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Geology, Alteration and Mineralization of a Silicic Volcanic Center, Glass Buttes, Oregon

Michael James Johnson
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AN ABSTRACT OF THE THESIS OF Michael J. Johnson for the
Master of Science in Geology presented May 17, 1984.

Title: Geology, Alteration and Mineralization of a Silicic
Volcanic Center, Glass Buttes, Oregon.

APPROVED BY MEMBERS OF THE THESIS COMMITTEE:

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Marvin H. Beeson

Glass Buttes, a Pliocene silicic volcanic complex within the High Lava Plains province of Oregon, was erupted approximately 5.0 to 5.8 million years ago. Geologic mapping revealed that the eastern portion of the complex is underlain by rhyolitic glass domes, flows and rare pyroclastic flows. Basalt flows are interlayered with and onlap the silicic glass. Younger basalt flows, erupted from local vents, overlie silicic glass and onlapping basalts.

The eastern end of Glass Buttes is hydrothermally altered at the surface; a weak geothermal anomaly coincides with the altered areas. Alteration, localized by northwest trending normal faults, occurs primarily as opalite

replacement of rhyolite glass with associated cinnabar, alunite, clay-rich vein material, hematite, and hyalite. Alteration paragenesis at the surface was defined, and physicochemical conditions during hydrothermal activity were inferred from alteration minerals and assemblages and trace element content of alteration minerals.

Alteration identified in the subsurface is interpreted to be related to an older hydrothermal system. Carbonate, pyrite, quartz, and minor smectite and chlorite occur in vugs and fractures, and partially replace subsurface basalt. Abundant fine-grained disseminated pyrite occurs in permeable units. Pyrite separates from disseminations and veins within basalt and permeable glassy units contain up to 13 ppm Au. The pyrite samples are also anomalous with respect to arsenic and antimony.

GEOLOGY, ALTERATION AND MINERALIZATION
OF A SILICIC VOLCANIC CENTER, GLASS BUTTES, OREGON

by

Michael James Johnson

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

Master of Science

in

Geology

Portland State University

1984

TO THE OFFICE OF GRADUATE STUDIES AND RESEARCH:

The members of the Committee approve the thesis of
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INTRODUCTION

The High Lava Plains Physiographic Province of central and southeast Oregon is underlain by numerous rhyolitic centers and basaltic vent complexes and flows of late Cenozoic age. These rocks produce the overall bimodal volcanic character of the province (MacLeod and others, 1976). These eruptive centers have been mapped on a reconnaissance level, and their individual genetic and evolutionary relationships and interrelations have not been determined.

Glass Buttes (Figure 1), a rhyolitic volcanic center, is one such complex which has been hydrothermally altered and mineralized by a geothermal system which has since become inactive.

This study is part of an ongoing study initiated in 1980 by M.L. Cummings of Portland State University to map the volcanic stratigraphy of the complex and to characterize the hydrothermal alteration and mineralization located therein. The purposes of this study were: to map the volcanic stratigraphy of the easternmost portion of the complex; to chemically and mineralogically characterize surface and subsurface hydrothermal alteration and mineralization; to model the hydrothermal system; and to make a preliminary evaluation of precious metal potential of the center.

GEOLOGIC MAP OF OREGON

Figure 1. Location map of Glass Buttes: Basin and Range faults occur south of the complex. The complex is cut by the Brothers Fault Zone which trends northwest through central Oregon (Walker and King, 1969).

Methodology

Drill cuttings from four stratigraphic test holes drilled by Phillips Petroleum Company as part of a geothermal exploration program at Glass Buttes were made available. The holes range in depth from 270 to 600 m and were drilled peripheral to surface alteration. Drill cuttings were studied using a binocular microscope. Mineral samples were hand-picked from the cuttings for chemical analysis as separates, in order to correlate chemistry with distinct mineral phases. In addition, a core which was drilled to a depth of 100 m was studied petrographically and chemically. Hecla Mining Company and Placer U.S. Inc. provided drill logs and technical reports for their drill holes. The cuttings, core and drill logs afforded a record of lithologic and mineralogic changes with depth. These data were incorporated with data on surface stratigraphy and alteration to develop the 3-dimensional patterns of the alteration system.

Field studies were undertaken during July and August, 1982, and additional field work was completed in October, 1983. Most rock descriptions in the text are based on surface exposures and exposures from shallow exploration pits unless otherwise indicated.

Major element analyses by X-ray fluorescence (XRF) were performed by Dr. Peter Hooper at Washington State University; instrumental neutron activation (INAA) and X-ray diffraction (XRD) analyses were performed by the author

at Portland State University; petrographic study of thin sections was undertaken by the author.

Previous Work

A.C. Waters (1927a; 1927b) defined the stratigraphy of the western part of the Glass Buttes complex as a Master's thesis for the University of Washington. He divided the volcanic rocks into three units. The oldest unit, a basalt, was believed to be correlative with the Steens basalt which is exposed in the Steens Mountains to the east. Younger dacites, perlites, obsidian and vitrophyre, overlie the basalts. The youngest unit is made up of the basalts of the surrounding mesa, which onlap the dacites, perlites and obsidian (Waters, 1927b).

Between 1933 and 1958 attention was concentrated on the exposed alteration and mercury mineralization at the eastern end of the complex. Mercury was mined periodically during these years, with a peak production of 87 flasks from Glass Buttes mine in 1957 (Brooks, 1971). Operations were abandoned within a year because the ore became subeconomic.

Greene and others (1972) and Walker and others (1967) included Glass Buttes in their reconnaissance mapping of the High Lava Plains (Figure 2), and Walker (1974) presented a K/Ar age determination of 4.9 ± 0.3 million years for obsidian from the north side of Little Glass Butte (Berri, 1982, Plate I). This date has been

Figure 2. Location of the High Lava Plains: Glass Buttes is shown in relation to the physiographic provinces of Oregon (modified from Baldwin, 1964).

subsequently recalculated to 5.03 ± 0.75 million years using the most recent decay constants (Walker, 1983, written commun.). From the mid-1970's, study was focused on the geothermal potential of Glass Buttes. Several shallow temperature-gradient holes were drilled (Bowen 1975; Bowen and others, 1977; Hull and others, 1975) and a dipole-dipole resistivity survey was completed (Hull, 1976) as part of a geothermal assessment project conducted by the Oregon Department of Geology and Mineral Industries (DOGAMI). In 1979 and 1980, a joint venture between Phillips Petroleum Company and Francana Resources Inc., investigated Glass Buttes for geothermal potential. Geologic mapping and a mercury soil survey were completed followed by drilling of temperature-gradient holes and 4 deeper stratigraphic test holes. A weak geothermal anomaly was identified and found to overlap the zone of surface alteration (Johnson and Ciancanelli, 1983).

A Master's thesis study of the eastern half of the complex by Berri (1982) included detailed mapping of volcanic stratigraphy and a preliminary investigation of hydrothermal alteration. The volcanic units are endogenous and exogenous domes and flows of variably vesiculated rhyolitic glass and obsidian surrounded and overlapped by younger plateau basalts. A basalt which differs petrographically from the plateau basalts was mapped as interfingering with the rhyolitic glasses and gave rise to Berri's suggestion of a bimodal character for the complex

(Berri, 1982; Berri and others, 1983).

Berri indicated that silicification and advanced argillic alteration are the most abundant types of alteration exposed at the surface. Hyalite, hematite, and cinnabar, as fracture-coatings and vug-linings were suggestive to Berri of vapor-phase alteration at the surface. Field relations supported by examination of cuttings from drill holes led her to conclude that alteration, at least in parts of the complex, predated some of the volcanism. She also presented evidence that multiple hydrothermal surges occurred, however, not all deposited mercury.

Unpublished mapping of Round Top Butte, the southeast portion of the complex, by Cummings (1984) revealed exogenous domes and flows of inflated glass and rhyolite glass, and a lesser volume of basalt which was extruded from vents within the butte. Varying levels of erosion of the glass domes has led Cummings to suggest that the complex was erupted over a considerable span of time.

Because of the prominent surface alteration and cinnabar mineralization, a number of mineral exploration companies presently consider Glass Buttes to be a target for mercury and/or epithermal precious metals. Companies have conducted surface sampling as recently as the 1983 summer field season.

REGIONAL GEOLOGY

Walker (1974) and MacLeod (1976, 1982), compiled K/Ar age determinations of the silicic volcanic rocks of the High Lava Plains, and were able to show a westward decrease in the age of these rocks (Figure 3). Two general trends of felsic volcanic rocks define this westward decrease in age. Glass Buttes is included in the northern trend which extends from Duck Butte east of Burns to Newberry Volcano. To the south, a less well-defined trend extends from Beatty's Butte to Yamsay Butte (Figure 3). There does not appear to be an explanation for this "younging westward" trend at this time.

A second feature which structurally dominates the High Lava Plains is the Brothers Fault Zone. This fault system trends northwesterly, and although the extent of its boundaries to the southeast (Stewart, 1975), the northwest (Beeson and others, 1984), and the north (Davis, 1981) are questioned, it is generally accepted to be a system of partly en echelon, high-angle normal faults which reflect a deeper structure, perhaps along which there has been dextral strike-slip motion (Lawrence, 1976). It is probable that the Brothers Fault Zone, the subparallel Eugene-Denio Fault Zone, and the Mt. McLoughlin Fault Zone are expressions of the transition from Basin and Range structure to the south to the Blue Mountain/Columbia

Figure 3. Silicic volcanic rocks in southeast Oregon (shown in black, modified from ¹⁴LacLeod and others, 1976).

Plateau province to the north.

The more northward trend of silicic volcanic complexes, from Duck Butte to Newberry Volcano (Figure 3), appears to roughly define a west-northwest linear trend. The Brothers Fault Zone may trend more northwesterly. Berri (1982) suggested that Glass Buttes lies at the intersection of these two trends, and called upon this intersection as a possible dilatationary mechanism to provide a conduit through which hydrothermal fluids were able to rise.

STRATIGRAPHY

The area which was mapped in this study is shown in Figure 4. The eastern and northern boundaries of the map area were chosen as the limits of felsic volcanic rocks associated with the Glass Buttes complex. The western boundary overlaps Berri's (1982) eastern map boundary; the southern boundary is conterminous with the northern boundary of mapping completed by Cummings (1984).

Numerous volcanic vents occur within the mapped area (Plate I) and most lavas extruded from these vents are of relatively low volume. Chronologic sequences among individual units are not always apparent, but stratigraphic units within the mapped area and units mapped to the west by Berri indicate that, in general, units to the west overlie units to the east.

Lithologic Units

All silicic units at the surface are aphyric and acrySTALLINE; most show variable vesiculation or are nonvesicular glass. Phenocrysts were observed neither in hand sample nor thin section. All extrusive felsic units, with the exception of pyroclastic units, are related to exogenous dome growth. Flow units are also described because they underlie areas immediately adjacent to the study area.

Figure 4. Thesis study area outline (diagonals). Area mapped by Berri is outlined to the west, area mapped by Cummings is outlined to the south. Glass Butte proper (farthest west) was studied by Waters.

