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Geology and Hydrothermal Alteration, Glass Buttes, Southeast Oregon

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AN ABSTRACT OF THE THESIS OF Dulcy A. Berri for the Master
of Science in Geology presented May 17, 1982.

Title: Geology and Hydrothermal Alteration, Glass Buttes,
Southeast Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

Michael L. Cummings, Chair

Paul E. Hammond

Ansel G. Johnson

The Glass Buttes volcanic complex consists of many
domes and individual vents that erupted both rhyolitic and
basaltic lavas during the late Miocene to early Pliocene.
The east half of the complex, in the vicinity of Little Glass
Butte, contains interfingering, finely flow-banded rhyolite
and black obsidian flows. The youngest unit, an obsidian,
has been dated at 4.9 m.y. East of Little Glass Butte lie
two northwest-trending ridges, Antelope and Cascade Ridges,
composed of two or more overlapping exogenous domes that
formed along northwest-trending faults.

The Brothers fault zone dominates local structure. Fault trends observed are northwesterly, and northeast trends may be conjugate fractures. The concentration of volcanism at Glass Buttes may be due to intersection of the Brothers fault zone with a west-northwest-trending silicic volcanic zone. Ensuing volcanism was bimodal, including glassy rhyolite, and the igneous body fostered a hydrothermal system.

Rhyolites are peraluminous, and silica ranges from 73 to 79%. Growth of spherulites occurred during devitrification of the glassy rhyolites, with slight silica-enrichment during vapor-phase alteration. Hydration and groundwater leaching depleted soda, alumina and silica in the glass. The plateau surrounding the buttes consists of olivine basalt, and a feldspathic basalt interfingers with rhyolite flows within the complex.

Hydrothermal alteration of rhyolite flows and glass was concentrated along faults in the eastern Glass Buttes. Massive cinnabar-bearing opalite was deposited from rising silica-rich geothermal waters accompanied by mercury-bearing vapors. Silicification occurred into footwall material, and irregular argillic alteration resulted from downward-percolating acidified groundwater.

The hydrothermal system has since cooled off or been plugged by opalite deposits. Eruption of lavas continued after alteration, further sealing the system. Late-stage fumarolic alteration indicates limited escape of gases occurred through faults in the opalite.

The geothermal reservoir is 600 m or more below the surface. Repeated fracturing and resultant boiling of fluids suggests the potential for precious metal deposits. Low temperature fluids producing surface alteration could not transport most epithermal elements, that subsequently were concentrated below the opalite cover. The steeply inclined zones of alteration imply a deep hydrothermal system, and great depths to potentially economic mineral deposits.

GEOLOGY AND HYDROTHERMAL ALTERATION

GLASS BUTTES, SOUTHEAST OREGON

by

DULCY ANNETTE BERRI

A thesis submitted in partial fulfillment of the
requirements for the degree of
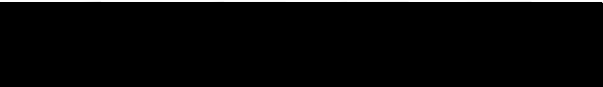
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TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of
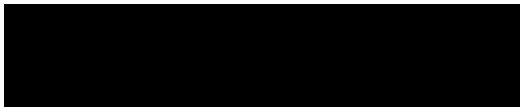Dulcy Annette Berri presented May 17, 1982.

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INTRODUCTION

PURPOSE AND SCOPE

The High Lava Plains province of central and eastern Oregon is a volcanic upland dominated by the northwest-trending Brothers fault zone, lava plateaus and volcanic centers of Cenozoic age. A west-northwest-trending zone of silicic dome, vent and caldera complexes crosses the province and intersects the Brothers fault zone. Glass Buttes is a rhyolitic dome and vent complex at the intersection of the Brothers fault zone and the silicic volcanic zone, that has been subjected to hydrothermal alteration and mercury mineralization.

The primary objective of this study was to describe the hydrothermal alteration located in the eastern Glass Buttes and to relate the alteration to cinnabar occurrence, structure and lithology. No published detailed geologic maps were available for the area, thus stratigraphy and structure of rocks outside of the area of alteration were studied first. This included examination of the sequence and styles of eruption from the numerous vents within the area and the degree to which faults localized these vents. Stratigraphic sequences are poorly understood between parts of the field area, but a rigorous study of the discontinuous units might in the future clarify these relations.

The characteristics of unaltered rocks were compared to altered rocks, within which could occasionally be seen remnant primary textures. Faults and joints were compared to structures outside the hydrothermally altered zones. Drilling chips from stratigraphic test wells drilled by Phillips Petroleum Company were examined to determine the variation of alteration with depth. A model was then developed for the fossil geothermal system, incorporating all field and laboratory data.

METHODS

Field work was conducted from August through September 1980, and in parts of November, 1980 and November, 1981.

Major element chemistry was performed by X-ray fluorescence spectrometry (XRF) by Peter Hooper at Washington State University. Additional analyses were performed using atomic absorption spectrometry (AAS) by the author at Portland State University. This data is tabulated in the Appendix. X-ray diffraction analyses were performed by the author on a General Electric XRD D/F X-ray unit at Portland State University. Petrographic studies of thin sections and polished sections were also completed by the author.

LOCATION AND ACCESSIBILITY

Located in northeast Lake County, Oregon, 80 km west of Burns and 128 km southeast of Bend, Glass Buttes extends over 20 km in a west-northwesterly direction along State

Highway 20 (Fig. 1). The maximum elevations of the buttes
are Glass Butte, 1946 m (6385 ft), on the west side of the
complex, and Little Glass Butte, 1862 m (6109 ft), in the
central portion (Fig. 2). The elevation of the complex
decreases from these high points to low hills and finally to
the surrounding basalt plateau at about 1200 m (3940 ft)
elevation.

Access to the Glass Buttes area is excellent via High-
way 20. The complex is parallel to, and about 1.5 km south
of the highway, and can be reached by several maintained
Bureau of Land Management gravel and dirt roads. Due to
frequent use by ranchers, hunters and rock collectors, most
roads within the buttes are kept passable to non-specialized
vehicles in dry weather.

Many geographic names referred to in this study for
locations within Glass Buttes are informal and were derived
from local usage or were applied informally by the author.

PREVIOUS WORK

The western and largest butte was not included in this
study. It was described by Waters (1927a; 1927b) and is
herein referred to as Glass Butte. Olivine and augite-
bearing basalts, interpreted by Waters to be the oldest unit
in the area, are locally porphyritic, with labradorite crys-
tals over 2 cm long. He suggested these basalts might
correlate with the Miocene-age Steens Basalt found in the
Steens Mountains to the southeast. His Glass Buttes Series
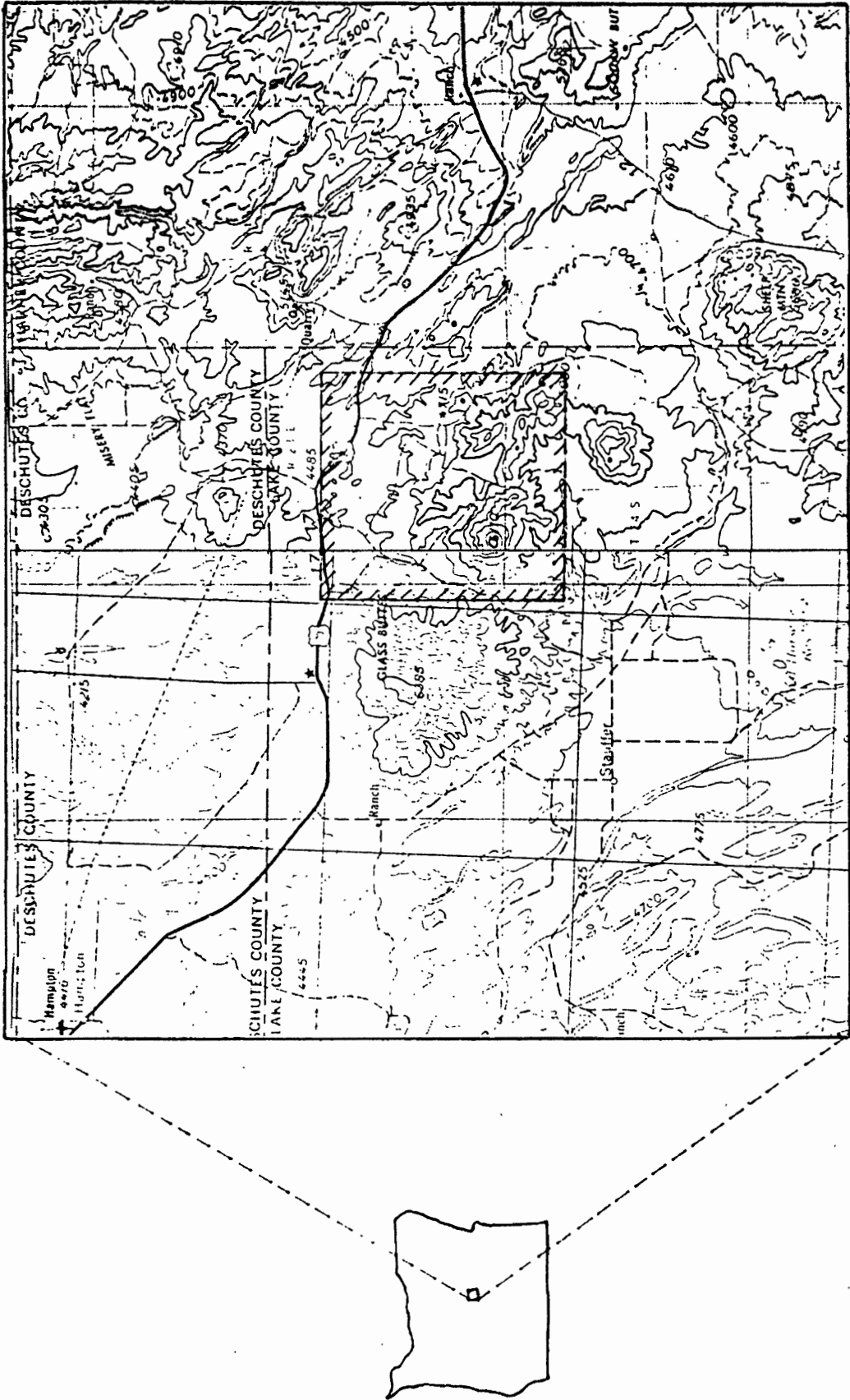
Figure 1. Location of Glass Buttes. (Scale 1:250,000, study area outlined.)
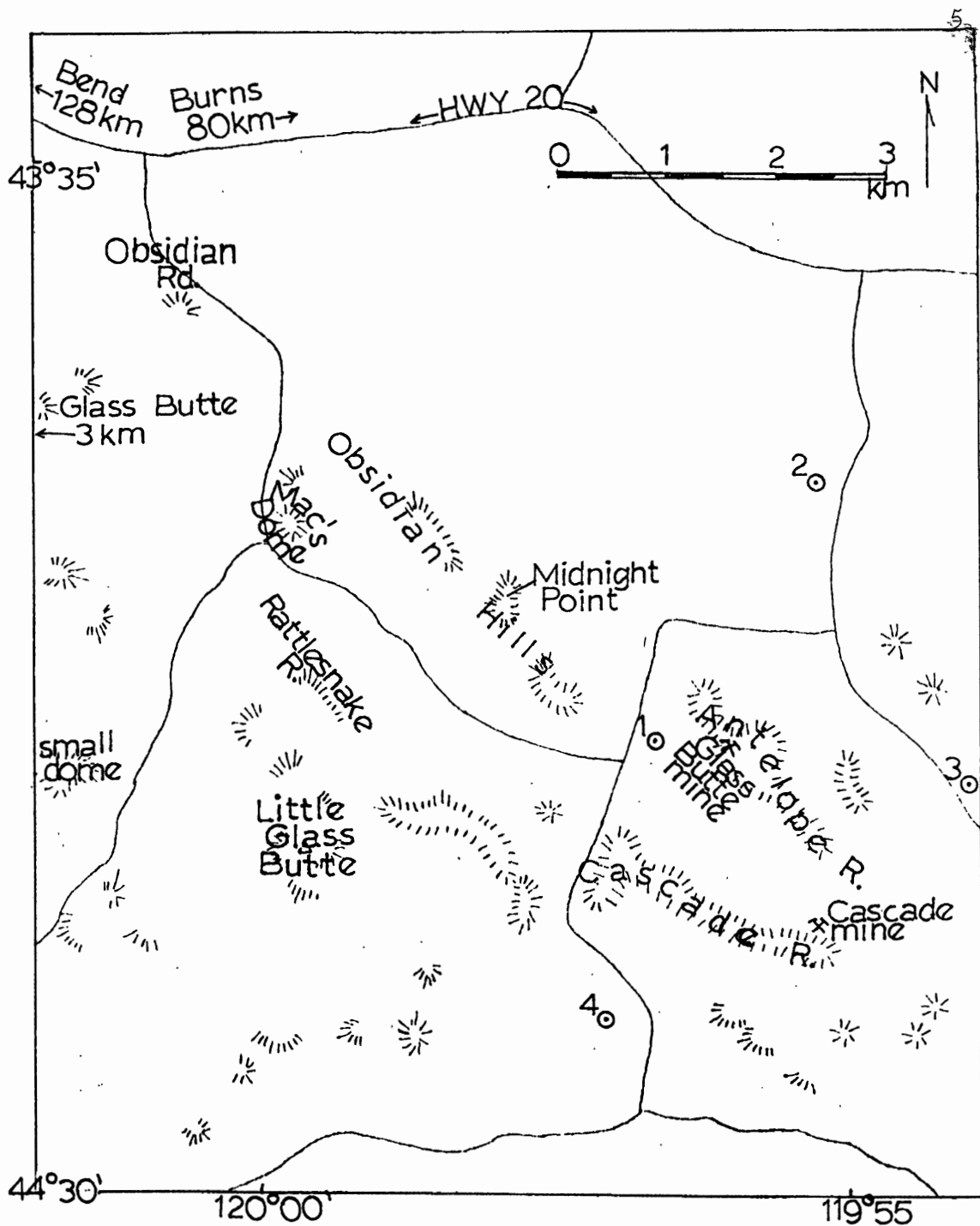
Figure 2. Sketch map of the study area in the eastern Glass Buttes, indicating informal names of features described in this study. Numbered points are drill hole locations.

overlies the basalts, and consists of over 120 m of andesite and dacite flows, as well as rhyolitic perlite, obsidian and vitrophyre. Tuffaceous sediments and plateau basalts over-lie the Glass Buttes Series. Waters interpreted the struc-ture of the buttes to be that of an anticline whose center has been down-dropped by a system of normal faults, result-ing in a west-northwest-trending longitudinal valley that extends across two-thirds of the complex (see Fig. 12).

Further study of Glass Buttes was associated with development of mercury mines between 1933 and 1958. Large scale mapping followed, including reconnaissance geologic mapping (1:250,000) of the Burns Quadrangle (Greene and others, 1972) and the East Half of the Crescent Quadrangle (Walker and others, 1967).

Anthropologists and rock collectors have long been interested in the ubiquitous obsidian at Glass Buttes. Heflin (1963) termed the buttes a "prehistoric munitions factory" for Indians whose ceremonial blades carved from the unique mahogany obsidian have been discovered as far east as burial mounds in Ohio. Today rock collectors seek black lace, mahogany, gold sheen, and rainbow obsidian, and other varieties for collections or gem work.

The most recent geologic interest in Glass Buttes was encouraged by the national energy shortage. K-Ar age deter-minations of silicic rocks in eastern Oregon defined a westward decrease in age of rhyolitic domes and ash-flow tuffs (Walker, 1974; MacLeod and others, 1976) with a

potential for discovery of usable geothermal systems in the areas of most recent volcanism. A gradient of 285°C/km was obtained at Newberry caldera at the west end of the silicic volcanic zone (see Geothermal Exploration).

There are no surface manifestations of present thermal activity at Glass Buttes. Four shallow temperature gradient holes drilled in 1975 by the Oregon Department of Geology and Mineral Industries (DOGAMI) indicated a poorly defined zone of high heat flow that appeared to be highest around the areas of most intense hydrothermal alteration in the east half of Glass Buttes (Bowen, 1975). Temperature gradients as high as 190°C/km were detected, including a bottom hole temperature of 48°C at a depth of 220 m. This thermal anomaly was investigated by Pheonix Geophysics, Inc., for DOGAMI (Hull, 1976). A dipole-dipole resistivity study indicated generally horizontal lithologic units at depth. Waters' (1927a) interpretation of an anticlinal structure across the complex is not supported by geophysical evidence from the east buttes. The upper-most unit was interpreted in the study to be impermeable volcanic flows from 90 to 600 m thick that overlie a more permeable, possibly thermal, zone.

Phillips Petroleum Company and Francana Resources, Inc., are the latest to investigate the Glass Buttes thermal anomaly. In 1979 and 1980, stratigraphic and temperature gradient test holes were drilled near old mercury mines on the east side of Glass Buttes.

REGIONAL GEOLOGY

REGIONAL SETTING

Southern Oregon east of the Cascades was divided by Dicken (1965) into three physiographic provinces: the Basin and Range, the Owyhee Uplands, and the High Lava Plains (Fig. 3). The southern Basin and Range region is characterized by high angle, normal fault-bounded horsts and grabens that are north to northeast-trending, and are cross-cut by numerous northwest-trending faults (Walker, 1973). The Owyhee Uplands to the east is a dissected plateau underlain primarily by Cenozoic volcanic rocks, that has undergone little tectonic deformation other than faulting. Structures trend north-northeasterly as well as northwesterly (Walker, 1973).

The High Lava Plains province (Fig. 3) is a broad expanse of basaltic lava flows, rhyolitic ash-flow tuff, lacustrine and eolian sediments. The flat, high desert country is moderately dissected by intermittent streams and is dotted with hundreds of silicic volcanic centers and basaltic cinder cones that rise to heights as great as 600 m above the surrounding plateau. Reconnaissance geologic mapping of the region was by Walker and others (1967) and by Greene and others (1972).

Figure 3. Physiographic provinces of southeast Oregon, after Dicken (1965). (Base map by Raisz (1941).)

Displacement along faults in southeast Oregon continues to the present. Quaternary basaltic volcanism occurred at Diamond Craters and Jordan Craters. Pleistocene cinder cones and basalt flows in the Klamath Falls area have been offset by Basin and Range faulting (Justus, 1979) and fault-related thermal springs occur throughout the region (MacLeod and others, 1976). The recent volcanism and deformation suggest considerable geothermal potential exists in southeast Oregon.

GENERAL GEOLOGIC HISTORY

Eastern Oregon Cenozoic volcanism began in the Eocene and is represented by the subduction-related volcanic rocks of the Clarno Formation, overlain by John Day Formation tuffs (Noblett, 1981). Early to Middle Miocene fissure basalts are correlative with the Columbia River Basalt Group to the north (Walker and others, 1967), and the Steens and Owyhee Basalts to the southeast (Greene and others, 1972). These Miocene basalts were erupted from north-south-trending high-angle faults or fissures throughout central and southeast Oregon. Miocene to Recent bimodal volcanism included fissure basalts and voluminous rhyolite lavas and ash eruptions. Collapse as a result of the Miocene eruption of tremendous volumes of ash formed three calderas in the Harney Basin. These rhyolitic ash-flow eruptions spread 1000 to 2000 km^3 of ash over nearly 50,000 km^2 (Walker, 1979; Walker and Nolf, 1981). From late Pliocene to Recent time,

basalt has been erupted from shield volcanoes and fissures. The basalts have buried older volcanic and sedimentary rocks and lap up against older silicic dome and vent complexes (Greene and others, 1972; Walker, 1979).

TECTONIC SETTING

The structural features of the High Lava Plains are dominated by the Brothers fault zone, a belt of closely spaced en echelon faults trending N60°W over 240 km from near Mount Jefferson in the west to the Oregon-Nevada border (Fig. 4). Also referred to as the Oregon-Nevada lineament (Stewart and others, 1975), the fault zone may continue south-southeast as far as Eureka County, Nevada. It is, however, poorly defined to the southeast beyond the north-northeast-trending Steens Mountain fault in southeast Oregon, and may in fact be terminated by the Steens fault.

Lawrence (1976) interprets the Brothers fault zone to be a deeply buried, right-lateral strike-slip fault zone forming the northern boundary of the Basin and Range province. The southern boundary, according to Lawrence (1976), occurs at the left-lateral Garlock fault in southern California. Crust between the two fault zones, i.e. the Basin and Range province, is extending westward.

The Eugene-Denio zone of lineaments, located south of the Brothers fault zone, trends N55°-60°W (Fig. 4).

A zone of silicic volcanic centers, trending N75°-80°W, extends from Duck Butte west to Newberry caldera.
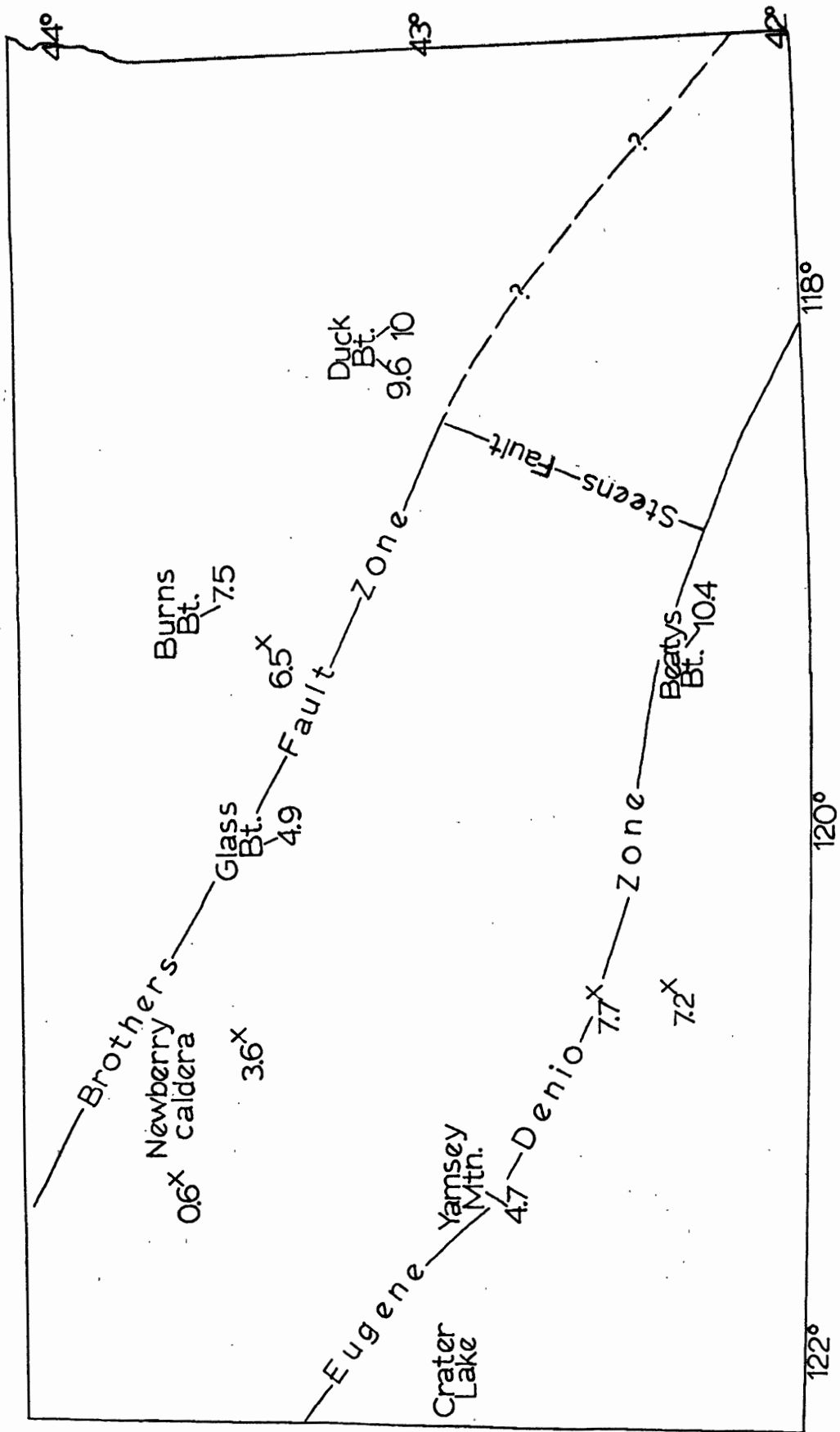
Figure 4. Structural setting, showing selected domes and ages within northern and southern silicic volcanic zones, Brothers fault zone and Eugene-Denio zone. (Modified from MacLeod and others, 1976).

