basalt	9	*GB-4C *GB-172	67.44	1.12	13.92	7.8 6.5	1.56	4.39	4.8 5.0	0,355	28 24	11 13	18 7	2.3 2.5	rri (1982) hnson (1984) 2. FeO, MgO, CaO, N ted. mined.
	Unit: C	Sample Origin:	Sample No.	si02	T102	A12 03	Fe0	0 <b>6</b> w	CaO	Na <sub>2</sub> J	P2 03	SC	Co	Cr	Ч	<pre>** Aphyric ** Aphyric ** PB-1 from Be *** PB-2 from Jo 5102, T102, A120 N.D2 = not detec = not deter</pre>

t



Figure 14. Scatter plot of Co and Cr concentrations for internal, contaminated, and plateau basalt samples. Several high-silica rhyolite samples are also given.



Figure 15. Scatter plot of FeO and Sc concentrations for internal, contaminated, and plateau basalt samples. Several high-silica rhyolite samples are also given.



Figure 16. REE abundances for internal basalt samples normalized to concentrations from Ekambaram and others (1984).

given in Table IX. Isotopic values for eastern Glass Buttes and Round Top Butte, 5.6  $\pm$  0.1 per mil and 3.9  $\pm$  0.1 per mil respectively, are anomalously low relative to the other samples.

TABLE	Ι	Х
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Sample	Unit	Origin	$\delta^{^{18}}$
EGB-1	Zoned Dome	eastern Glass Buttes	5.6 <u>+</u> 0.1
RTB-19	Zoned Dome	Round Top Butte	3.9 <u>+</u> 0.1
G8 <b>-</b> 44A	Zoned Flow	Glass Butte Quad.	7.1 <u>+</u> 0.1
GB <b>-</b> 131	Biotite phyric Dome	Glass Butte Quad.	7.7 <u>+</u> 0.1
RB-1	Rhyolite	Little Glass Butte	6.8 <u>+</u> 0.1
GB-38	Intrusive Rhyodacite	Glass Butte	7.0 <u>+</u> 0.1
G8-568	Rhyodacite	Glass Butte	6.8 <u>+</u> 0.1
GB-106A	Internal Basalt	Glass Butte Quad.	7.1 <u>+</u> 0.1

#### ISOTOPE GEOCHEMISTRY

## GEOCHEMISTRY SUMMARY

Major and trace element variations within the high-silica rhyolite sequence are related to the geographic distribution of samples (see Table VI). FeO, CaO, MgO, TiO, Co, LREE, Eu, and Ba 2 concentrations increase, whereas Sc, Rb, Cs, Ta, HREE, U, and Th concentrations decrease from east to west across the Glass Buttes complex.

The geochemical data do not show evidence of consistant variations among the different high-silica rhyolite units for a

given geographic location, as indicated by the similarity among late erupted zoned flows and domes (GB-152, GB-148, and GB-116) and the felsite flows (GB-155 and GB-169) of the Glass Butte quadrangle (see Table V).

Johnson (1984a) suggested that the stratigraphic units to the west overlie the stratigraphic units to the east. This suggests that the high-silica rhyolite volcanism was initiated in the eastern Glass Buttes and Round Top Butte areas, later migrating westward toward Little Glass Butte and Glass Butte. The observed major and trace element variations within the high-silica rhyolite sequence are consistant with this hypothesis.

The geochemical differences between high-silica rhyolite samples from Round Top Butte and eastern Glass Buttes and those of Little Glass Butte and the Glass Butte guadrangle were not produced by the hydrothermal alteration systems which were active in the eastern Glass Buttes area. The mercury mineralization occurred in an oxidizing system (Johnson, 1984a). Under such conditions, Na O, K O, Cs, Rb, and U are leached from rhyolitic 2 rocks (Zielinski, 1981, 1982). The high-silica rhyolite samples of Round Top Butte and eastern Glass Buttes do not show evidence of Na O or K O leaching and the Cs, Rb, and U concentrations are the highest within the complex, trends inconsistant with alteration by oxidizing fluids. However, the low  $\delta$  O values for eastern Glass Buttes and Round Top Butte, 5.6 + 0.1 per mil and  $3.9 \pm 0.1$  per mil respectively, are interpreted to be the result of the interaction between meteoric water and the rock samples

(Taylor, 1974; Lipman and Friedman, 1975; Faure, 1977; I. Barnes, personal communication, April, 1987). If these values were lowered during the hydrothermal alteration events it may suggest that  $\delta^{18}$  0 isotopic values are a more sensitive indicator of hydrothermal alteration than are major and trace element mobility (I. Barnes, personal communication, April, 1987). This may also suggest that the hydrothermal alteration cell was much larger than that defined by Johnson (1984a) on the basis of visible alteration (see Plate I).

Barium concentrations of Glass Butte high-silica rhyolites are two to three times the concentrations observed in samples from eastern Glass Buttes and Round Top Butte. The large difference in the barium concentrations from east to west is consistant with variations observed in the eruptive sequences of other high-silica rhyolite systems (Hildreth, 1981; Vogel and others, 1987).

The rhyolite and rhyodacite sequence exhibits relatively large major and trace element variations. Geochemically, the rhyolite of Little Glass Butte is a more differentiated rhyolite than that exposed in the Glass Butte quadrangle. Systematic variations in the geochemistry of rhyodacite units relative to 1) time of eruption, 2) the elevation of the sample, and 3) the geographic origin of samples could not be established.

Geochemical comparisons of the high-silica rhyolite, rhyolite and rhyodacite units indicate: 1) the major element geochemistry exhibits linear trends beween the different units but, 2) the trace element geochemistry often shows separate trends for the high-silica rhyolite sequence and the rhyolite and rhyodacite sequence. Figure 17, a comparison of the concentrations of SiO and CaO, indicates a negative linear 2 relationship between high-silica rhyolite, rhyolite, and rhyodacite units. There are gaps in the CaO concentrations, suggesting that there may not be a continuous series between the different rock units. A comparison of Rb and Sc concentrations (Figure 18) shows two separate geochemical trends: 1) the Rb concentrations of high-silica rhyolites decrease from east to west across the complex while the Sc concentrations remain fairly constant, and 2) the Sc concentrations of the rhyolite and rhyodacite units increase with a corresponding decrease in Rb.

In order to quantify the geochemical grouping, major element concentrations for high-silica rhyolite, rhyolite, and rhyodacite samples were subjected to cluster analysis. Bacon and others (1981) divided the cluster analysis process into the following steps: 1) a similarity matrix is computed between samples and the two samples with the highest similarity are combined into a pair group, 2) the similarity matrix is then recomputed with the pair treated as a single sample, and 3) pair and larger groups in subsequent iterations are weighted according to the number of original analyzed samples they contained. The degree of similarity between samples is expressed as the distance function, as shown in Figure 19. The high-silica rhyolite samples (Group II) exhibit very strong similarities between samples, but do not correlate well to the rhyodacite samples (Group I). Similarities



Figure 17. Comparison of CaO and  $SiO_2^2$  concentrations for the different silicic rock types.



Figure 18. Comparison of Sc and Rb concentrations for the different silicic rock types. Rb concentrations of highsilica-rhyolite samples decrease from east to west across the complex.



Figure 19. Dendrogram linking statistically similar analyses on the basis of the distance function calculated from data for the major elements using cluster analysis. Degree of difference between samples is proportional to horizontal distance from left margin to connecting vertical line.

between rhyodacite samples are not as strong as those observed for the high-silica rhyolites, reflecting more distinct geochemical variations in the former. GB-16, a rhyolite sample, lies between the high-silica rhyolite and rhyodacite samples, as expected. Thus, the the high-silica rhyolite sequence and rhyolite and rhyodacite sequence may be separated on the basis of geochemistry.

The internal basalt geochemistry of eleven samples indicate similarities in the Na O, FeO, Sc, and Th concentrations (see Table VIII). Differences in the Co, Cr, and Yb concentrations for different flows have been identified (see Figures 14, 15, and 16). The geochemistry of contaminated basalt samples indicates that there has been contamination by rocks of rhyolitic composition (see Figures 14 and 15). Evidence which may indicate that the basalts were contaminated by the high-silica rhyolite sequence includes: 1) the lack of phenocrysts within the xenoliths observed in the contaminated basalts, and 2) the basalts overlie the highsilica rhyolite sequence in several locations, suggesting that the basaltic magma had to travel through the high-silica rhyolite sequence in order to reach the surface. The contaminated basalts are enriched in SiO and Na O, while being depleted in Al O, TiO , FeO, CaO, MgO, P O , Co, and Cr relative to uncontaminated internal basalts (see Table VIII). GB-172, a contaminated basalt, is shown in Figure 19 to be more similar to rocks of silicic composition than to a uncontaminated basalt sample (GB-106A). Johnson and Ciancanelli (1983) reported the presence of a

large andesite flow on the northwest flank of Glass Butte. It is believed that their data may represent a contaminated basalt, similar to GB-172.