Exogenous Domes

Domes are exogenous in that they extruded radially from their source vents. Figure 5 is a map of one dome which exhibits many of the characteristics of domes within the mapped area. The volcanic stratigraphy of a dome, from the core to its outer surface is as follows:

- 1.) Core obsidian. Core obsidian, where present, occupies the centers of the domes and occurs as patches of float locally covering the ground. The sizes of float pieces average 25 cm in diameter. They are black, nonvesicular and conchoidally fractured. Buff to light brown weathered surfaces are sometimes present on the float. Domes in which obsidian cores are exposed (Plate I) are generally of lower relief than those in which obsidian cores are not exposed. These domes are more numerous along the eastern margin of the mapped area than elsewhere. The stratigraphy of one dome mapped within the study area shows a small patch of core obsidian at its topographic summit that is surrounded by a gray glass unit. The dips of flow layering in the glass are away from the obsidian float and define a crude outward dipping radial pattern. This relationship was observed within a dome of rather high topographic relief, whereas, in general, higher relief domes do not exhibit obsidian cores.

Obsidian float which resembles core obsidian in abundance, size, and color was mapped within one dome (Plate I) in linear patterns approximately two m wide and

Figure 5. Map of an exogenous dome showing spatial and areal relations among lithologic units (see Plate I for dome locations).

four m long. This distribution pattern is different from that commonly encountered in most domes where the core obsidian usually forms a roughly circular pattern. These float concentrations do not occupy topographic depressions, nor were they concentrated by downslope-movement.

2.) Gray glass. Dark to light gray glass occurs stratigraphically above and outward from core obsidian, and comprises the main volume of exogenous domes. Varying degrees of inflation or vesiculation of the gray glass produce changes in luster, which ranges outward from vitreous gray to chalky, lighter gray to light gray glass in which vesicles can be seen with a hand lens. Vesicles are locally concentrated and aligned along flow planes. The dip of flow layering in the gray glass may steepen and define a radial pattern at the crests of topographic rises underlain by a single dome. Away from the crests of these rises the dip of flow layering is gentle and subparallel to the topographic slope.

Folding of flow layering is common where the upper or outer contacts of the gray glass unit can be identified. Close to these contacts dips of the flow layering begin to steepen and strike and angle of dip become variable. Flow layering is locally overturned or buckled into a series of open to tight folds. The orientations of the fold axes vary from place to place within the domes and are most variable near the outer lateral contacts of the unit.

3.) Carapace obsidian. Carapace obsidian is

differentiated from core obsidian by the following criteria: a.) It occurs as float pieces of average diameter of three cm, often exhibiting oxidized and pitted surfaces. b.) It occurs in common association with the domes, but never in patches. Rather, it occurs in low but often consistent concentrations on dome flanks. Carapace obsidian is often concentrated by mechanical erosion downslope and in gullies. c.) Carapace obsidian occurs stratigraphically above gray glass in contrast to core obsidian, which occurs beneath gray glass. Rarely found in outcrop, carapace obsidian was observed in one case to occur as small lenses with an average diameter of three cm within an outcrop of inflated glass at the edge of a dome.

4.) Glass breccias. Glass breccias associated with domes are most often poorly sorted, matrix-supported clasts of black to brown to buff glass which exhibit varying degrees of inflation and flow layering. Clasts range in size from sand to boulder and are of variable shapes. Those clasts which do not exhibit flow banding tend to be equidimensioned, whereas those which are flow banded have a general platy shape, since fractures have developed preferentially along flow planes. The matrix is often orange-brown and distinctively darker colored than clasts. Brown glass breccias occur stratigraphically outward from and above gray glass. They are volumetrically less abundant than gray glass units with which they are associated, but can be found in association with both obsidian-cored domes

and those domes in which obsidian cores have not been observed.

Flows

Flows are here differentiated from exogenous domes by geometry. If lithologic units of extrusive felsic units were distributed radially from a point source, it was defined as an exogenous dome. The unit was defined as a flow if unidirectional extrusive flow was evident. None of the units mapped in the study area appear to meet this criterion for a flow, and so all have been classified as exogenous domes. However, the northwest edge of the mapped area is conterminous with a flow which was mapped by Berri (1982: Plate I, Tra). The rhyolitic glass flow flowed north down the north flank of Antelope Ridge from a vent located at the eastern end of the ridge (Berri, 1982). The flow stratigraphically overlies the gray glass unit of an older dome. The gray glass of the dome is bordered on its east and northeast sides by a brown glass breccia. The stratigraphic relations of these units are shown in Figure 6.

Pyroclastic Units

Volcanic units which exhibit bedding features crop out on the south side of Cascade Ridge (Plate I). These units can be traced in east-west trending drainages and are overlain to the west by an obsidian flow which erupted from Little Glass Butte. Toward the east end of Cascade Ridge

Figure 6. Stratigraphic relations of perlitic glass and brown glass breccia with overlying rhyolite glass mapped by Berri (1982).

they are overlain by a glass block breccia (Figure 7). The bedded units apparently thin to the east and disappear beneath the glass block breccia. The source of the bedded units was not located, but clast size and angularity indicate a proximal source, and dip directions indicate a source area to the west or northwest.

The bedded units contain primarily glass fragments supported by abundant white ashy glass matrix. Fragments are poorly sorted, ranging from coarse sand size up to 0.5 m diameter. Fragments include mainly gray glass, inflated gray to white glass, pumiceous fragments, black obsidian fragments, and rare white opalite fragments. Flow structures within gray, white and pumiceous glass fragments are variable in quality of development.

Planar bedding in the units varies from massive to laminar; coarsening upward sequences occur locally. Planar bedding dips gently to the east and northeast. Glass fragments vary in diameter from bed to bed. Massive beds contain block-size fragments, while laminar beds contain sand-size fragments. Broad, sweeping festoon-type cross bedding also occurs within these units (Figure 8). Cross beds are approximately one m in height and dip in an easterly direction.

Overlying the bedded units at the eastern end of Cascade Ridge is a matrix-supported glass block breccia. The matrix is composed of fine glass and pumiceous glass fragments. Blocks are chalky inflated gray glass, pumiceous

Figure 7. Contact of overlying glass block breccia with underlying bedded unit.

Figure 8. Cross-bedded unit.

Figure 9. Source vent for glass block breccia.

gray glass, highly vitreous translucent gray glass, and inflated white glass. The block breccia unit was traced northward to vents near the crest of Cascade Ridge (Figure 9). At the vent, the breccia forms a resistant ridge in which crude layering can be discerned where accentuated by weathering. The breccia unit does not underlie the crest nor the north side of Cascade Ridge. The block breccia flow rapidly thins southward off the flank of Cascade Ridge and is ten m thick in the east-west drainage where it overlies the bedded units described above. It appears to terminate at the east end of this drainage. The flow front of the unit appears to have been steep and abrupt, as suggested by isolated three-m-high spires of the breccia at the eastern end of the drainage. East of these erosional spires, breccia outcrops were not observed.

Stratigraphic Relations

Relative age relationships among domes cannot always be determined. However, locally stratigraphic relations are clearly defined. These relations in the mapped area and in the area mapped by Berri (1982) indicate, in general that stratigraphic units to the west overlie stratigraphic units to the east. These relations were determined for Cascade Ridge, Antelope Ridge and Little Glass Butte.

This stratigraphic sequence is illustrated by the bedded pyroclastic unit on the south flank of Cascade Ridge which was funneled eastward through a drainage valley along the southeastern side of the older dome complex of Cascade

Ridge. This bedded unit is overlain by an obsidian flow (Berri, 1982) which is overlain to the west by Berri's "Try" unit (1982, Plate I), which was extruded from Little Glass Butte. These stratigraphic relations occur over a distance of approximately four kilometers.

Deviation from the general trend is illustrated by the glass block breccia which was vented from Cascade Ridge and stratigraphically overlies the bedded pyroclastic units whose source areas are covered by units erupted from Little Glass Butte. However, the breccia was apparently the last unit extruded from Cascade Ridge, whereas several units were extruded subsequently from Little Glass Butte to the west.

The relative age relations among units underlying the eastern end of the Glass Buttes units and Round Top Butte immediately south are not clear. Alluvium and onlapping basalt have obscured stratigraphic contacts among these silicic units.

Basalts

Basalts are abundant within the mapped area, where they underlie the plateau surrounding the felsic dome complex. Along the eastern margin of the map area, northwest trending drainages expose older rhyolitic volcanic rocks beneath the basalts. The surfaces of the basalts are oxidized, vesicular, and locally scoreaceous flow tops which grade downward into less vesicular rocks in

the flow interiors. Plateau basalts also underlie the northern and southern limits of the map area. Basalt similar to the plateau basalt occurs in Phillips hole 1 (Plate I), covered by a thin layer of alluvium. The basalts are cut by young northwest trending fault scarps which locally are up to three m high. The plateau basalts, described in detail by Waters (1927a; 1927b) and Berri (1982), are fine-grained subporphyritic basalts with plagioclase and pyroxene (augite) phenocrysts in a groundmass of plagioclase microlites, pyroxene, olivine, magnetite and glass (also see Hart and others, 1984). Waters and Berri indicated that the plateau basalts are younger than, and onlap the Glass Buttes silicic volcanics. Johnson and Ciancanelli (1983) described the youngest volcanic units surrounding the silicic complex as basalts and andesites which define a crude ring-shape.

In addition to the plateau basalts several other basalt occurrences are present. Two small cinder cones, one approximately two km to the south and one approximately fifteen km to the north of the east end of the complex can be seen to rise above the plateau. Berri (1982) and Berri and others (1983) report a texturally distinct glomeroporphyritic basalt with plagioclase phenocrysts up to one cm in diameter interfingering with silicic units within the complex.

A small basalt flow in the southeast portion of the mapped area (Plate I) stratigraphically overlies silicic

units. Flow layering dips gently to the southeast. To the north and west, silicic volcanics rise in relief above the basalt flow. The probable vent for the basalt is located at the westernmost margin of the flow. A small island-like topographic high of felsic rock is surrounded by the basalt, which can be traced southeastward for more than a kilometer to the margin of silicic volcanic rock and a short distance onto the plateau where the flow overlies plateau basalt. The basalt is glomeroporphyritic, containing phenocrysts of plagioclase and lesser amounts of pyroxene in an extremely fine-grained groundmass of felty plagioclase, magnetite, pyroxene, and dark glass. The composition of plagioclase phenocrysts ranges from An₅₂ to An₆₂ with an average composition of An₅₈ (Labradorite). Most plagioclase phenocrysts display sharp extinction, but approximately 10% exhibit clouded extinction, and about 5% are compositionally zoned. Zoned plagioclase commonly shows reverse zoning with outer rims having an average composition of An₆₀. The glomeroporphyrocrysts make up approximately 25% of the basalt, whereas solitary phenocrysts comprise 10%.

Cummings (1984) reports that basalt units were extruded from vents within Round Top Butte and stratigraphically overlie rhyolite glass domes and plateau basalt.

Field studies indicate that basalts and rhyolitic glasses show the following relations: 1.) basaltic

volcanism was coeval with rhyolitic volcanism within the complex. 2.) Plateau basalts developed after the rhyolitic complex and onlap the glasses. 3.) Volumetrically small basalt flows extruded from within the complex and postdate both rhyolitic rocks and onlapping plateau basalts.