Within the zone are a number of late Cenozoic basalt fields
(Walker and Nolf, 1981). A parallel but less well-defined
zone of rhyolitic domes exists to the south from Beatys
Butte to Yamsey Mountain (Fig. 4; MacLeod and others, 1976).
This southern silicic volcanic zone is intersected by the
Eugene-Denio lineament zone.

Geologic investigations in the past have not satis-
factorily dealt with the origin or possible interplay of the
two possibly independent regional structures: 1) the north-
west-trending fault and lineament zones, and 2) the west-
northwest-trending zones of silicic volcanic centers.
Walker and Nolf (1981) ascribe distribution of vents to the
Brothers fault zone, but their interpretation may be too
simplistic. The silicic volcanic zones described by MacLeod
and others (1976) are not parallel to nearby regional fault
zones. Although the degree of parallelism is subject to
individual interpretation, certain aspects of the northern
silicic zone suggest its independence from the Brothers
fault zone, as outlined below.

Using forty-seven K-Ar dates on rhyolitic dome rocks
of southeast Oregon, MacLeod and others (1976) defined two
belts of volcanic centers, each showing a westward decrease
in ages (Fig. 4). Domes younger than 5 m.y. show three sig-
nificant features: 1) the rate of westward growth of the zone
slowed after 5 m.y.; 2) the volume of materials erupted from
the domes decreased, and 3) the orientation of the zone
became more northerly. Also significant is that at 5 m.y.

the northern silicic zone intersected the Brothers fault
zone: domes older than 5 m.y. lie generally east and north
of the fault zone, whereas younger domes lie west and to the
south. Glass Buttes, in the vicinity of this structural
intersection, has been dated at 4.9 m.y. (Walker, 1974).

These features suggest that the northern silicic
volcanic zone developed after formation of the Brothers
fault zone and intersected the fault zone about 5 m.y.
The intersection slowed the rate of westward progression
and decreased the volume of the dome complexes, as well as
bent the trend of successive domes into closer alignment
with the Brothers fault zone. The fault zone shows no
change in orientation from one side of the intersection to
the other. If the fault zone is the older of the two struc-
tures, it has been active at least since 5 m.y. ago, as well
as in more recent times.

A different interpretation may result in considering
a larger regional setting. The silicic volcanic zone may
signify volcanism occurring through a west-northwest-trending
strike-slip fault zone, similar to a transform fault zone
adjacent to a mid-ocean ridge spreading center. The west-
ward migration of the volcanic front implies a north-south-
trending spreading center exists near the east end of the
zone, near the Oregon-Idaho border. Volcanism east of the
proposed spreading center has, in fact, mirrored that occur-
ring to the west across Oregon. The Pliocene volcanic rocks

of the Snake River Plains in Idaho show an eastward decrease of ages and volumes (Walker and MacLeod, 1977).

A change in regional stress orientations occurring about 5 m.y. ago may have altered the character and course of the silicic volcanic zone in Oregon. The Brothers fault zone, oblique to the volcanic zone, represents fracturing initiated by a new stress regime, post-dating that of the volcanic zone and still active today.

Further discussion of the Brothers fault zone may be found in Structural Geology.

STRATIGRAPHY

REGIONAL STRATIGRAPHY

Western and eastern portions of the High Lava Plains
experienced similar styles of volcanism during the late
Miocene and Pliocene (Fig. 5). From this it is assumed
that Glass Buttes is underlain by lavas correlative with
Columbia River Basalt Group and Steens Basalt lavas and that
rhyolitic volcanism began around 9 m.y. ago, but by at least
5 m.y. ago.

Reconnaissance geologic maps (Walker and others, 1967;
Greene and others, 1972) indicate the late Miocene to Plio-
cene Glass Buttes silicic rocks are dacitic to rhyolitic
lava flows and ash-flow tuffs, with lesser amounts of obsid-
ian and perlitic glass. Tuffs dated at 6.5 m.y. from the
Harney Basin to the east reached nearly as far west as Glass
Buttes (Walker, 1979). Explosive volcanic rocks are limited
within the eastern Glass Buttes. Late Pliocene diktytaxitic
olivine basalts are widespread to the east, northeast and
west of Glass Buttes, forming a broad plateau of lava flows.

Tertiary and Quaternary alluvial sediments were ob-
served surrounding the Glass Buttes complex, interfingering
with Pliocene plateau basalts, and include lacustrine and
fluvial sediments. A large fault-bounded basin to the south

	West High Lava Plains	Glass Buttes	East High Lava Plains
	olivine basalt of Twelvemile Table	plateau olivine basalt internal basalt	olivine basalt
	welded tuff of Twelvemile Table	rhyolitic dome and vent complex	volcanic sediments Rattlesnake Ash-flow Tuff Prater Creek Ash-flow Tuff Devine Canyon Ash-flow Tuff
	CRB-related basalt and andesite	basalt	Steens and Owyhee Basalts

Figure 5. General stratigraphic correlation chart of the High Lava Plains for late Miocene to Pliocene time (from Greene and others, 1972; Walker, 1979; using time scale of Lowrie and Alvarez, 1981).

near the old town of Stauffer, contains Quaternary playa
deposits (Walker and others, 1967).

LITHOLOGIC GROUPS AT GLASS BUTTES

The stratigraphy is complicated by the building of
the volcanic complex by successive eruptions of small volume.
Only a small proportion of the exposed volcanic rocks are
tuffs; most are siliceous lavas which erupted as flows and
domes having limited areal extent. The viscous nature of
the siliceous flows raises questions about attempted corre-
lation of similar-appearing rhyolites separated by nearly a
kilometer across the study area. Exposures of the contacts
between these units are rare, so relative age relationships
are not definable. Lithologic types, therefore, were mapped
without striving to locate and trace depositional contacts.

With the exception of the basalts, all rock units are
highly glassy and many are totally composed of glass. The
few phenocryst-bearing units are nearly aphyric rhyolite
flows, so stratigraphic distinctions based on petrography
(e.g. feldspar compositions) are not reliable.

Methods of determining local stratigraphic sequences
are as follows: 1) observation of topography. Because the
present topographic surfaces do not appear deeply eroded,
these surfaces are assumed to represent original flow tops.
Thus, elevations of flow surfaces and dips of flow layering
suggest possible directions to the source for the flows.
2) Float types provided information about rock underlying

the soil, as well as indicating the topographically highest
occurrence of unexposed units. 3) Data from drill holes
placed important constraints on stratigraphic relations,
especially the extent and to some degree the age of basalt.
4) Eruptive processes (e.g. dome development) were found to
form varying volcanic textures and weathering products.

Processes of crystallization of glassy volcanic rocks,
as well as development of flow banding, have occurred to
varying degrees in the rhyolitic rocks of Glass Buttes.
Crystallization is accomplished through devitrification and
vapor phase alteration. Natural amorphous glass is unstable
under surface conditions and tends to crystallize, or
devitrify, to a more crystalline rock generally composed of
feldspar and silica with minor pyroxene and iron oxides.
This commonly is in the form of spherulites, fibrous radi-
ating intergrowths of cristobalite and sanidine (Williams
and others, 1954; Ewart, 1971), 1 to 5 mm in diameter, with
concentric zoning. The polygonal shapes of spherulites usu-
ally coalesce, leaving patches of residual glass that even-
tually devitrify to microcrystalline non-spherulitic aggre-
gates (Ewart, 1971).

The glass contains volatiles in solution, and release
of the volatiles upon devitrification forms vesicular cavi-
ties. The volatiles, as well as others derived from the
cooling flow (e.g. heated groundwater), migrate upward along
fractures and flow planes. Crystallization from this vapor
phase consists of tridymite and feldspar forming in open

spaces (Ross and Smith, 1961). Pores may be the vesicular cavities in pumiceous fragments or layers. The resulting lithophysal zone occurs near the top of the flow.

Silicic lavas tend to show development of flow structure in the interior of the flow, arising from differential laminar flowage. This structure is referred to as flow layering, fluidal layering or flow banding. The fluidal layering is commonly contorted and folded at flow edges or on steep slopes, where flow of viscous lavas becomes chaotic and slight differential cooling of layers in the flow causes drag that may detach and shear flow bands. Dips of such flow layers are not, of course, useful as source or stratigraphic indicators.

Float of pumiceous glass overlying outcrops of rhyolite flow has been weathered from frothy flow-top material. Flow-top glass is poorly preserved, suggesting a deep level of erosion into the interior of rhyolite flows. As discussed below, thick deposits of obsidian and pumiceous glass overlying rhyolite flow units may also represent chilled flow-top material, but this relationship could not be directly observed.

The siliceous volcanic units of Glass Buttes described below were mapped by Walker and others (1967) as Pliocene-Pleistocene dacite-rhyolite, and by Greene and others (1972) as upper Miocene-Pliocene rhyolite-rhyodacite. The 4.9 m.y. obsidian dated by Walker (1974) is believed to be the

youngest unit in the west part of the study area. Much of
the eastern Glass Buttes volcanic complex had, therefore,
formed by the early Pliocene.

Characteristics of rock types and units identified in
the eastern Glass Buttes are summarized in Table I. For
ease of discussion, the silicic volcanic units in the study
area will be described in groups related by similar proc-
esses of formation. These include 1) lava flows (A and B,
Table I), 2) rhyolitic glass and pumice forming exogenous
domes (C and D), 3) rhyolitic glass forming endogenous domes
(C), and 4) pyroclastic air-fall deposits (E). Basalt and
volcaniclastic sediments are described following the silicic
rocks.

Lava Flows

Units formed by eruption of flows from a vent source
include rhyolite and obsidian flows, described separately
below. The vent areas for the flows generally lie in the
vicinity of blocky jointed outcrops at the crests of these
major topographic features. Hillsides slope gently away
from these probable vent areas. Crossections A-A' and B-B'
of Plate II illustrate the sequence of rhyolite flows and
obsidian. (Plates I and II located in rear pocket.)

Older Rhyolites. Rhyolitic lavas are found on Little
Glass Butte and Antelope Ridge (see Fig. 2). Located in the
west-central part of the study area, Little Glass Butte is a
prominent peak surrounded by low hills. The butte slopes

TABLE I

SUMMARY OF LITHOLOGIC TYPES, EASTERN GLASS BUTTES

Rock Name	Unit Name (Map Symbol)	Source	Location	Color	Characteristics
Rhyolite flow	Older Little Glass Butte rhyolite (Tro); Antelope rhyolite (Tra); Younger Little Glass Butte rhyolite (Try).	isolated vents	Little Glass Butte; Antelope Ridge.	blue to grey	Flow banded, platy jointed. Sparsely porphyritic, felsitic groundmass often spherulitic in Tro and Tra units.
Obsidian flow	Oldest Obsidian (To); Obsidian flow (Tof); Obsidian Hills (Toh).	isolated vents	Little Glass Butte; Obsidian Hills.	mostly black some reddish brown	Oxidized pumice capping, layers of perlite within, some flow folding. Not devitrified, flow alignment of microlites.
Glass flow	Rhyolitic glass (Trg); Old rhyolitic rocks (Trr).	exogenous domes	Cascade Ridge; Antelope Ridge.	bluish-grey to dark blue and grey	Structureless though may be flow banded on dome flanks; may contain beads or lenses of obsidian. Aphyric; often devitrified (spherulitic, frothy, inflated), hydrated to perlite, perlitic glass.
	Rhyolite plugs (Trp).	endogenous domes	Mac's Dome; Oasis.		
Pumice (or glass) breccia	Pumice flow breccia (Tbx).	exogenous domes	Cascade Ridge	bluish-grey to grey	Near vent(s) along dome crest, often poorly cemented. Blocks up to 1 m across. Fragments are frothy glass or pumice.
Lithic tuff	Lithic airfall tuff (Tt).	unknown	Cascade Ridge (southern flank)	white to tan	Unwelded, uniform particle size, unbedded. Fragments are glass, some pumiceous, some perlitic; obsidian.
Basalt flow	Plateau basalt (Tbp).	fissures, cinder cones	Plateau around silicic complex	dark grey	Columnar jointing. Porphyritic intergranular; labradorite and augite phenocrysts, groundmass olivine.
	Internal basalt (Tbi).	fissures	Scattered within silicic complex	dark grey to black	Highly weathered, interfingers with rhyolitic units. Glomeroporphyritic plagioclase up to 1 cm long, glassy groundmass.
Alluvium	(Qal)	Glass Buttes complex	Surrounding the complex, in valleys	varies	Unconsolidated fluviatile, lacustrine sediments, also talus, slope wash.

* For relative ages of units, see Plate I.

steeply off to the south but more gently to the north, suggesting most lavas flowed down the northern flanks.

Low on the steep southeast side of Little Glass Butte is a blue, finely flow-banded rhyolite (Tro, Plate I) that originated from near the present summit of Little Glass Butte. This is the older of the two Little Glass Butte rhyolite flows, and forms a 5-m high outcrop that trends N10°-20°W for over 900 m, containing contorted flow banding (Fig. 6) and northwest-trending extensional joints. Flow

Figure 6. Contorted flow banding. Older Little Glass Butte rhyolite, southeast flank Little Glass Butte. Pencil is 27 cm long.

bands dip away from the peak; this and the contorted nature of the banding suggest the outcrop may be the edge of a flow. Weathering along pink-colored flow-band surfaces

results in flaking of layers about 5 cm thick that produces
a platy appearance in outcrop. This rhyolite is also exposed
in deeply eroded gullies in the hills to the east of Little
Glass Butte.

The older Little Glass Butte rhyolite flow is indis-
tinguishable petrographically from the Antelope rhyolite
(Tra, Plate I) found 0.8 km to the northeast on Antelope
Ridge. Due to the viscous nature of these two units, a
separate source is proposed for each though the lavas are
chemically (see Fig. 18) and petrographically similar.

Natural and unaltered rock outcrops are found in only
a few locations on the northwest-trending Antelope Ridge.
The blue, finely flow-banded Antelope rhyolite flow origi-
nated from near the east peak of the ridge (a nearby topo-
graphic high). A massive and irregularly jointed outcrop
can be found at the site of a possible vent.

The older Little Glass Butte and Antelope rhyolites
are composed of devitrified flow-banded glass that is over
90 percent spherulites (Fig. 7). Long wavy parallel threads
of isotropic or dark brown glass extend across the section,
and are bounded by spherulites; this banded texture repre-
sents fractures formed by flowage and shearing during early
cooling of the viscous lava, as the banding is often highly
contorted and broken. These flow planes became sites for
devitrification. X-ray diffraction study of the nearly
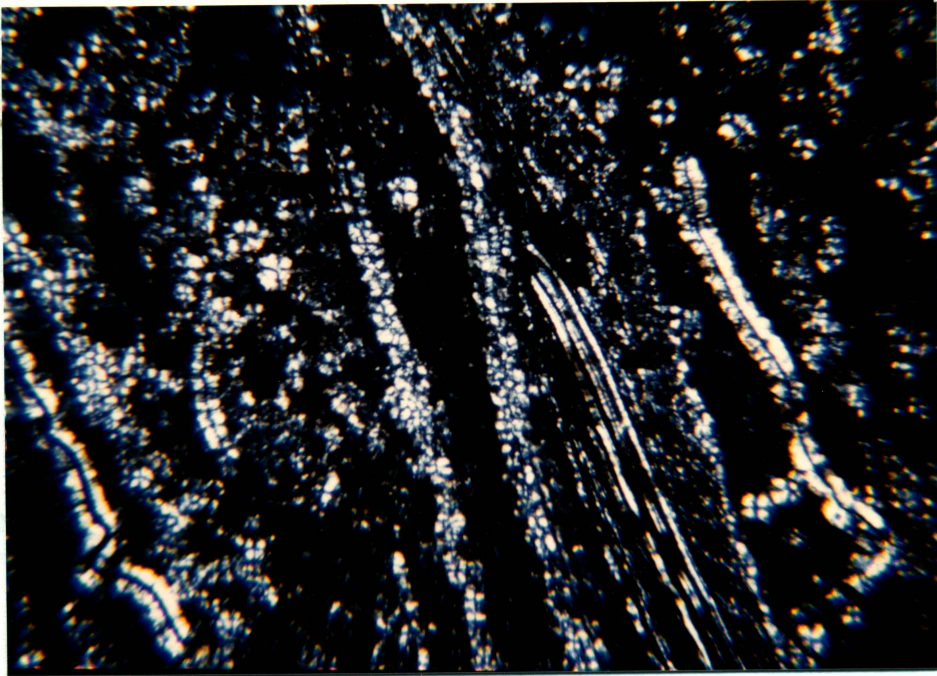
Figure 7. Spherulites, older Little Glass Butte rhyolite. Cross polars, x 2.5 .

aphyric rhyolites indicated cristobalite with feldspar (Fig. 8a-c), probably representing the composition of the spherulites.

The formation of spherulites in the glassy rocks seems characteristic, in contrast to the dense amorphous glass of the younger Little Glass Butte rhyolite; these units are more thoroughly devitrified than the younger rhyolite. X-ray diffraction analyses also show greater crystallinity in the older rhyolites, in which the main constituents are cristobalite and plagioclase (Fig. 8a, b and c). The diffuse or incipient cristobalite "peak", or rise, centered roughly about 4.04 A or 22 20 in Fig. 8d, represents poorer crystallinity (Tatlock, 1966) of the glassy, younger
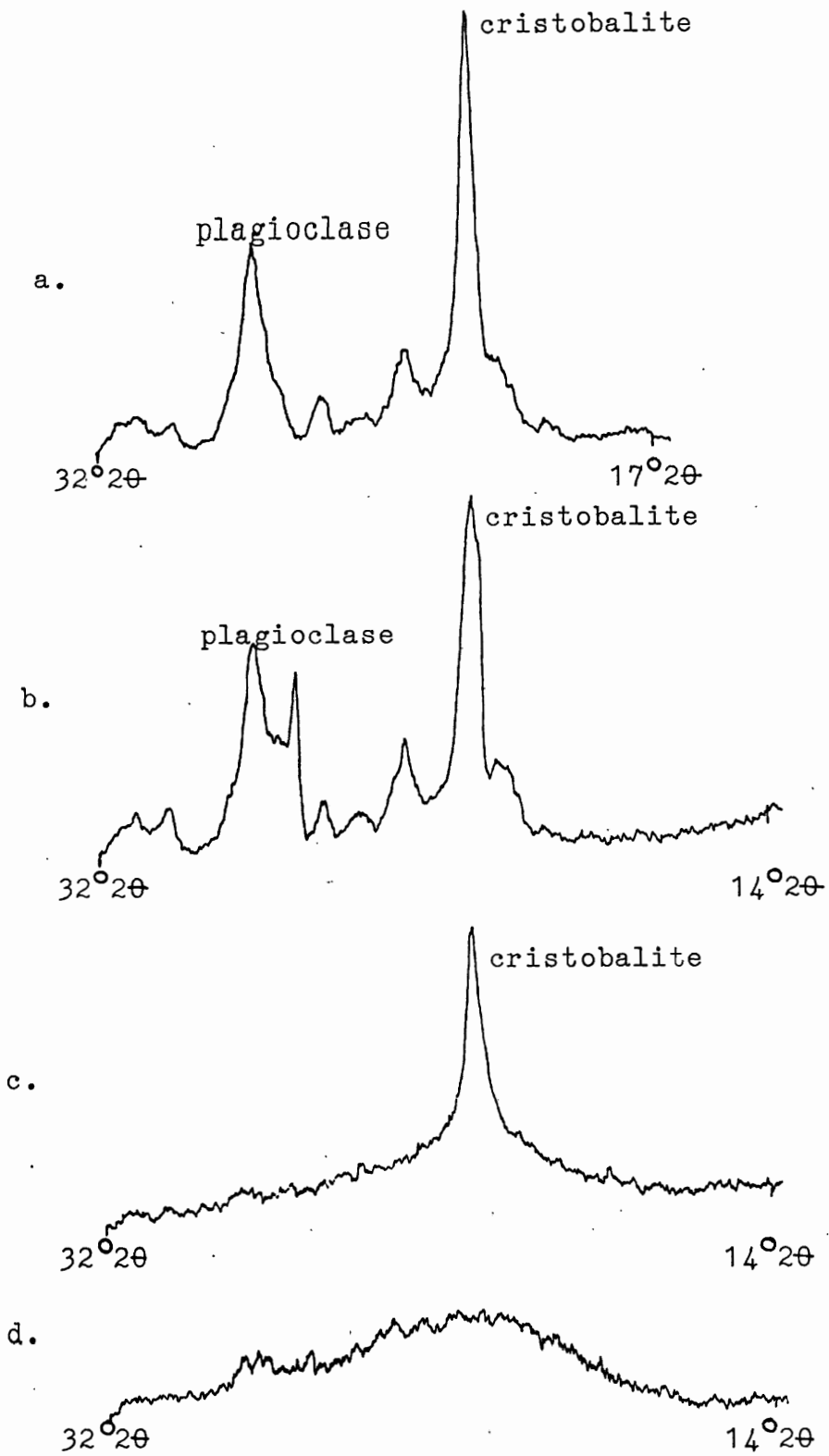
Figure 8. X-ray diffraction patterns, Little Glass Butte rhyolites. a-c. Older rhyolites. b. Younger rhyolite.

rhyolite. The older rhyolites may have had a higher vol-
atile content, promoting more thorough devitrification.

Phenocrysts are commonly glomeroporphyritic and in-
clude anhedral pyroxene, sanidine, zoned plagioclase micro-
lites (An_{11-28}) and corroded quartz. One perthitic feldspar
grain was observed. Determination of feldspar compositions
was hampered by sparseness and size (less than 0.3 mm) of
untwinned phenocrysts.

Younger Rhyolite. The younger Little Glass Butte
rhyolite (Try, Plate I) is a dark grey to black, glassy,
flow-banded rhyolite that spread down the northern slopes
of the butte and laterally for over 2 km north-northeast
from the vent. The flat summit of Little Glass Butte is
underlain by rubbly, dark reddish-brown, low-lying outcrops
of rhyolite. Platy jointing occurs along flow layers
(Fig. 9), often coincident with weathering lenses of iron
oxides and clay that also formed along flow planes.

Several prominent ridges composed of the younger
Little Glass Butte rhyolite extend down the west and north
slopes of the butte. Two irregularly jointed, bouldery out-
crops on the northwest flank form parallel ridges and are
separated horizontally by about 75 m of float-strewn, pumice
covered slope. These ridges become isolated, long linear
outcrops, trending about N40°W, that can be traced downhill
to the west. They can be connected to fault traces bounding
the longitudinal valley across the main butte at the west
side of the complex, thus may be fault controlled.

Figure 9. Platy jointing. Younger Little Glass Butte rhyolite, northwest flank Little Glass Butte. Hammer handle is 60 cm long.