Major and trace element concentrations of plateau basalts determined in this study and reported by Berri (1982) and Johnson (1984a) indicate considerable differences in the elemental concentrations of different basalt flows. The small data set, poor sample distribution, and poor understanding of the plateau basalt stratigraphy do not allow one to make statistically valid comparisons or conclusions about the plateau basalts.

## CHAPTER IV

#### DISCUSSION

The stratigraphic and geochemical trends of the Glass Buttes complex are representative of the style of volcanism which occurs in extensional tectonic settings. The 'bimodal' association of high-silica rhyolite and tholeiitic or alkalic basalt also exists at Little Glass Mountain, California (Fink, 1983), the Coso Volcanic field, California (Bacon, 1982; Bacon and others, 1981), Long Valley Caldera, California (Hildreth', 1979, 1981; Michael, 1983), Twin Peaks, Utah (Crecraft and others, 1981), and La Primavera, Mexico (Mahood, 1981).

## STRATIGRAPHY

The stratigraphic and geochemical data indicate that the high-silica rhyolite volcanism was initiated on Round Top Butte and eastern Glass Buttes, later migrating westward toward the Little Glass Butte and Glass Butte areas. High-silica rhyolites were erupted mainly as low-volume flows and domes with minor pyroclastic deposits; a situation that contrasts the voluminous caldera forming eruptions, such as those which formed the Bishop and Tala tuffs of Long Valley Caldera (Hildreth, 1979, 1981; Hildreth and Mahood, 1986) and La Primavera (Mahood, 1981) respectively. The high-silica rhyolite sequence contains 1) zoned
flows and domes, 2) obsidian flows, 3) felsite flows, and 4) biotite-phyric flows and domes. The textural differences between the different units may reflect 1) the distribution of volatiles in the magma and 2) variable degassing within the lava flows at the surface (Fink, 1983; Wilson and Emmons, 1985). A model for the emplacement and textural development of the Glass Buttes high-silica rhyolite sequence, derived from a model proposed by Fink (1983), includes:

1) As the magma body approaches the surface, the volatiles exsolve and rise to the top. The lowering of the confining pressure as the magma rises leads to frothing of the volatile-rich carapace. The interaction with shallow groundwater also contributes to the formation of a gas-rich carapace. The vesiculation may initiate the eruption of pyroclastic materials, such as those exposed on the southern slope of Glass Butte and in the eastern Glass Buttes area.

2) Once extruded, the flow will continue to vesiculate until the viscosity, which increases with decreasing temperature, becomes too high to permit vesiculation. The lava flows due to the relatively low viscosity of the glass septa between vesicules. The vesicules become flattened and elongate during the flow of the lava. The obsidian and felsite layers, which have high temperatures and low viscosities relative to the pumiceous layers (Figure 20), behave as viscous fluids during the flow of the lava. Strongly-folded flow banding in the obsidian and felsite layers and the annealing of obsidian breccia clasts in an obsidian matrix



<u>Figure 20</u>. Rhyolitic obsidian flow profiles. (a) Stratigraphy for a hypothetical 35 meter thick zoned flow or dome (not to scale). (b) Density profile. (c) Temperature profile, assuming constant internal temperature; note steep surface-temperature gradient. (d) Viscosity profile; note rapid decrease of viscosity with depth near upper surface (modified after fink, 1903).

within the obsidian layers are indicators of the deformation which occurs during the lava flowage. The pumiceous layers have high viscosities and low temperatures, resulting in brittle failure during deformation. The formation of the carapace breccia in flow units results from the movement of the lava, which causes the upper surface to fracture into blocks and cascade off the flow front. In domal units, the carapace breccia forms as a result of the expansion of the dome. The transition between the pumice layers and the underlying obsidian occurs when the gas pressure in the vesicles is no longer sufficient to overcome the tensile strength of the magma. The felsite layers, representing the core of most flows, may have cooled slowly enough so that a crystalline texture started to develop.

3) The final magma in the conduits may have been biotitephyric, resulting in the eruption of the biotite-phyric flows and domes such as those observed on Round Top Butte, Little Glass Butte, and the 1,805 meter peak in the Glass Butte quadrangle.

4) The perlitic fracturing observed within the pumiceous layers formed during the secondary hydration of the glass by groundwater (Zielinski, 1981; Fisher and Schmincke, 1984).

The rhyolite and rhyodacite sequence is texturally distinct from the high-silica rhyolite sequence. Variations in the phenocryst type and abundance and the relatively small volume eruptions suggest that the different rhyolite and rhyodacite units represent distinct magma batches.

Phyric and aphyric tholeiitic basalts of the plateau and

internal basalt sequences were erupted from numerous vents located mainly on the perimeter of the silicic complex. Several basalt flows which were erupted from vents within the silicic complex show petrographic and geochemical evidence of silicic contamination. The stratigraphic and geochemical relationships between different basalt flows, and the lateral continuity of individual flows is poorly understood. The presence of volcaniclastic beds between plateau basalt flows indicates that the basalts were erupted in several stages.

### GEOCHEMISTRY

The geochemical trends within the high-silica rhyolite sequence are characteristic of highly evolved magmas, similar in composition to the Coso Volcanic field (Bacon, 1982; Bacon and others, 1981), the Bishop tuff (Hildreth, 1979, 1981), and the Tala tuff (Mahood, 1981). The majority of the elements analyzed within the Glass Buttes high-silica rhyolite sequence fall into two groups that display similar behavior: 1) Sc, Rb, Cs, Sm, Tb, Yb, Lu, Ta, Th, U, and 2) Mg, Ca, Ti, Fe, Co, Ba, La, Ce, Nd, Eu, and P. Elements within each group generally show positive correlations with each other, but negative correlations with elements of the other group. The variations between the two groups is a reflection of the chemical stratification present within the silicic magma chamber prior to the eruption of the sequence (Hildreth, 1979, 1981; Bacon and Metz, 1984). Group 1 elements are interpreted to represent those elements concentrated towards the roof of the magma chamber, while group 2 represent those concentrated at the deepest level tapped during the eruption of the high-silica rhyolite sequence. Si, Al, Mn, Na, K, Cr, and Hf remain constant throughout the eruptive sequence, indicating that they were not zoned in the magma chamber. On the basis of stratigraphy and geochemistry, the high-silica rhyolites of Round Top Butte and eastern Glass Buttes are interpreted to represent the magmas which were derived from the roof or upper portion of the magma chamber. The high-silica rhyolites of Little Glass Butte and the Glass Butte quadrangle are interpreted to represent the deepest levels tapped during the eruption of the sequence. The chemical zonation within the high-silica rhyolite sequence of Glass Buttes is similar to the zonation observed within the highsilica rhyolites of the Coso Volcanic field and the Bishop tuff (Figure 21). Elemental variations within the Bishop tuff are generally greater than those observed within the Glass Buttes or the Coso volcanic field volcanic sequences.

The differentiation processes that produced the major element compositions and the enrichments and depletions in many trace elements of the Glass Buttes high-silica rhyolite sequence are evidently the same as those which brought about the vertical compositional zonation in the magama chambers of the other highsilica rhyolite systems previously mentioned. The compositional zonation present within the Glass Buttes and Coso volcanic field magma chambers persisted through several eruptive cycles, while the zonation within the Bishop tuff represents a single eruptive



Figure 21. Comparison of the chemical zonation of the Glass Buttes high-silica rhyolites with the Bishop tuff and the Coso volcanic field. Enrichment factors are concentrations of the early erupted divided by the late erupted. The first bar in each group represents Glass Buttes, the second represents the Coso volcanic field, and the third the Bishop tuff.

episode. The compositional zonation observed in these systems has not been explained by conventional models including:

1) Crystal Settling: most of the high-silica rhyolites of the Glass Buttes complex are aphyric, thus if crystal settling occurred within the magma chamber either all of the phenocrysts settled out, or the magmas became superheated prior to eruption and the phenocrysts were resorbed. Plagioclase and sanidine phenocrysts within the biotite-phyric flows and domes are sub- to euhedral, showing no evidence of resorbtion. The following chemical and physical observations also indicate that the chemical zonation within the high-silica rhyolite sequence is not the product of crystal settling: 1) Sc and HREE are enriched roofward, while Fe and Mg are enriched downward, and Mn, Co and Cr are unzoned. These trends are inconsistant with the removal of dense early-formed zircon, apatite, and pyroxenes, which are strongly enriched relative to glass in these elements (Arth, 1976; Clark, 1984), 2) to produce the observed 1.5 to 2 fold roofward enrichment in elements such as Cs, Rb, U, Th, and Sc would require the crystallization of unrealistic proportions of magma. Mahood (1981) used crystal fractionation models to estimate that nearly one-half of the magma would have to crystallize and settle out in order to produce a two-fold roofward enrichment of elements such as Ta, U, Rb, and Cs in the early-erupted portion of the Tala tuff, and 3) the high viscosities within the Glass Buttes highsilica rhyolite magmas, as estimated from Shaw (1972) and Blake and Ivey (1986), would make crystal settling an unrealistic

mechanism (I. Barnes, personal communication, April 1987).