Subsurface Lithologies

Four stratigraphic test holes ranging in depth from 270 to 600 m were rotary-drilled by Phillips Petroleum Co. in 1979 and 1980. The holes were drilled marginal to the main zone of surface hydrothermal alteration. Samples of uncleaned cuttings representing approximately 3 m intervals for holes 2, 3, and 4 were made available for examination. Samples of cleaned cuttings from hole 1 representing three m intervals collected every three m were also made available. The locations of the holes are shown in Plate I and the general stratigraphy for the holes is represented in Figure 10. Descriptions of lithologies are included in Appendix A.

Stratigraphic hole 2 is 380 m deep. Units in hole 2 are primarily volcanoclastic sediments, finely flow banded glass and perlitic glass. Basalt was not intercepted in this hole, indicating a more extensive pile of silicic units than indicated by topographic features.

Stratigraphic hole 3 is near the eastern margin of, but still within the silicic volcanic complex. Lithologic units consist of glass sands and gravels interbedded with rhyolitic glass, inflated glass, and obsidian. No basalts

Legend

Figure 10a. Lithology and alteration in Phillips holes.

Phillips Stratigraphic Test Hole 1

Collar Elevation 4880'

Alteration Minerals

Figure 10a., cont.

Phillips Stratigraphic Test Hole 2

29

Collar Elevation 4625'

Alteration Minerals

Figure 10a., cont.

Phillips Stratigraphic Test Hole 3

Collar Elevation 4780'

Figure 10a., cont.

Phillips Stratigraphic Test Hole 4

Collar Elevation 4960'

Alteration Minerals

Figure 10a., cont.

Diamond Drill Core

Figure 10b. Lithology and alteration minerals for diamond drill core from Antelope Ridge.

occur downhole. Pink flow-banded glass between 25 and 100 m depth in Stratigraphic hole 3 resembles the pink to gray glass between 60 and 175 m in Stratigraphic hole 2, and may represent the same unit.

Stratigraphic hole 1 is located in a topographic low between Antelope Ridge and Cascade Ridge. Volcaniclastic sediments overlie 20 m of fine-grained basalt which is similar to plateau basalt in both chemical composition and texture. All rocks beneath 240 m have been hydrothermally altered.

Stratigraphic hole 4 is located within the silicic complex on the southwest flank of Cascade Ridge. The uppermost 62 m are perlitic gray glass which grades into flow-banded glass. This unit is the obsidian flow which extruded from Little Glass Butte (Berri, 1982, Plate I). Beneath the glass unit is the bedded pyroclastic unit mapped at the surface (described earlier). Two separate basalt units occur in Stratigraphic hole 4 between depths of 130 and 300 m. In addition, the two upper pitted siliceous units contain phenocrysts, while deeper pitted units do not. The upper basalt unit, and all other units beneath it in Stratigraphic hole 4 have been hydrothermally altered.

STRUCTURE

Structures which occur in the eastern Glass Buttes area are described and discussed by Berri (1982), and this study is in general agreement with her findings. Prominent faults which strike generally northwest cut the complex and surrounding mesa basalts. The fault planes have near vertical dip angles and are interpreted to have normal displacements with north side down. Mineralized fault zones contain brecciated replacement opal in hanging walls, indicating continued faulting after mineralization. A subordinate set of northeast striking joints occur in conjugate relationship with the northwest trending fault system. Fault scarps, especially on the plateau, are youthful in appearance. Analysis of aerial photographs of the western end of the complex (outside the study area) reveal two northwest trending scarps on the plateau proximal to the silicic rocks. One scarp is on the north side of the silicic complex and dips steeply south. The other scarp is on the south side of the felsic rocks and dips steeply to the north. These relations suggest at least local graben structures. Berri (1982), Berri and others (1983), and Johnson and Ciancanelli (1983) mapped graben-like structures within and outside the complex, and believe that the complex may be in an area of local subsidence.

The basalt in Stratigraphic hole 1 is correlated with

plateau basalt to the north of the complex. The top of this basalt is at least 60 m higher than plateau basalts to the north of the complex. Three prominent faults, one to the north and two to the northeast of Stratigraphic hole 1 have been mapped as having north sides down (see Plate I). The difference in elevation for the top of the basalt in Phillips hole 1 and the plateau basalts reflects the displacements along these three faults. The total combined displacement on faults northeast of Stratigraphic hole 1 which occurred after the incursion of plateau basalt into the valley is approximately 60 m.

Although the general trend of most recent faulting is to the northwest, the overall distribution of the silicic volcanic rocks and location of silicic vents appears to be along a west-northwest trend (Berri, 1982; Berri and others, 1983). The volcanic rocks which underlie Cascade Ridge were erupted from a series of vents aligned along the crest of the ridge in a west-northwest direction. The more northwest-striking normal fault system may not be related to the structures which controlled the distribution of the silicic rocks.

GEOCHEMISTRY

Basalts

Chemical 'fingerprints', established by comparison of trace element concentrations (determined by INAA) are powerful tools in correlation of units where field relations have been obscured. Such techniques have been successfully applied to correlation of flows of the Columbia River Basalt Group. Numerous samples of a given unit must be analyzed to ascertain the degree of variance and average concentrations for individual trace elements and ratios between elements for that unit. Due to the small sample population available for the basalts at Glass Buttes, the concentrations presented here are of low statistical confidence.

Figure 11 contains the absolute concentrations of selected major and trace elements for five basalts within and surrounding the Glass Buttes complex. Locations of basalt samples analyzed are shown in Appendix B. Samples 1, 3 and 5 are petrographically and mineralogically similar; samples 2 and 4 are similar in that they are both glomeroporphyritic and have similar mineralogy. They differ in that sample 2 (Berri's internal basalt) has phenocrysts up to one cm in length, whereas sample 4 phenocrysts are on the mm scale, the largest phenocrysts being two mm in length.

Figure 11. Elemental concentration patterns for 5 basalts from study area (see App. B for sample locations).

The elemental concentration patterns in Figure 11 for Na, La, Sm, Eu, Lu, and Hf are somewhat similar for all samples. Co, Fe, Cr, Sc, Ta, and Yb give highly variable concentration patterns; Berri's internal basalt (sample 2) exhibits a pattern distinct from the others in shape. The high concentrations of Eu and Yb and the low concentrations of Co and Cr for sample 2 relative to concentrations of the other basalt samples may be related to its greater plagioclase content and phenocryst size. Sample 5, also irregular, resembles the patterns of samples 1, 3 and 4 more closely than it resembles sample 2. Concentration patterns for the plateau basalt (sample 1), valley basalt (sample 3), and the small southeastern flow (sample 4) appear to be somewhat similar to one another.

Table I contains trace element ratios for the five basalts analyzed. It is apparent that ratio similarities exist between samples 1 and 3. All four ratios shown in the figure are very close for the two samples, and even at this confidence level, these two basalts appear to be correlative. Sample 5, however, is not chemically similar to samples 1 and 3, and may indicate a different source for plateau basalt in this location (see Appendix B). The basalts of the plateau surrounding Glass Buttes are high-alumina olivine tholeiites, less alkalic than Great Basin-type basalts (Christiansen and others, 1978; Hart and others, 1984), and less voluminous than the basalts of the Columbia River Group. High-alumina olivine tholeiites are

TABLE I

<u>sample number</u>	<u>Eu/Sm</u>	<u>La/Sm</u>	<u>Co/Cr</u>	<u>Sc/Cr</u>
1	0.294	1.93	0.145	0.109
2	0.240	2.15	0.539	0.510
3	0.296	1.91	0.142	0.125
4	0.302	2.00	0.349	0.261
5	0.368	3.14	0.236	0.137

Trace element ratios for basalt samples
from the study area.

common in the Steens basalt sequence (Helmke and Haskins, 1973). REE patterns for basalt samples from Glass Buttes normalized to chondrite values are shown in figure 12.

Silicic Rocks

The rhyolite glasses of the Glass Buttes complex are generally high-silica and peraluminous (Table II). REE patterns normalized to chondrite are shown in Figure 13.

DISCUSSION

The following discussion addresses physical patterns and trends observed in the field, and physical and chemical trends from laboratory analyses of Glass Buttes rocks. Specifically, the following areas will be discussed: dome formation at Glass Buttes, patterns related to phenocryst abundance and composition, implications of bimodality at Glass Buttes, and implications of geochemical trends of silicic rocks at Glass Buttes.

Dome Formation

Volcanic stratigraphy within domes includes a core obsidian unit, gray glass unit, carapace obsidian unit, and brown glass breccia unit. Core obsidian was observed in three eroded domes at the east end of the complex. It is suspected that other domes may have obsidian cores which have not yet been exposed by erosion. The location of the obsidian cores and the steep crudely radial dip angles in surrounding gray glass strongly suggest that the obsidian

Figure 12. REE patterns for 5 basalts from study area. Values for Steens basalt from Helmke and Haskins, 1973.

TABLE II

	Younger LCB Rhyolite			Obsidian	Older LCB-Anlelope Rhyolites					
	1	2	3		5	6	7	8	9	10
SiO ₂	72.73	72.78	73.77	74.57	75.06	75.30	75.44	75.88	75.95	76.34
TiO ₂	0.25	0.30	0.18	0.21	0.07	0.09	0.10	0.04	0.07	0.04
Al ₂ O ₃	13.97	14.09	13.46	13.78	13.30	13.24	13.08	13.22	13.03	13.16
Fe ₂ O ₃	0.73	0.92	0.54	0.59	0.15	0.21	0.21	0.03	0.03	0.12
FeO	0.84	1.05	0.61	0.68	0.17	0.24	0.25	0.03	0.03	0.14
MnO	0.03	0.06	0.04	0.05	0.04	0.04	0.03	0.02	0.01	0.05
MgO	0.23	0.53	0.49	0.42	0.20	0.25	0.27	0.22	0.29	0.26
CaO	1.54	1.91	1.34	1.36	0.67	0.68	0.90	0.27	0.16	0.41
K ₂ O	3.12	3.20	3.01	3.15	3.36	2.76	2.87	3.12	2.29	3.40
K ₂ O	3.71	3.51	3.88	3.84	4.37	4.39	4.27	4.60	4.62	4.51
P ₂ O ₅	0.07	0.09	0.04	0.05	0.01	0.03	0.10	0.02	0.01	0.07
Total	97.22	98.44	97.36	98.70	97.40	97.23	97.52	97.45	96.49	98.50

Major oxides for rhyolitic glass and obsidian samples
from Glass Buttes (data reproduced from Berri, 1982).

Figure 13. REE patterns for rhyolite glass samples from Glass Buttes.

cores are developed in the vents for the domes. Away from the vents, dips of flow layers in gray glass units become more gentle. Vesiculation within gray glass units increases stratigraphically upward. In the outermost levels of gray glass units vesicles are along flow bands. Vesiculation may have taken place while the lava was still flowing or escaping gases may have become trapped along these planes of weakness after flow had ceased. Vesicles, although concentrated along flow bands, are not stretched or elongate as may be expected if developed during flow.

Local float concentrations of core obsidian in elongate patterns may represent local anticlinal folding within gray glass and underlying core obsidian (Fink, 1983) with subsequent erosion having exposed the obsidian.

Carapace obsidian may have developed as thin, chilled selvages on dome surfaces. It is widespread float at the stratigraphic level above the gray glass units, but is not abundant. It also occurs as small lenses and beads in extremely inflated gray glass at the edges of domes. Obsidian beads found as scattered float were likely contained within similar inflated glass which has been eroded.