Rattlesnake Ridge (see Fig. 2), on the north slope of Little Glass Butte, is underlain by a series of northwest-trending step-like cliffs of rhyolite, as are low hills farther to the north. The ridge forms the south face of a northwest-trending fault valley about 1 km wide, bounded on the north by the Obsidian Hills. Weathering along dark red, contorted flow-band surfaces about 5 cm thick causes large wavy sheets to spall off, forming boulder-sized talus below the north-facing cliffs of the ridge. Similar outcrops with north-facing exposures occur along two northwest-trending faults north of Rattlesnake Ridge (Plate I). The rhyolite, hidden elsewhere by a layer of obsidian and soil, is exposed along these three faults.

The younger Little Glass Butte rhyolite, like the older rhyolites described previously, is a glassy, sparsely porphyritic lava but generally shows little to no evidence of devitrification in thin section or in X-ray diffraction analyses (see Fig. 8d). Phenocrysts are slightly more abundant than in the older rhyolites, comprising 5 to 10 percent of an otherwise opaque to brown, glassy rock. Euhedral andesine phenocrysts (An_{45}) are albite-twinned and commonly zoned. Rounded and fractured pyroxene heavily included with iron oxides, as well as small, unidentified phenocrysts of feldspar, are also present.

Obsidian. Black rhyolitic glass, or obsidian, is ubiquitous in the west half of the study area, especially north and east of Little Glass Butte. Outcrops are non-resistant and thus usually evident only as float that characteristically forms anastomosing talus streams on hillsides. Scattered excavations by rock collectors have exposed obsidian beneath the soil.

On the basis of topographic character and its indication of relative ages, three separate obsidian units were mapped around Little Glass Butte and Obsidian Hills to the north. These units are not, however, separable on the basis of hand sample appearance alone. Further chemical work may correlate them with underlying rhyolite flows but because of their thicknesses, 1 m or more, the obsidian is not believed to simply represent the glassy selvage of the underlying rhyolite flow, and therefore is treated as a separate unit.

The distribution of the obsidian is related to obsid-
ian flows, capped by a pumiceous, frothy and oxidized glass
(Fig. 10). Hydration and oxidation of this rind may have

Figure 10. Obsidian outcrop; east lobe, Obsidian
flow southeast of Little Glass Butte.

been caused by escaping gases or heated groundwater circu-
lating through the cooling lava (Noble, 1967). Hydration
produces thin layers of grey perlite within which may be
found rounded remnants of the original black obsidian
(Fig. 10). The total lack of devitrification of the obsid-
ian implies low content of volatiles in the lavas upon
eruption.

The obsidian is highly variable in color, from dense
black glass, black glassy shards in a red-brown matrix, thin
black and red banded glass, to nearly pure reddish-brown

glass (Fig. 11). A study of this type of Glass Buttes obsidian by Fuller (reprinted in Waters, 1927a) concluded that the varied colors are due to oxidation of iron during flow of the viscous obsidian, and mixing of this red glass with unoxidized black fragments. Fusion may have further changed the red and black glass to the point of intimate, microscopic mixtures.

Figure 11. Obsidian varieties. From left to right: red-brown, red-brown breccia, red and black banded, and black with red lenses.

Low on the west and southwest flanks of Little Glass Butte, surface float is primarily angular obsidian. An excavation northwest of the butte exposed nearly 1 m of black obsidian with perlite and oxidized glass layers. The base of the obsidian was not exposed. This obsidian (To,

Plate I) appears topographically and spatially distinct from the obsidian flow described below, as well as from the Obsidian Hills north of Little Glass Butte, and is considered the oldest obsidian. It underlies both of the Little Glass Butte rhyolite flows and the obsidian flow and its vent may be near Little Glass Butte.

A distinct multiple-lobed flow of obsidian southeast of Little Glass Butte (Tof, Plate I) probably originated from the east side of the butte. Several thick exposures were found in this area of massive black obsidian with reddish-orange frothy glass cappings. The obsidian flowed south-southeast over and around the older Little Glass Butte rhyolite. Although no vent was located, it is presumed to be under the younger Little Glass Butte rhyolite, which may have issued from the same vent but flowed to the north.

Obsidian forms rolling hills north of Little Glass Butte (Toh, Plate I). It overlies the younger Little Glass Butte rhyolite, and so is the youngest of the obsidian units. This may be the obsidian dated by Walker (1974) at 4.9 m.y. Possible sources lie within the Obsidian Hills area, for example the prominence 800 m southeast of Midnight Point, or Mac's Dome, as well as the area of Little Glass Butte. As discussed earlier, the obsidian may also be part of a glass and pumice carapace capping a rhyolite flow.

Exogenous Domes

Domes with primarily exogenous character form by
eruption of viscous lavas from a summit vent. The glassy
carapace is repeatedly fractured by upwelling magma, and is
often covered with pumice blocks and spines of lava. Well-
known domes of this type include Lassen Peak and Mono Craters
in California. Domes of the Coso Range, California, have
recently been well documented by geothermal investigators
(Duffield and others, 1980; Bacon and Duffield, 1980;
Roquemore, 1980; Bacon, 1982).

In Oregon, the west-northwest-trending belt of volcanic
vent and dome complexes described by MacLeod and others
(1976) consists of exogenous domes of rhyolite and obsidian
flows and flow breccia, that are commonly elongated sub-
parallel to the trend of the volcanic belt. Glass Buttes
contains many exogenous domes throughout the complex. Vari-
ations in dome rocks are best illustrated by a small dome
west of Little Glass Butte (see Fig. 2), described below.
This dome served as a model for development of other exog-
enous domes in the Glass Buttes area.

The dome is elongated approximately west-northwest,
and lies on a west-trending structural lineament that ex-
tends west through Glass Butte and to the east along the
south flank of Little Glass Butte. Glass flows found in
outcrops low on the flanks of this dome are flow-banded.
The flow banding dips steeply downslope and locally is
folded and overturned. Infrequent lenses of obsidian up to

4 cm thick occur between flow layers. Nearer the ridge crest, the glass is more vesicular and frothy, and contains flow layers of gentler dip. The dip of such banding is generally towards the center of the dome.

Littering the top of the dome are fragments from a glass breccia. Rarely found as consolidated rock, pieces of the breccia more often occur as fragments or rounded cobbles of frothy glass averaging 10 cm long, covering the ground. This matrix-free breccia could have formed by surface autobrecciation of erupting glass flows, by sub-surface brecciation before eruption (Williams and McBirney, 1979), or by fracturing of the carapace glass. Breccia fragments are oxidized to a light orangish-brown color. Fine, rounded obsidian float, weathered out of glass, is also found here.

Evidence of lithophysal development was observed at the crest of the dome as well as at the nose of the flanking flows where flow interiors are exposed, and is due to crystallization from gases escaping from the dome. At the nose of the flows, these lithophysae are filled or lined with undetermined secondary minerals. A similar lithophysal zone occurs at the crest of the dome, crosscuts flow banding and has a vertical contact with surrounding flow-banded, non-lithophysal glass. A fracture may have opened here, allowing gases from deep within the dome to permeate vesicular glass in the vicinity of the fracture.

Recognition of dome-related rock types, including flow-banded glass, frothy glass, frothy glass breccia and lithophysal glass aided in interpreting partial assemblages of dome rocks found elsewhere in the area.

Cascade Ridge is an area of dome building. Sequences of volcanic materials observed here are similar to the pattern described previously for the small dome west of Little Glass Butte. The ridge trends N65°W for nearly 3 km and rises to a high point of nearly 1700 m at its east end. From the south, gullied slopes rise gradually to the ridge crest and are characterized by sparse rock outcrops. Several trenches related to mercury mining activity are present on the south side. The north-facing slopes, in contrast, are steep and smooth and lack natural rock exposures. On the basis of topographic expression, the ridge is believed to be bounded on its north side by a northwest-trending fault (Fig. 12), active after the dome developed.

The southwest and southeast flanks of Cascade Ridge contain south-dipping, blue-grey glass. Upslope at the ridge crest is a pumice breccia containing fragments up to 1 m long, that has in places been silicified and/or altered by fumarolic activity (see Fig. 23).

Endogenous Domes

Domes with mostly endogenous character form by expansion from within, by internal doming, with little eruption of viscous lavas. The two small domes described below are

Figure 12. Cascade Ridge fault valley, looking southwest down central valley: Cascade Ridge at left, Little Glass Butte left of center, and Glass Butte right of center in distance.

circular mounds distinct from other topographic features, from which thick glassy lava flowed only short distances.

Mac's Dome is located about 3 km north of Little Glass Butte on an obsidian-covered hillside, and along the trend of the Cascade Ridge fault. This small, circular plug is about 150 m in diameter, and consists of crudely jointed, dense, grey glass. Toward the west side of the dome is a small spine, composed of blocks of light blue, vesicular glass piled up to a height of over 12 m, that contains lenses of obsidian beads. The material in the spine is generally more inflated and perlitic than that found else-where on the dome.

The Oasis is a circular rise from the alluvial valley at the west end of Cascade Ridge, also on the Cascade Ridge fault trend. The area is vegetated with dense juniper and thick, unusually tall (1 to 2 m high) sage bushes, providing shade for cattle. Hydrothermal alteration associated with extrusion may have formed a clayey surface layer with greater-than-normal water-holding capacity, thus supporting the lush vegetation. Several outcrops of red oxidation-coated, dense grey glass are found on the dome. Breadcrust cooling surface textures are common, as are very thin fracture coatings of hyalite (clear, amorphous silica). No extremely vesicular outcrops were observed, thus extruded material may have had a lower water content than the perlitic glass of Mac's Dome.

Pyroclastic Air-fall Deposits

A single tuff unit crops out south of Cascade Ridge, lining a broad, east-west-trending drainage. The lithic tuff weathers to form a white, ashy soil. Exposures up to 2 m thick show moderate sorting of dark and light blue glass, obsidian, glass containing obsidian beads, and pumiceous glass. Fragments of dense glass are up to 15 cm long, while frothy glass is generally about 2 cm in size. The tuff is well indurated but not welded. No bedding or size gradation was observed. Because of the tuff's nearly uniform particle size, it is believed to be an air-fall tuff rather than having originated from a pyroclastic flow.

Crossection C-C' (Plate II) shows the position of this tuff overlying obsidian and rhyolite units south of Cascade Ridge.

Basalt

Two distinctively different types of basalt occur in the eastern part of Glass Buttes. Plateau basalts are fine-grained, vesicular lavas that lap onto the silicic volcanic complex. Internal basalts are coarsely porphyritic lavas of limited extent, believed to have erupted from vents within the dome complex.

The voluminous fine-grained, dark grey, porphyritic plateau basalts (Tbp, Plate I) lap onto the Glass Buttes complex (Plate II) and form the extensive surrounding plateau. Crossection B-B' (Plate II) shows an incursion of plateau basalt into the buttes. At this location, plateau basalt is over 90 m higher in elevation than the surrounding plateau, uplifted by a northwest-trending fault that extends across the Obsidian Hills (Plate I).

Plateau basalt flows are exposed in outcrops of 2 to 6 m in height along intermittent stream channels. Moderate to highly vesicular outcrops suggest exposures may represent flow tops, but total thickness is unknown. Weathering to a dark red-brown color, outcrops have rubbly bases and usually are overlain by less than 30 cm of fine soil.

Stratigraphic test holes numbers 2 and 3 are located north and northeast of Antelope Ridge, respectively (for locations, see Fig. 2; for lithologic logs, see Fig. 28).

Neither drill hole intersected basalt. Instead, alluvial material similar to that found in Test hole no. 1 (within the central valley) suggests a thick pile of volcanic sedimentary debris derived from Glass Buttes accumulated before the eruption of the plateau basalts and formed a partial barrier to the onlapping basalt flows. An apron of alluvium today obscures the contact of basalt with rhyolitic units (Plate II).

The fine-grained, dark grey to black, plateau basalt has a sub-porphyritic, intergranular texture with 24 percent plagioclase and 20 percent pyroxene phenocrysts in a groundmass of plagioclase microlites (An_{50}), pyroxene, olivine, iron oxide and glass (Fig. 13). Plagioclase grains
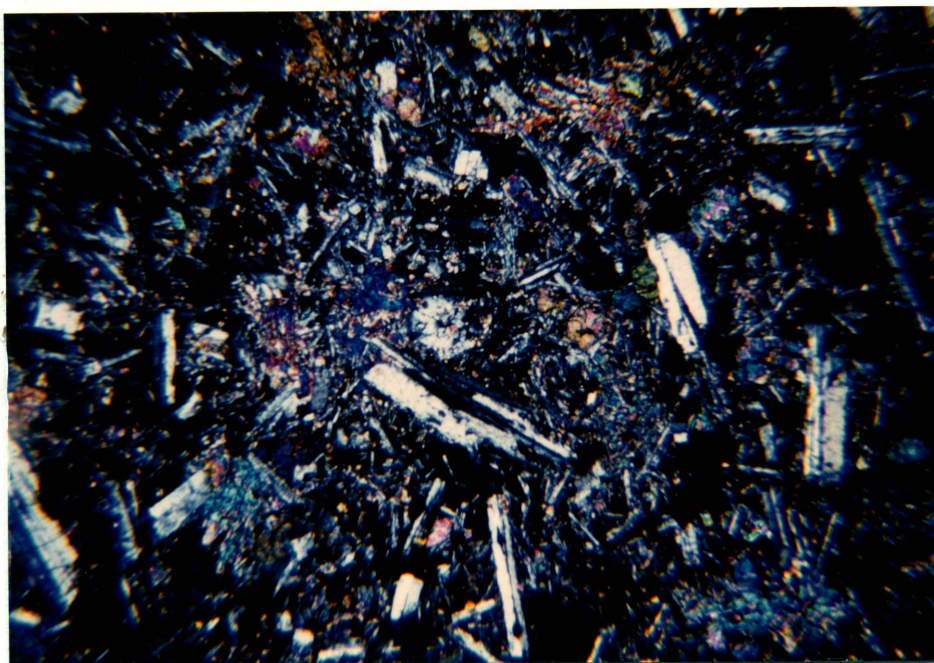
Figure 13. Plateau basalt, photomicrograph, crossed polars, x 2.5 .

occur in a wide range of sizes from 0.2 to 0.7 mm long. The
larger plagioclase grains (An_{54}) are subhedral laths aver-
aging 0.7 mm long, occasionally containing inclusions of
bleb-shaped pyroxene and iron oxides along twin planes.
Subhedral augite grains are ophitic to poikilitic, having
developed after formation of much of the plagioclase. The
groundmass contains anhedral olivine weakly altered to
iddingsite, pyroxene, and plagioclase laths. Minor ground-
mass constituents are included in the modal analysis below.

Phenocrysts:	plagioclase (An_{54})	24.1 %
	augite	20.7
Groundmass:	plagioclase (An_{50})	17.4
	vesicles	13.1
	olivine	8.1
	glass	7.1
	pyroxene	4.9
	iron oxides	4.6
		100.0 %

(Based on a total of 1000 points counted.)

The plateau basalts are similar microscopically to
equivalent Pliocene lavas of southeast Oregon described by
Greene and others (1972).

Internal-type basalt (Tib, Plate I) occurs west of
Little Glass Butte, where porphyritic basalt, rich in plagi-
oclase phenocrysts, appears to lap onto the rolling, east
flanks of Glass Butte, and may be overlain by the small dome
described above, to the south (Plate I). Basalt flows can
not be traced out of this area, thus a vent must have existed
within the buttes for this small body of basalt.

The highly feldspathic internal basalt contains glomeroporphyritic plagioclase phenocrysts up to 1 cm long in a dense, very fine-grained groundmass. Outcrops are highly weathered and difficult to sample. Outcrops west of Little Glass Butte are 4 to 6 m high and correspond to northeast and west-trending lineaments in the area. Vesicles in the basalt are often lined with light green clayey material, possibly nontronite (Williams and others, 1954). Hyalite was found coating some fractures.

While relative ages of the plateau and internal basalt types could not be determined, further work might show that the internal basalt, suggested by Waters (1927a) to predate silicic volcanism, represents vents reactivated during eruption of the plateau basalts, which may be the youngest unit in the area. It is more likely, however, that these internal basalts, in places interfingering with rhyolite, are part of the bimodal eruptions that formed Glass Buttes. This possibility requires further study.

Volcaniclastic Sediments

Sedimentary materials are widespread in the area and occur as thick valley-fill and low hills that slope down from the buttes to the plateau. These unlithified sediments generally include rounded fragments of obsidian, pumice and perlite in a matrix of light brown, clayey soil, or, as Waters (1927a) termed the unit, "pumiceous sand". Rounded obsidian float is commonly over 15 cm in diameter, and one

boulder unearthed by rock collectors was nearly 1 m in diameter. This larger float probably is not far from its source; excavations show a thick weathering zone atop obsidian flows that contains similar loose blocks.

These young sedimentary units formed primarily by fluvial deposition, sheet wash, and talus composed of material eroded from the developing silicic volcanic complex.

SUMMARY OF STRATIGRAPHY

Stratigraphic relationships are largely based on topography, float type, and drill hole data. Because units continuous over large areas and definite depositional contacts are lacking, stratigraphic relations are apparent only in small areas and relations between units in the west and east portions of the study area are unknown.

Following deposition of late Miocene basalts, equivalent to the Columbia River Basalt Group and Steens basalts, which are not known to be exposed in the Glass Buttes area, vent and dome-related rhyolitic lavas, glass flows and ash erupted from Antelope Ridge-Cascade Ridge vents. The Little Glass Butte rhyolites flowed out to the north and east of the butte, probably at about the same time as eruptions to the east. Stratigraphic relations with the rhyolite and pumice flows occurring to the east are not known.

The older Little Glass Butte rhyolite overlies obsidian, and is topographically lower than the younger rhyolite, which is in turn overlain by a possibly separate obsidian

unit north of Little Glass Butte. The two rhyolite flows
are separated by obsidian occurring east and southeast of
Little Glass Buttes. Evidence of a vent for the latter
obsidian is lacking, but probably has been covered by the
younger rhyolite.

The process of dome development occurred repeatedly
in the Glass Buttes complex. The blue to grey glass of
Cascade Ridge is topographically lower than a glass breccia
that can be found along the dome crest. Two or more vents
are postulated for Cascade Ridge and each presumably had a
similar pattern of development. Detailed examination of the
many small hills within the buttes might reveal as many
separate domes.

The plateau basalt may post-date silicic units in the
eastern Glass Buttes. The internal basalt, believed by
Waters (1927a) to have preceded silicic volcanism, instead
erupted during and perhaps after the rhyolitic lavas. While
the basalt west of Little Glass Butte overlies rhyolitic
rocks to the west, it underlies the small, glassy dome to
the south. A better understanding of the internal basalt
would come from isotopic age determinations or further
drilling.

Waters (1927a) described field aspects of rhyolitic
rocks that he observed on the west butte that are similar to
those found in the east Glass Buttes, including a striking
banded appearance to the lavas that becomes very contorted
toward the flow top. Lacking chemical analyses, he named

sparsely porphyritic rocks dacites and andesites, as one might easily have named the glassy, dark bluish-grey rhyolites found in the eastern buttes.

Waters described obsidian and pumice capping a "dacite" flow, and obsidian blocks within perlite, as have been found to the east. He apparently overlooked a young-looking lobe of obsidian that flowed out the west side of Glass Butte, covering several square kilometers.

The style of volcanism was, therefore, similar throughout Glass Buttes. Hydrothermal alteration has been exposed at the surface only in the eastern buttes; if alteration exists in the western buttes, it lies at levels deeper than erosion has reached today.

PETROGENESIS

The Glass Buttes complex was formed by eruption of rhyolitic and basaltic materials from individual vents or complex domes having overlapping flows. Eruptions occurred along northwest-trending structural weaknesses associated with the Brothers fault zone and the silicic volcanic zone, that provided conduits for rapid eruption of glassy rhyolitic lavas.

Exogenous domes are elongated along the zones of weakness, or faults, and produced viscous glass flows. This glass became inflated by vesiculation and de-gassing that occurred during eruption and cooling of the flow.

Inflation results in expansion of the volume of glass, which cracks under the tension. Spherulitic or perlitic textures are the result. On a larger scale, the volume increase would serve to inflate the domes from within, and suggests many domes at Glass Buttes have an endogenous nature of formation, for at least part of their development.

Dome-related grey, perlitic glass often contains obsidian lenses or pockets up to 15 cm thick, or finer stringers of obsidian beads. Mayo (1944) suggested the grey glass is actually obsidian that has been remelted by heat from an overlying flow, but gradation of grey glass downward into obsidian was not observed at Glass Buttes. Segmenting and

stretching as well as folding of these obsidian lenses
does, however, suggest they behaved as plastic slip surfaces
during movement of the grey glass flow.

It is believed the obsidian and grey glass are geneti-
cally related. Obsidian lenses are uninflated, undevitrified
portions of the glass flow, representing planes of reheating
and remelting of glass, or more likely, glass that was
insulated from gases. Weak flow planes, along which hot
exsolving gases stream, are sites for early devitrification,
which has not occurred in the obsidian lenses.

Other silicic lavas at Glass Buttes formed individual
vents, and may have been derived from less volatile-rich
magmas, e.g. the Little Glass Butte-Antelope rhyolites and
the obsidian flows. Only thin bands of grey, perlitic glass
occur in these units, commonly near flow tops and oxidized
zones, and reflect lower volatile contents producing less
inflated glass than found in dome-related flows. It is not
known if they represent lavas from a different magma or
level of a magma reservoir, than that of the domes. Their
differing volatile contents could result from deep circula-
tion of groundwater, contaminating only certain parts of the
magma reservoir underlying Glass Buttes, but no evidence has
been obtained to support this possibility.

Intersection of regional fracture systems at Glass
Buttes facilitated the eruption of primarily viscous rhyo-
litic lavas. Roof rocks over the magma were weak or dis-
continuous, therefore pressure was never built up within and

only minor explosive eruptions occurred. Periodic deep
faulting may have defused the system, repressing migration
of the reservoir to shallow depths, as suggested by Bacon
(1982) for the Coso bimodal volcanic field.

A generally-accepted model for bimodal volcanism is
lacking. Further investigations are required before the
basalts and rhyolites of Glass Buttes can be genetically
related, and is beyond the scope of this study. If they
prove to be unrelated, models for generation of independent
basaltic and rhyolitic magmas may then be tested.

STRUCTURAL GEOLOGY

LOCAL STRUCTURES

Lineaments

Aerial photographs of Glass Buttes indicate abundant linear features (Fig. 14). The lineaments are defined on photographs by vegetation changes, stream channels and shadows. In many cases, lineaments are fault scarps that are continuous for over 3 km across the barren plateau. The scarps trend N50°W in the vicinity of the eastern Glass Buttes but may be of variable trend from N5°W to N75°W locally, producing a sinuous pattern in the scarps. Northeast-trending lineaments are much less frequent.