2) <u>Partial Melting</u>: the observed compositional zonation within the high-silica rhyolite sequence of Glass Buttes cannot be explained by partial melting. Problems with the partial melting model include: 1) the LREE and HREE antithetic enrichment trends (see Figure 12) cannot be modeled by the partial melting of any realistic source rocks, irrespective of how the roles of allanite, sphene, apatite, zircon, and the major phases are varied during melting (Hildreth, 1981), and 2) conflicting fractionation patterns among elements of the first transition series; Sc is enriched roofward, while Fe, Ti, and Co are enriched downward, and Mn and Cr are unzoned.

3) <u>Basalt-Rhyolite Mixing</u>: The following observations appear to rule out basalt-rhyolite mixing as the mechanism for the formation of the compositional zonation: 1) Ba, LREE, and Sc fractionation patterns within the high-silica rhyolites would be opposite of those observed, 2) the Mn, Cr, Co, and Fe concentrations would be greatly enriched in those samples thought to represent magma from the deepest level tapped in the chamber, and 3) the mixing of basaltic and rhyolitic magmas seems unlikely because of the large differences in the melt viscosities and densities (Shaw, 1972; Blake and Ivey, 1986).

In order to derive a valid model to explain the compositional zonation within silicic chambers there needs to be better understanding of 1) the behavior of halogens within the magma chamber, 2) Soret diffusion, 3) the relative importance of thermal, gravitational, viscosity, and melt structural gradients as mechanisms of transport (Blake and Ivey, 1986), 4) which species diffuse as discrete ions and which as complex molecules, and 5) the role (if any) of a free-vapor phase.

The rhyolite and rhyodacite sequence have steep, fractionated REE patterns. Most of the geochemical characteristics would appear to be explained by a model involving crystal-liquid equilibria:

1) Crystal Setting: a liquid of the composition of RB-1 or GB-16 (rhyolitic) could be derived from a liquid of the composition of GB-93 or GB-20B (rhyodacitic) by the separation of early formed plagioclase, hornblende, and pyroxene phenocrysts found in the later, but the following inconsistancies argue against separation of phenocrysts alone to produce the frationation trends shown in Table X: 1) a comparison of GB-27 to GB-173 reveals no noticeable change in the FeO, MgO, or Sc concentrations, but the percentage of mafic phenocrysts, which are strongly enriched in these elements relative to coexisting glass (Arth, 1976; Clark, 1984), rises sharply from 1.4% to 12.1% respectively, and 2) GB-16 and GB-27 have approximately the same total plagioclase content (phenocrysts plus groundmass), but the Eu, which is strongly enriched in plagioclase relative to coexisting glass (Arth, 1976; Clark, 1984), concentration in GB-16 is more than double that observed in GB-27.

2) <u>Incremental Melting</u>: most of the geochemical trends within the rhyolite and rhyodacite sequence can be explained by the

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# FRACTIONATION TRENDS WITHIN THE RHYOLITE AND RHYDDACITE SEQUENCE: SAMPLES BECOME MORE MAFIC FROM LEFT TO RIGHT

UNIT:	R	HYOL ITE			внуо	DACITE			
SAMPLE No.	RB-1	<u>G8-16</u>	68-27	68-173	CB-95	CB-56B	69-93	68-208	
510 2 Fe0 2	74.9 2.0	75.9 2.7	71.92	72.51 2.9		70.82	3.7	4.8	
ngu CaO	U.24 1.58	U. 22 1.72	3.31	2.95	1   1   1   1   1	3.45			
К2 D 50	5.4 5.6	3.7 8.8	2.9	3.1 7.2	2.4	л. 5 В. В	2.4	2.7 15.3	
Ba Eu	1380 1.84	1240	1040 0.81	1100 0.82	1090 0.90	1170 0,95	1030 2.17	990 2.34	
SlO2, FeO, Sc, Ba, an	MgO, CaO, d Eu given	and K <sub>2</sub> D given in ppm.	in weight	percent.					

incremental melting of a source rock. The initial magmas extracted from the zone of partial melting would be of rhyolitic composition, representing the melting of quartz, potassium feldspar, biotite, and possibly hornblende. The melting of quartz would enrich the magma in SiO, the potassium feldspar and biotite 2 would cause enrichments in Ba, K O, and Eu, while the hornblende would enrich the magma in the REE (Arth, 1976; Clark, 1984). The progressive melting of the residue, including plagioclase, pyroxene, and oxide phases to produce magmas of rhyodacitic composition would cause enrichment trends in FeO, MgO, CaO, Sc, and Eu (see Table X). A problem with the incremental melting model is the large depletion of Eu between rocks of rhyolite composition and the most highly-evolved rhyodacite samples (GB-27, GB-173).

A representative model for the generation of the geochemical trends within the rhyolite and rhyodacite sequence would contain a combination of both crystal setting and incremental melting, with the later being the dominant process.

### MAGMA GENERATION

The 'bimodal' association of high-silica rhyolite and tholeiitic or alkalic basalt is interpreted to be indicative of extensional tectonic settings (Martin and Piwinskii, 1972; Hildreth, 1979, 1981; Barker, 1981; Bacon and others, 1984; Bacon, 1985). The generation of the Glass Buttes silicic magmas may reflect the tectonic extension at the northern margin of the Basin

and Range province. Models for the generation of rhyolitic magma within extensional tectonic settings include 1) the partial melting of older crustal rocks, and 2) closed-system crystalliquid fractionation, during which less siliceous minerals crystallize and settle or float out of the magma and thereby cause the remaining liquid to become more siliceous (Barker, 1981). The partial melting model is preferred for the generation of the magmas of Glass Buttes because of several problems with the crystal-liquid fractionation model, including 1) the relatively small yield of rhyolite from a basaltic liquid during crystalliquid fractionation; 100 parts basalt liquid yields 8-10 parts rhyolite (Barker, 1981), 2) the aggregation of the small magma batches formed during crystal-liquid fractionation into a single magma body would be a problem, 3) the lack of intermediatecomposition rocks within the Glass Buttes complex, and 4) the lack of basaltic xenoliths or olivine phenocrysts within the highsilica rhyolite or rhyolite and rhyodacite units. The partial melting of crustal rocks is brought about principally by the intrusion of mafic magma from the mantle (Hildreth, 1979, 1981; Ishihara, 1981).

Whole rock  $\delta^{18}$  O values give an indication of the source rock composition for magmas derived by partial melting (Bacon, 1981b; I. Barnes, personal communication, April 1987). The  $\delta^{18}$  O values from analyses completed on high-silica rhyolite, rhyolite, and rhyodacite samples from the Glass Buttes complex (6.8-7.7 per mil) are consistant with the melting of igneous source rocks of granitic to basaltic composition (Bacon and Duffield, 1981; I. Barnes, personal communication, April, 1987). Metamorphic and sedimentary rocks have  $\int_{10}^{18}$  0 values which range from 7 per mil to 36 per mil, too high to be the source rock for the Glass Buttes magmas (Brownlow, 1979).

Magmas of the high-silica rhyolite sequence probably originated from a relatively shallow magma chamber (Figure 22). With the following set of assumptions, a rough estimate for the depth of the high-silica rhyolite magma chamber can be derived based on the presence of biotite phenocrysts in the biotite-phyric flows and domes: 1) the biotite crystallized at temperatures of 700-800°C (Speer, 1982), 2) the pressure during biotite crystallization was 5-6 kilobars (Speer, 1982), and 3) the pressure within the crust increases at a rate of 1/3 kilobar/kilometer. Using these assumptions, a depth of 15-18 kilometers is calculated for the depth of the magma chamber. This depth, coupled with the relatively low-volume eruptions may explain why there was not a caldera-forming eruption within the Glass Buttes complex. The emplacement of silicic magma chambers at crustal depths less than 10 kilometers coupled with the rapid rise of magma to the surface, resulting in the expansion of volatiles, are thought to be the conditions which result in caldera-forming eruptions and the formation of large volume pyroclastic deposits, such as the Bishop tuff (Hildreth, 1979, 1981) and the Tala tuff (Mahood, 1981).