Just slightly beyond, and sometimes stratigraphically above gray glass units are brown glass breccias. The matrix of the breccias is consistently more inflated than the glass clasts which it supports. The breccias are interpreted to be outer dome material. The clasts are

believed to have formed from partially solidified glass near the outer surface of the developing dome at a time when the interior of the unit was still being emplaced. The upper glass was broken up by expansion of the dome and carried, mainly passively, outward and down the flanks of the dome toward its margins. In thin section, oxidized iron and higher microvesicularity was observed in the matrix. Flow texture in matrix glass around glass clasts was also observed. Accumulations of brown glass breccias are common at the margins of eroded domes. These concentrations may be related to folding and overturning of gray glass at dome edges while brown glass breccia was carried stratigraphically above it, conveyor-belt style, to accumulate at the margins. The abundance of brown glass breccia decreases away from dome margins toward dome cores, but can be found on dome flanks as float strewn over gray glass, much like carapace obsidian. This would suggest it was once over the gray glass.

The paucity of pyroclastic units exposed at the surface in association with the silicic volcanic rocks of Glass Buttes suggests that dome emplacement was not initiated by explosive volcanism. The suggested mechanism of dome development is by nonexplosive inflation of an endogenous nature, which, with continued evolution, expands and grades into exogenous growth. Brown glass breccias represent the brittle outer surfaces of domes, while gray glass represents deeper, more ductile flow.

Field relations indicate that stratigraphic units to the west generally overlie stratigraphic units to the east. A generalized depiction of stratigraphic relations, phenocryst abundance and topography for the eastern half of the complex is shown in Figure 14. The oldest stratigraphic units of the complex, those northeast and east of Antelope Ridge, are aphyric and acrySTALLINE.

The older and younger units in Berri's (1982) area of study are described as sparsely porphyritic, containing phenocrysts of pyroxene, sanidine, plagioclase, and quartz. Plagioclase in the older unit has a composition of An₁₁₋₂₈; the younger unit's plagioclase has a composition of An₄₅. Berri notes that phenocrysts are slightly more abundant in the younger rhyolite. The silicic rocks which underlie the western portion of the Buttes contain plagioclase (andesine), abundant pyroxene, and quartz phenocrysts (Waters, 1927b). Whether individual units show variations in abundance or types of phenocrysts was not indicated.

Erosional levels also vary from east to west within the Glass Buttes complex. Those domes to the east are more deeply eroded than those to the west. With increasing distance westward, both relief and elevation increase. Erosional levels in the western half of the complex are not known, but this is where the highest elevations within the complex occur.

The volcanic rocks of the High Lava Plains are chemically bimodal (basalt-rhyolite). Since no rocks of

Figure 14. General stratigraphic relations of units at Glass Buttes. Numbers refer to per cent phenocrysts (phenocryst percentages from Berri, 1982).

intermediate composition have been chemically identified to date associated with Glass Buttes, rhyolite-basalt bimodality is assumed to exist here also. This type of bimodal volcanism is found in association with extension-type tectonics (e.g. Christiansen and McKee, 1978; Hildreth, 1981). One explanation for this affiliation is that heat is supplied by basaltic intrusion into the lower crust, but extension prevents an extended residence time of the basalt within the crust. The basalt rises relatively rapidly through the crust, promoted by extension, and partial melts are developed and extruded as relatively small-volume, highly differentiated lavas. Because of the short residence time of the basalts within the crust and easy access to the surface, development of hybrid melts is not likely to occur. Thus, basalt and rhyolite in this setting are derived from two separate sources (Hildreth, 1981). In the model, basalts are much more voluminous than the associated rhyolites, and are extruded before, during, and after rhyolitic extrusion. This pattern is noted at Glass Buttes, and if regional extensional tectonics of the Basin and Range are considered to have some influence here the bimodal associations at Glass Buttes may be compatible with the model described above.

Chemistry Related to Stratigraphy

The Glass Buttes silicic volcanic rocks exhibit chemical variations which are related to stratigraphic

sequence. In this section, these chemical variations are compared with other high-silica rhyolite systems and these changes, along with other patterns observed at Glass Buttes are discussed in light of petrogenetic implications.

Berri, from her detailed mapping immediately west of and conterminous with this study area, was able to define relative stratigraphic relationships for a number of rhyolitic units by superposition (1982, Plate I). Eighteen major element analyses were performed on representative samples, some of which are reproduced here as mean values in Table III. The locations of the samples are shown in Appendix B. Field relations, major element chemistry and petrographic study has established that the samples can be clearly divided; six belong to older units, and three belong to a younger unit (Berri, 1982). The six samples representing the older unit had two different vent sources (three samples from one, three from the other), but Berri concluded that the units came from the same reservoir and were probably erupted coevally. One of the older units is overlain by the younger unit.

Two additional samples were selected (from the author's study area) which represent an older unit and a younger unit, presumably relatively closely related in time of extrusion to one another, and were analyzed for trace element concentrations. The locations of the two samples are shown Appendix B. The sample considered to represent the older unit is a gray to orange fresh glass which came

from Phillips hole 1 at a depth of 80 m, and is interpreted to be a primary volcanic deposit. The sample of the younger unit came from an outcropping rhyolite flow proximal to Phillips hole 1. This younger unit which was analyzed for trace elements is believed to be correlative with Berri's older unit which was analyzed for major elements.

Figure 15 is a graphical representation of ratios for various major and trace elements for the samples discussed above. Major element concentrations used to calculate ratios were averages. In addition, elemental ratios for other high-silica rhyolite systems are included for comparison. Figure 15 is a graph of the ratios of elements from early erupted material to later erupted material (i.e., older/younger) for four separate upper Cenozoic high-silica rhyolite eruptive systems. The Bishop Tuff (Hildreth, 1981) and the Tala Tuff (Mahood, 1981) represent ash-flow units, while Coso (Bacon and others, 1981) and Glass Buttes represent erupted silicic lavas. Because ash flow tuffs are essentially the stratigraphic reverse of material in the magma chamber just prior to eruption of that material, chemistry of early erupted material (stratigraphically low at the surface) is interpreted to represent chemical relations which existed highest in the magma chamber. The material at the top of the ash flow represents material which was deeper in the magma chamber at the time of eruption (e.g. Beeson, 1969; Hildreth, 1981; Mahood, 1981). Because element concentrations are

Z →

Figure 15. Trace element ratios compared with other high-silica rhyolite systems: first line in each box represents Bishop Tuff ratios (Hildreth, 1981); second line represents Tala Tuff (Mahood, 1981); third line represents Coso rhyolites (Macon, 1981); fourth line represents Glass Buttes rhyolite (this study). See text for explanation.

represented as ratios of early/late, Figure 15 can be thought of, in a general sense, as a qualitative spatial representation of a magma chamber. The upper portion of the diagram coincides with the roofward portion of the chamber, the lower portion is deeper. This is only in the sense of where specific elements are enriched (and depleted). With reference to the diagram, it can be noted that several elements show consistent enrichment, while others show consistent depletion in relation to early vs. later eruptive products. Other elements do not behave consistently or appear to have remained constant over the course of eruption. Those elements which are interpreted to have been most consistently enriched roofward within the chamber are Na, Cs, Sm, Yb, Lu, Hf, and Th. Those most consistently depleted roofward are Mg, probably P, Ca, Ti, Fe, La, Ce and Eu. Elements which apparently behave inconsistently are K, Sc and Mn; Al and Si show an apparent constant concentration. Na and K values have been shown to be affected by hydration over time (Na generally decreased, K can be slightly enriched; Bacon, 1981). Both of these elements from Glass Buttes samples behave in an opposite manner when compared with the other high-silica rhyolite systems in Figure 15. One explanation for this is related to the considerable age difference of Glass Buttes when compared to the other three systems (Glass Buttes is at least five m y old, while the other three systems are all less than one m y old). Hydrational effects and

devitrification processes are factors which have influenced the K and Na values of Glass Buttes rocks over a greater period of time than for rocks of the other systems.

Mahood (1981) points out that chemical changes within a magma chamber are affected by the following parameters:

- 1.) the size of the magma chamber;
- 2.) rate of eruption- volume relative to time;
- 3.) volatile content as related to its effect on viscosity, liquid-crystal equilibria, and its role in convection- concentration of elements;
- 4.) depth of the magma chamber.

A fundamental difference exists between the tuffs (Bishop and Tala) and the lavas (Coso and Glass Buttes) with reference to the parameters listed above: the length of time over which lavas extrude is much greater than the length of time it takes for an ash-flow tuff to erupt. Essentially, ash-flow tuffs represent an instant in time, and thus are inverted reflections of the zonation, both chemical and physical, within the magma chamber at that particular instant. On the other hand, domes and flows are erupted and built up over potentially considerable periods of time. The chemical similarities illustrated by Figure 15 suggest that the length of time over which Coso and Glass Buttes were erupted was not so long that magmatic differentiation processes had evolved to such a point that the chemistries deviated from those predicted by the Bishop and Tala tuffs.

Study of the Bishop Tuff led Hildreth (1981) to propose that some of the compositional zonation in high-silica rhyolite magma bodies may take place in the silicate liquid itself, largely independent of crystal-liquid equilibria. Studies of other high-silica systems support these conclusions (e.g. Mahood, 1981; Smith, 1979; Bacon, 1981; Crecraft and others 1981). Hildreth (1981) discusses at length a model in which thermogravitational convection coupled with Soret diffusion may serve as a mechanism to develop chemical zonation without development of a free vapor phase due to volatile saturation (Hildreth 1979, 1981; also see Shaw, 1974). Concentration of volatiles and associated enrichments of specific elements can be related to spontaneous growth of concentration gradients when or where a temperature gradient exists. The diffusion, combined with temperature-related convection, can cause a gravitationally stable volatile-rich zone to develop at the top of the chamber.

Whatever the mechanism(s) responsible for chemical zonation observed in high-silica rhyolite systems, it seems that those mechanisms have affected ash-flows and rhyolitic extrusions in a similar way. This would imply that chemical evolution within a magma chamber over time (although numerous physico-chemical variables affect that evolution) maintains a qualitative degree of consistency which can be related, from observation of ash-flow tuff chemistry, to a spatial (i.e. vertical) zonation within the

chamber. Chemistry of the Coso and Glass Buttes systems also reflects this character.

Hildreth (1981) also presents evidence (Table 2, p. 10,162) for a relationship between abundance of phenocrysts and depth within the magma chamber for pyroclastic flows. Toward the roof of the chamber, phenocryst abundances often show a marked decline. This appears to contradict the generally accepted precept that magma chambers crystallize from the walls inward, but in fact, as Hildreth points out, illustrates the complexities of both physical and chemical evolution which occurs within a magma chamber over space and time. Changes in phenocryst abundances with depth suggest a progressive roofward depression of the liquidus by the upward enrichment of dissolved volatiles. Hildreth presents evidence that

in many voluminous magmas, neither accumulation of phenocrysts nor a gradient in liquidus temperature due to the bulk compositional gradient is likely to account for the increase in crystallinity with depth in the erupting chamber.

His studies of the Bishop Tuff show that temperature only increased 70 degrees C, SiO_2 content only decreased by 2% but total phenocryst content changed from 5% to 30% during progressive eruption.