Within the eastern Glass Buttes, two major linear features are evident. The first trends N40°-50°W and lies along Antelope Ridge and may be traced across the low, obsidian-covered hills to the northwest. This trend is subparallel to the strike of the main scarps noted in the plateau basalts surrounding the buttes. A second well-developed feature parallels Cascade Ridge. It trends about N65°W, and, in the vicinity of Little Glass Butte, changes to a trend of N35°W, a pattern that is similar to the trend of scarps in basalt on the plateau. North and northeast-trending lineaments visible on aerial photographs may be
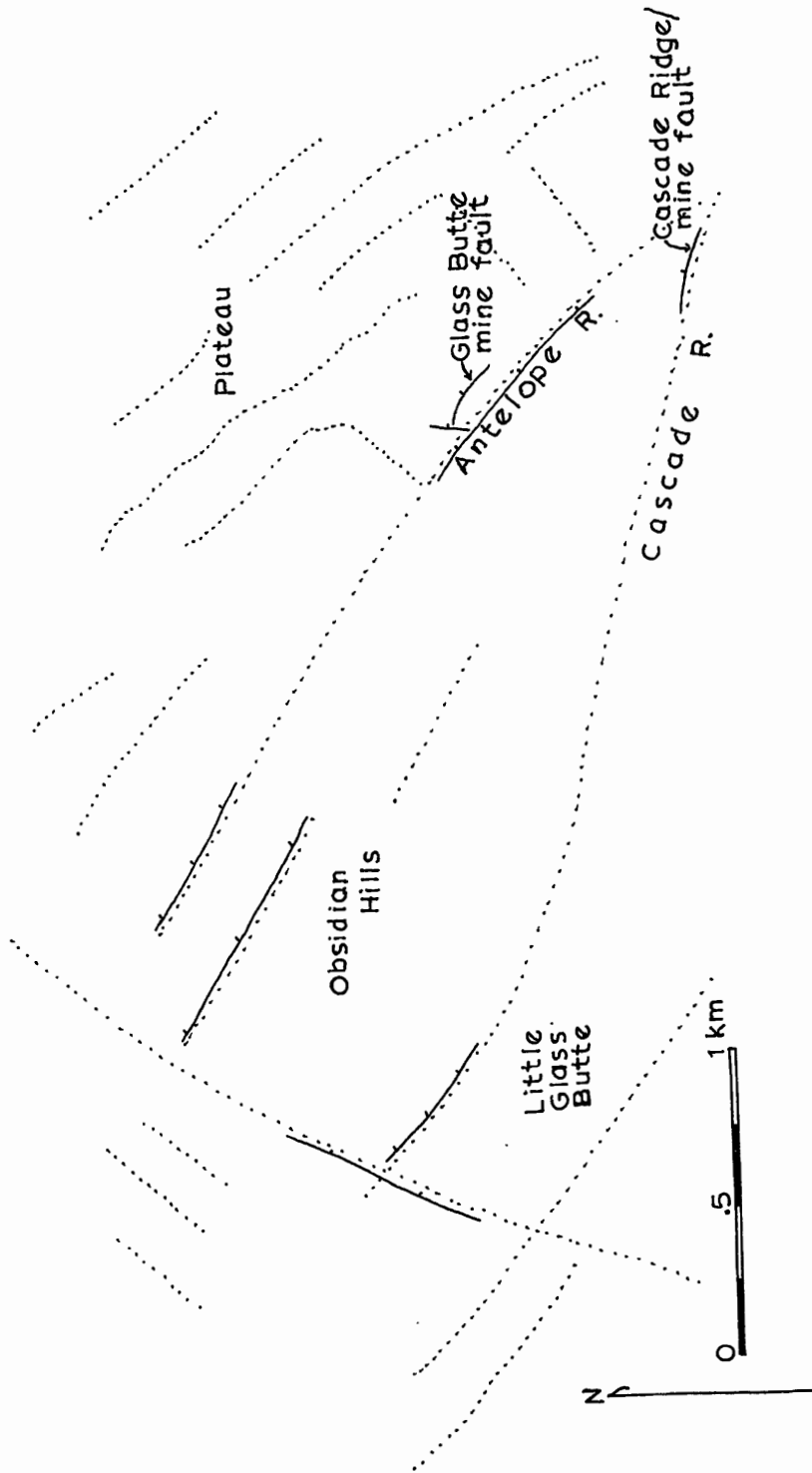
Figure 14. Lineaments and faults, eastern Glass Buttes. Dotted
lines - lineaments, solid lines - faults, with tics on down-
thrown side.

directly fault-controlled, or may be the result of erosional channels trending perpendicular to structural trends.

Faults

The youthful Glass Buttes topography shows many scarps in rhyolite that are believed to be fault scarps despite lack of field observation of grooves, slickensides or fault gouge (Fig. 14). The locations of faults in the east Glass Buttes were, in fact, inferred in nearly all cases from topographic character, and supported by loci of hydrothermal alteration and/or linear scarp trends that parallelled regional structure.

Displacement on the faults is probably moderate to small. Step-like fault scarps on the north flank of Little Glass Butte average about 5 m in height, and faults in the plateau basalt expose cliffs up to 10 m high in the vicinity of Glass Buttes. Plateau basalt that flowed into the eastern buttes has been fault-displaced about 90 m. Walker and Nolf (1981) state that vertical displacements on the Brothers fault zone have generally been from 10 to 100 m. Fault displacement at Glass Buttes probably falls in this range.

The Cascade Ridge fault is exposed at the Cascade mine, southeast Cascade Ridge (Fig. 14). The near-vertical scarp trends N60°-70°W, curving slightly north-northwest at the east edge of the exposure. The fault surface is a resistant, opalite-cemented breccia, and the footwall is silicified. Horizontal ridges about 30 cm wide appear high on the scarp

(see Fig. 24). While slickensides were lacking, these ridges imply horizontal strike-slip motion on this curving fault.

The Glass Butte mine fault (Fig. 14) is a similarly curving, north-dipping fault with an opalite-breccia surface and silicified footwall. Neither slickensides nor horizontal ridges were observed here. Another fault on Antelope Ridge is north-trending, east-dipping, and displaces opalite against unaltered glass, thus post-dates alteration (see Structure Related to Alteration).

The Antelope Ridge and Cascade Ridge-Little Glass Butte lineaments described above are believed to represent extensions of the Glass Butte mine fault and Cascade Ridge fault, respectively.

The valley between Antelope Ridge and Cascade Ridge suggests either a large amount of vertical displacement on the Cascade Ridge fault, or a wide separation of the original Cascade and Antelope volcanic centers that was accented by the Cascade Ridge fault. The location of these eruptive centers may have been controlled by structures that represented zones of weakness during development of the buttes and the present trends of Antelope and Cascade Ridges reflect these structures. Continued activity along these faults further dropped the central valley within the eastern buttes, but, in keeping with the regional pattern of low fault displacements, the central valley is more likely a low spot between two rising volcanic features.

Joints

While structural data from faults are limited, the
orientation of joints provides more detailed information.
Over two hundred joint attitudes were collected from densely
jointed outcrops. To analyze this data, four geographic
domains were distinguished on the basis of prominent topo-
graphic features. For each domain, the poles to the joints
were plotted in the upper hemisphere of an equal area net,
and the data were contoured. This was accomplished by use
of a joint analysis computer program developed by Fred
Gullixson, Portland State University.

The contour diagrams are presented on Figures 15 and
16. Antelope and Cascade Ridges (Fig. 15) show a high con-
centration of flat-lying joints. Much of the Antelope Ridge
data represents platy-type jointing, low dipping to hori-
zontal, corresponding to primary flow layers in the Antelope
rhyolite. Joints formed normal to the direction of contrac-
tion in the cooling lava, in many cases coinciding with flow
planes. The slight development of northwest dips may reflect
the northwest-dipping Antelope rhyolite flows. Data from
Cascade Ridge also show shallow west and southwest-dipping
platy jointing also related to local primary flow directions.
North-south joints and trends of $N45°-90°W$ may be related to
regional stresses described earlier including the north-
dipping Cascade Ridge fault.

The Little Glass Butte joint data (Fig. 16) show a
weak ring of fracture orientations having moderate to high

Figure 15. Stereograms of poles to joints, eastern study area. Contours are in the sequence 2%, 5%, 10%, 15%, 20%, 25%, 30% per 1% area; number of data points at lower right.
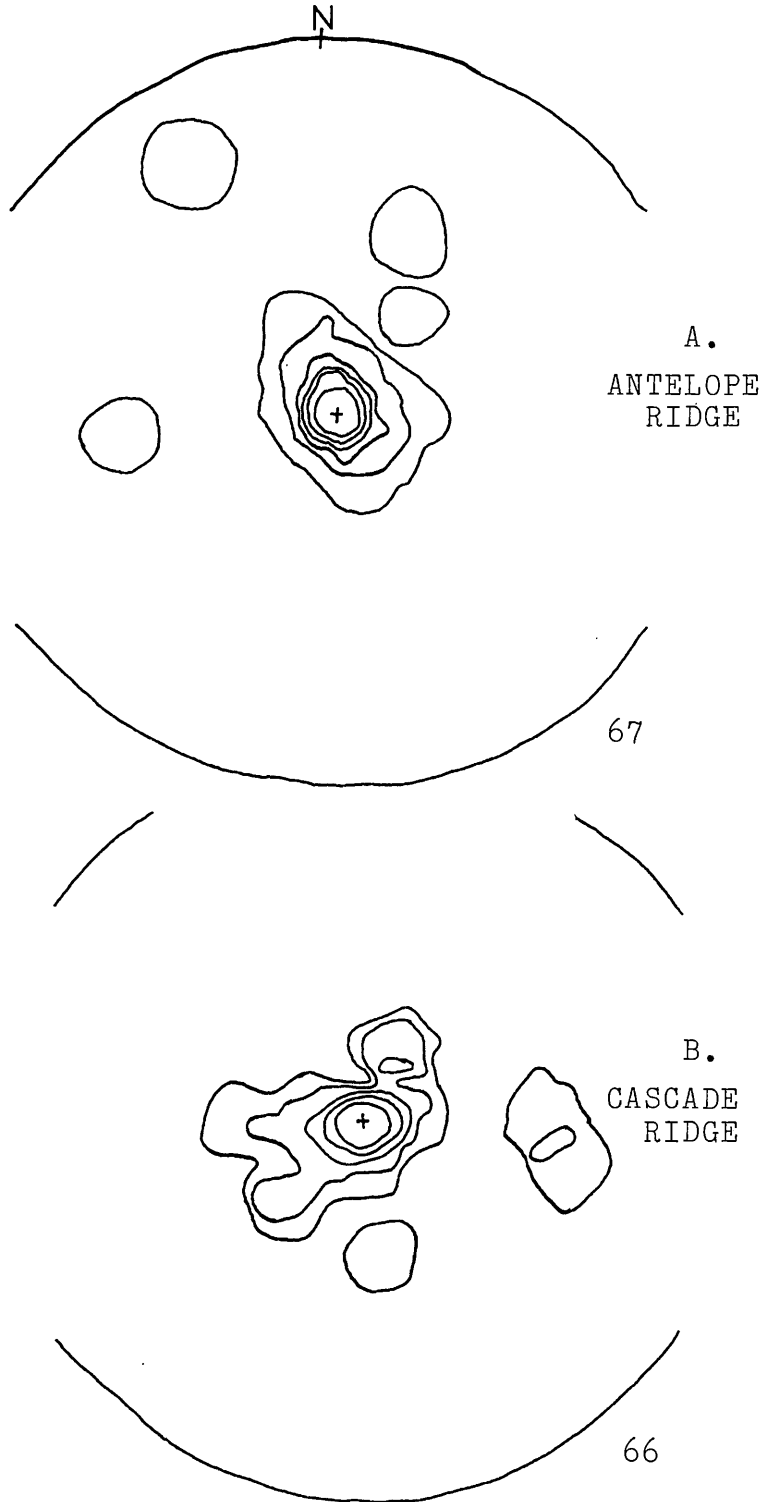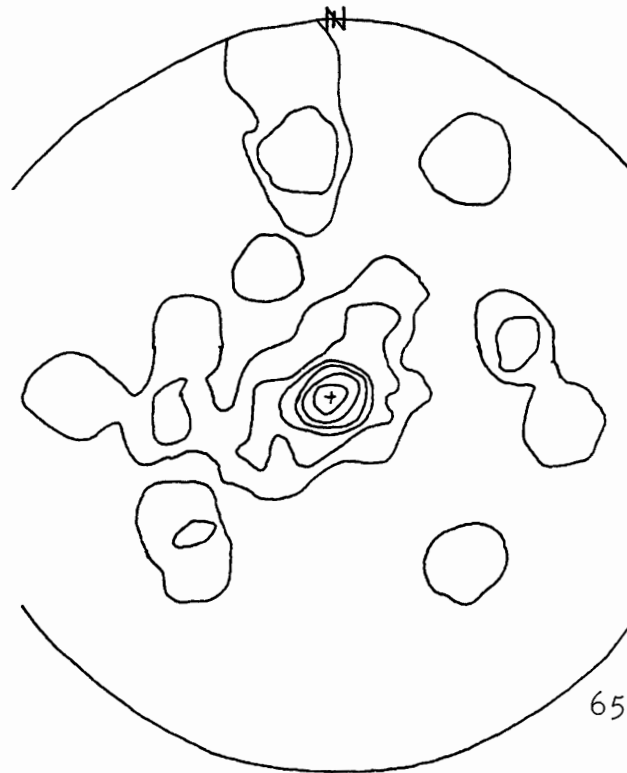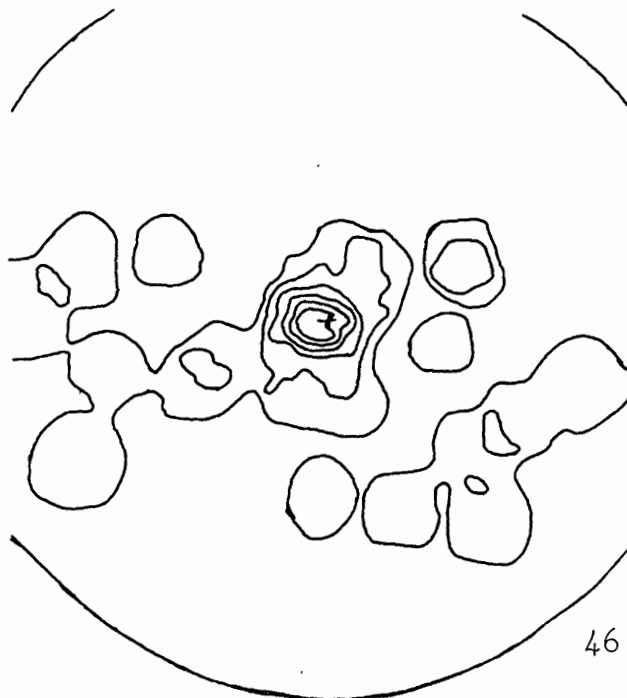
Figure 16. Stereograms of poles to joints, western study area. Contours are in the sequence 2%, 5%, 10%, 15%, 20%, 25%, 30% per 1% area; number of data points at lower right.

dips, in addition to a concentration of shallow-dipping to horizontal platy joints. This group of diversely oriented joints could have formed by doming of the butte after eruption of the rhyolite and obsidian flows (Wells, 1979; Steven and Lipman, 1976). Outcrops are not, however, continuous around the butte, and so doming is not supported by field evidence. The variety of joint attitudes may represent cooling fractures that formed along irregular flow bands.

In the Obsidian Hills area (Fig. 16), a wide range of joint orientations dip to the south, that is, toward Little Glass Butte. Fractures ringing a dome were found by Steven and Lipman (1976) and Wells (1979) to dip toward the dome. This might partially support doming of Little Glass Butte, though data west and south of the butte are lacking. These joints could also reflect gravity sliding to the south into the fault valley running between the Obsidian Hills and Little Glass Buttes domains.

Joint analysis only weakly supports the existence of the Cascade Ridge fault but illustrates some local influences (e.g. north-south structures) on the overall trend of the curving fault line. These local influences are a result of rock inhomogeneity, more than one period of fracturing, or nonuniformity of stress orientation or intensity (McKinstry, 1955). An example of nonuniform stresses is the intersection of dominant structures (northwest-trending) with subordinate structures (north-south or northeast-trending).

Joint intensity contour mapping could be applied in the Glass Buttes area. Pohn (1981) used joint intensity to locate the surface traces of faults, suggesting the observed decrease in intensity toward known faults resulted from release by faulting of stresses in adjacent rocks, thus inhibiting jointing. A study by Guth and others (1981) supported this conclusion, but joint intensity has elsewhere been found to increase in the vicinity of faults (Wheeler and Dixon, 1980). The technique might be tested in areas of known faults, but otherwise appears unreliable.

RELATION OF LOCAL TO REGIONAL STRUCTURES

The Brothers fault zone contains discontinuous high angle en echelon normal faults trending N25°-50°W and shorter conjugate faults trending N40°-60°E, while the fracture zone has an overall trend of about N60°W. Experimentally produced shear zones contain similar configurations of fractures (Tchalenko, 1970), that is, have a dominant shear direction (for example, northwesterly) and a conjugate shear set that trends normal to the dominant set (or northeasterly).

The Brothers fault zone may be only the northeast side of a northwest-trending right-lateral strike-slip system that is bounded to the southwest by the Eugene-Denio fault zone (see Fig. 4), and that encloses an area of north-northeast-trending Basin and Range faults (Lawrence, 1976).

The Cascade Ridge fault has features suggesting strike-slip motion, but younger plateau basalt shows only

normal faults. The lack of developed strike-slip faults at
the surface may be due to concealment of the right-lateral
structure by young volcanic and sedimentary rocks. Surface
structures are known to develop in successive stages as a
fault zone matures, or in the case of the Brothers fault
zone, as the fault zone reappears through overlying strata.
Initial structures are normal to the underlying fault, but
with time the fractures become parallel (Fig. 17). The
Brothers fault zone, according to this model, is in an
early stage of development with respect to Cenozoic volcanic
rock cover, with normal faults trending at a high angle to
the underlying strike-slip fault and no through-going
northwesterly faults.

Large dome, vent or caldera complexes are not located
directly on the Brothers fault zone. The belt of silicic
centers defined by MacLeod and others (1976) trends more
westerly. The exact relationship of these intersecting zones
is an interesting tectonics problem, as described earlier,
but beyond the scope of this study. It is not clear if the
Brothers fault zone played any role in localizing eruptive
centers, therefore dating fault zone activity by ages of
nearby silicic rocks may not be valid.

Glass Buttes is at the intersection of the Brothers
fault zone and the silicic volcanic zone. Its occurrence
is related to the silicic volcanic zone, as well as to the
dilational effect of the two intersecting systems. The
influence of the regional structures can not be separated at
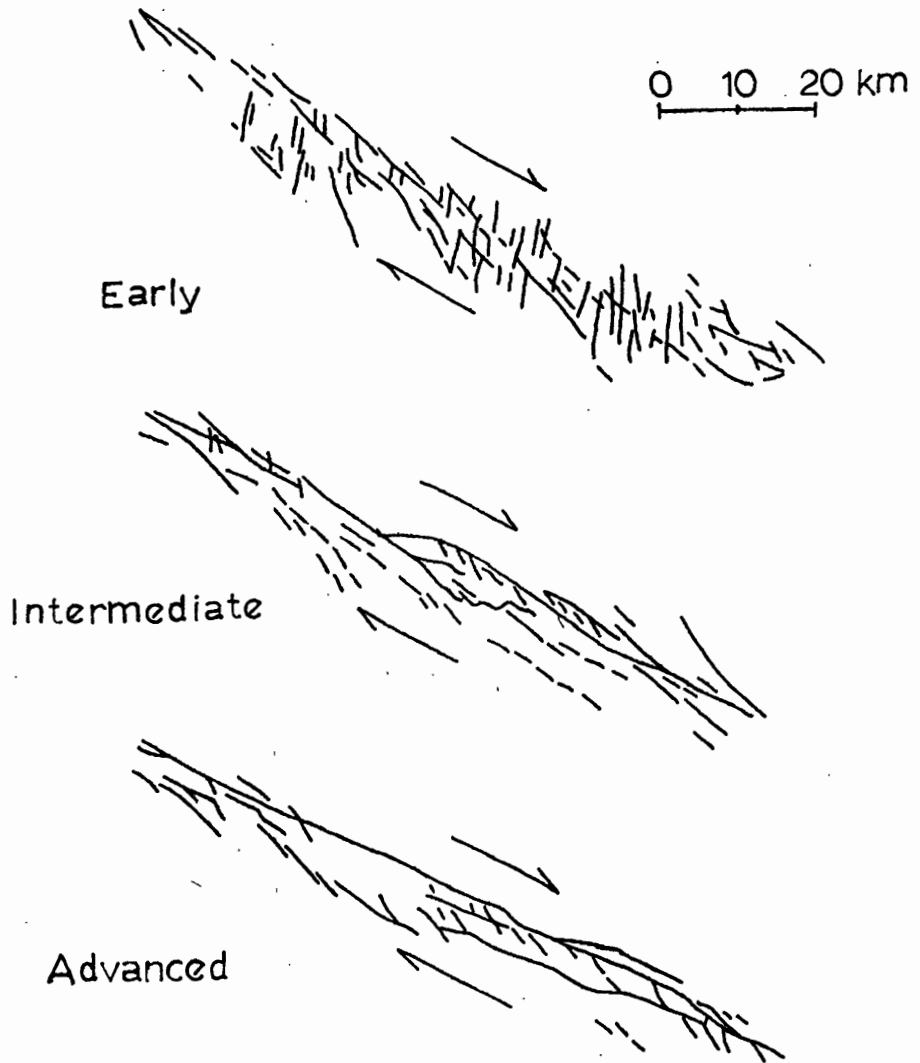
Figure 17. Successive development of surface struc-
tures overlying a right-lateral strike-slip fault.
(Modified from Fig. 9.6, Hobbs and others, 1976.)

Glass Buttes; as indicated earlier, there is only about a 20° difference in the northwesterly trends of the two systems. Hydrothermal alteration and extremely glassy lavas, however, set Glass Buttes apart from most other complexes of the silicic zone, thus the structural intersection played a role in the rapid eruption of rhyolite as well as concentration of geothermal fluids.

Structures within and surrounding the eastern Glass Buttes are summarized in Table II. Joint and fault trends of N40°-60°W are common throughout the region and are related to the Brothers fault zone. The northeast-trending shears on the Brothers fault zone are expressed in the east Glass Buttes as abundant northeast-trending joints rather than fault scarps, and common trends are N40°-60°E.

TABLE II

SUMMARY OF STRUCTURES IN THE EASTERN GLASS BUTTES

	Joints	Faults	Faults in plateau	Brothers f.z.
N90°W	+			
	+	+		
	+	+	+average	+
		+		+
	+			
	+			
N0°W	+	+		
				+
	+			
	+			
N90°E	+			

More westerly joint and fault trends may represent
the influence of the silicic volcanic zone. As can be seen
in the joint trends, the result of this intersection is a
variety of fracture orientations. It is unclear if the two
mineralized faults in the area, Cascade Ridge and Glass Butte
mine faults, each trending N60°-70°W, are related solely to
the Brothers fault zone or to the silicic zone. They may in
fact be the product of both systems.

The possibility of strike-slip motion on faults at
Glass Buttes deserves further study. Are curving fault
planes with variable dips known to have greater horizontal
than vertical displacements? Is strike-slip movement
observed in other buttes of the silicic zone, away from the
Brothers fault zone? Further structural analysis and
definition of these two zones might help distinguish their
effects upon Glass Buttes, at their point of intersection.

GEOCHEMISTRY

Analyses were performed in order to chemically characterize the volcanic units at Glass Buttes. Major element chemistry of unaltered rocks was then compared with that of highly altered rocks to determine the effects of hydrothermal alteration on major element abundances. Chemistry of alteration is discussed in a later section.

Eighteen unaltered rocks were analysed, including rhyolite and obsidian flows, dome-related glass flows and flow breccias, and plateau basalt. Raw data are presented in Table III and were used in all graphic figures. Analyses normalized to 100 percent volatile-free with total iron as FeO may be found in the Appendix. These recalculations remove most effects of surface hydration and oxidation upon major element abundances. As indicated in the Appendix, AAS analyses are considered most reliable for K_2O, while varying up to 20 percent from XRF values for other major oxides. In the following discussion, XRF data (pre-normalized) are used and appear the more reliable.

Included in the Appendix with new analyses from Glass Buttes are previously published chemical compositions of Glass Buttes rhyolite and obsidian and trace and rare earth element data for Glass Buttes rhyolitic lava and obsidian.