The stratigraphic and geochemical data suggest that the





rhyolite and rhyodacite sequence represent distinct, but genetically related magma batches (see Figure 22). The presence of hornblende, ortho- and clinopyroxene, and magnetite along with the higher concentrations of MgO, FeO, CaO, Co, Cr, Eu, Sc, and lower concentrations of SiO, Rb, Ta, U, and Th may indicate that 2 the magma for the rhyolite and rhyodacite sequence was generated under higher temperatures, relative to the high-silica rhyolite sequence. Attempts to use hornblende to estimate the depth of crystallization were unsuccessful because the stability field for hornblende in rhyolitic rocks is virtually undefined (Helz, 1982).

The northwest-trending rhyodacite spines, sympathetic to the trend of the Brothers fault zone, indicate that vent locations were structurally controlled. The spines may define the orientation of the maximum horizontal compressive stress during emplacement (Bacon, 1985).

Basaltic volcanism is thought to have occurred during the entire silicic eruptive sequence. The basaltic magma was apparently unable to reach the surface in the Glass Buttes complex during the eruption of the high-silica rhyolite sequence due to the presence of relatively low density, high viscosity silicic magma within the crust (Hildreth, 1979, 1981). The basaltic vents which occur within the complex may have formed after the highsilica rhyolite chamber had crystallized.

### CHAPTER V

### CONCLUSIONS

The high-silica rhyolite sequence represents the initial phase of silicic volcanism within the Glass Buttes complex. Volcanism was initiated in the eastern Glass Buttes and Round Top Butte areas, later migrating westward toward Little Glass Butte and the Glass Butte quadrangle. The sequence is divided on the basis of texture into 1) zoned flows and domes, 2) obsidian flows, 3) felsite flows, and 4) biotite-phyric flows and domes. The different textures observed within the sequence are the result of the distribution of volatiles in the magma and the variable degassing within the lava flows at the surface. The geochemical trends observed within the sequence are recognized to be a reflection of the compositional zonation within the magma chamber prior to eruption. The high-silica rhyolites of eastern Glass Buttes and Round Top Butte are thought to represent the roof or upper portion of the magma chamber, while those of Little Glass Butte and the Glass Butte quadrangle represent the magmas from the deepest level tapped during the eruption of the sequence. The magma chamber is thought to have been emplaced at relatively shallow crustal levels. The lack of a caldera-forming eruption may indicate that the chamber remained fairly deep, and that the magma ascended to the surface at a slow rate.

The rhyolite and rhyodacite sequence represents the most recent silicic volcanism within the Glass Buttes complex. Petrographic and geochemical data indicate that this sequence is unrelated to the high-silica rhyolite episode of volcanism. The presence of plagioclase, hornblende, quartz, biotite, and orthoand clinopyroxene, along with the higher concentrations of Fe, Mg, Ca, Ti, Sc, Co, Cr, and Eu may indicate that the rhyolite and rhyodacite magmas were generated under higher temperature melting conditions than the magma for the high-silica rhyolite sequence.

Episodes of basaltic volcanism occurred during the eruption of the high-silica rhyolite and rhyolite and rhyodacite sequences. The intrusion of basaltic magma into the crust provided the heat source responsible for generating the silicic magmas. The high viscosity and low density of the high-silica rhyolite magma chamber apparently prevented basalts from reaching the surface within the complex during the high-silica rhyolite episode of volcanism. Basalts which were erupted from vents located within the complex show petrographic and geochemical evidence of silicic contamination.

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APPENDICES

TABLE XI

1

HIGH-SILICA RHYOLITE SEQUENCE Trace element geochemistry (PPM)

SAMPLE N	0. 84	ERR	Cs	ERR	Rb	ERR	Ta Ef	R	Ę	ERR	5	ERR	Ľ	ERR	C	ERR	Sc	ERR	ΗĘ	ERR
G8-7	1310	50	2.7	0.2	80	5.0	1.02	.07	7.3	.15	2.5	6.0	2.9	0.8	۲٤.		4.15	.05	4.5	.15
68-12	129(	) 50	2.6	0.2	84	5.0	1.02	.07	7.8	.15	2.7	1.0	3.9	0.8	N.D		4.14	.05	4.5	.15
GB-33	1 390	) 50	2.8	0.2	81	5.0	1.08	.08	1.7	.17	N.		4.5	0.9	N.D		4.47	.05	4.8	.16
GB-43A	142(	) 50	2.9	0.3	84	5.0	1.05	.08	7.8	.16	N.C		3.2	0.9	.37	.09	4.45	.05	5.0	.16
GB-44A	146(	) 60	2.7	0.2	86	5.0	1.07	.06	8.1	.17	N.C		N.C		.23	.07	4.50	.05	5.1	.17
GB-46	1350	) 50	2.9	0.2	66	6.0	1.03	.08	8.1	.17	N.C		3.5	0.9	N.C		4.36	.05	5.0	.16
G8-57	1 300	) 50	2.6	0.2	80	5.0	1.00	.08	1.1	.16	N.C		4.5	0.9	N.D		4.19	.05	4.G	.16
<b>GB-6</b> 0	1 38(	) 60	2.8	0.2	86	5.0	0.99	.08	7.8	.17	N.C		5.1	0.9	N.O		4.39	.05	4.6	.16
68~65	136(	) 60	2.9	0.2	06	6.0	1.07	.08	1.7	.2	5.2	1.8	5.2	1.0	N.C		4.36	.06	4.8	.17
CB-67	128(	) 50	2.6	0.2	92	7.0	1.03	.08	8.0	.17	5.5	1.9	4.2	0.9	.32	.08	4.46	.05	4.9	.17
GB-82	1340	09 (	2.8	0.3	88	6.0	1.08	60.	7.9	.18	N.C		4.7	1.0	N.0		4.45	90.	5.0	.18
68-85 *	1050	) 60	4.6	0.4	121	6.0	0.95	.07	9.7	.2	7.0	2.0	N.C		.5	.1	3.82	.05	4.0	.16