The low abundance of phenocrysts in the two units mapped by Berri (1982: Plate I, Tra, Tro) and their chemical similarities suggest that both flows tapped the same magma chamber at a high level; however, from subtle chemical differences in major element ratios of

older/younger; the increase in phenocryst abundance in the younger unit; and the change in An content from An₁₁₋₂₈ to An₄₅ from older to younger, it is argued here that the younger flow erupted from the same chamber as the older flow, but tapped a deeper level of that chamber.

It is also suggested here, from: 1.) chemical trends; 2.) apparent increase in phenocryst abundance from east to west; 3.) apparent deeper dissection of the east end of the complex by erosion; and 4.) stratigraphic relations from east to west in the complex; that a younging westward trend may exist within the complex. If this is the case, then Glass Buttes may be a localized reflection of the larger trend of silicic volcanics in central Oregon which shows a regular westward decline in age (e.g. MacLeod, 1976). A total of 5 K/Ar dates on obsidian within the complex (Table IV) cannot be used to support this postulation because four of the five dates, average 5.5 million years, all fall within the error limits of one another and the fifth date (7.7 million years) is suspect because it came from an area proximal to surface hydrothermal alteration (W. Benoit, 1983, written commun.).

TABLE IV

<u>SOURCE</u>	<u>LOCATION</u>	<u>AGE (m y)</u>
PHILLIPS	SE $\frac{1}{4}$ SE $\frac{1}{4}$ 19 T23S R22E	5.5 $\pm$ 0.3
PHILLIPS	SE $\frac{1}{4}$ NW $\frac{1}{4}$ 5 T24S R23E	5.8 $\pm$ 0.3
PHILLIPS	SE $\frac{1}{4}$ SE $\frac{1}{4}$ 35 T23S R22E	5.8 $\pm$ 0.3
PHILLIPS	NW $\frac{1}{4}$ NW $\frac{1}{4}$ 34 T23S R23E	7.7 $\pm$ 0.4
G.W. WALKER	SW $\frac{1}{4}$ NE $\frac{1}{4}$ 30 T23S R23E	5.04 $\pm$ 0.75

K/Ar dates for Glass Buttes.

HYDROTHERMAL ALTERATION AND MINERALIZATION

During the magmatic processes which formed Glass Buttes hydrothermal activity developed producing alteration and mercury mineralization near the surface. Altered rocks identified in the subsurface are overlain by unaltered units, evidence for a separate, older hydrothermal system. Surface altered areas are spatially associated with a weak heat-flow anomaly which is slightly west of and partially overlapping the zone of surface alteration (Johnson and Ciancanelli, 1983). A dipole-dipole resistivity survey (Hull, 1976) indicates a zone of low resistivity at a depth of 600 m. Its strongest definition is west of, but partially overlapping the heat-flow anomaly. Figure 16 shows the spatial relationships and extents of these three features. Near-surface rocks in the altered area contain low-grade cinnabar mineralization at the surface, and low-level gold and silver mineralization have been detected at the surface and in the subsurface.

Alteration and mineralization were described, the paragenesis was defined, and the mineralogy was determined for surface and subsurface materials. Laboratory analyses have allowed preliminary study of the chemical changes from non-altered to altered rocks in the study area. In addition to the chemical character of alteration, the physical and chemical conditions associated with low-grade mercury, gold and silver mineralization were defined. The relative timing

Figure 16. Limits of surface alteration (horizontal lines to the east), thermal anomaly (vertical lines) and area of lowest resistivity (horizontal lines to the west).

of volcanism and alteration was established, and relation of surface to subsurface alteration was defined.

Surface alteration

The distribution of hydrothermal alteration exposed at the surface is patchy, but is primarily localized along prominent northwest trending faults. The mineralogy of surface alteration includes opal and other silica phases, sulfide minerals, alunite and oxides. Plate II shows the distribution of alteration mineralogy at the surface. Appendix C lists those samples which were X-rayed and analyzed, and Appendix B shows the sample locations.

Silica Phases

A number of silica phases were identified as alteration materials at the surface, including opal, alpha quartz, chalcedony, and water-clear botryoidal silica (hyalite). Opal comprises by far the greatest volumetric portion of surface alteration of any of the silica phases present. Table V summarizes characteristics of the different silica phases.

Opal

Opal is here used to include all of the natural hydrous silicas as defined by Jones and Segnit (1971). X-ray patterns for different types of opal according to this classification scheme are shown in Figure 17. The two main types of opal which occur at Glass Buttes in association

TABLE V

	<u>relative abundance</u>	<u>nature of occurrence</u>	<u>relative time of emplacement</u>	<u>location</u>	<u>associations</u>
opal {	opal-CT	great	mainly as replacement; minor precipitate	early	replaces rhyolite
	milky opal-A	low	precipitate	late	crystalline quartz, chalcedony
	hyalite (opal-A)	low	precipitate	late	Fe oxide
	crystalline quartz	low	precipitate	late	milky opal-A, chalcedony
	chalcedony	low?	?	late	milky opal-A, crystalline quartz

Characteristics of silica phases sampled from study area.

Figure 17. X-ray patterns for opal-CT (A, B, C, D) and opal-A (E, F). T = tridymite; Q = quartz (from Jones and Segnit, 1971).

with hydrothermal alteration are opal-CT (disordered alpha cristobalite, alpha tridymite) and opal-A (highly disordered, nearly amorphous).

The most abundant type of opal is opal-CT, which occurs in two settings: 1.) replacement, and 2.) as breccia cement. Replacement-type opal-CT has a pearly to waxy luster, is nonporous, and varies in color from dull buff to bright orange and yellow to pure white. It has been observed to grade into unaltered rhyolitic glass; flow banding in the glass is occasionally preserved after replacement. The most intense replacement occurs in unit "Tra", the relatively non-porous flow banded glass flow on Antelope Ridge (Plate I), whereas replacement of underlying inflated gray glasses of a dome in the same area is more patchy and irregular. Although its occurrence is in general often lens-like and patchy, replacement-type opal-CT is mainly concentrated in broad zones localized by northwest trending faults.

Replacement-type opal-CT was observed in three prominent northwest trending fault zones to have been brecciated and cemented by opal-CT plus finely disseminated cinnabar. These breccia zones are from a few cm to one or two m wide, and occur only along fault planes. Barren replacement-type opal-CT fragments cemented by opal-CT plus cinnabar were observed by Brooks (1971) in his description of Glass Buttes, and by Berri (1982). In more numerous, but smaller fracture and breccia zones which extend into the

hanging walls of faults, replacement opal-CT has been brecciated, but not subsequently cemented.

Opal-CT plus alunite veins occur in the shallow subsurface, and are described under the heading of alunite.

The other type of opal which occurs in the study area is opal-A, which occurs as milky fracture coatings near the summit of Antelope Ridge (Plate II), or as water-clear thin botryoidal coatings.

Milky opal-A has been found only at the highest elevations on Antelope Ridge on open fracture surfaces. It is commonly off-white in color and translucent, with a pearly to vitreous luster. It has been found only on high-angle fracture surfaces. A 'ribbed' pattern has been observed on outer surfaces of milky opal-A (Figure 18). In one case where milky opal-A was precipitated on a fracture cutting rhyolitic glass, the glass was leached white for two cm away from depositional contact, but retained its original coloration beyond this zone. At one location, it was observed to be alternately deposited with finely crystalline quartz and minor chalcedony. Milky opal-A can be distinguished from opal-CT by its X-ray diffraction pattern which lacks definable peaks, indicating the material is amorphous. In all cases observed, milky opal-A occurs as a precipitated coating on fracture surfaces.

The second type of opal-A is a water-clear, finely botryoidal silica which has been called hyalite (Berri, 1982; Berri and others, 1983). Hyalite occurs as thin,

often less than one mm thick coatings on fracture surfaces and vug linings. X-ray diffraction patterns show some variability, but it is believed that hyalite is primarily opal-A. Of six samples studied by X-ray diffraction methods, two gave weak disordered alpha cristobalite peaks, and may suggest variations in the degree of crystallization in hyalite. Hyalite rarely contains microscopic-size particles of cinnabar and what appear to be iron oxides. Hyalite is a common fracture coating within and peripheral to the central zone of the most extensive surface alteration. Hyalite only occurs as a precipitate on fracture surfaces.

Quartz and chalcedony

Gray quartz and minor chalcedony have been observed to alternate in mm-scale bands with milky opal-A on open fracture surfaces (Figure 18) high on Antelope Ridge. The wall-rocks are rhyolitic glass that appear unaltered. Quartz is dense, gray, translucent, and locally botryoidal. Bands up to 3 cm thick have been observed on open fractures. Thin bands of chalcedony less than 0.1 mm thick are interlayered with the milky opal-A and quartz in this setting.

Sulfides

Cinnabar occurs at the surface primarily localized along northwest trending structures. Pyrite was observed at the surface at only one location, and is believed to occur

Figure 18. Alternating quartz, chalcedony and milky opal-A in an open fracture.

in low abundance at the surface.

Cinnabar

Bright red cinnabar is associated with precipitated opal-CT in northwest trending faults. The most productive mercury mining was spatially associated with the larger faults. The important concentrations of cinnabar in these zones appear to be as fracture coatings and microveinlets deposited as free cinnabar rather than disseminations in opal-CT. In those areas where fractures are most abundant, typically at intersections of faults or splay zones between faults, cinnabar is concentrated in breccia zones. Minor cinnabar occurs in many fractures and vug linings marginal to the main faults. Its texture is sometimes felted or dusty where it coats fractures or lines vugs.

Brooks (1963) observed that the Glass Buttes mine fault exhibits a curved surface, and suggested that the curvature may have acted as a cap to localize mercury mineralization.

Johnson and Ciancanelli (1983) illustrated the strong structural influence on mercury deposition at Glass Buttes with a mercury soil survey which was conducted within the area of alteration. Soils not immediately proximal to mercury-mineralized fault zones essentially carried no mercury. They concluded that a mercury soil survey was not an effective tool to help define concealed alteration at Glass Buttes.

Pyrite

Pyrite is the only other sulfide found at the surface and was observed at only one location on the north-central side of Cascade Ridge (Plate II). Unfortunately, this outcrop was in an exploration pit that was studied in July of 1982, but which has since been covered. The pyrite occurs as fine veinlets and disseminations in rhyolite glass. The rhyolite glass does not appear to be altered, as suggested by hand sample appearance and thin section analysis.

Alunite

Alunite occurs at and near the surface in adits and shallow exploration pits on the north side of Antelope Ridge and the north side of Cascade Ridge. Three types of occurrence are noted:

- 1.) Alunite plus opal-CT veins. Veins range in thickness from less than 0.1 mm up to two cm. Vein alunite is pale pink in color. Contacts with rhyolite glass host rock are sharp, and there is no evidence of host rock alteration in hand samples. Angular glass fragments are incorporated within the alunite plus opalite veins. Thin iron oxide coatings cover alunite vein surfaces, an indication that the alunite veins antedate at least some of the iron oxide deposition. An alunite veinlet was observed in thin section to have filled a fracture after cinnabar had been deposited on the walls of the fracture. Fragments of cinnabar were ripped up and incorporated into the

alunite, indicating that alunite was deposited after cinnabar.