TABLE III

CHEMICAL ANALYSES OF GLASS BUTTES RHYOLITE AND OBSIDIAN FLOWS, DOME-RELATED GLASS AND BASALT

	Younger LCB Rhyolite			Obsidian	Older LGB-Antelope Rhyolites						Basalt
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	72.73	72.78	73.77	74.57	75.06	75.30	75.44	75.88	75.95	76.34	48.31
TiO_2	0.25	0.30	0.18	0.21	0.07	0.09	0.10	0.04	0.07	0.04	2.24
Al_2O_3	13.97	14.09	13.46	13.78	13.30	13.24	13.08	13.22	13.03	13.16	16.53
Fe_2O_3	0.73	0.92	0.54	0.59	0.15	0.21	0.21	0.03	0.03	0.12	5.83
FeO	0.84	1.05	0.61	0.68	0.17	0.24	0.25	0.03	0.03	0.14	6.68
MnO	0.03	0.06	0.04	0.05	0.04	0.04	0.03	0.02	0.01	0.05	0.21
MgO	0.23	0.53	0.49	0.42	0.20	0.25	0.27	0.22	0.29	0.26	6.63
CaO	1.54	1.91	1.34	1.36	0.67	0.68	0.90	0.27	0.16	0.41	9.96
Na_2O	3.12	3.20	3.01	3.15	3.36	2.76	2.87	3.12	2.29	3.40	2.74
K_2O	3.71	3.51	3.88	3.84	4.37	4.39	4.27	4.60	4.62	4.51	0.32
P_2O_5	0.07	0.09	0.04	0.05	0.01	0.03	0.10	0.02	0.01	0.07	0.54
Total	97.22	98.44	97.36	98.70	97.40	97.23	97.52	97.45	96.49	98.50	99.98

	Dome-related Glass						
	12	13	14	15	16	17	18
SiO_2	74.07	75.14	76.27	77.36	77.53	77.82	78.96
TiO_2	0.04	0.04	0.05	0.04	0.06	0.04	0.04
Al_2O_3	12.98	13.75	12.82	12.78	10.91	11.11	12.78
Fe_2O_3	0.10	0.24	0.01	0.01	0.03	0.02	0.03
FeO	0.12	0.28	0.05	0.01	0.04	0.03	0.03
MnO	0.04	0.06	0.05	0.01	0.04	0.04	0.01
MgO	0.10	0.23	0.26	0.14	0.16	0.17	0.19
CaO	0.25	0.22	0.22	0.05	0.08	0.08	0.06
Na_2O	3.08	0.34	0.18	2.23	0.15	0.20	0.72
K_2O	4.95	4.17	3.95	4.48	3.82	3.43	2.82
P_2O_5	0.00	0.01	0.01	0.00	0.01	0.00	0.01
Total	95.73	94.48	93.90	97.11	92.83	92.94	95.65

(Obsidian is from Obsidian Hills unit.)

Normative minerals:

	1	6
QZ	35.6	39.1
OR	23.1	26.9
AB	29.6	25.9
AN	7.0	3.5
CO	2.6	3.1
EN	0.6	0.8
FS	0.4	0.2
MT	0.8	0.3
IL	0.4	0.2
AP	0.3	0.0

CHEMICAL CHARACTERISTICS

On the basis of silica content, all rocks are of rhyolitic composition (74 to 84 percent SiO_2), except the basalt (48 percent SiO_2), and are peraluminous. Harker variation diagrams of six major elements versus silica are presented in Fig. 18 for rhyolitic rocks.

Distinct chemical differences can be seen between the younger Little Glass Butte (LGB) rhyolite flow and the older LGB-Antelope rhyolite flows. The younger LGB rhyolite is lower in SiO_2 and K_2O and higher in TiO_2, total iron, CaO and MgO. Obsidian Hills obsidian overlying younger LGB rhyolite north of Little Glass Butte compares closely to the composition of the younger LGB rhyolite (Fig. 18) and suggests a genetic relationship; the obsidian may be the chilled selvage of the younger LGB rhyolite flow.

Dome rocks include massive glass flows, blocky pumice breccias, and finer flow breccias occurring on Antelope and Cascade Ridges. These rhyolitic rocks range from 80 to 84 percent SiO_2. The dome rocks are very low in Na_2O, with the exception of a glass occurring at the southwest end of Cascade Ridge (sample number 12), that appears more closely related chemically to the older LGB-Antelope rhyolites group.

An AF'M diagram for rhyolite and plateau basalt analyses (Fig. 19) shows a bimodal pattern of volcanic composition that is typical of the nearby Basin-Range province. The absence of intermediate-composition rocks is probably real,
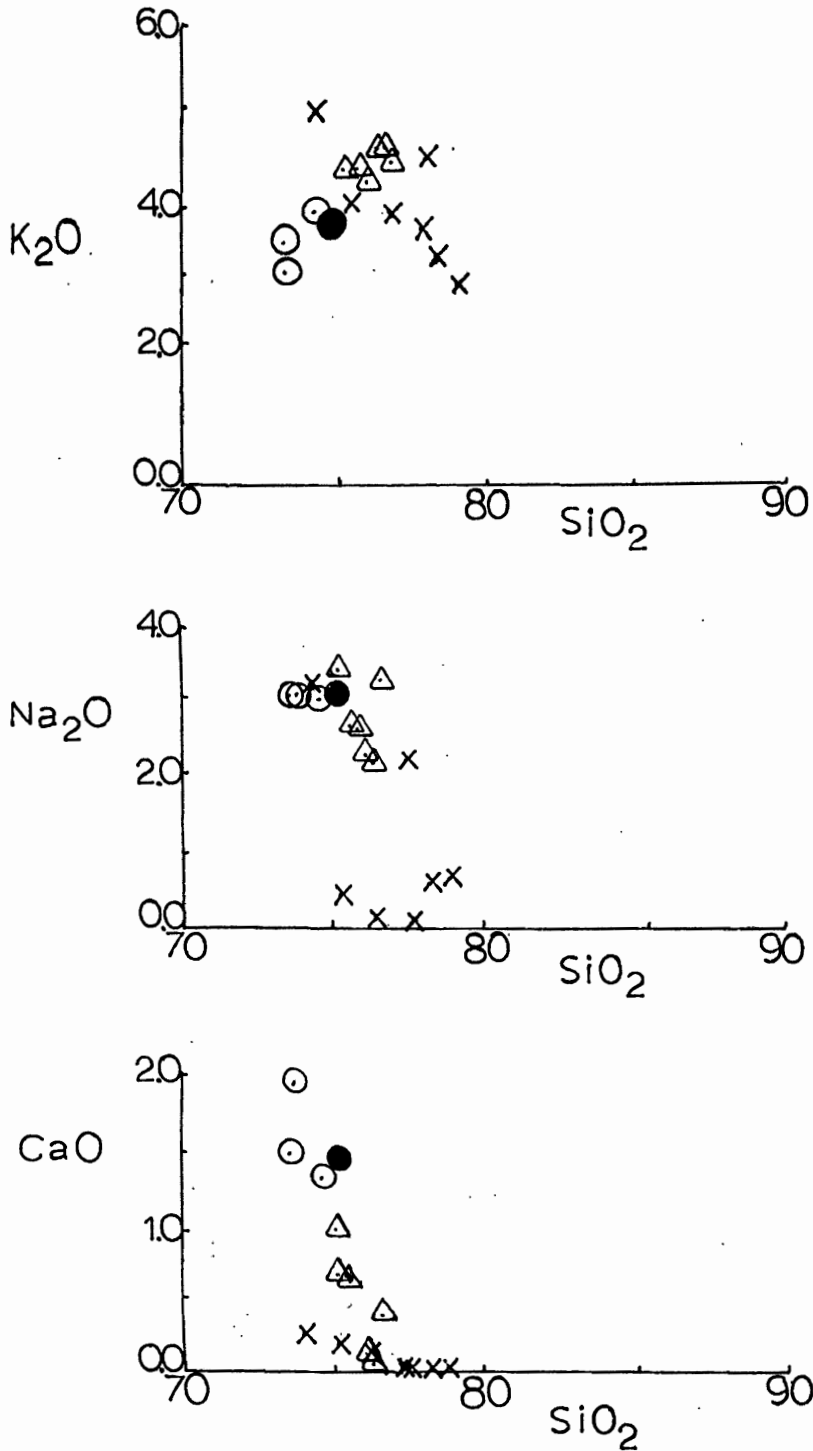
Figure 18. Major oxide variations versus silica.
Key to symbols: open circles- younger LGB rhyolite
flow; closed circle- Obsidian Hills obsidian flow;
triangles- Antelope and older LGB rhyolite flows;
X's- Cascade and Antelope Ridges (dome-related rocks).
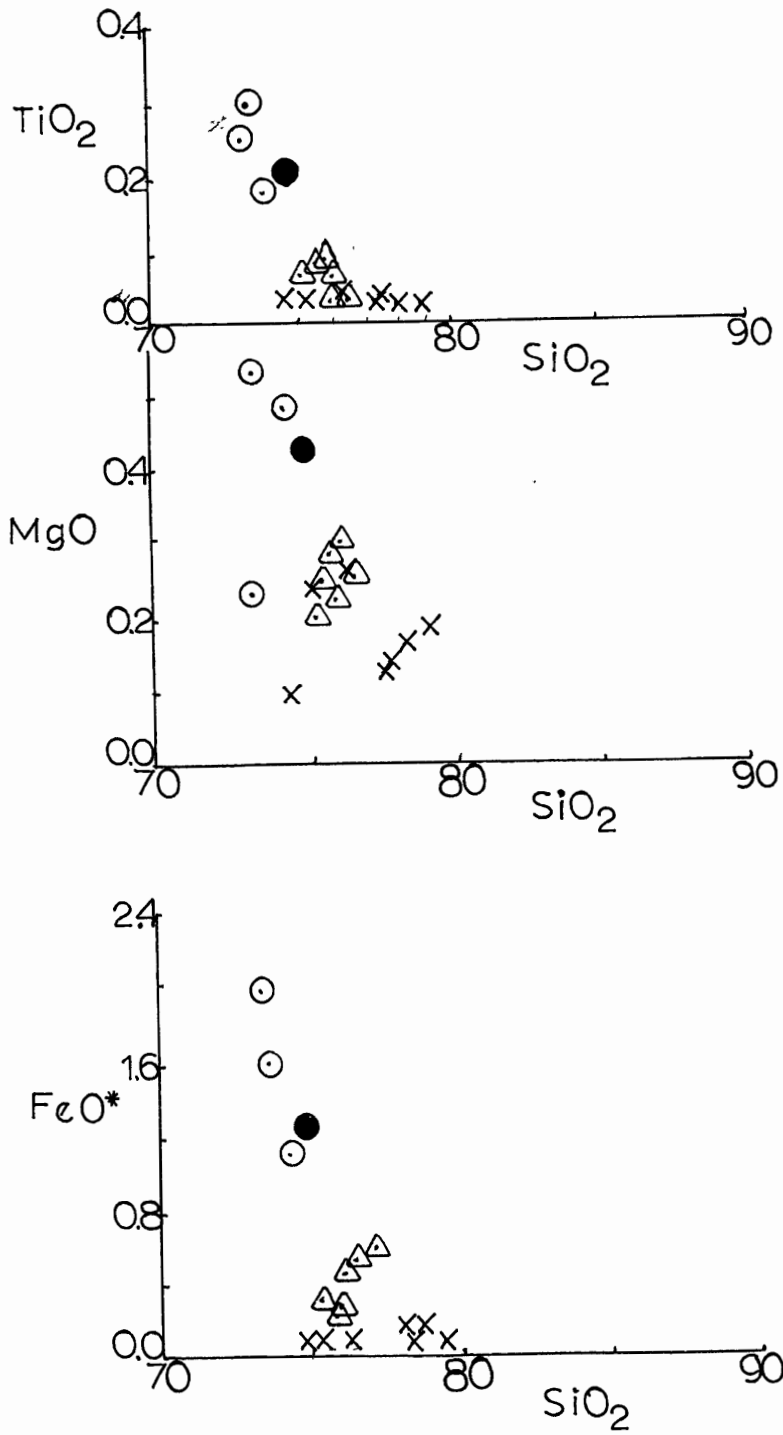
Figure 18. Continued.
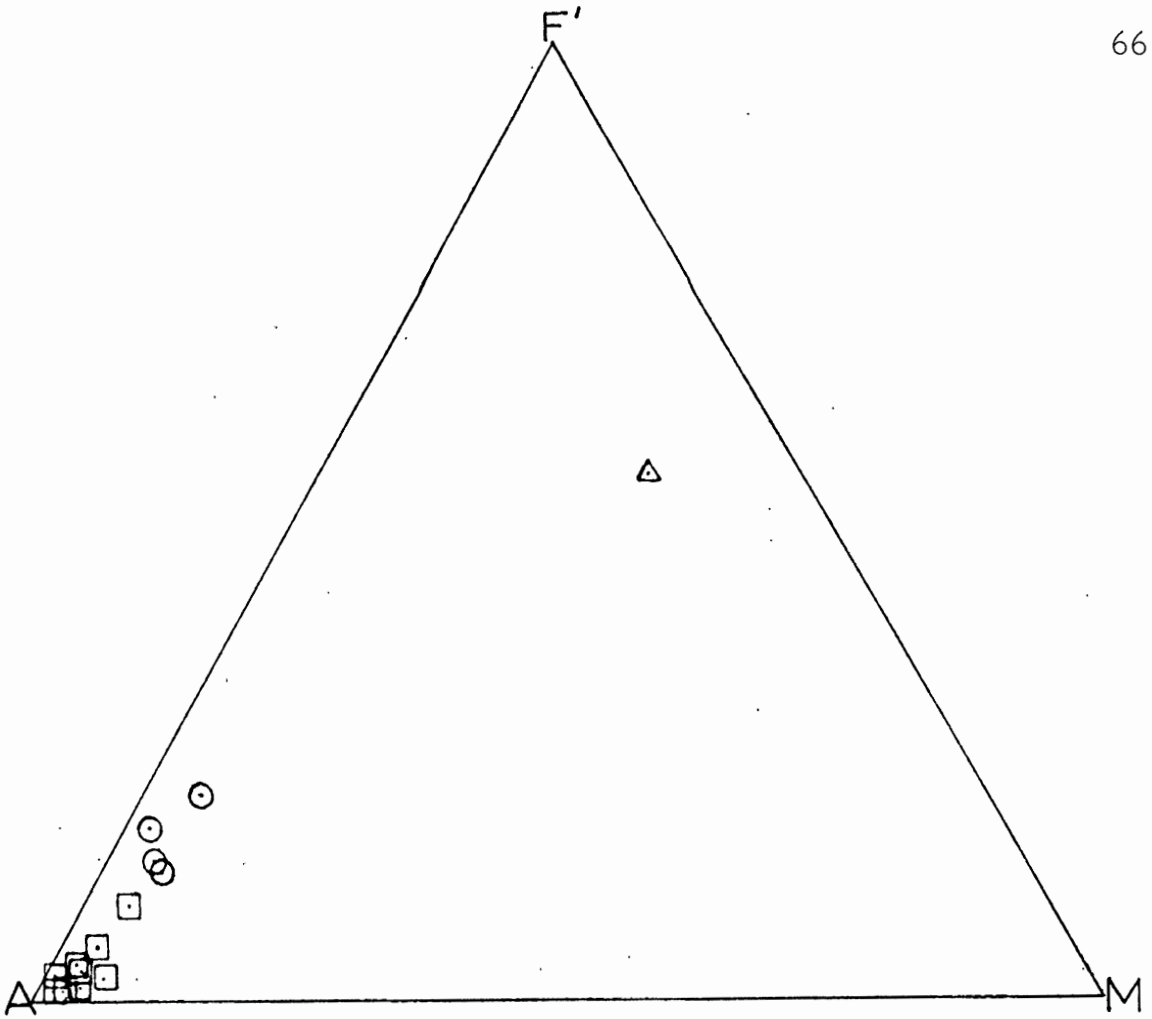
Figure 19. AF'M plot (F'=FeO+0.9Fe$_2$O$_3$+MnO). Symbols: triangle- plateau basalt; circles- younger Little Glass Butte rhyolite; squares- older LGB-Antelope rhyolites.

although a detailed sampling and analysis program could reveal rocks formed from very low-volume eruptions that are andesitic in composition.

DEVITRIFICATION AND HYDRATION

Following eruption and emplacement, rhyolitic lavas undergo physical and chemical changes. The glassy envelope eventually devitrifies, or crystallizes, to cristobalite that may eventually hydrate to perlitic glass (Zielinski and others, 1977). The flow interior will have undergone vapor-phase crystallization that formed alkali feldspar and cristobalite.

Segregation of elements by devitrification has been observed in spherulites. Ewart (1971) showed spherulites are enriched in Na_2O, SiO_2 and CaO compared to the glassy groundmass.

Hydration may occur after the flow has cooled, at which time the unstable natural glass, initially containing only 0.1 or 0.2 percent H_2O, may absorb substantial water (Lipman, 1965). Lipman (1965) and Noble (1967) found hydrated glass contained less Na_2O and SiO_2 compared to unhydrated obsidian nodules within the glass, while behavior of K_2O was variable. Groundwater leaching further removes Na_2O from glassy rocks (Noble, 1965).

DISCUSSION

If the deviation of pre-normalized totals from 100
percent is largely volatile constituents, the following
comparisons may be drawn. Volatile contents are up to
7 percent in the rhyolitic rocks and indicates alteration
has occurred in varying amounts by hydration and vapor phase
crystallization. Dome rocks (samples 12 through 18) contain
the highest amount of volatiles, suggesting extensive
hydration or absorption of H_2O by the glass. Sodium deple-
tion in most of these glasses also indicates hydration has
occurred, as well as groundwater leaching of the inflated
and frothy rocks. Hydration may decrease silica contents,
but SiO_2 is unusually high in the glasses. Volcanic gases,
or vapor phase crystallization, may have silicified these
rocks to some extent. Leaching of many other chemical
components could also concentrate silica relative to other
constituents.

The rhyolite and obsidian flows (samples 1 through 10)
in contrast, show only slightly depleted Na_2O (Brownlow,
1979). Samples 5 through 10 contain 1 to 2 percent more SiO_2
than the average for rhyolites reported by Brownlow (1979).
Volatile contents are also low, especially for obsidian
(sample 4). Less hydration and leaching has occurred, there-
fore, than in the dome rocks, due to the higher density of

the flow rocks. The slightly elevated silica contents could result from crystallization and/or silicification by a vapor phase much less voluminous than existed in the dome rocks.

Major element chemistry shows Glass Buttes compares closely with rhyolite and obsidian dome complexes in the western U. S. and within eastern Oregon (Boyd, 1961; Higgins 1973; Parker, 1974; Lipman, 1975; Walker, 1979; Wells, 1979). Its compositions show no deviation from that of other domes in the silicic volcanic zone of MacLeod and others (1976).

Until intermediate rock types are found at Glass Buttes, a bimodal style of volcanism is presumed. Waters (1927a) describes an older basalt unit found in the west buttes that he believed was correlative with the late Miocene Steens Basalt. This older basalt may represent the low-silica end of a genetic suite of rocks that has culminated in the rhyolite observed in the east buttes, but it is more likely that Waters' older basalt is actually an interfinger-ing internal basalt as found in the eastern buttes and part of a bimodal eruption suite.

Strong europium depletions found here and elsewhere in eastern Oregon (Beeson, 1969) indicate the rhyolitic rocks formed from a relatively low-temperature partial melt of the crust that was removed from parent material. The siliceous magma was then routed to the surface along fault channels.

Temperature and depth of melting were such that europium-bearing feldspar minerals remained stable. If no hydrous minerals remained in the parent rock, the next stage of melting would occur at an elevated temperature and be of basaltic composition (Yoder, 1973). Hence, no lavas of intermediate composition would have formed.

Isotopic and trace element data for the feldspar-rich internal basalt of the eastern Glass Buttes may in the future reveal its mode of origin, contamination by silicic crustal rocks, and any relationship to the plateau basalt.

HYDROTHERMAL ALTERATION

ALTERED SURFACE ROCKS

Alteration of rhyolitic rocks by thermal fluids has occurred in the eastern Glass Buttes, and is confined to the northeast flanks of Cascade Ridge and the west half of Antelope Ridge. Silicification is the dominant type of hydrothermal alteration, in which silica-saturated fluids replaced wall rock and formed opalite. Advanced argillic alteration zones occur irregularly with opalite. Isolated fossil fumaroles show leached and oxidized surroundings.

Following the discovery of cinnabar deposits, numerous trenches and pits were excavated across the east part of the field area. Natural outcrop of silicified rocks was not found, so the following described rocks are loosely termed "surface rocks".

Opalized Rhyolite

Most commonly found at the west end of Antelope Ridge, thoroughly silicified, flow-banded rhyolite varies in color from brilliant white to pink, beige, or brown. The luster of the rock varies from dull and chalky to translucent and glassy. Bright red granular cinnabar coats fracture surfaces and is often finely disseminated within the opalite. Disseminated hematite may impart an orangish-brown color to the opalite.

Often a remnant layered structure can be seen in these rocks that is similar to nearby outcrops of unaltered Antelope rhyolite. Silicification is incomplete in places, leaving irregular lenses of fresh-looking banded rhyolite (Fig. 20) within the opalite.

Figure 20. Incomplete opalization of rhyolitic glass; pit 1, west flank Antelope Ridge.

The brittle, opalized rocks are often broken by fractures that may or may not be resealed with opalite. Cementing opalite locally may contain disseminated cinnabar. These breccia zones commonly trend N50°-85°E.

Opalized Tuff

A single sample of opalized tuff was found in pits on the west flank of Antelope Ridge. Colored a striking

pinkish-brown, the rock is fine-grained, containing rare orangish-brown fragments up to 2 cm across that show basalt textures of iron oxide surrounding skeletal lath-shaped grains. Smaller fragments are rounded pumiceous glass, white to yellow in color.

No other explosive volcanic rocks were found on Antelope Ridge. This opalized tuff underlies unaltered Antelope rhyolite flows, but its relationship to dome glass flows is uncertain.

Argillic Alteration

Scattered occurrences of argillized rocks can be found, the largest mass being adjacent to the fault scarp exposed in the Cascade mine pit at the east end of Cascade Ridge (see Fig. 2). Incoherent masses of yellowish-brown clay extend into the hanging wall of the Cascade Ridge fault for at least 4 m. Much opalite on Antelope Ridge shows similar argillaceous material forming irregular pockets or lenses within the opalite (Fig. 21).