TABLE XI: CONTINUED

HF ERR	5.2 .19	3.6 .17	5.1 .18	5 U 17		5.1 .17	4.9 .18	4.8 .18	4.5 .16 4.5 .18 4.8 .18	5.1 .17 5.1 .17 4.9 .18 4.8 .18 4.5 .16 5.1 .17	5.1 .17 5.1 .17 4.9 .18 4.8 .18 4.8 .18 4.5 .16 5.1 .17 5.1 .17	4.9 .18 4.9 .18 4.8 .18 4.8 .18 4.5 .15 5.1 .17 5.3 .18	5.1 .17 5.1 .17 4.9 .18 4.8 .18 4.5 .16 5.1 .17 4.9 .17 5.3 .18 5.0 .18
ERR	.06	.05	.06	.05	,	.05	. 05 . 06	. 05 . 06 . 06	. 05 . 06 . 06	. 05 . 06 . 06 . 06 . 06	. 05 . 06 . 06 . 06 . 05 . 05		
Sc	4.66	3.95	4.53	4.46		4.23	4.23 4.55	4.23 4.55 4.52	4.23 4.55 4.52 4.51	4.23 4.55 4.52 4.51 4.51	4.23 4.55 4.52 4.51 4.51	4.23 4.55 4.51 4.51 4.51 4.15	4.23 4.55 4.52 4.51 4.51 4.49 4.49 4.15
Co ERR	.43 .12	.39 .12	N.D.	N.D.		N.D.	N.D. .45 .13	N.D. .45 .13 N.D.	N.D. 45 .13 N.D. N.D.	N.D. 45 .13 N.D. N.D. N.D.	N.D. 45 .13 N.D. N.D. N.D. N.D.	N.D. 45 .13 N.D. N.D. N.D. N.D. .36 .09	N.D. .45 .13 N.D. N.D. N.D. N.D. .36 .09 .38 .11
Cr EAR	3.6 1.0	N.D.	4.5 1.0	3.8 0.9		4.3 0.9	4.3 0.9 N.D.	4.3 0.9 N.D. N.D.	4.3 2.4 .0.N .0.N	4.3 0.9 N.O. N.O. N.O. 1.0.	4.3 0.9 N.D. N.D. N.D. N.D. 3.3 1.0	4.3 0.9 N.D. N.D. N.D. J.3 1.0 5.1 1.2 5.1 1.2	4.3 0.9 N.D. N.D. 3.3 1.0 5.1 1.2 3.5 0.9 N.D.
U ERR	N.D.	4.5 1.8	7.0 2.0	N.D.		N.D.	N.O. 7.0 2.0	N.D. 7.D 2.O N.D.	N.D. 7.D 2.O N.D. N.D.	N.D. 7.0 2.0 N.D. N.D. N.D.	7.0 2.0 7.0 2.0 N.D. N.D. N.D.	N.D. 7.D 2.0 N.D. N.D. N.D. N.D.	7.0 2.0 7.0 2.0 N.D. N.D. N.D. N.D.
ERR	.18	.2	.18	.17		.17	.17 .18	.17 .18 .20	.17 .18 .20	.17 .18 .20 .17 .18	.17 .18 .17 .18 .18	.17 .18 .11 .18 .18 .11	.17 .18 .18 .17 .18 .118 .118
ų	8.6	10.3	8.0	7.8		B.1	8.1 8.1	8.1 8.3	8.1 8.3 7.3	8.1 8.3 8.3 8.0 8.0	8.1 8.3 7.3 8.0 8.0	8.1 8.3 8.0 8.0 8.1 8.1	8.1 8.3 8.0 8.0 8.1 8.1 8.1
ЯВ	60.	60.	60.	.08		.08	.08 .08	.08 .08	.08 .13 .08	.08 .08 .13 .08	.08 .13 .08 .08 .08	.08 .13 .08 .08 .08	.08 .13 .08 .08 .08 .08 .08
Ta E	1.01	0.97	1.13	0.96		1.14	1.14	1.14 1.08 1.04	1.14 1.08 1.04 1.01	1.14 1.08 1.04 1.01	1.14 1.08 1.04 1.01 1.03	1.14 1.08 1.04 1.01 1.03 1.04 0.98	1.14 1.08 1.04 1.01 1.03 1.03 1.04 0.98
ERR	6.0	9.0	6.0	6.0		5.0	5.0 5.0	5.0 5.0 7.0	5.0 5.0 7.0 5.0	5.0 5.0 7.0 5.0 6.0	5.0 5.0 7.0 5.0 6.0	5.0 5.0 7.0 5.0 6.0 5.0	5.0 5.0 5.0 6.0 5.0 5.0
å	6	126	68	16		76	76 77	77 77 93	77 77 89	97 77 79 89	76 77 89 88	76 77 93 93 98 90 72	76 77 93 98 98 90 72 72
ERR	0.3	0.4	0.3	0.2		0.2	0.2 0.3	0.2 0.3 0.3	0.2 0.3 0.3 0.2	0.3 0.3 0.2 0.2 0.2	0.2 0.3 0.3 0.2 0.2 0.2	0.2 0.3 0.3 0.2 0.2 0.2 0.2	0.2 0.3 0.3 0.2 0.2 0.2 0.2 0.2
c s	3.0	5.4	3.1	2.7		2.6	2.6 3.0	2.6 3.0 3.0	2.6 3.0 3.0 2.4	2.6 3.0 3.0 2.4 2.8	2.6 3.0 3.0 2.4 2.8 2.8	2.6 3.0 3.0 2.4 2.8 2.8 2.8 2.8	2.6 3.0 3.0 2.8 2.8 2.8 2.8 2.7 2.5
ERR	60	06	60	60		60	60 60	60 90	60 60 60	60 60 60	60 60 60 60	60 60 60 60 80	60 60 60 60 80 50
ßa	1490	960	1420	1320		1540	1540 1330	1540 1330 1230	1540 1330 1230 1360	1540 1330 1230 1360 1360	1540 1330 1230 1360 1360 1380	1540 1330 1360 1360 1360 1360	1540 1330 1230 1360 1360 1360 1450
SAMPLE Na.	G8-86A	G8-878 *	68-107	68-111		G8-116	G8-116 G8-131 *	68-116 68-131 * 68-1318*	G8-116 G8-131 * G8-1318* G8-133 *	68-116 68-131 * 68-1318* 68-133 * 68-134	68-116 68-131 * 68-1318* 68-133 * 68-134 68-141	68-116 68-131 * 68-1318* 68-133 * 68-134 68-141 68-148	68-116 68-131 * 68-1318* 68-133 * 68-134 68-148 68-148 68-151

TABLE XI ; CONTINUED

SAMPLE NG	. Ba	ERR	C.a	ERR	Чр	ERA	Ta E	нR	Ţ'n	ERR	3	ERR	Cr f	НR	Co E	AR	Sc	ERR	Ĩ	ERR
68-155	1590	011	2.5	0.3	23	8.O	1.00	1.	8.6	~	N,		N.D.	•	42.	12	4.38	.06	5.2	.1 <sup>9</sup>
691-89	1520	011	3.0	0.3	38	8.0	0.89	۲۵.	9.0	. 2	u. z		N.D.	•	66.	51	4.28	.06	5.4	вt.
66-178	1350	90	2.8	0.2	96	6.0	1.06	.08	1.8	<b>8</b> 1.	z.		N.D.		N.D.		4.38	, 06	4.8	<b>θ</b> l'
68-182	1040	50	2.9	0.2	92	6.U	1.24	<b>60</b> .	1.8	âí.	z.		N.D.		N.D.		5.13	<b>.</b> 06	5.0	.20
FC-14	1210	40	4.5	0.4	111	4.0	10.1	٠0٦	10.4	.12	3.0	0.9	5.6 O		48.	10	3.83	•04	4.4	
L.G.B-1-MN	1 500	011	£.4	0.3	105	9.0	0.77	.06	£.01	.2			4.3 1	. 2	4 Đ	60	3.56	• D5	4.4	.20
EGB-1	850	60	4.3	0.3	116	1.0	1.06	.09	12.5	.2	6.O	2.0	3.5 1	-	N.D.		1.26	<b>0</b> 8	5.3	, 20
AKW-2	260	10	5.2	0.4	150	7.0	1.54	10.	13.2	.2	10.0	4.0	4.6 1		35 .	01	8,2G	60.	5.7	. 20
81-91V	440	06	1.1	0.5	140	9.0	1.26	טו.	11.4	.2	1.0	2.0	N.D.		N.D.		4.54	<b>.</b> 06	3.8	,20
ATB-70 -	015	90	7.0	0.5	145	10.0	1.23	10.	11.7	.2	9.0	3.0	N.D.		N.D.		4.63	,06	3.6	, 20
RTB-82 "	370	10	5.8	0.8	103	0.11	81.I	[1]	9.9	.2	4.2	0.6	5.3 1	· .	25	, D5	3.75	.02	2.8	.12
R T B - BG	420	10	5.B	0.8	103	0.11	1.25	.14	10.6	٢.	4.B	0.7	N.D.	·	8.	дŋ,	3.87	tơ.	1.1	÷1.
* Blottte N.D. * ne	e-phyrl. ot dete	c punt	tceous	gles	æ															

TABLE XII

## HIGH-SILICA RHYOLITE SEQUENCE RARE EARTH ELEMENT GEOCHEMISTRY (PPM)

Vo. La ERR	La ERR	ERR		C e	ERR	PN	ERR	ĒS	ERR	Eu	ERR	ГÞ	ERR	۲b	ERR	٢٩	ERR
28.6 0.8 53.6 1.0	.6 0.8 53.6 1.0	0.8 53.6 1.0	53.6 1.0	1.0		23	2.0	0.6	.12	0.64	.02	0.77	.08	5.3	.78	0.84	.10
27.7 0.7 54.8 1.0	.7 0.7 54.8 1.0	0.7 54.8 1.0	54.8 1.0	1.0		28	3.0	0.7	.13	0.58	.02	0.76	.00	4.7	.70	0.87	Ξ.
33.6 0.8 56.6 1.1	.6 0.8 56.6 1.1	0.8 56.6 1.1	56.6 1.1			27	3.0	10.8	.14	0.62	.02	0.86	.10	5.1	ш.	0.87	Ξ.
34.2 0.8 57.8 1.1 2	2 0.8 57.8 1.1 2	0.8 57.8 1.1 2	57.8 1.1 2	1.1		2	3.0	11.3	.15	0.63	.03	0.88	.10	5.4	.80	0.92	Ξ.
31.5 0.7 59.0 1.1 3	.5 0.7 59.0 1.1 3	0.7 59.0 1.1 3	59.0 1.1 3	1.1 3	-	-	3.0	10.2	.14	0.63	.02	0.84	.07	5.1	.76	0.99	.12
31.4 0.7 57.5 1.1 2	.4 0.7 57.5 1.1 2	0.7 57.5 1.1 2	57.5 1.1 2	1.1 2	2	6	3.0	10.0	.17	0.60	.02	0.84	.09	5.7	.85	0.95	.12
33.2 0.7 61.2 1.1 29	.2 0.7 61.2 1.1 29	0.7 61.2 1.1 29	61.2 1.1 29	1.1 29	29	_	3.0	9.3	.13	0.75	.02	0.75	60'	5.1	.76	06.0	Ξ.
29.7 0.7 56.6 1.1 2	1.7 0.7 56.6 1.1 2	0.7 56.6 1.1 2	56.6 1.1 2	1.1 2	N	~	3.0	10.0	.14	0.59	. 02	0.79	60.	5.4	.80	0.95	.12
28.7 0.7 55.9 1.1 2	7 07 55.9 1.1 2	0.7 55.9 1.1 2	55.9 1.1 2	1.1 ZI	2	æ	3. O	9.1	.13	0.65	.02	0.86	.09	5.0	41.	10.0	-
29.5 0.7 60.0 1.1 2	5 0.7 60.0 1.1 2	0.7 60.0 1.1 2	60.0 1.1 2	1.1 2	2	Ś	3.0	9.5	.13	0.62	.02	0.80	.09	5,6	.83	0.94	.12
29.5 0.8 57.3 1.2 26	1.5 0.8 57.3 1.2 26	0.8 57.3 1.2 26	57.3 1.2 26	1.2 26	26	~	4.0	9.2	.14	0.67	,02	06.0	.10	5.2	.78	10.97	.12
* 24.9 0.7 48.4 1.3 2	1.9 0.7 48.4 1.3 2	0.7 48.4 1.3 2	48.4 1.3 2	1.3 2	2	0	3.0	5.5	Ξ.	0.61	.02	0.52	.07	1.1	.47	0.53	.07