Vein alunite does not occur at the surface but in the shallow subsurface, subparallel and in proximity to major faults. The observed occurrences were either in exploration trenches on the sides of hills, or, as in one case, in a mine adit. It is believed that this type of alunite occurs perhaps three to ten meters beneath the present surface.

2.) Euhedral (pseudocubic) monomineralic, white translucent alunite occurs in vugs and veinlets in the shallow subsurface. Euhedral alunite is often thinly coated or surficially spotted with orange iron oxide. Euhedral alunite was found only in areas in proximity to major faults.

3.) Alunite also occurs in a boxwork pattern, filling fractures in friable, pitted glass (Figure 19). The distribution of boxwork alunite is uncertain. It was observed on the north side of Antelope Ridge away from major faults, and the northeast side of Cascade Ridge along a small fault. In this location, a lateral sequence was observed in which unaltered gray glass grades into a boxwork of alunite-filled microfractures in pitted glass. Gradation takes place over a distance of less than two m. The gray glass becomes increasingly bleached as abundance of alunite veins increases until a dull white porous material plus alunite remains. A thin coating of hyalite coats the altered material.

Figure 19. Alunite and pitted glass,
forming boxwork pattern.

Iron Oxide

Ruby red and orange botryoidal hematite coatings on fractures and vugs are relatively common in the area of surface alteration, and orange iron oxide staining is ubiquitous. Surficial orange iron oxide staining has a wide spatial distribution, and can be seen as surface stain on otherwise unaltered rhyolitic glass, and as concentrations along flow layering in glass that extend far beyond the area of opalite (Plate II). Rubbly patches of deep orange iron oxide-stained rock approximately two m in diameter occur near the crest of Antelope Ridge.

Where hematite is observed to occur with other alteration minerals, it is commonly late stage. It coats fractures in replacement-type opal-CT, and often occurs as coatings on cinnabar; it has been observed to coat alunite surfaces. The only precipitate which consistently occurs later than hematite is hyalite. Orange hematite can be disseminated within hyalite, suggesting coprecipitation, but this is rare.

Brown Clay-rich Material

A material which filled fractures at the surface and in the shallow subsurface was found in three locations (Plate II). The material is dark brown and has a very waxy feel; it is nonindurated and when moist, can be rolled between the fingers. Preparation of the sample in powder mounts that were analyzed by X-ray diffraction failed to

establish a positive identity for the substance, but it appears to contain up to 50% poorly crystalline smectite with lesser amounts of mixed-layer chlorite-smectite (R. Gabor, 1984, pers. commun.). Small breccia fragments of opal-CT are commonly included within it. The brown vein material occurs on the north side of Antelope Ridge in an adit, and was observed to cross cut replacement-type opal-CT in a fault breccia zone. Smectite-rich veins also occur on the south side of Antelope Ridge, and were observed to be cross cut by cinnabar veinlets in altered glass. A third occurrence was observed in a splay zone of the Cascade fault, on the north side of Cascade Ridge, filling fractures in bleached glass. In all three cases, clay-rich veins occur in proximity to major faults, and are paragenetically early in the alteration sequence.

Clay-Zeolites

A yellow material was found locally along a drainage on the south side of Cascade Ridge (Plate II). Analysis by X-ray diffraction revealed the material to be comprised of approximately 40% kaolin, chlorite and zeolite, up to 30% quartz, and minor amounts of feldspar, opal, and possibly carbonate (M.L. Cummings, 1984, pers. commun.). No other occurrences of similar material were noted, and the relationship of the clay-zeolite to other alteration minerals is not clear.

Diamond Drill Core

Diamond drill core to 115 m depth was found in an old mining shack on the north flank of Antelope Ridge. Although the exact location of the core hole could not be determined, it is presumed that the core was drilled on Antelope Ridge proximal to the Glass Buttes mine (Plate II).

The unit through which the core was drilled is the flow-banded glass flow of Berri (1982, Plate I:Tra). The paragenetic sequence observed in the core is as follows:

- 1.) fracturing, bleaching and replacement of host rock by opal-CT, followed by cinnabar veining.
- 2.) Local brecciation and introduction of opal-A plus disseminated pyrite.
- 3.) Alunite veins cross-cut opal-A plus disseminated pyrite veins.
- 4.) Alunite is coated with orange iron oxide.

Neither hyalite nor cinnabar are abundant in core. Variation in the normal paragenetic sequence was noted at a depth of 70 m, where, in an open cavity, euhedral alunite was thinly coated by cinnabar which was coated by hyalite. Figure 10b shows alteration minerals and their distribution in drill core.

Hecla and Union Carbide Drill Holes

Nine reverse circulation rotary holes ranging in depth from 45 m to 165 m were drilled by Hecla Mining Company in 1981. Hole locations, confined to Antelope Ridge, are shown on Plate II. Drill logs, along with the

results of fire assays for Hg, Au, and Ag were made available for this study.

Alteration minerals from Hecla holes are opalite, cinnabar, and iron oxide staining. The opalite mentioned is presumed to be replacement-type opal-CT, which was mapped and sampled at the surface in this area by the author. Opalite occurs in all Hecla drill holes, but occurs in much lower abundance in holes H8 and H9. These two holes penetrate gray perlitic glass rather than the overlying flow-banded rhyolite (Berri's Tra unit). A zone rich in cinnabar occurs in hole H4, and is likely associated with a north trending fault which occurs at the surface at this location (see Plate I and Plate II).

Thirty-one reverse circulation rotary holes were drilled by Union Carbide in 1970 as part of an exploration program to evaluate the potential for mercury mineralization. Five holes were drilled in brecciated areas on Antelope Ridge and twenty-six holes were drilled along the Cascade fault. The holes on Antelope Ridge range in depth from 21 to 65 m and the holes along Cascade Ridge range in depth from 14 to 83 m. Lithologic and mineralogic descriptions in the logs are brief. Opalite was noted to locally carry sparse disseminated cinnabar. In the hanging wall of the Cascade fault cinnabar mineralization decreases, whereas brecciated opalite persists.

In two holes which were drilled to depths of 25 m and 11 m along the fault, lithology was described as "brown

sticky mud" and "brown sticky clay", with one zone of the material being over three m thick. These holes are located a few hundred meters from where brown clay-rich smectite veins were observed in outcrop. The drill logs may be describing this same material. If this is the case, these clays occur in greater abundance along the Cascade fault than is indicated in outcrop, and since small veins of the same material are found on both the south and north sides of Antelope Ridge, it may be more abundant in the altered area overall than indicated by surface exposures.

Summary of Surface Alteration

Surface and near-surface alteration exhibits diffuse overlapping lateral zonation in association with northwest trending faults within the silicic complex (Plate II). Figure 20 shows spatial and temporal relations among alteration phases which are localized tightly along the Cascade fault. Similar patterns were observed along other prominent faults within the alteration zone. Localized immediately along faults are replacement-type opal-CT, veins of poorly crystalline smectite, cinnabar, hematite, alunite plus opal-CT veins, and rare pyrite veinlets. Partial replacement by opal-CT continues away from faults up to 500 m. Quartz, chalcedony and opal-A occur as alternating precipitates on open fractures at the crest of Antelope Ridge. Localized clay-zeolites occur on the south side of Cascade Ridge. Extending farthest from alteration centers is a broad, diffuse zone of iron oxide staining and

Figure 20. Alteration assemblage proximal to major faults.

hyalite coatings. Figure 21 is a generalized summary of paragenesis of surface and near-surface alteration.

ALTERATION GEOCHEMISTRY

Preliminary geochemical investigation of alteration and mineralization at Glass Buttes provides information on the hydrothermal system. Since a number of silica phases occur within the system, the geochemistry of silica phases was studied to relate these patterns to degree of crystallinity and overall distribution, abundance, and spatial relationships among silica phases.

Table VI shows trace and major element concentrations for various silica phases related to hydrothermal activity at Glass Buttes. Sample locations are shown in Appendix B.

Five samples of replacement-type opal-CT were analyzed for major element concentrations. Figure 22 shows weight percent of major elements present in the five replacement opal-CT samples and four unaltered rhyolitic glasses from Glass Buttes, plotted against weight percent silica. As Berri (1982) points out, major element abundances are radically depleted in the opalized rock.

Figure 23 is a graph of REE concentrations in two of the unaltered rhyolitic glasses and four of the samples of replacement opal-CT normalized to chondrite values. Although absolute abundances are greatly depleted in the replacement opal-CT, the relative shapes of the REE plots do not change much from fresh to opalized samples.

Figure 21. Relative time of emplacement for surface and near - surface alteration assemblage.

Chemical concentrations in selected samples from Glass Buttes.
Values given in parts per million.

	<u>Cs</u>	<u>La</u>	<u>Ce</u>	<u>Sm</u>	<u>Eu</u>	<u>Yb</u>
milky opal-A (21)	ND	ND	ND	0.16 ± 0.02	ND	ND
milky opal-A (22)	ND	ND	3.00 ± 0.90	ND	ND	ND
hyalite (23)	ND	ND	4.40 ± 0.90	ND	ND	ND
hyalite (24)	ND	ND	ND	ND	0.10 ± 0.02	2.90 ± 0.40
hyalite (25)	1.46 ± 0.15	1.44 ± 0.14	5.20 ± 1.10	ND	ND	1.30 ± 0.20
crystalline quartz (26)	ND	3.40 ± 0.20	29.90 ± 1.30	ND	ND	3.30 ± 0.40
crystalline quartz (27)	ND	ND	ND	4.05 ± 0.06	ND	ND
boxwork alunite (28)	ND	11.90 ± 0.50	28.90 ± 1.50	2.21 ± 0.04	0.24 ± 0.02	ND
brown clay-rich vein material (29)	6.30 ± 0.50	9.00 ± 0.30	97.00 ± 3.00	6.83 ± 0.09	1.20 ± 0.04	5.60 ± 0.70

	<u>Lu</u>	<u>Th</u>	<u>Hf</u>	<u>Sc</u>	<u>Sb</u>	<u>As</u>
milky opal-A (21)	ND	ND	ND	0.39 ± 0.04	ND	ND
milky opal-A (22)	ND	ND	ND	0.09 ± 0.01	0.35 ± 0.07	ND
hyalite (23)	ND	ND	ND	ND	0.21 ± 0.05	ND
hyalite (24)	ND	ND	ND	0.80 ± 0.04	0.21 ± 0.07	0.42 ± 0.11
hyalite (25)	ND	ND	1.24 ± 0.19	2.30 ± 0.10	ND	ND
crystalline quartz (26)	0.60 ± 0.07	4.20 ± 0.90	ND	0.40 ± 0.03	0.79 ± 0.13	ND
crystalline quartz (27)	ND	ND	1.71 ± 0.12	ND	0.35 ± 0.06	ND
boxwork alunite (28)	ND	ND	1.50 ± 0.20	5.40 ± 0.15	ND	ND
brown clay-rich vein material (29)	0.71 ± 0.09	20.00 ± 4.00	13.80 ± 0.60	53.80 ± 0.50	ND	ND

TABLE VI

TABLE VI cont.

Chemical concentrations in selected samples from Glass Buttes.
Values given in parts per million.