X-ray diffraction analyses of these clays produced a broad, diffuse peak centered about cristobalite, indicating amorphous, noncrystalline material, as obtained from the glassy rhyolite in Fig. 7d. Amorphous clays are often associated with advanced argillic alteration common in supergene environments, where clays grade into opaline silica (Meyer and Hemley, 1967). Dickite, kaolinite, seri-cite, quartz, pyrite and alunite may accompany amorphous
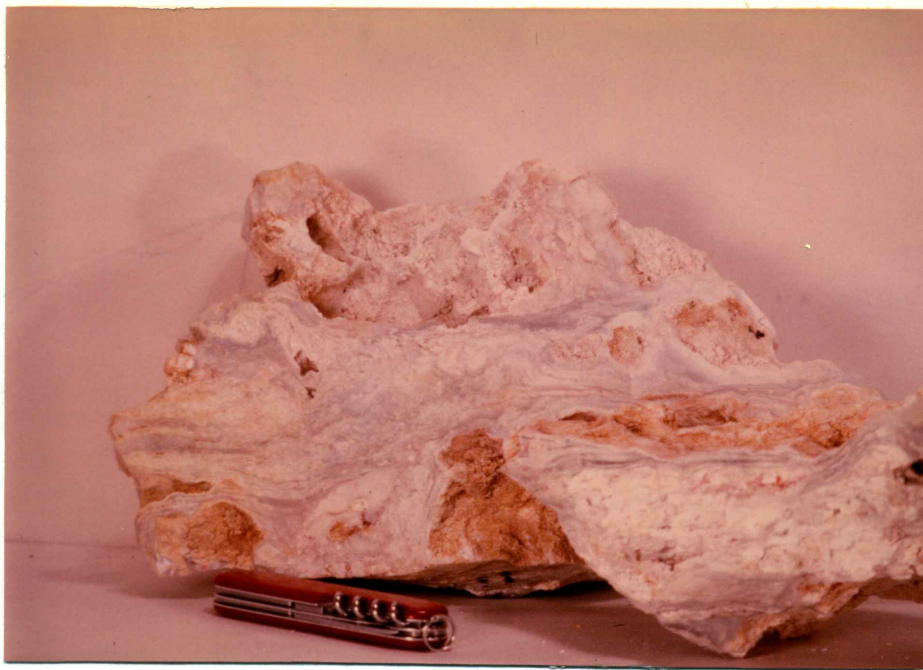
Figure 21. Leached opalite with clay lenses. From mining pits, west flank Antelope Ridge.

clays. Figure 22 is an X-ray diffraction pattern of amorphous clay from the Cascade mine area, showing two alunite peaks, first order at 2.99 Å (29.9°2θ), second order peak at 2.89 Å (30.9°2θ). A broad and diffuse cristobalite rise was also obtained, but no other crystalline material was detected with the amorphous clays.

Fumarolic Alteration

Several small, isolated areas are located on both Cascade Ridge and Antelope Ridge in which a 4 to 6 m^2 section of rhyolitic bedrock is altered to friable, rubbly exposures of dark red-brown rock. Bits of unaltered rock can be found within the piles. Fumarolic alteration of the pumice breccia of Cascade Ridge has thoroughly decomposed and permeated the rocks. The frothy pumice blocks in the
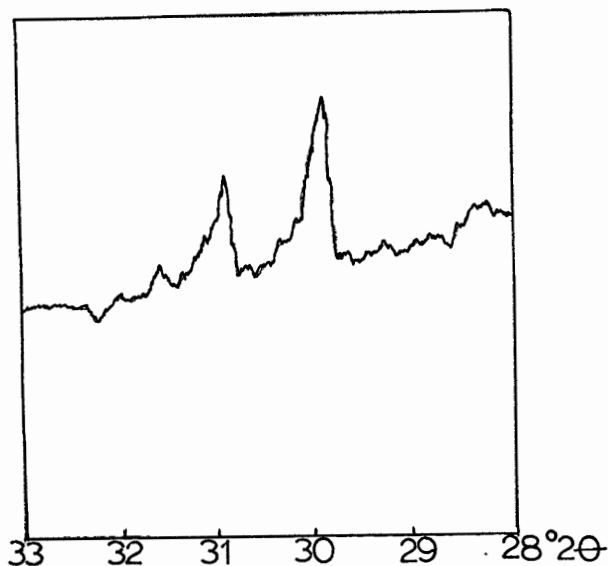
Figure 22. X-ray diffraction pattern from 28° to 33°2θ of amorphous clay from Cascade mine area. First and second order peaks of alunite are shown, at 29.9° 2θ (2.99 Å) and at 30.9°2θ (2.89 Å), respectively.

pumice breccia are reddish-orange and color intensifies toward the margins of the blocks (Fig. 23). The less permeable matrix material is chalky white.

Numerous exposures on Antelope Ridge show flow-banded rhyolite locally having dark reddish-brown fracture coating. Where concentrated, this iron oxide material is botryoidal and often coated with clear silica (hyalite).

These zones are believed to be the result of fumarolic activity (White, 1955) that leaked fluid from the larger hydrothermal system underlying Antelope and Cascade Ridges.

Bleached Rocks

Strongly bleached rocks are a guide to alteration (Schwartz, 1955) and were found along the entire length of

Figure 23. Stained pumice blocks in pumice breccia, fumarolically altered. West end, Cascade Ridge.

Antelope Ridge. Bleached Antelope rhyolite is variously discolored, from pink to red to purple, but with a dull, chalky luster. X-ray diffraction detected no clay minerals, and so bleaching may have resulted by leaching of iron from mafic minerals in the rhyolite, as suggested by Hulen (1978) in a study of the Coso Geothermal Area, California. Scattered reddish-brown fumarolic fracture coating also found in the rhyolite suggests leaching was accomplished by vapors escaping the underlying hydrothermal system on Antelope Ridge.

Sulfides

Cinnabar is abundant in the highly altered west Antelope Ridge opalite (vicinity of Glass Butte mine) and the east Cascade Ridge opalite (vicinity of Cascade mine).

It occurs as a fine, granular coating or thin film on
fractured surfaces and cavities, in very thin veins within
opalite, or as finely disseminated grains in large opalite
masses. The cinnabar may be confused with the reddish-
brown granular hematite that often coats fractures in
cinnabar-bearing opalite. The bright red to pink color of
the cinnabar generally distinguished it from hematite.

 Pyrite is not present in surface rocks, though it is
common in drill cuttings, as described below. At higher
levels in the hydrothermal system, iron was apparently
oxidized to hematite.

Hyalite

 Botryoidal or smooth fracture coatings of hyalite
(clear amorphous silica) are found throughout the field
area, but only in the eastern portion is it found coating
hematite in fumarolically altered sites. Hyalite is rarely
found in areas of extensive silicification. Since the
hyalite is commonly associated with fumarolic alteration, it
may have been a constituent of a vapor that transported iron
in the eastern buttes. Elsewhere, the occurrence of hyalite
alone may indicate a lower temperature hydrothermal vapor or
liquid (e.g. volcanic gases) penetrated the surface, but was
unable to thoroughly alter surrounding rocks as in the
fumarole areas to the east.

 The fumaroles at Glass Buttes are believed to post-
date opalite formation, thus the hyalite in the eastern

buttes also post-dates the opalite. Hyalite lines vugs in opal veinlets of the Coso Geothermal Area (Hulen, 1978), indicating it formed separately and after the opal.

The temperature relations of hyalite are unknown. Its existence in the western buttes with no other signs of thermal activity suggests, 1) it may be of relatively low temperature, 2) if it represents last gasps from the hydro-thermal system, the system may be shifting westward at the same time as it is receding to depth, and 3) the hyalite may represent volcanic gases from sources separate from the eastern hydrothermal system, e.g. related to cooling lavas or gas-effusion along the axis of a dome. These possibil-ities deserve further study.

STRUCTURES RELATED TO ALTERATION

The northwest-trending Cascade Ridge and Glass Butte mine faults are the major loci of alteration at Glass Buttes. Sites of past fumarolic activity, intensive silicification and mercury mineralization are localized along the trend of these two faults.

Cascade Ridge

The Cascade mine, located at the east end of Cascade Ridge (Fig. 24), consists of a large open pit exposing a fault scarp about 16 m high. The scarp trends about N45°W at the east edge and curves to about N65°W at the west edge of the exposure, dipping 60°N at the center to 70°N at

Figure 24. Cascade mine, northeast Cascade Ridge. View is to southeast, showing Cascade Ridge fault scarp. Note horizontal ridges in upper right half of scarp. Person at lower left for scale.

the edges of the scarp. Trenches throughout the north flank of Cascade Ridge expose masses of white opalite, but cinnabar is associated with the opalite only at the Cascade mine area. The previously suggested intersection of the Cascade Ridge and Glass Butte mine faults at the Cascade mine area provides a favorable site for ore concentration. Brooks (1963) found cinnabar concentrated in brecciated opalite along northwest-trending fractures in the tunnel pictured at the center in Figure 24.

The surface of the scarp is a cemented opalite breccia. Both cement and breccia fragments contain cinnabar. Silicification has occurred into the footwall, and the hanging wall material is argillized, grading outward into fresh, massive

dome-type rhyolitic glass. Horizontal ridges across the
scarp noted earlier are suggestive of strike-slip movement
along the fault.

Antelope Ridge

Brooks' investigation of quicksilver deposits in
Oregon also describes the Glass Butte mine, located on the
north-central flank of Antelope Ridge (see Fig. 2; Brooks,
1963). Concentration of cinnabar occurs along a fault
surface curving from N58°W at the east to N80°W at the west
end. The fault dips steeply to the north at each end, and
less steeply at its center. The dipping fault surface is a
thick opaline breccia recemented with cinnabar-bearing
silica, similar to the Cascade Ridge fault scarp. This type
of structure formed a cap on rising ore fluids, which concen-
trated cinnabar in the footwall zone of both the Glass Butte
mine fault and the Cascade Ridge fault.

The surface attitude of the Glass Butte mine fault was
N53°W, 53°N; less than 2 m southwest of the fault scarp is
a large smooth joint surface in the opalized footwall that
trended N87°E, 70°N.

Pits on the northwest flank of Antelope Ridge have
exposed a dark blue to grey rhyolitic glass. In the southern
pit 1 (Fig. 25), the glass shows progressive replacement by
opaline material from east to west; the replacing material
is at first clay, then brittle opalite veins, and finally
massive mineralized opalite, over a lateral distance of
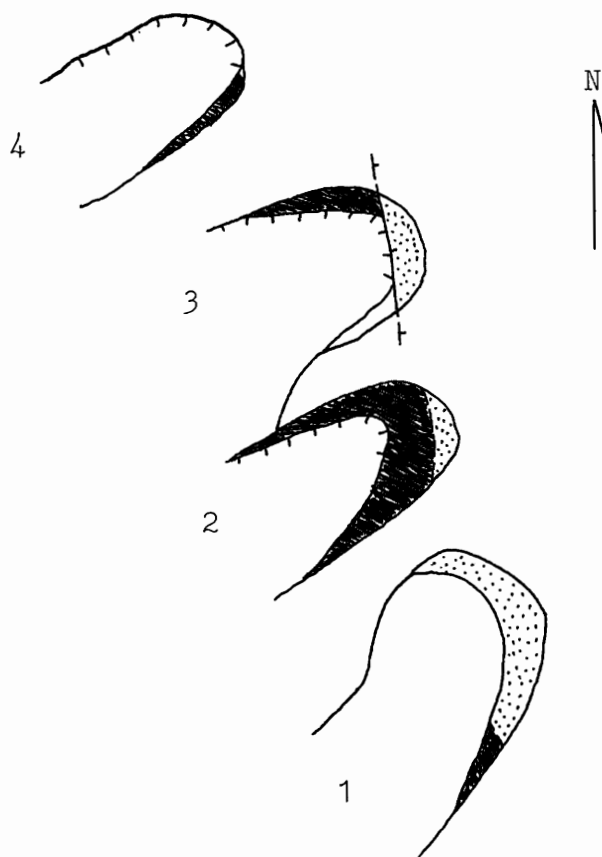
Figure 25. Mining pits, west flank Antelope Ridge.
Showing relations of opalite (stippled) to blue glass
(shaded), and fault in pit 3 trending N0-10°W. Pit
numbers refer to text. (Scale 1 cm = 0.3 km)

15 m. The next pit to the north, pit 2, also exposes this

gradation. Further north in pit 3, the glass forms the north

and south walls of the pit while the east wall is opalite.

The borders of the opalite trend about N0-10°W across the

pits. Unaltered glass is exposed in the northern pit 4.

The sharp vertical contact of glass with opalite in pit 3 suggests this is a faulted surface trending N0-10°W. Although banding in the glass is slightly contorted, there is no evidence of flow breccia, as expected if this were a depositional contact of glass against an up-faulted mass of opalite. A 6-cm thick, sharply defined zone of contact alteration is present, and the glass does not show obvious chemical alteration. Fragments of fresh, dark blue glass are found within the soft, clayey gouge zone. The clayey zone also contains concentrations of pink to bright red cinnabar, and grades into leached opalite having pockets and lenses of argillaceous material. About 26 cm away from the gouge zone, opalite becomes more dense and unaltered.

The clay zone corresponds to a fault surface that fractured the opalite, displacing it next to dense rhyolitic glass, and allowed cinnabar-bearing fluids to leach opalite in a zone at least 25 cm wide, while the clayey fault gouge trapped cinnabar. Cinnabar may be related to a fluid either transporting mercury from depth, or leaching it from neigh-boring opalite. Curiously, the fault is not sealed with opalite, despite leaching by the hydrothermal fluid of opaline wall rock.

Another north-northeast-trending structure, inter-secting Cascade and Antelope Ridges, could be proposed to tie together fumarolically altered areas on the ridges, but lack of further field evidence does not justify this.

Discussion

The relation of certain fracture sets to different styles of silicification (including opalization with or without cinnabar, brecciation of opalite, or hyalite fracture coating) remains relatively unknown. Silicification and mineralization must have occurred in at least two episodes; brecciated opalite is itself cemented by opalite. It has not, however, been possible to describe fractures dominant during one specific hydrothermal surge. The major faults described above are northwest-trending, while conjugate fractures such as breccia zones and large joint sets in opalite trend N50°-85°E. Although many of these breccia zones are filled with silica and cinnabar, an equal number are barren and not recemented. Fracturing, then, continued after alteration had ceased.

Additional evidence exists for faulting and volcanism occurring after alteration. The fault cutting opalite in pit 3 on Antelope Ridge indicates faulting occurred after opalite development. Opalized pumice breccia common on the northeast flank of Cascade Ridge has an abrupt depositional contact with overlying unaltered flow breccia. A similar contact was observed in drill cuttings from north of Antelope Ridge, described later.

Continued eruptions during or after operation of the near-surface hydrothermal system may have capped or choked-off fluid circulation that formed massive opalite bodies,

although fumaroles continued to leak fluids from isolated points along Cascade Ridge and Antelope Ridge, altering younger rocks.

CHEMISTRY OF ALTERATION

The principal types of alteration at Glass Buttes are silicification and advanced argillic alteration. Silicification is accomplished by hydrothermal addition or selective leaching of cations leaving only residual silica. Removal of aluminum may be complete, and calcium and sodium are often strongly depleted; potassium may be depleted if alkali feldspars are destroyed (Meyer and Hemley, 1967). The advanced argillic assemblage, associated with and grading into opaline silica, includes clays, alunite, pyrite and quartz. Amorphous clays of this assemblage are common in a supergene environment described in the next section, and represent a zone of lower aluminum mobility.

The predominant type of alteration is silicification by water-saturated fluids, supersaturated with amorphous silica. These altered rocks contain 86 to 94 percent SiO_2, and are strongly to totally depleted in alkalis, iron, and aluminum (Table IV). The extremely high volatile contents, inferred from pre-normalization totals of 88 to 95 percent, reflect the large amount of H_2O in opaline silica.

Patterns in distribution of major element abundances for rhyolitic rocks show distinctly the areas of most intense

TABLE IV

CHEMICAL ANALYSES OF SILICIFIED ROCKS

	Antelope Ridge					Cascade Ridge	
	19	20	21	22	23	24	25
SiO_2	86.33	88.86	91.64	93.65	94.44	90.72	91.38
TiO_2	0.04	0.08	0.08	0.06	0.04	0.06	0.04
Al_2O_3	1.03	0.23	0.26	0.03	0.11	0.11	0.24
Fe_2O_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00
FeO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MnO	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.15	0.15	0.12	0.06	0.11	0.14	0.16
CaO	0.02	0.03	0.04	0.03	0.03	0.03	0.03
Na_2O	0.00	0.00	0.01	0.15	0.20	0.00	0.09
K_2O	0.05	0.06	0.05	0.05	0.05	0.05	0.07
P_2O_5	0.00	0.01	0.01	0.01	0.01	0.01	0.01
Total	87.62	89.42	92.21	94.31	94.99	91.12	92.02

hydrothermal alteration in the eastern Glass Buttes.
Figure 26 illustrates the geographic distribution of nine
major oxide abundances across the field area.

Titanium and magnesium are exceptions to the nearly
total leaching of major elements in opalized rocks. With
the exception of the younger Little Glass Butte rhyolite and
obsidian (samples 1 through 4, Table IV), titanium contents
are consistent over most of the study area, ranging from
0.04 to 0.10 percent, with no gain or loss of titanium over
areas of alteration. Finlow-Bates and Stumpfl (1981) demon-
strated this immobility of titanium during intense hydro-
thermal alteration.

The TiO_2 versus SiO_2 graph in Figure 27 indicates TiO_2
values for opalite fall in a range similar to that of
Cascade Ridge dome rocks having silica values of 74 to 79

86
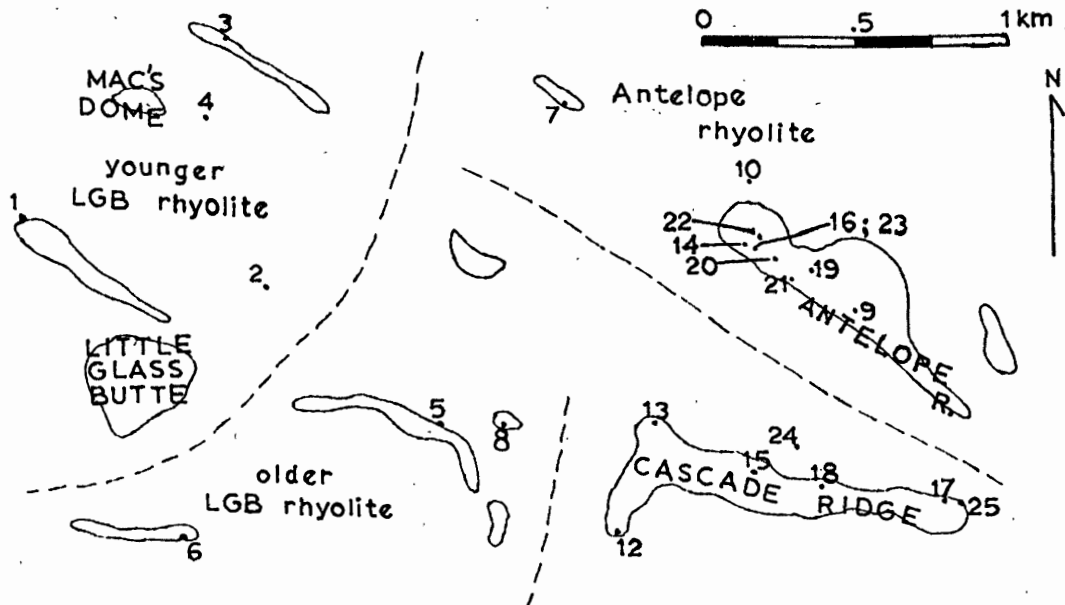
General outcrop areas, geographic names, sample locations
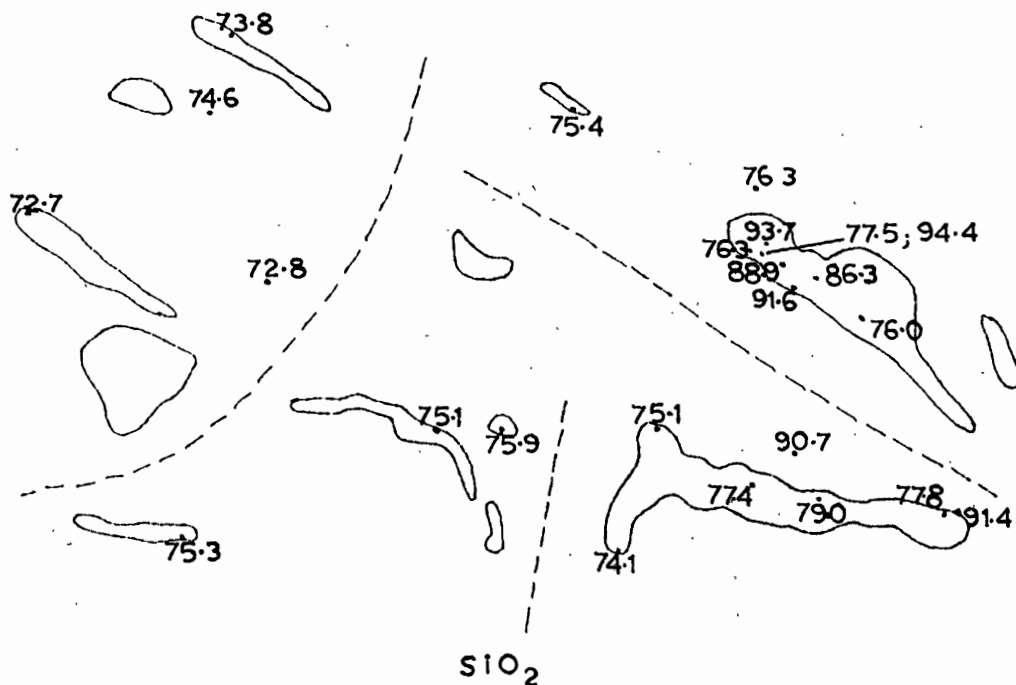
SiO_2