TABLE XII : CONTINUED

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SAMPLE NO.	L B	ERR	e C	ERR	PN	ERR	Sm	ERR	Eu	ERR	ql	ERR	۲b	ERR	۲n	ERI
G8-86A	28.3	0.8	58.1	1.2	28	3.0	8.9	.14	0.65	.02	0.94	60.	5.0	.76	1.02	
G8-878 M	23.9	0.6	43.7	1.1	z.		4.1	.07	0.89	.04	0.70	.16	2.7	.50	0.50	
GB-107	13.7	0.9	57.4	1.2	27	3.0	11.3	.16	0.64	.02	0,95	Ξ.	5.8	.86	06.0	-
G8-111	31.8	0.9	58.1	1.1	29	3.0	10.6	.17	0.61	.02	0,92	.10	5.1	۲۲.	06.0	-
GB-116	38.5	0.7	75.6	1.3	38	3.0	9.2	.13	1.10	.03	0.84	60.	4.9	.72	0.84	÷
68-131 "	29.2	0.7	57.6	1.1	27	3.0	8.6	.13	0.59	.02	0.79	60.	5.4	.81	0.94	-
GB-131B*	26.8	0.6	50.2	1.1	25	4.0	6.2	.09	0.72	.04	0.94	.19	5.5	.90	0.67	Ξ.
68-133 "	26.3	0.7	49.9	1.0	29	3.0	8.0	.12	0.69	.02	0.84	60.	4.8	.73	0.88	-
GB-134	33.7	0.8	57.3	1.1	29	4.0	11.1	.18	0.64	.02	0.84	.09	5.2	.78	94.0	-
GB-141	31.0	0.8	57.6	1.1	27	3.0	9.9	.14	0.65	.02	0.82	60.	5.2	۲۲.	1.01	-
G8-148	47.7	0.9	74.5	1.3	39	3.0	11.8	.15	1.08	60.	0.78	.10	4.8	.73	0.86	-
68-151	25.2	0.7	51.4	1.0	26	3.0	9.5	.13	0.88	.03	1.02	.10	6.0	.90	1.08	-
GB-152	44.3	1.0	78.8	1.3	37	3.0	6.6	.14	1.17	.03	0.85	60 <b>.</b>	414	.67	0.83	=

TABLE XII ; CONFINUED

SAMPLE No.	<b>9</b> 	ERR	C e	ERR	PN	ERR	۳S	ERR	Eu	ERR	Тb	ERR	۲b	ERR	۲n	ERR
GB-155	44.0	0.8	81.4	1.5	43	6.0	7.4	.10	1.37	.05	1.30	.20	5.5	. 90	0,80	, 20
GB - 169	46.5	0.8	83.1	1.5	43	6.0	7.8	60 <b>'</b>	1.27	.05	0.94	19	5.0	.80	0.67	.18
GB-178	28.8	0.7	57.5	1.1	29	3.0	9.4	.14	0.61	.02	0.82	<b>.</b> 00	5.7	.86	0,96	.12
GB-182	20.8	0.7	49.5	1.4	27	3.0	11.9	.18	0.57	.02	0.97	:	6.1	, 91	1.16	.14
FC-14	35.2	3.0	52.0	1.0	25	1.9	7.4	.07	0.63	,02	0.53	.07	3.2	48	0.57	.07
L.G.B - 1 - MN	30.2	0.7	53.3	1.2	24	5.0	4.0	.07	0.75	.04	0.79	.16	2.8	, 50	0.30	.10
EG8-1	28.4	1.0	57,8	1.5	35	3.0	10.7	.16	0.48	.03	1,05	.12	6.7	66'	1.12	.14
ARW-2	18.5	0.7	41.7	1.1	27	3.0	13.9	.19	0.21	.01	1.22	.10	7.4	1.1	1.39	.17
RTB-19	20.4	0.6	40.0	1.1	ż	0.	4.5	.07	0.45	,03	0.70	.17	3.5	. 60	0.46	.14
RT8-70 *	20.6	0.6	39.3	1.1	20	5.0	4.B	.07	0,45	£0.	0.72	.17	3.8	, 60	0.51	.15
R18-82 M	16.5	0.3	35.6	0.9	17	2.0	4.0	.05	0.44	.02	0.95	.05	3.9	.30	0.48	, 05
R T 8 - 86	16.7	0.4	37.9	6.0	16	2.0	4.0	,05	0.42	,02	86.0	.05	3.9	.30	0.52	<b>.</b> 05
* Biotita- N.D. * not	phyric detec	pumic ted	ceous g	lass												

TABLE XIII

HIGH-SILICA RHYOLITE SEQUENCE Major element geochemistry (PCT)

SAMPLE No	• Na 0	ERR	к 0 2	ERR	Fe0	ERR	SAMPLE No.	. Na () 2	ERR	к 0 2	ERR	Fe0	ERR
G8-7	4.46	.0	4.50	ERR	0.87	.02	GB-12	4.39	.01	4.40	.40	0.84	.02
GB-33	5.26	.02	5,50	.40	0.94	.03	GB-43A	5.30	.02	5.30	.40	96.0	.03
GB-44A	4,96	.02	5.00	.40	0.96	.03	GB - 46	4.96	.02	4.90	.40	0.89	.03
<b>GB-57</b>	4.61	.01	4.70	.40	0.94	.03	<b>CB - 6</b> 0	4.81	.02	4,90	.40	0.85	.03
C8-65	4.58	.01	4.30	.40	0.92	.03	G8-67	4.71	.01	4.70	.40	0.93	.03
GB-82	4.58	.01	4.80	.40	0.91	.03	68-85 *	3.63	.01	4.80	.40	0.85	.03
C8-86A	4.49	.01	4.80	.40	0.93	.03	G8-878 *	3.50	.01	3.80	.40	0.83	03
GB-107	5.52	.02	6.40	.60	0.91	.03	G8-111	5.18	.02	4.90	.40	0.91	.03
G8-116	4.15	.01	4.30	.40	1.02	.03	G8-131 *	4.35	.01	5.40	.40	0.91	.03

TABLE XIII: CONTINUED

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SAMPLE 1	No.	Na 0 2	ERR	к 0 2	ERR	f eO	ERR	SAMPLE NG	. Na 0 2	ERR	k 0 2	ERR	f eO	ERR
GB-133		4.04	.01	4.50	.40	0.83	.02	GB-134	5.41	.02	5.50	.50	0.96	.03
68-141		4.80	.02	4.60	.50	0.93	.03	GB-14B	5.30	.02	5.00	.50	1.02	.03
G8-151		4.50	.01	4.30	.40	0.84	.03	GB-152	4.59	.01	3.90	.50	1.03	.03
GB-155		3.99	.02	4.20	.40	1.09	.03	GB - 169	4.63	.02	4.40	.50	1.11	.03
GB-178		4.61	.02	4.60	.70	0.91	.03	GB-182	5.18	.02	5.50	.60	0.90	.0.
FC-14		5.12	.01	6.26	.32	0.99	.02	LG8-1-MN	4.24	.02	4.30	.40	1.04	.03
EG8-1		4.49	.02	5.00	. 50	0.82	.03	ARW-2	5.51	.02	6.40	.60	0.85	.01
R 78-19		4.42	.02	3.70	.40	0.76	.03	R18-70 #	4.03	.02	5.10	.50	0.74	.01
R T B - B 2	*	.40	.06	5.10	.40	0.65	.01	R 18-86	3.93	.07	4.50	.50	0.72	6.
<pre># Biotl</pre>	terp	hyrlc	pumle	snoac	glass									

TABLE XIV

RHYDLITE AND RHYDDACITE SEQUENCE TRACE ELEMENT GEOCHEMISTRY (PPM)