Sample #	Cs	La	Ce	Sm	Eu	Yb	Lu
6	3.20 ± 0.60	13.10 ± 0.40	82.00 ± 7.00	6.90 ± 0.09	0.18 ± 0.02	6.30 ± 0.50	1.21 ± 0.14
7	2.60 ± 0.50	8.70 ± 0.30	51.00 ± 4.00	4.37 ± 0.07	0.14 ± 0.02	6.10 ± 0.50	1.12 ± 0.13
8	1.40 ± 0.30	2.65 ± 0.14	18.00 ± 1.80	2.13 ± 0.03	0.07 ± 0.01	2.10 ± 0.20	0.43 ± 0.05
9	0.89 ± 0.17	2.04 ± 0.12	9.10 ± 1.10	1.17 ± 0.03	0.08 ± 0.01	1.64 ± 0.16	0.36 ± 0.05
10	0.89 ± 0.18	1.14 ± 0.09	9.70 ± 1.10	1.10 ± 0.02	N.D.	1.62 ± 0.15	0.32 ± 0.04
11	0.77 ± 0.14	1.14 ± 0.10	12.60 ± 1.40	1.63 ± 0.03	0.03 ± 0.01	2.19 ± 0.19	0.43 ± 0.05
12	0.70 ± 0.13	0.17 ± 0.04	2.50 ± 0.70	0.47 ± 0.02	0.03 ± 0.01	0.95 ± 0.11	0.20 ± 0.03

Sample #	Th	Hf	Ta	Sc	Sb	As
6	12.80 ± 0.90	4.00 ± 0.30	1.15 ± 0.10	6.31 ± 0.16	0.48 ± 0.18	2.50 ± 1.20
7	12.90 ± 0.90	4.00 ± 0.30	1.13 ± 0.10	6.68 ± 0.14	0.49 ± 0.15	N.D.
8	10.40 ± 0.70	4.10 ± 0.30	1.18 ± 0.12	1.73 ± 0.06	0.47 ± 0.08	N.D.
9	7.10 ± 0.50	6.90 ± 0.40	1.75 ± 0.16	1.14 ± 0.05	0.30 ± 0.06	N.D.
10	6.00 ± 0.40	4.30 ± 0.30	1.31 ± 0.12	1.41 ± 0.05	0.23 ± 0.06	N.D.
11	6.50 ± 0.40	3.80 ± 0.30	1.07 ± 0.10	1.38 ± 0.05	0.60 ± 0.10	N.D.
12	2.49 ± 0.18	4.30 ± 0.30	1.35 ± 0.13	0.38 ± 0.03	0.35 ± 0.06	N.D.

TABLE VI cont.

Chemical concentrations in selected samples from Glass Buttes.
Values given in weight per cent.

<u>Sample #</u>	<u>SiO₂</u>	<u>Al₂O₃</u>	<u>TiO₂</u>	<u>Fe₂O₃</u>	<u>FeO</u>	<u>MnO</u>	<u>CaO</u>	<u>MgO</u>	<u>K₂O</u>	<u>Na₂O</u>	<u>P₂O₅</u>
6	76.79	14.03	0.06	0.11	0.12	0.03	0.35	0.05	4.80	3.64	0.03
7	80.15	13.24	0.06	0.10	0.11	0.01	0.07	0.03	4.47	1.76	0.02
8	96.25	2.80	0.06	0.04	0.05	0.01	0.03	0.02	0.37	0.35	0.02
9	98.09	0.94	0.08	0.05	0.06	0.00	0.03	0.03	0.07	0.62	0.02
10	98.33	1.02	0.05	0.04	0.04	0.00	0.02	0.02	0.08	0.38	0.02
11	99.25	0.30	0.04	0.04	0.04	0.00	0.02	0.02	0.08	0.19	0.03
13	98.89	0.38	0.05	0.04	0.04	0.00	0.02	0.02	0.08	0.48	0.00

Figure 22. Major oxides vs. SiO_2 for unaltered rhyolite glass samples (open circles) and samples of glass replaced by opal-CT (filled circles). Values on graphs are per cents.

Figure 23. REE concentrations for unaltered rhyolite glasses (6,7) and rhyolite glasses replaced by opal - CT (8-12).

In Figure 24, REE for the five replacement opal-CT samples have been normalized to average values of unaltered rhyolitic glass. In general, La shows a strong depletion in all silicified samples. Eu, although depleted in absolute abundance during silicification, tends to exhibit less depletion relative to other REE in at least three of the samples. Yb and Lu are depleted in a uniform way, but appear to be slightly less depleted than light REE.

Other trace element concentrations in rhyolitic glass replaced by opal-CT, normalized to unaltered Glass Buttes rhyolitic glass, are shown in Figure 25. Notable here are the relatively greater depletions of Cs and Sc compared to Hf and Ta. Sb does not show significant change. In general, replacement opal-CT sampled closest to major faults shows greatest depletion (Appendix B).

Table VI includes concentrations of trace elements for two milky opal-A precipitates. The low concentrations of trace elements in both samples is striking. Sample 21 contains only Sm and Sc in low concentrations, and the other contains low concentrations of Ce, Sc, and Sb. Sample 22 occurs with alternating depositional layers of finely crystalline quartz and very small amounts of chalcedony.

Trace element concentrations for three samples of hyalite which were extracted from fracture surfaces are also included in Table VI. All three samples yield amorphous X-ray diffraction patterns. Sample 23 contains low concentrations of Ce and Sb. No other trace elements

Figure 24. REE patterns of replaced rhyolite glass normalized to unreplaced glass from Glass Buttes (see App. B for sample locations).

Figure 25. Trace element concentrations in replaced glasses normalized to unreplaced glass from Glass Buttes (see App. B for sample locations).

were detected in this sample. Sample 23 was removed from a fracture whose surface showed no other evidence of alteration or mineralization other than surficial iron oxide staining. Sample 24 contains Eu, Yb, Sc, Sb and As. This sample came from an area marginal to the main zone of surface alteration. Sample 24 was collected from a fracture which was observed to contain, in sequence beneath the hyalite, cinnabar, an unidentified bright yellow-green mineral, and iron oxide staining. No physical difference between the hyalite from the two samples could be discerned under the binocular microscope.

Trace element concentrations for samples of precipitated crystalline quartz (Table VI) show a consistent low-level enrichment of Sb. Sample 26 was taken from the same fracture surface as milky opal-A sample 22.

Trace element concentrations for the various hydrothermal silica phases present at Glass Buttes exhibit the following characteristics: replacement-type opal-CT becomes increasingly depleted in trace elements as silica content increases and replaced rock becomes whiter. Overall concentration levels of trace elements in replacement opal-CT, however, are in general greater than milky opal-A, hyalite, and crystalline quartz, although in those samples where replacement by opal-CT is greatest, very low concentrations of most trace elements are also noted. La, Cs and Sc show greatest depletion relative to other trace element concentrations in replacement opal-CT,

whereas Hf and Ta show relatively low depletion. Samples of milky opal-A, hyalite, and crystalline quartz which contain Ce were all taken from the crest of Antelope Ridge, within the main zone of surface alteration. Those samples in which Ce was not detected were taken from areas peripheral to the main zone (see sample locations, Appendix B).

In addition to trace element analyses of silica phases, a sample of boxwork alunite and a sample of smectite-rich vein material were analyzed. Concentrations for these two samples are listed in Table VI. Iron was not detected in the boxwork alunite, but Na was detected, suggesting a substitution by Na for K, but no substitution for Al by Fe.

Smectite-rich vein material contains notably high concentrations of several trace elements, particularly Sc and Ce. This material also contains high iron content.

Hecla Mining Company provided geochemical data for thirty-four surface samples (mostly grab-type) collected in 1981 and analyzed for Ag, Au (standard fire assay) and Hg. Most samples contained no detectable Au and a trace of Ag, or traces (less than 0.03 ppm) of both. Three samples contained between two and three ppm Ag and two contained 0.03 ppm Au. There does not appear to be a correlation between the concentration of Hg and that of Ag (+ Au). Two of the precious metal-bearing samples came from the north side of Antelope Ridge from the area of the drill holes (Plate II). The other was collected from the Cascade mine

area. The three samples are proximal to prominent faults.

Au and Ag concentrations from the Hecla holes on Antelope Ridge show maximum abundance of Au to be 1.6 ppm Au in Hole H1 at a depth of 10 m and 9.0 ppm Ag in Hole H3 at a depth of 10 m (values are averages taken over three m intervals). Anomalous values for Au and Ag persist through the flow banded glass and into the gray perlite unit beneath it (holes H7, H8, H9). Average precious metal concentrations, however, appear to be higher in the flow banded glass unit.

Discussion

The genetic differences between replacement type opal-CT and precipitated forms of silica is supported and further characterized by differences in trace element concentrations and patterns. In addition, trace element concentrations in replacement opal-CT samples allow inferences to be made regarding individual trace element mobilities.

The similarity in shapes of the REE patterns from fresh to increasingly altered rocks (see Figure 23) suggests that silicification was incomplete. Patterns reflect those portions of analyzed samples which effectively remained unaltered and maintained the same ratios of REE as unaltered rocks. Absolute depletions are an indication of the extent of alteration, and is a measure of how far the replacement process progressed before it was

arrested.

Figures 24 and 25 illustrate the differences in mobilities of trace elements subjected to the hydrothermal environment which produced replacement-type opal-CT. Of the REE analyzed, La appears to be the most mobile. Sample 12, which shows the most profound depletion of La, is also the most thoroughly replaced sample, as indicated by SiO_2 concentration of 99% and waxy white appearance. Ce and Sm are relatively mobile, but not to as high a degree as La (Figure 24). Eu, in three of the five samples of opal-CT analyzed, exhibits a small positive anomaly, evidence of its relative low mobility. Yb and Lu show uniform depletions and appear to be less mobile than the light REE, but more mobile than Eu.

Mobilities of other trace elements are illustrated in Figure 25. In summary, the graph illustrates moderate mobility of Cs, Th, and Sb, relative immobility of Hf and Ta, and a high mobility for Sc.

Although studies of relative mobilities of trace elements are sparse, the high mobility of La and the relative immobility of Eu in hot fluids was observed by Martin and others (1978) and Finlow-Bates and Stumpfl (1981). Lower mobility of Ce in comparison to La was also illustrated by Finlow-Bates and Stumpfl (1981). The apparently high mobility of Sc is not consistent with cation mobilities during such processes as spilitization and metamorphism (Cann, 1970; Field and Elliott, 1974). The

difference in Sc mobility may be related to the chemistry of the system affecting the rock.

Replacement-type opal-CT can be regarded as a reflection of which elements were depleted by fluids interacting with the rock at the time of replacement. Conversely, trace element abundances in precipitated silica phases are, in part, a reflection of which elements were carried by the fluids at the time of precipitation. The graphs in the previous section (Figures 24, 25) suggest that transport of trace elements by fluids which precipitated silica phases was very low. The low concentrations in milky opal-A and crystalline quartz, their occurrence primarily in topographically high settings on Antelope Ridge on open fractures, and what may be dessication-related surface morphology suggests that these silica phases are late stage or were deposited in a cooler part of the system, a conclusion supported by field evidence.