Figure 26. Geographic distribution of major oxide abundances.
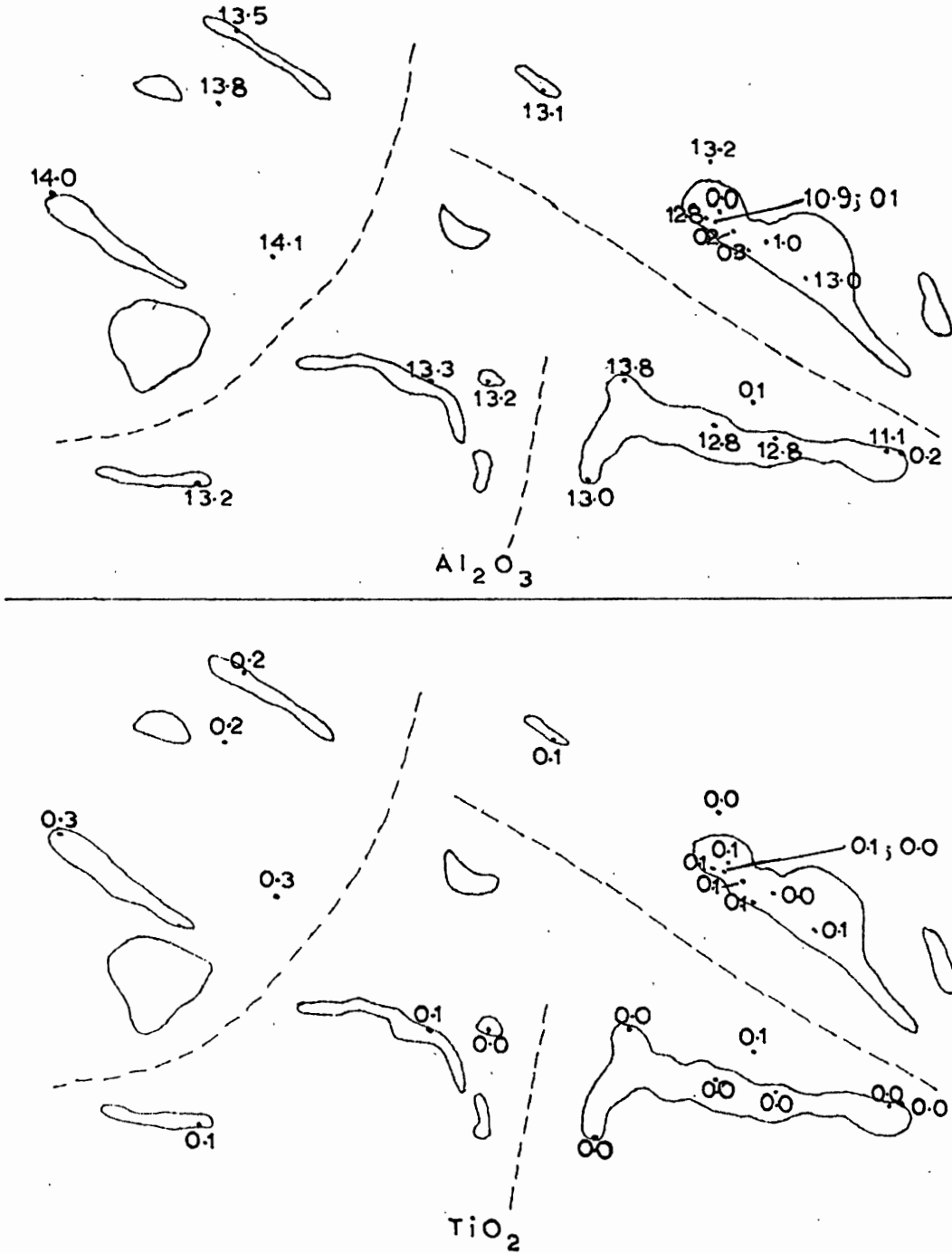
Figure 26. Continued.
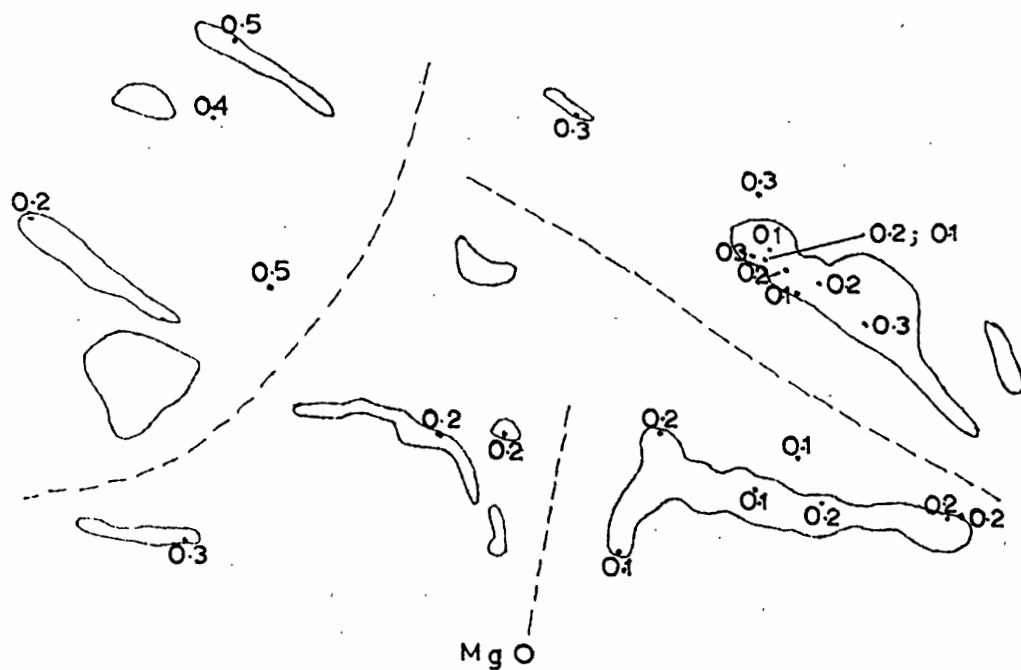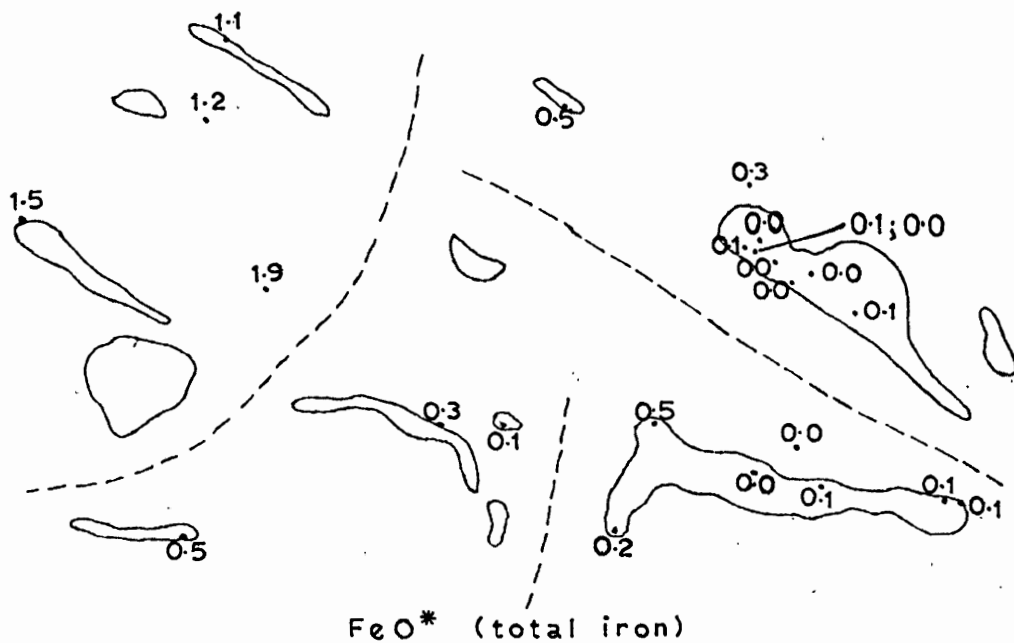
Figure 26. Continued.
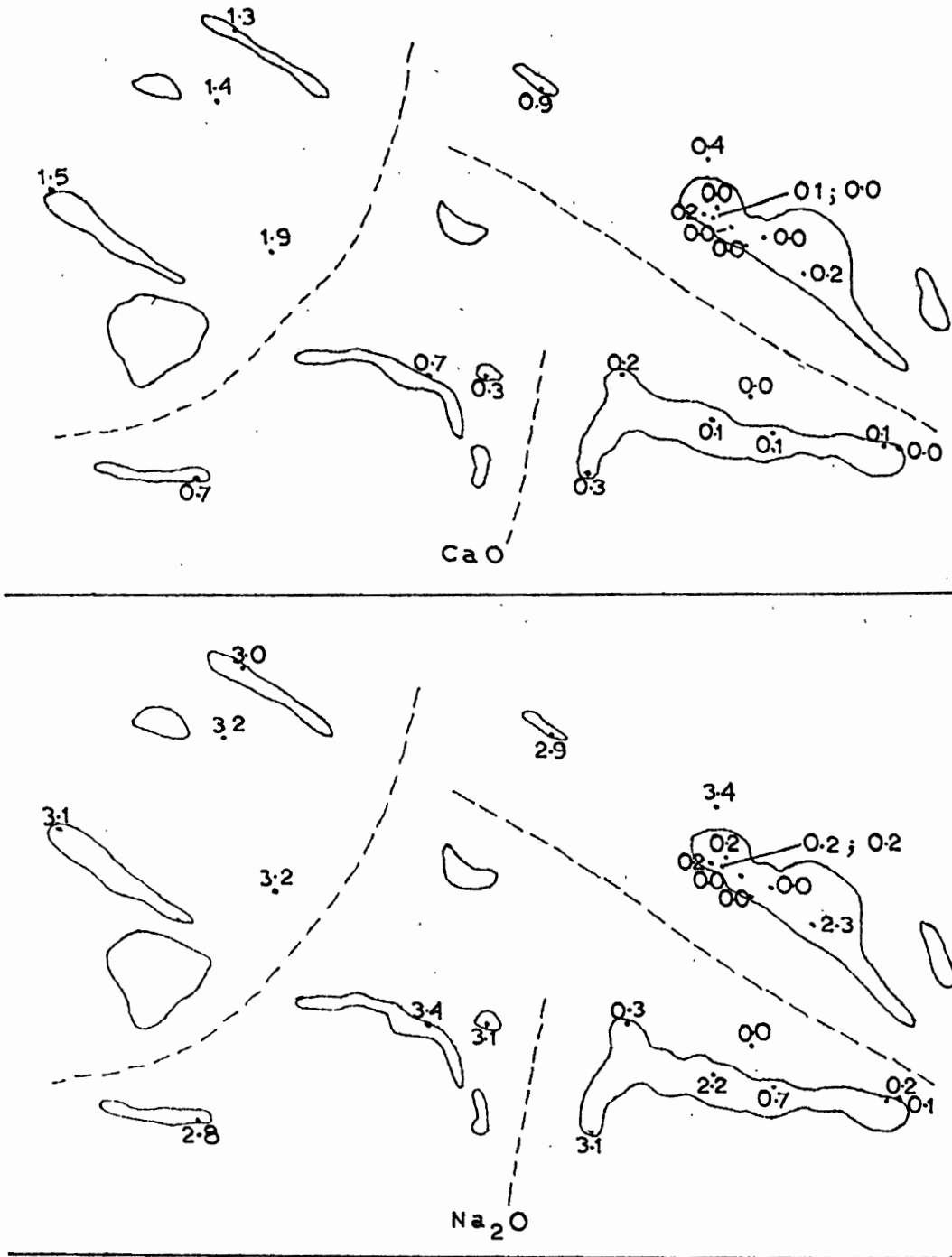
Figure 26. Continued.
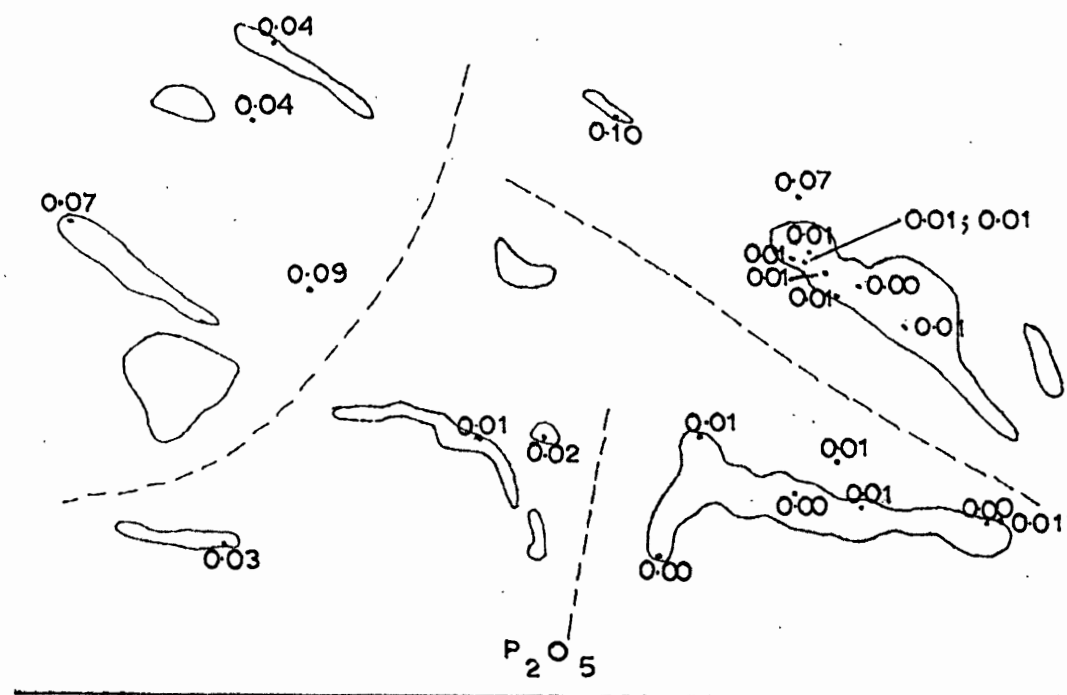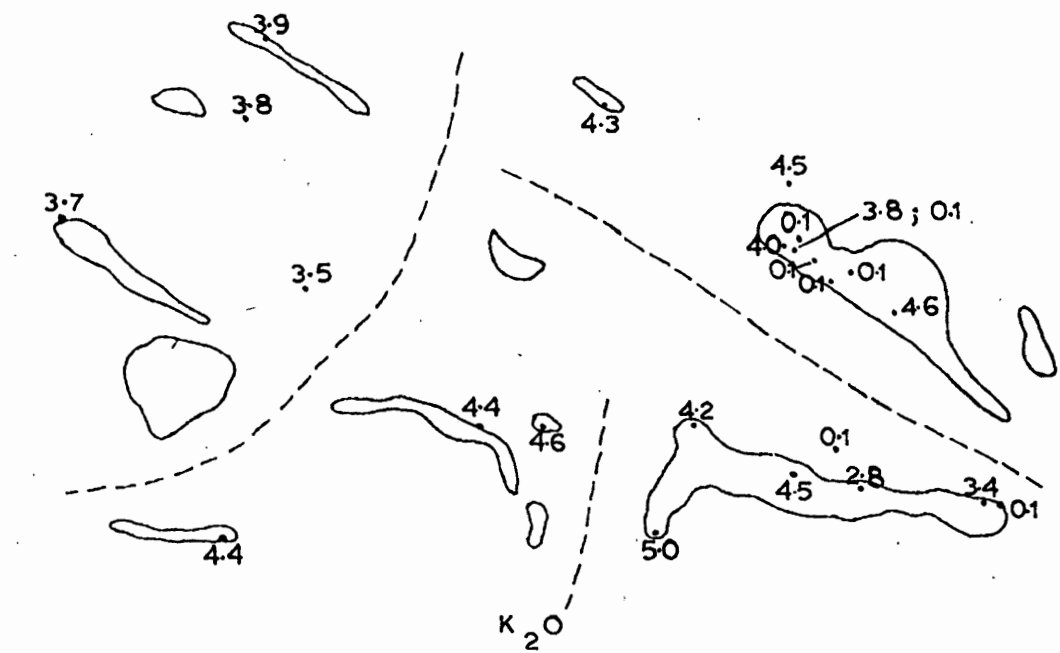
Figure 26. Continued.
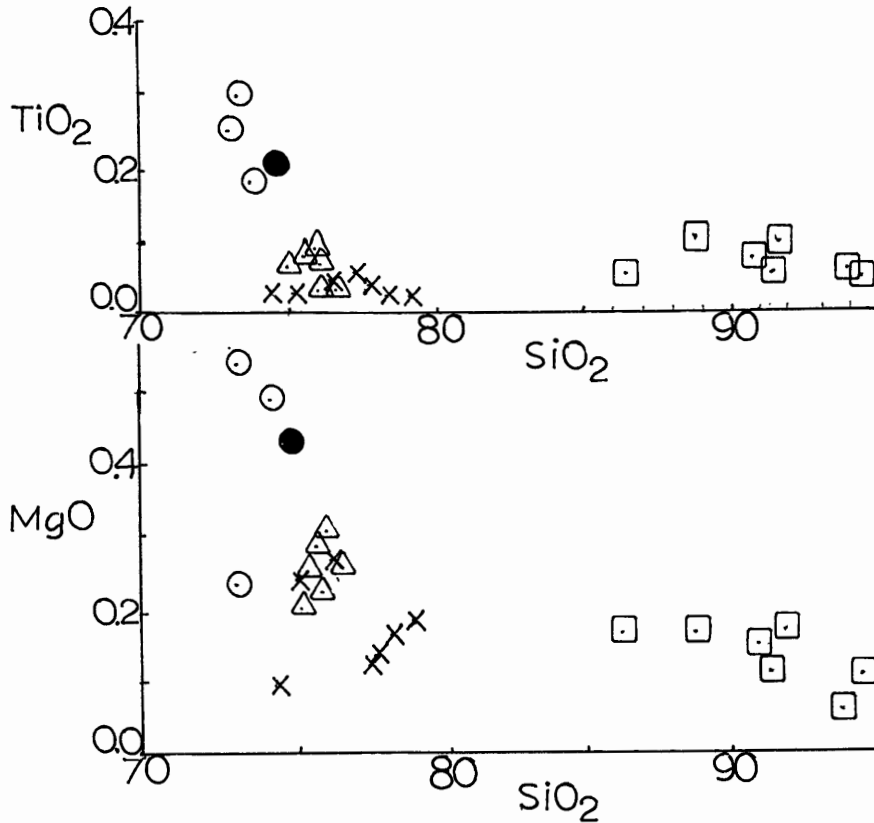
Figure 27. Variation of TiO_2 and MgO versus SiO_2, including opalized rocks, using same symbols as Figure 25, plus squares- opalite.

percent. The dome rocks, therefore, may represent parent material to the opalite, as supported by hand-sample textural comparison of altered with unaltered rocks.

Only a moderate depletion of MgO occurred in the opalite (Fig. 27). Magnesium may have remained nearly immobile under hydrothermal alteration. Alternatively, thermal fluids leached magnesium from wall rocks, which was subsequently replaced by magnesium from descending surface water, i.e. addition of MgO balanced subtraction. Acid near-surface groundwaters may contain magnesium, as well as iron, calcium and aluminum, and lesser amounts of sodium and

potassium (Rose and Burt, 1979). While downward-percolating
waters might have replaced magnesium in the leached rhyo-
litic rocks, there has been no addition of calcium, iron or
aluminum from the groundwater.

Because magnesium abundances in opalite samples are
low compared to unaltered rocks, no appreciable magnesium
metasomatism has occurred. Instead, minor breakdown and
leaching of magnesium components in the rhyolites (biotite
or hornblende) has taken place, but magnesium generally has
remained immobile.

Opalite Deposition

Two different mechanisms are possible for opalite
deposition, through the action of either descending or
ascending fluids. In the first model, H_2S vapors rising
from a boiling water table are oxidized near the surface by
descending groundwater. The sulfuric acid-enriched water
then seeps downward, leaching host rocks. The result is a
near-surface opalite blanket, roughly conforming to the
topography, that overlies a strongly argillized zone (Hulen,
1978). Such opalite blankets are described by Steiner
(1953), Keller and Hanson (1968), Schoen and others (1974),
Hulen (1978), and Parry and others (1980).

The nature of opalite deposits formed by sulfuric acid
leaching differs from deposits at Glass Buttes. At Glass
Buttes, large masses of apparently amorphous clays occur
irregularly throughout the opalite, and a single occurrence

of alunite has been identified. Formation of blanket-
type opalites is favored by horizontally bedded volcanic
sediments, which are not found at Glass Buttes. Instead,
the impermeable glassy rocks may have prohibited lateral
movement of descending acid waters. The resulting opalite
and argillic alteration would form steeply inclined zones,
being dependent upon fault permeability.

The second model involves concentration of silica by
ascending geothermal waters. Silica solubility is reduced
by lowered temperatures and pressures, causing silica to
precipitate near the surface. Considering rock permeability
and opalite geometry at Glass Buttes, opalite was deposited
from hot liquid or vapor rising along fault zones that
replaced rhyolitic wall rock, although minor contributions
of opalite derived from supergene processes (i.e. alteration
by descending groundwater) are probable.

Silica and Mercury-bearing Solutions

Upon cooling below 80° to $100^{\circ}C$, solubility of silica
in ascending geothermal waters is reduced and the fluid
becomes supersaturated with amorphous silica (Browne, 1978),
leading to precipitation of opaline silica. Cinnabar could
be transported by such a fluid at temperatures from 25° to
$75^{\circ}C$; precipitation of cinnabar in this range of temperatures
is triggered by groundwater dilution or by reaction with an
acidic solution (Dickson and Tunell, 1958). Cooled, diluted,

oxidized and/or acidified hydrothermal waters, therefore, allow coprecipitation of cinnabar and silica.

White (1981) presents evidence that, in many of the mercury-depositing active geothermal areaa, mercury transport is largely in a vapor phase at temperatures as low as 35°C, that often is accompanied by a water-saturated liquid or vapor phase that condenses and deposits silica. Because only mercury appears to be present with silica in Glass Buttes opalite, vapor is clearly the mode of transportation; temperature may have been too low for transport of other mobile elements (e.g. silver, antimony, arsenic) in solution.

Cinnabar and minor hematite are the only constituents of the opalite abundant enough to be visible in hand sample. Favorable conditions of pressure and temperature for vapor transport of iron are unknown, as well as if iron persists with mercury in lower temperature vapors, while other elements precipitate. Small amounts of iron may have been carried by either the mercury vapor or by a coexisting silica-saturated water or steam, and precipitated with silica and cinnabar.

Iron and hyalite of fumarolically-altered areas represent different conditions of deposition than those of cinnabar-bearing opalite. Hematite predominates, and cinnabar, if present, is not a visible constituent. Clear amorphous silica, or hyalite, is deposited - never opalite - suggesting a dry, water-free fluid carrier, or vapor.

Fumarolic alteration, then, was achieved by leaching
and decomposition of surrounding rock by a thermal vapor,
followed by precipitation of iron and silica at the surface.
Opalite was deposited by a lower-temperature, water-
saturated liquid, accompanied by a low temperature vapor
that was incapable of transporting significant iron or
mobile epithermal elements other than mercury. As discussed
below, iron/hyalite and cinnabar/opalite deposition may
have been cyclic; one alteration type does not appear to
post-date the other.

Subsurface Alteration

Drilling in the study area by Phillips Petroleum
Company to depths of 600 m encountered relatively low
temperatures. Lithologic logs are presented in Figure 28,
showing zones of leached and bleached rock, brecciated rock,
and occurrences of pyrite, cinnabar, opalite, hyalite and
hematite. Generalized lithologic units are illustrated.
Indicated intervals of unaltered glass may vary in color and
degree of devitrification. Drill hole locations are given
in Figure 28 and are plotted on Plate I.

Zones of leaching intersected by drilling are numer-
ous. Skeletal, dull white to light green glass is commonly
coated with granular sulfides or may contain tiny crystals
of pyrite. Only in drill hole No. 1 does a fault breccia
accompany this leaching, where oxidizing conditions caused
hematite to precipitate from circulating fluids.
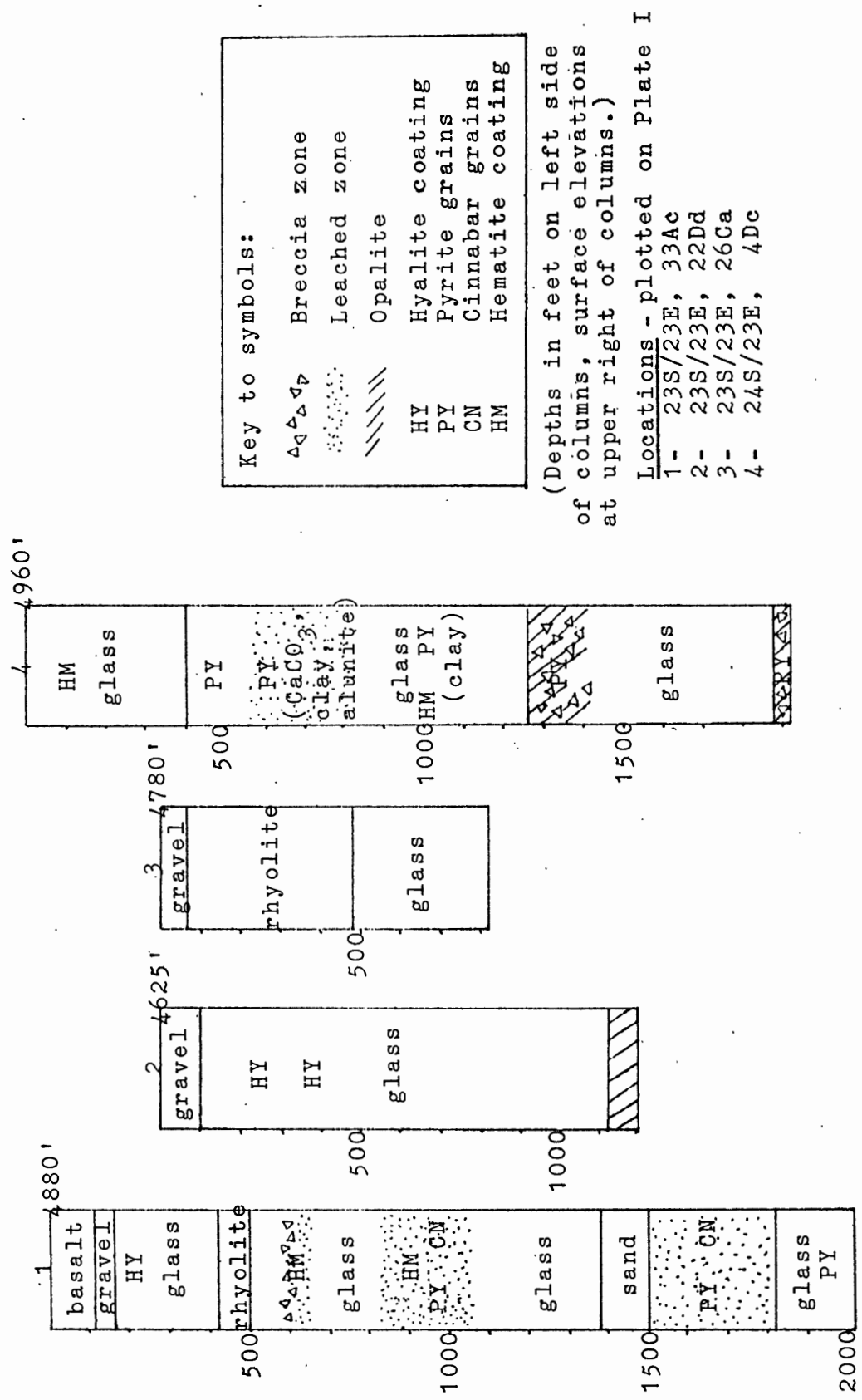
Figure 28. General lithologic logs, showing alteration features.