SAMPLE No	. Ba	ERR	C s	ERR	Ŗ	ERR	la E	RR	۹Ľ	ERR	n	ERR	Сr	ERR	Co	ERR	Sc	ERR	HF	ERR
68-16 "	1240	60	1.5	0.2	54	6.0	0.68	.07	5,9	.17	N.D		5.2	۲.	3.1	.20	8,85	60.	9.5	.20
GB-20B	066	120	1.1	0.2	41	12.0	0.61	.10	4.7	.20	N.0		N.D	÷	7.9	.40	15.33	41.	9.1	.30
G8-26A	1200	60	1.5	0.2	69	6.0	0.47	.07	6.9	.17	N.D		6.4	1.2	7.6	.40	7.55	Đ0.	4.5	.19
G8-27	1040	50	1.3	0.2	65	5.0	0.34	, 04	5.8	.15	N.D	•	7.3	1.1	6.7	.30	7.21	.07	4.0	.17
GB - 28	1140	100	1.7	0.3	64	0.0	0.47	60.	6.3	.20	N.D		9.5	1.7	10.7	.50	8.94	.10	4.3	.20
68-35	1120	50	1.9	0.2	70	5.0	0.52	.07	6.3	.16	N.D		0.0	1.1	8.5	.40	7.63	.08	5.0	.18
68-38	1120	60	2.4	0.2	70	6.0	0.61	.07	6,5	.17	N.D		6.5	1.2	6.6	.40	7.68	.08	4.6	.19
68-398	1150	1 00	2.4	0.3	73	8,0	0.55	.06	6.2	.20	N.D		6.1	1.5	8.3	.40	8.22	Đ0.	4.1	.19
69-568	1170	60	2.2	0.2	66	6,0	0.57	.08	6.8	.18	N.D		6.8	1.2	8.6	.40	8.77	.09	4,6	.20
68-93	1030	120	1.1	0.3	50	9.0	0.76	11.	6.0	.20	N.D		N.C		6.1	.40	12,49	.12	9.8	.30
69-95	1090	100	2.4	0.3	82	9.0	0.55	60.	7.3	.20	N.D		6.2	1.5	7.6	.40	7.86	.00	4.3	, 20
G8-138	1170	100	2.5	0.3	78	8.0	0.52	.06	7.0	.20	5.0	2.0	7.8	1.6	7.B	.40	1,42	.08	4.7	. 20
68-173	1100	60	2.3	0.2	87	8.0	0.50	.06	6.4	.18	N.D		5.4	1.2	6.2	.30	7.21	. OB	4.7	.19
RB-1 *	1380	60	2.3	0.2	87	6.0	0.67	.07	7.3	.18	6.0	2.0	4.5	1.1	2.0	.19	5.62	.06	5.7	. 20
R8-1-86 M	1630	100	3.1	0.3	93	8.0	0.69	.12	8.8	.20	5.0	2.0	6.1	1.4	1.9	.20	5.52	.07	5.2	.20
* Rhyollt N.D. * ∩o	e Unit t dete	cted																		

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TABLE XV

## RHYOLITE AND RHYODACITE SEQUENCE RAHE EARTH ELEMENT GEOCHEMISTRY (PPM)

SAMPLE Na.	La	E RR	Ce	ERR	NG	ERR	Sm	E RR	Εu	ERR	٩L	ERR	۲b	ERR	Lu	ERR
G8-16 ×	39.0	0.9	63.8	1.2	34	3.0	11.6	.14	1.73	.04	0.82	.10	4.8	٤٢.	0.91	1
68-208	33.6	0.7	60.2	1.5	53	6.0	8.8	60.	2.34	.05	1.25	.19	5.6	.90	0.60	.20
68-27	21.6	0.6	35.8	0.9	18	2.0	5.3	.10	0.81	.02	0.41	.07	1.7	.29	0.36	.05
68-28	23.8	0.6	40.5	1.2	18	5.0	4.0	.07	0.97	.05	0.26	.02	2.3	.50	0.28	60.
GB-35	32.1	0.8	42.5	1.0	25	2.0	<b>B.</b> 2	11.	1.09	0.	0.56	.08	2.8	44.	0.51	.07
GB - 38	26.9	0.7	44.9	1.1	12	3.0	6.9	.12	0.85	£0.	0.54	.08	2.7	64.	0.50	.07
68-398	21.0	0.6	40.7	1.2	18	5,0	3.6	.07	0.83	.04	0.22	.02	2.1	.40	0.37	Ξ.
68-568	24.2	0.7	42.B	1.1	19	3.0	6.2	.12	0.95	£0.	0.43	.08	2.0	, 34	0.43	.06
68-93	34.1	0.7	63.7	1.5	28	6.0	1.8	60.	2.17	.08	1.20	.20	5.0	.80	0.66	.18
GB-95	24.5	0.6	43.1	1.5	N. 1		4.1	.07	05.0	.06	0.24	.02	2.5	.40	0.34	.10
68-138	23.7	0.6	41.0	1.2	18	4.0	3.8	.07	05.0	<b>•</b> 0 <b>•</b>	0.55	.17	2.4	.40	0.36	Ξ
69-173	23.3	0.6	42.B	1.1	22	3.0	5.5	11.	0,82	.09	0.49	<b>6</b> 0.	2.5	40	0.54	۰۵.
RB-1 *	52.5	1.0	48.9	1.2	40	4.0	12.9	.16	1.84	.04	0.86	.12	4.3	, 66	0.81	.10
RB-1-86 #	33.2	0.7	48.9	1.5	22	5.0	5.3	.07	1.31	.05	0.88	.20	3.1	.50	0.47	٤١.
∎ Rhyollte N.D. = nat	Unit detec	ted														

TABLE XVI

### RHYOLITE AND RHYODACITE SEQUENCE MAJOR ELEMENT GEOCHEMISTRY (PCT)

SAMPLE No	. Na O 2	ERR	к 0 2	ERR	f e ()	ERR	SAMPLE No	. Na ()	ERR	к 0 2	ERR	f e()	ERR
G8-16 #	5,59	.01	3.70	.30	2.66	.05	<b>GB-2</b> 08	5.07	.02	2.70	.40	4.82	.07
G8-26A	4.44	.01	3.70	.30	2.91	.05	G8-27	4.07	.01	2.90	.30	2.71	.05
68-28	4.07	.02	2.50	.40	3.17	.06	G0-35	4.79	.01	3.20	.30	2.77	• 05
GB-38	4.66	.01	3.50	.30	2.79	.05	G8-398	3.92	.02	3.40	.40	3.13	• 05
68-568	4.30	.01	3.50	.30	3.29	.06	68-93	4.99	.02	2.40	.40	3.73	.07
C8-95	3.90	.02	2.90	.40	2.87	. 05	68-138	4.09	żo.	3.00	.40	2.80	.05
RB-1 #	5,05	.02	5.40	.60	2.01	.04	RB-1-86	4.32	.02	4.60	40	2.06	•04
# Rhyαlit N.D. = nσ	e Unit t detec	cted											

TABLE XVII

### INTERNAL AND PLATEAU BASALT SEQUENCES TRACE ELEMENT GEOCHEMISTRY (PPM)

													the second se	Contraction of the local division of the loc		And a					
SAMPLE	. ON	Ba	ERR	C s	ERR	Rb	ERR	Ta E	RR	ų	Еяв	n	ERR	Cr	ERR	Co	ERR	Sc	ERR	JH H	ERR
GB-48		1400	300	ż	D.	N.D		0.58	. 10	2.4	.40	z.		11.0	4.0	43.7	1.5	35.9	.30	6.1	.40
GB-4C	=	1 0 0 0	200	ż	0.	N.D		0.31	.08	2.3	.30	N. N		18.0	3.0	19.3	0.8	28,0	. 20	4.8	06.
C8-76		1100	300	ż		N.D		0,66	.10	2.3	.40	N. I		25.D	4.0	45.7	1.5	36.0	.30	6.6	.40
GB-96		1200	200	ż		0.N		0.57	.10	2.0	.40	z		92.0	4.0	44.7	1.5	36.4	. 30	6.6	.40
GB-98A		1100	200	ż		N.D		0.57	.10	2.1	.40	N. 1		<b>35.0</b>	5.0	42.8	1.5	35.1	.30	5.8	. 40
GB-102/	:	1200	300	ż	0.	N.D		0.66	.16	z	.0	N		17.0	4.0	54.4	1.8	41.3	.30	6.7	. 40
C8-106/	_	780	100	ż	р.	N.O		0,50	.10	2.0	.30	N. 1		0.0	<b>J.</b> D	41.6	1.3	35.6	.30	6.3	.30
68-172	*	690	100	ż	0.	N.0		0.57	.10	2.5	.20	N. 1		1.1	1.6	1.11	. 50	23.6	.19	6.1	.30
68-174		1000	300	ż	р.	N.D		0.76	.15	1.6	.30	z.		0.0	4.0	45.0	1.8	35.2	JD.	6.0	.40
68-175		N.D		ż	р.	0.N		0.73	.15	2.2	.40	z		24.0	4.0	46.2	1.5	7.95	. 30	6.5	.40
69-186/	_	1200	300	z	р.	N. 0		0.64	.10	2.4	.40	z		27.0	4.D	47.5	1.6	41.5	.30	6,9	.40
GB-1956	~	N.0		ż	0.	N. 0		0.38	.10	z		Z		38.0 1	4.0	71.0	2.0	42.1	.30	3.3	. 40
* Conte ** Plat N.D	amine teau not	ated 8 Basal detec	asalt t ted																		
TABLE XVIII

## INTERNAL AND PLATEAU BASALT SEQUENCES RARE EARTH ELEMENT GEOCHEMISTRY (PPM)

SAMPLE NO	œ ب	ERR	e L	ERR	Nd ERR	ES	ERR	Eu	ERR	1 b	ERR	۲b	ERR	۲n	ERR
GB-4B	24.0	0.6	51.0	2.0	N.O.	8.1	60.	2.59	60.	1.30	.30	2.9	.60	06.0	.30
GB-4C *	16.6	0.6	34.0	1.8	N.D.	6.5	.08	2.01	.08	1.40	.30	4.6	.90	0.60	.30
GB-76	24.5	0.6	50.0	2.0	N.D.	B.4	.09	2.68	60,	1.20	.30	3.3	.70	06,0	.30
68-96	25.4	0.6	50.0	2.0	N.D.	B.4	<b>6</b> 0.	2.61	· 06	1.80	40	3,6	.70	0.90	.30
GB-98A	23.7	0.6	47.0	2.0	N.D.	7.9	60.	2.56	60.	1.50	.30	4.8	.90	0.70	.30
GB-102A *	* 25.5	0.6	52.0	2.0	N.D.	8.6	<b>6</b> 0.	3.04	.10	1.40	.40	N. [		ż	
GB-106A	22.4	0.7	43.8	1.8	28 4.0	10.3	.13	2.22	.06	0.77	.15	4.1	.74	0.73	١١.
GB-172 W	22.7	0.6	37.0	1.3	30 5.0	11.4	.14	2.22	. 05	0.89	.13	4.5	.73	0.85	.12
GB-174	22.6	0.6	49.0	2.0	N.D.	7.9	60.	2.58	60.	1.60	.40	2.6	.60	0.70	.30
GB-175	27.2	0.6	50.0	2.0	37 11.0	8.9	60.	2,95	60.	1.40	.30	5.2	1.0	0.80	.30
GB~186A	26.8	0.6	54.0	2.0	N.D.	8.9	.00	2.83	.09	1.30	.30	5.9	1.1	1.0	.30
GB-186B	13.5	0.5	28.0	2.0	N.D.	5.5	.07	2.18	.08	0.25	,04	3.5	.80	N.D	
* Contamí ** Platea N.D. = no	nated u Basa t dete	Basalt lt cted													

TABLE XIX

## INTERNAL AND PLATEAU BASALT SEQUENCES Major element geochemistry (PCT)

SAMPLE NO.	. Na D 2	ERR	K D ERR 2	fe0	ERR	SAMPLE No.	Na O 2	ERR	k o 2	RR	Fe0 E	RR
C 8 _ A 8	10 4	20	N.D.	12.54	.15	GB-4C *	4.77	.02	1.60 .	40	7.76	.10
68-76 68-76	4.06	.02	1.70 .5	0 12.84	.16	68-96	3.84	.02	2.40 .	40 1	12.50	.16
CR-984	3.95	. 02	1:70 .4	0 12.34	.15	GB-102A **	4.12	.02	N.D.	•	16.17	.18
GB-106A	4.34	10	1.70 .3	0 12.34	.15	G8-172 *	5.01	.02	N.D.		6.53	60.
GB-174	4.11	.02	1.50 .4	0 12.31	.15	GB-175	3.77	.02	1.50 .	40	13.67	.17
CB-186A	4.05	.02	2.10 .4	0 14.12	.17	68-1868	3.50	.02	N.D.		12.84	.16
* Contami ** Platea N.D. = no	nated   u Basa. t deter	Basalt lt cted										

TABLE XX

HIGH-SILICA RHYOLITE SEQUENCE X-RAY FLUORESCENCE DATA MAJOR ELEMENT GEOCHEMISTRY (PCT)

SAMPLE	No.	si0 2	A1 0 2 3	T10 2	Fe 0 2 3	f e0	Quw	CaO	DΘM	2 0 2	Na D 2	Р 0 2 5
GB-7		78.43	13.15	0.08	0.15	0.17	0.04	0.50	N.D.	4.16	3.31	0.019
68-44A		78.73	12.86	0.08	0.17	0.19	0.04	0.50	N.D.	4.21	3.21	0.021
68-67	-	78.75	12.84	0.08	0.14	0.16	0.04	0.49	N.D.	4.19	3.28	0.024
G8-82		78.61	12.89	0,09	0.18	0.21	0.04	0.49	N.D.	4.19	3.30	0.018
C8-85 I	*	77.57	13.16	0.13	0.27	0.31	0.05	0.91	0.07	4.59	2,89	0,048
GB-131		78.71	13.12	0.09	0.13	0.15	0.04	0.48	N.D.	4.34	2.92	0,028
68-151		78.43	13.12	0.08	0.13	0.15	0.06	0,49	N.D.	4.23	3.27	0,024
GB-152		78.43	13.24	0.12	0.23	0.27	0.04	0.75	0.11	3.51	3.27	0.023
68-178		78.77	12.86	0,08	0.14	0.16	0.04	0.47	N.D.	4.19	3.28	0.016
68-182		78.44	13.11	0.07	0.14	0.16	0.04	0.43	N.D.	4.46	3.12	0.027
EGB-1		78.50	13.19	0.09	0,08	0.09	0.05	0.45	0.06	4.42	3.06	0.011
" Blot! N.D 1	te-p not	hyric p detecte	oum!ceous id	glass								

TABLE XXI

## RHYDLITE AND RHYDDACITE SEQUENCE X-RAY FLUDRESCENCE DATA MAJOR ELEMENT GEOCHEMISTRY (PCI)

1

SAMPLE NO.	, 510 2	A1 0 2 3	110 2	Fe 0 2 3	f e()	۵n۳	CaO	Ŋΰ	к 0 2	Na D 2	Р. 0 2 5
GB-16 ¥	75.89	13.21	0.38	1.01	1.16	0.05	1.72	0.22	2.65	3.62	0.077
GB-26A	72.23	15.34	0.31	1.26	1.44	0.05	3.22	0.60	2.59	2.B4	0.116
68-27	71.92	15.12	0.31	1.27	1.46	0.05	16.6	0.91	2.55	3.00	0.096
G8 - 38	73.21	14.36	0.31	1.16	1.33	0.06	2,88	0.78	2.89	2.92	0,092
GB-56B	70.82	15.31	0.36	1.42	1.63	0.07	3.45	1.34	2.67	2.82	0.110
68-173	72.51	14.69	0.31	1.17	1.34	0.07	2.95	1.04	2.92	2.90	0.101
RB-1 **	74.87	14.38	0.25	67.0	0.84	0.03	1.54	0.23	17.5	3.12	0.070
NOH-24 WW	74.00	14.33	0.31	0.92	1.05	0.06	1.94	0.54	3.56	3.25	060.0
NOH-16 **	75.83	13.83	0.18	0.54	0.61	0.04	1.37	0.51	3.98	3.09	0,040
<ul><li>Rhyal</li><li>Rhyal</li><li>Rhyal</li></ul>	ite ite from	Berri (	1982)								

TABLE XXII

## INTERNAL AND PLATEAU BASALT SEQUENCES X-RAY FLUORESCENCE DATA Major Element geochemistry (PCT)

SAMPLE Na.	510 2	A1 0 2 3	710 2	Fe 0 2 3	f e0	MnO	Ca0	ŊġŴ	к 0 2	Na () 2	P 0 2 5
G8-106A	55.80	16.27	1.73	4.94	5.66	0.16	7.58	3.54	0.98	2.93	0.404
G8-172 *	67.44	13.92	1.12	3.12	3.57	0.13	4.39	1.56	1.07	3,33	0.355
PB-1 ##	48.60	16.63	2.25	5.83	6.68	0.21	96.96	6,63	0.32	2.74	0.540
рв-2 кин	49.92	16.83	1.61	5.12	5.87	0.18	9.15	6.93	0.48	3.53	0.370
<pre>h Contam h Contam h Platea h Platea</pre>	inated B u Basalt u Basalt	asalt from Be from Je	arri (19 Dhnson (	1984a)							