Leaching is not entirely coincident with groundwater levels existing today. Static water levels in three wells around the buttes are in the range of 141 to 155 m (462 to 509 ft) deep (Hull, 1976), which is considerably higher than the occurrence of leached zones in holes No. 1 and No. 4 (Fig. 28). Sulfide deposition should occur only below the water table where reducing conditions exist; while hole No. 1 shows sulfides below the leached zone, sulfides in No. 4 are above and below the zone.

High temperature and/or pressurized fluids, such as vapor, attacked a permeable zone in No. 4 at around 213 m (700 ft) in depth. Subsequent faulting, releasing pressure, formed a breccia zone at a depth of 384 m (1260 ft) in No. 4 as well as a channel for ascending silica-saturated hydro-thermal fluid. If the channel sealed through deposition of silica, pressure again might have built up and renewed the cycle. This cycle of episodic boiling was used by Buchanan (1981) in modeling sixty epithermal deposits.

The opalite appearing deep in No. 2, located north of Antelope Ridge, is not brecciated at its contact with a thick overlying glass unit; instead, the contact is sharp. Another such depositional contact has already been described as occurring at the surface on Cascade Ridge, and both cases indicate eruptive activity continued after major opalization. In contrast, the two opalized zones in No. 4 are brecciated and contain pyrite at their upper contacts. These latter

two zones may have been fault channels through which silica-saturated fluids circulated, replacing wall rock and cementing the zone with opalite.

In many cases strongly iron-oxidized contacts were observed in drill cuttings between individual glass flows, related to baking of older flows by younger flows of rhyolitic glass. Iron weathered from surface rocks and carried by surface and subsurface waters (Davis and DeWiest, 1966) may migrate in solution and be deposited along fractures (Keith and Boden, 1980), such as could develop between glass flows.

Near-surface opalite does not occur in the vicinity of the individual holes, including No. 1, situated off the northwest flank of Antelope Ridge and nearest to known surface alteration. No. 4 is located on the south-central slope of Cascade Ridge, and shows two zones of brecciated opalite at depth in the hole. The opalite, therefore, is not laterally extensive. It occurs in isolated pockets near the surface, or along steeply dipping fault zones where near-surface conditions of temperature and pressure temporarily existed.

The results of these four drill holes indicate several features of the hydrothermal system. The system is complex and involves more than simple near-surface deposition of opalite and cinnabar. Where structures are not present to release hydrothermal fluids to the surface, pressurized vapors etched and disintegrated rhyolitic glass. If country

rock is faulted, the pressure release causes boiling and cooling, and formation of opalite at depth.

Leached zones represent high permeability that allowed vapor or liquid to penetrate. This could have resulted from faulting, or intersection of faults with permeable units such as flow breccia or sediments that allowed local lateral alteration. Some supergene acid leaching, described earlier, may have occurred above the groundwater table and contributed to permeability. Therefore, some combination of faults, formational permeability and groundwater pathways that may have varied in level through time, led to formation of zones of leaching.

ECONOMIC ASPECTS OF GLASS BUTTES

CINNABAR DEPOSITS

Mercury mineralization was discovered in 1933, and
production peaked in 1957 when 1300 tons of ore yielded 87
flasks of quicksilver (Brooks, 1971). Since that time,
mining has ceased due to poor economic returns. Claims are,
however, still held active.

Underground workings include several tunnels and
shafts on western Antelope Ridge, as well as eastern Cascade
Ridge (see Fig. 24). Opencuts and trenches are abundant
throughout the entire eastern portion of the study area,
and greatly increase the amount of rock exposed for inspec-
tion. Native mercury has not been noted and cinnabar
concentrated in brecciated opalite averages less than 3
pounds of mercury per ton (Brooks, 1963).

Nearby mercury deposits include the Ochoco Quicksilver
District (Schuette, 1938), east of Prineville and north-
northeast of Glass Buttes, that lies along northwest or
northeast-trending faults, and, although silicification is
extensive, no massive opalite is associated with the cinna-
bar. The Opalite Quicksilver District (Schuette, 1938)
includes the McDermitt, Bretz and Opalite mines in the
McDermitt area on the southeast Oregon-Nevada border, where

cinnabar is localized in tuffaceous sediments. Fault-controlled hot springs deposited massive opaline sinter. Brecciation of the opalite was followed by another surge of cinnabar-bearing silica-rich fluid (Rytuba and Glanzman, 1979). While the Glass Buttes mines belong in the Opalite District, probably no hot spring sinter was deposited there, but instead large amounts of silica-rich fluid replaced wall rock and cemented fault zones.

Due to the volatile nature of mercury, most, if not all mercury in the hydrothermal system was transported to the near-surface where it precipitated with silica. The potential, then, for economic grades of cinnabar or native mercury deposits existing beneath the opalite is insignificant.

GEOTHERMAL EXPLORATION

Exploration of volcanic features subparallel to the Brothers fault zone led geothermal investigators to the younger, west end of the volcanic zone, where testing of drill holes at Newberry caldera recently indicated a temperature gradient of 285°C/km (anonymous, 1981a; anonymous, 1981b). Eastward along the zone of silicic centers, progressively older volcanic rocks are found, with a corresponding decrease in geothermal potential (Walker, 1974). Exploration in these areas has been limited.

Alteration and cinnabar deposits at Glass Buttes encouraged geothermal exploration. Studies have been

conducted from 1975 to the present, including resistivity
(Hull, 1976) and geochemical surveys, mapping and drilling.
Phillips Petroleum Company drilled four deep stratigraphic
test holes around the eastern Glass Buttes and the Oregon
Department of Geology and Mineral Industries has drilled
temperature gradient holes in the area (see Bowen, 1975; Hull
and others, 1975; Bowen and others, 1977).

Heat flow, the product of geothermal gradient and
rock conductivity, is anomalous at Glass Buttes; 4.6 Heat
Flow Units (Bowen and others, 1977), which is more than
twice the average for the Basin and Range province. The
source of heat most likely is a cooling igneous body at
depth beneath the buttes; radiogenic heat may also be a
contributing factor. The anomaly diminishes rapidly away
from the areas of alteration. About 9 km west of Antelope
Ridge, between Little Glass Butte and Glass Butte, heat
flow has been measured at 2.9 HFU, and 7 km farther south-
west is 1.8 HFU (Bowen and others, 1977).

The heat flow anomaly is centered near the west end of
Antelope Ridge where a temperature of 48°C was measured at
a depth of 220 m in a water well (Bowen and others, 1977).
This well is near the mining pits on Antelope Ridge that
show extensive alteration. Temperature gradients measured
nearby were 144°C/km and 120°C/km (Justus, 1979).

The presence of a layer at depth having low electrical
resistivity, capped by a more impermeable layer (hull, 1976),
suggests deep circulating, heated groundwater exists,

producing the heat flow anomaly. The age of the complex (around 5 m.y., Walker, 1974) is, however, relatively old compared to active geothermal areas where volcanism occurred less than one million years ago, e.g. the Geysers; New Zealand; Steamboat Springs, Nevada, and Roosevelt Hot Springs, Utah.

MODEL OF THE GEOTHERMAL RESERVOIR

From the data presented, the geothermal system at Glass Buttes probably extends to depths over 600 m, as indicated by 1) a lack of ash-flow deposits and no evidence of caldera collapse, as expected in a relatively shallow-seated magma reservoir, and 2) the presence of opalite in drill holes as deep as 550 m (see Fig. 28). If leached zones and opalite observed in drill holes represent leaks from a deeper system, then much deeper drilling (over 600 m) may be required to reach the actual geothermal reservoir. This assumes there is still a heat source at Glass Buttes; high heat flow and warm water wells suggest this is true.

The resistivity study conducted in the area shows a high resistivity cap rock, probably glassy rhyolitic lavas, about 200 m thick in the eastern buttes. This cap overlies a more permeable layer of unknown thickness, represented by opalized and leached zones in the lower half of holes No. 1 and 4 (see Fig. 28). The capping rhyolite may insulate the system, preventing loss of fluids and heat. The silica-saturated fluids or vapors inferred to have been part of the

geothermal system at Glass Buttes would also have plugged whatever fracture permeability that existed, and prevented the ascent of solutions.

Lack of surface phenomena such as hot springs or active fumaroles indicate either the system has cooled or that the opalite deposits have plugged all avenues of leakage. In the first case, depths to useable hot water should be economically prohibitive. In the latter case, it is possible that a viable geothermal reservoir exists beneath the opalite. Leakage from the system has been only in isolated areas along major northwest-trending faults, i.e. the Antelope and Cascade Ridge faults, and also at fault intersections, i.e. Cascade mine, east Cascade Ridge. Due to the vertical nature of the faults, deep drilling very close to, or within, areas of surface alteration might reach the primary aquifer, but drilling to date has not revealed its existence.

Because of the relative coolness or great depth of the hydrothermal system, exploration efforts might best be directed toward precious metals associated with mercury. A gold-dominated deposit may be trapped below the impermeable surface layer, not transported by vapor to the surface. Arsenic and antimony, as well as mercury, as associated with such deposits, while base metal sulfides are lacking (Levinson, 1974; White, 1981). Such a concealed system is suggested by large amounts of silica containing highly mobile epithermal ores such as mercury, appearing only in leaks (White, 1981).

The model proposed by Buchanan (1918) for epithermal
systems should be investigated, in which periodic fracturing
permits boiling of the hydrothermal fluids, development of
fumaroles at the surface, and deposition of base and precious
metals at great depths. Boiling is followed by resealing
and pressurizing of the system, relieved by subsequent
fracturing and boiling. This model is suggested by the high
pressure etching found overlying low temperature opalite
in hole No. 4 at Glass Buttes, described earlier. The
precious metals horizon may, however, be at substantially
greater depths.

SUMMARY AND CONCLUSIONS

The Glass Buttes volcanic complex in southeast Oregon
consists of many domes and individual vents that erupted
both rhyolitic and basaltic lavas during the late Miocene to
early Pliocene. The major volcanic feature in the east half
of the complex is Little Glass Butte, where interfinger-
ing rhyolite and obsidian flows are present. The youngest
unit here, an obsidian, has been dated at 4.9 m.y. East of
Little Glass Butte lie two northwest-trending ridges,
Antelope and Cascade Ridges, composed of two or more exo-
genous domes that formed along northwest-trending faults.

Dome-related rhyolitic rocks include flanking flow-
banded glass and viscous perlitic glass flows, while at the
crest are found blocky pumice breccias and glassy flow-
breccia. Frothy, inflated dome rocks show strong depletions
in Na_2O because of greater susceptibility to hydration and
groundwater leaching. Vapor-phase crystallization has sig-
nificantly enriched silica contents.

Vent-related rhyolite and obsidian flows probably
erupted from near Little Glass Butte. The rhyolites are
nearly aphyric, and the older of the units is thoroughly
devitrified by growth of spherulites. Obsidian units are
black aphyric flows, often showing remixing of oxidized
surface glass during flow, as well as thin layers of grey,

hydrated glass (perlite). Less secondary chemical alter-
ation occurred, compared to the dome rocks.

Coarsely feldspathic basalt interfingers with rhyo-
litic units, and originated from fissures or vents within
the buttes. Finer-grained olivine basalt covers the plateau
surrounding the complex. Its age relative to silicic
volcanism is unclear.

Glass Buttes lies at the intersection of the northwest-
trending Brothers fault zone with a west-northwest-trending
silicic volcanic zone. Major faults in the buttes follow
these trends, and northeast-trending joints are expressions
of fracturing conjugate to the regional trends. Rapid
eruption of glassy rhyolite and mafic lavas occurred as well
as development of a heat source at depth that fostered a
hydrothermal system.

The Glass Butte mine fault and the Cascade Ridge fault
are northwest-trending, curving fault zones with variable
dips. Possible evidence of strike-slip motion was observed
on the Cascade Ridge fault. The curving fault planes served
as impermeable barriers to rising cinnabar-bearing fluids.

Hydrothermal alteration was concentrated along faults
and involved silicification and advanced argillic alteration
of wall rocks by silica-saturated fluids. Opalite forms
vertically elongated masses within fault zones as deep as
600 m, or isolated pockets near the surface. Rising hydro-
thermal fluids replaced wall rock and upon cooling precipi-
tated amorphous hydrous silica that sealed fault breccia.

Lack of other metals in the opalite suggest the fluid was a water-saturated liquid, accompanied by a vapor as low as 35°C capable of transporting only the relatively volatile mercury and minor iron.

Drill hole data show zones of leaching and etching, higher in elevation than presumably lower-temperature opalite. Pressurized fluids etched slightly permeable rock layers, and, when faults released pressure on the system, opalite formed under lower temperature and pressure from water- and silica-saturated fluids, effectively resealing the system. This cycle of alteration probably repeated many times.

Volcanism and faulting occurred during and after the main alteration event. Faulting that relieved pressure build-up in the hydrothermal system also provided conduits for magma to reach the surface. Continued volcanism may have partially sealed the hydrothermal system. Fumaroles vented through rhyolitic glass that overlies opalite. Sites of fumarolic activity may be related to faults developed after the main period of surface opalization ceased.

Hydrothermal alteration was not a recent geologic event at Glass Buttes. Lacking surface deposits and active surface phenomena, at best only a very deep heat source remains. High heat flow in the area may be due to heated, deep-circulating groundwater. Steeply inclined zones of hydrothermal alteration and recurrent fracturing are evidence

of a deep system at Glass Buttes, below that of presently
drilled depths, that may contain economic precious metal
deposits.

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APPENDIX

The following chemical analyses are presented here:
XRF major oxide data performed for this study on 25 rock
samples, including 1) raw data, and 2) data recalculated to
100 percent volatile-free and total iron as FeO; AAS K_2O data
for 8 samples. All values are in weight percent.

Five other oxides were analyzed for, using AAS methods.
A large amount of error was introduced in these analyses
by repeated dilutions required to lower element concentra-
tions into instrument detection ranges. The AAS technique
further requires precise chemical treatments of solutions
to minimize interference to ionization, as well as to enhance
or prevent excessive ionization. Due to this complex
procedure, data obtained by AAS was compared to XRF analyses
by an outside laboratory, which indicated close agreement of
K_2O data, while other oxides varied as much as several weight
percent. Because of the greater completeness and relia-
bility of the XRF data, it has been used exclusively in
this report.

Previously published analyses of Glass Buttes rocks
are also included here. Operating parameters for X-ray
diffraction are listed following all chemical analyses.

Analytical procedures followed for AAS and X-ray
diffraction studies are given by Carroll (1970), Kirkbright

and Sargent (1974), Langmyhr and Paus (1968), Rantala and
Loring (1973), and Thompson and Reynolds (1978).

CHEMICAL ANALYSES OF THIS STUDY, PRE-NORMALIZED (RAW DATA)

	Younger LGB Rhyolite			Obsidian	Older LGB-Antelope Rhyolites						Basalt
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	72.73	72.78	73.77	74.57	75.06	75.30	75.44	75.88	75.95	76.34	48.31
TiO_2	0.25	0.30	0.18	0.21	0.07	0.09	0.10	0.04	0.07	0.04	2.24
Al_2O_3	13.97	14.09	13.46	13.78	13.30	13.24	13.08	13.22	13.03	13.16	16.53
Fe_2O_3	0.73	0.92	0.54	0.59	0.15	0.21	0.21	0.03	0.03	0.12	5.83
FeO	0.84	1.05	0.61	0.68	0.17	0.24	0.25	0.03	0.03	0.14	6.68
MnO	0.03	0.06	0.04	0.05	0.04	0.04	0.03	0.02	0.01	0.05	0.21
MgO	0.23	0.53	0.49	0.42	0.20	0.25	0.27	0.22	0.29	0.26	6.63
CaO	1.54	1.91	1.34	1.36	0.67	0.68	0.90	0.27	0.16	0.41	9.96
Na_2O	3.12	3.20	3.01	3.15	3.36	2.76	2.87	3.12	2.29	3.40	2.74
K_2O	3.71	3.51	3.88	3.84	4.37	4.39	4.27	4.60	4.62	4.51	0.32
P_2O_5	0.07	0.09	0.04	0.05	0.01	0.03	0.10	0.02	0.01	0.07	0.54
Total	97.22	98.44	97.36	98.70	97.40	97.23	97.52	97.45	96.49	98.50	99.98

	Dome-related Glass						
	12	13	14	15	16	17	18
SiO_2	74.07	75.14	76.27	77.36	77.53	77.82	78.96
TiO_2	0.04	0.04	0.05	0.04	0.06	0.04	0.04
Al_2O_3	12.98	13.75	12.82	12.78	10.91	11.11	12.78
Fe_2O_3	0.10	0.24	0.01	0.01	0.03	0.02	0.03
FeO	0.12	0.28	0.05	0.01	0.04	0.03	0.03
MnO	0.04	0.06	0.05	0.01	0.04	0.04	0.01
MgO	0.10	0.23	0.26	0.14	0.16	0.17	0.19
CaO	0.25	0.22	0.22	0.05	0.08	0.08	0.06
Na_2O	3.08	0.34	0.18	2.23	0.15	0.20	0.72
K_2O	4.95	4.17	3.95	4.48	3.82	3.43	2.82
P_2O_5	0.00	0.01	0.01	0.00	0.01	0.00	0.01
Total	95.73	94.48	93.90	97.11	92.83	92.94	95.65

(Obsidian is from Obsidian Hills unit.)

Normative minerals:

	1	6
QZ	35.6	39.1
OR	23.1	26.9
AB	29.6	25.9
AN	7.0	3.5
CO	2.6	3.1
EN	0.6	0.8
FS	0.4	0.2
MT	0.8	0.3
IL	0.4	0.2
AP	0.3	0.0

CHEMICAL ANALYSES OF THIS STUDY, NORMALIZED 100% VOLATILE-FREE

	Younger LGB Rhyolite			Obsidian	Older LGB-Antelope Rhyolites						Basalt
	1	2	3	4	5	6	7	8	9	10	11
SiO_2	74.87	74.00	75.83	75.61	77.07	77.37	77.46	77.51	77.85	78.71	48.60
TiO_2	0.25	0.31	0.18	0.21	0.08	0.10	0.10	0.05	0.04	0.07	2.25
Al_2O_3	14.38	14.33	13.83	13.97	13.66	13.41	13.62	13.36	13.57	13.50	16.63
$FeO*$	1.54	1.91	1.13	1.22	0.31	0.45	0.45	0.26	0.06	0.06	12.00
MnO	0.03	0.06	0.04	0.05	0.04	0.23	0.04	0.05	0.02	0.01	0.21
MgO	0.24	0.54	0.51	0.43	0.21	0.28	0.25	0.26	0.23	0.30	6.67
CaO	1.58	1.94	1.37	1.37	0.68	0.92	0.70	0.41	0.27	0.17	10.02
Na_2O	3.21	3.25	3.09	3.20	3.45	2.95	2.84	3.45	3.21	2.38	2.76
K_2O	3.82	3.56	3.98	3.89	4.49	4.38	4.51	4.58	4.72	4.79	0.32
P_2O_5	0.07	0.09	0.04	0.05	0.01	0.11	0.03	0.07	0.02	0.01	0.54
Total	99.99	99.99	100.00	100.00	100.00	100.20	100.00	100.00	99.99	100.00	100.00

$(FeO*=FeO+0.9Fe_2O_3)$

	Dome-related Glass						
	12	13	14	15	16	17	18
SiO_2	77.39	79.55	79.65	81.23	82.55	83.51	83.73
TiO_2	0.04	0.05	0.04	0.05	0.04	0.06	0.04
Al_2O_3	13.56	14.55	13.16	13.66	13.36	11.76	11.95
$FeO*$	0.22	0.52	0.02	0.09	0.06	0.08	0.05
MnO	0.05	0.06	0.02	0.06	0.01	0.04	0.04
MgO	0.11	0.25	0.14	0.28	0.20	0.17	0.18
CaO	0.26	0.24	0.05	0.24	0.06	0.08	0.09
Na_2O	3.22	0.36	2.30	0.19	0.75	0.17	0.21
K_2O	5.17	4.42	4.62	4.20	2.94	4.11	3.69
P_2O_5	0.00	0.01	0.00	0.01	0.01	0.01	0.00
Total	100.02	100.01	100.00	100.01	99.98	99.99	99.98

Analyses from Beeson (1969)

Rhyolitic lava (0-10) and rhyolitic obsidian (0-11) from Glass Buttes, Oregon.

	0-10	0-11
Na%	2.89±0.5	2.85±0.5
Cs	4.3 ± .2	4.8 ± .2
La	21 ± 3	14.2± .6
Ce	41 ± 3	32.1±1.2
Sm	4.57±.12	9.1± .2
Eu	0.56±.04	0.28±.03
Lu	0.85±.10	1.56±.05
Th	11.7± .7	16.9± .6
Hf	4.76±.13	5.3± .5
Ta	0.9 ± .2	1.24±.18
Mn	347 ± 11	420 ± 60
Co	0.43±.13	not counted
Fe%	0.529±.016	0.48±.17
Sc	3.26±.06	8.4 ± .3
Eu/Sm	0.122	0.031
La/Sm	4.6	1.56

Analysis from MacLeod and others (1976)

Glass Butte dome rock, sample no. 7

SiO_2	75.7
Al_2O_3	13.4
Fe_2O_3	0.26
FeO	0.56
MgO	0.09
CaO	0.90
Na_2O	3.8
K_2O	3.7
H_2O^-	0.39
H_2O^+	0.04
TiO_2	0.10
P_2O_5	----
MnO	0.06

Analysis from Jack and Carmichael (1969)

Glass Butte, Oregon, sample no. 4 (Cǎm 146)

K	3.26
Ti	520
Mn	405
Co	20
Ni	5
Cu	5
Zn	30
Ga	15
Rb	80
Sr	30
Y	45
Zr	95
Nb	10
Ba	1300
La	40
Ce	90
Pr	5
Nd	25
Pb	10
Th	10

X-ray Diffraction Operating Parameters:

40 KV

20 Ma

Soller Slit MR

Time constant 4.0 seconds

Rate meter 500 cps

Beam Tunnel 1°

Detector slit 0.1°

Gain 16/87

Scan speed 2°2θ/minute

Chart speed 1 inch/minute