Hyalite, milky opal-A, and crystalline quartz samples taken from the central core areas of surface alteration contain Ce, while those samples of silica precipitates which came from areas peripheral to the central alteration area do not. This suggests that the presence of Ce in these samples may be related to nearness to the main thermal sources responsible for surface alteration, those samples which contain Ce being closer to the thermal sources than those which do not. This suggestion is supported by the

presence of bleached host rock at the contact surface of milky opal-A deposition in an open fracture at the crest of Antelope Ridge, an indication of elevated temperatures for fluids responsible for the opal-A deposition. No bleaching of host rock was observed to be associated with milky opal-A which occurs marginal to the alteration core. It will also be recalled that smectite-rich veins, interpreted to be relatively early stage, contain high Ce concentrations, which suggests that earlier stage alteration was higher temperature than later waning stages.

The difference in crystallinity of opal-CT vs opal-A reflects the temperature of fluids during deposition of the respective forms of silica. Rytuba and Glanzman (1977) used the degree of crystallinity of opal-CT at McDermitt Caldera to infer relative temperatures of formation, and were able to infer the locations of former thermal cores (former loci of highest degree of heat) in this manner. The crystallinity of alpha cristobalite is determined by its $d(101)$ spacing; highest crystallinity is at 4.04 angstroms, lowest is a diffuse peak produced by a 4.12 angstrom spacing. Gradational decrease in temperature was inferred by Rytuba and Glanzman from gradational increase in $d(101)$ spacing in opal-CT samples over a change in lateral distance (see also Murata and Randall, 1975). No detailed sampling across zones of replacement-type opal-CT was done at Glass Buttes, but it is reasonable to assume that the difference in crystallinity between opal-CT and opal-A

phases is, in part, to be related to temperature of fluids at the times of their deposition. Opal-CT was deposited at higher temperatures than opal-A phases. The range of temperature which has produced opal-CT in varying degrees of crystallinity in the laboratory is 100-300 degrees C, the range in epithermal systems (Rytuba and Glanzman, 1977). Thus, the probable temperature of formation of opal-CT at Glass Buttes is within this range. Opal-A phases at Glass Buttes are interpreted to have formed at lower temperatures and later than opal-CT.

From distribution relations, trace element data, and crystallinity variations among hydrothermal silica phases, replacement-type opal-CT was formed at higher temperatures than any of the other silica phases. Faults provided access to the surface for hydrothermal fluids. Opal-CT development was early stage. Away from prominent fault zones, opal-A phases developed at lower temperatures. Trace element concentrations in opal-A phases allow further temperature zonation away from large faults, which were thermal cores. Closer to the cores, silica precipitates carried Ce, and in one case deposition was associated with bleaching of country rock. Marginal to the central thermal core, Ce was no longer able to be carried by fluids which were still transporting amorphous silica, nor were the fluids hot enough to leach country rock at contacts with depositional surfaces.

From spatial and temporal relations of alteration

minerals associated with the Glass Buttes surface hydrothermal system, it is argued that replacement-type opal-CT, hypogene alunite plus opal-CT veins, cinnabar mineralization, and smectite-rich veining are early-stage higher temperature phases, while opal-A phases, crystalline quartz, boxwork alunite and Fe-oxide staining represent lower temperature, and generally later stage alteration.

Brown clay-rich material, which is an early-stage alteration product, carries high concentrations of certain elements (Table VI). In addition to very high Sc concentrations, the material carries elevated Hf concentrations (relative to other alteration products). These two elements are interpreted to represent high and low mobilities, respectively, during replacement opalization of glass. Because brown clay-rich vein material was early stage, but its deposition was subsequent to the development of replacement opal-CT, its high trace element concentrations are believed to be directly related to elemental depletions in glass in proximity to faults during the process of replacement by opal-CT. Depletion values of Sc and Hf during replacement of glass by opal-CT, and enrichment values of these two elements in brown clay-rich material, are compatible with this interpretation. Sc is strongly depleted in opal-CT, and strongly enriched in the clay-rich material. Hf is very slightly depleted during replacement.

The mineral assemblage at the surface, which includes

opal, alunite and cinnabar is somewhat characteristic of acid-sulfate alteration (e.g. White, 1981; Buchanan, 1981), which occurs at or above the water table. A decrease in pH can be achieved in the upper portion of an epithermal hydrothermal system by deeper boiling near the water table, which allows partitioning of H_2S and CO_2 into a vapor phase. With upward transport of the vapor, cooling will cause condensation and oxidation of these compounds, which, in turn, causes a lowering of pH and produces acidic type alteration. No evidence of boiling was observed in association with surface alteration at Glass Buttes, although if boiling approximately coincided with water table levels, it may have been too deep to be expressed at the surface.

THE OLDER HYDROTHERMAL SYSTEM

The older hydrothermal system at Glass Buttes is known only from cuttings from the four Phillips stratigraphic test holes. Alteration related to this system was found in holes 1, 2 and 4 and will be described briefly. A summary of lithologic units and alteration was presented in Figure 10 and should be referred to for this section.

For ease of discussion, findings from the four test holes are ordered relative to the extent of alteration.

Hole 2

In hole 2, at approximately 360 m depth, a volcanoclastic unit is in sharp contact with an underlying unit comprised of approximately equal amounts of perlitic glass and opal-CT. Drill cuttings did not indicate whether opal-CT is replacement-type or a precipitate. Fracture surfaces in the perlitic glass and the opal-CT are coated with hyalite.

The interpretation of this contact and similar contacts is the key to the existence of an older, buried hydrothermal system. Three interpretations of the contact relations between the volcanoclastic unit and underlying opalized unit are suggested:

1.) The opal-CT developed within a stratigraphic layer. The overlying volcanoclastic sediments were present at the time of opalization, but were not altered.

2.) The volcanoclastic sediments and underlying opalized unit are in fault contact. The units were juxtaposed some time after alteration.

3.) Opal-CT alteration developed at or near a paleosurface, and the volcanoclastic sediments were deposited over the opal-CT unconformably (suggested by Berri, 1982).

The first alternative can be discarded immediately. If both volcanoclastic sediments and underlying pre-opal-CT lithology (glass) were in contact at the time of hydrothermal alteration of the lower unit, there does not

appear to be an acceptable explanation of why fluids carrying the silica which opalized the lower unit would not have penetrated the porous overlying volcanoclastic unit. No evidence of a permeability barrier has been found at the contact.

The data does not allow differentiation of the second and third interpretations. A fault zone might be easily obscured in drill cuttings, and cannot be dismissed. Sharp boundaries between altered glass and unaltered glass are prominent at the surface on Antelope Ridge across post-alteration faults.

Clasts of opal-CT in the volcanoclastic unit would be evidence of an unconformable contact. The presence of opal-CT clasts cannot be verified, because of the mixing of cuttings which takes place as the fragments are carried uphole to the surface. This mixing is often especially prominent at a lithologic contact which produces a change in penetration rate of the drill. Erosional clasts of opal-CT were not identified in the cuttings. Based primarily on the lack of evidence for a fault contact, namely, lack of clays, microslickensides, material resembling gouge, or any localization of mineralization at the contact, it seems that an unconformable contact is a reasonable possibility. This conclusion is in agreement with Berri (1982).

Hole 1

Units comprising the upper 240 m of hole 1 are

essentially unaltered. At approximately 240 m depth, alteration minerals are present and continue downhole to the bottom. Alteration consists of disseminated pyrite grains in skeletal white amorphous materials, opal-A plus disseminated pyrite, minor cinnabar, and hydrothermal quartz veins. Since quartz veins cement pitted material, they are later than the alteration which produced the pitted texture.

Hole 4

There is no evidence of alteration in upper units of glass and volcanoclastic material in hole 4 (Figure 10) except for minor localized surficial iron oxide staining and hyalite coatings. The first occurrence of abundant alteration is in association with basalt which appears in cuttings at a depth of 125 m. Alteration minerals are present from this depth to the bottom of the hole. Pyrite veinlets, carbonate, chlorite, clay, and quartz are associated with basalt units. Alteration minerals in basalt fragments occur as fracture and vesicle fillings, and clay (pale green smectite) has partially replaced host basalt in some cases. Fine-grained disseminated pyrite is abundant deeper in the hole and red quartz-plus-pyrite veins occur late at the bottom of the hole.

Pyrite grains separated from chips at selected depths in Phillips stratigraphic test hole 4 were analyzed for Au and associated trace elements. A total of twenty-eight samples of pyrite were analyzed. Trace element

concentrations for these samples are shown in Table VII. In addition to pyrite analyses from hole 4, three samples of pyrite separates from hole 1 were analyzed. These samples represent averages of 3 m at depths of 304, 480 and 500 m. Trace element concentrations for these samples are shown in Table VIII.

There are several changes in trace element character associated with pyrite in hole 4 (Figure 26). Pyrite in altered basalt at a depth of 160 m is the first occurrence of pyrite in the hole. Au concentrations of approximately 0.4 ppm for four pyrite samples from this unit are not associated with detectable As or Sb except for a small show of As near the lower contact of the basalt against a pyroclastic unit. Zn and Br were detected in pyrites from the basalt and may decrease slightly toward the lower contact.

Although pyrite is quite abundant in the underlying pyroclastic unit, Au was not detected in the five pyrite samples analyzed from this unit.

In a second altered basalt unit, at the upper contact against tuff, pyrite samples exhibit the highest concentrations of Au, Zn, and Br for downhole samples. Au, Zn and Br concentrations decrease toward the interior of the basalt unit, but an increase in the concentration of all three elements occurs again in pyrite samples taken from near the lower contact of the basalt. Arsenic appears to behave antithetically to Au, Zn and Br in that its

TABLE VII

Depth Interval ft.	Depth Interval m.	Au (ppm)	Ag (ppm)	Sb (ppm)	Zn (norm.)	Br (norm.)
450 - 460	136 - 139	0.49 ± 0.10	N.D.	N.D.	1.40 ± 0.20	0.24 ± 0.04
490 - 500	148 - 151	0.44 ± 0.10	N.D.	N.D.	1.10 ± 0.20	1.00 ± 0.07
540 - 550	164 - 167	0.42 ± 0.05	10.70 ± 0.60	N.D.	0.80 ± 0.13	N.D.
580 - 590	176 - 179	N.D.	13.40 ± 1.20	N.D.	1.00 ± 0.16	0.10 ± 0.04
660 - 670	200 - 203	N.D.	12.60 ± 1.00	6.50 ± 1.90	0.72 ± 0.12	0.13 ± 0.03
720 - 730	218 - 221	N.D.	6.60 ± 0.90	1.80 ± 0.60	N.D.	N.D.
760 - 770	230 - 233	N.D.	2.00 ± 0.70	N.D.	N.D.	N.D.
810 - 820	245 - 248	N.D.	N.D.	N.D.	3.00 ± 0.40	0.31 ± 0.09
880 - 890	267 - 270	13.10 ± 1.10	22.00 ± 8.00	N.D.	33.00 ± 4.00	1.70 ± 0.30
920 - 930	279 - 282	0.71 ± 0.19	284.00 ± 5.00	N.D.	3.30 ± 0.50	N.D.
1000 - 1010	303 - 306	0.45 ± 0.13	103.00 ± 2.00	N.D.	1.00 ± 0.20	N.D.
1030 - 1040	312 - 315	N.D.	568.00 ± 5.00	7.00 ± 1.30	N.D.	N.D.
1090 - 1100	330 - 333	0.98 ± 0.18	537.00 ± 6.00	12.00 ± 3.00	2.30 ± 0.30	0.14 ± 0.05
1240 - 1250	376 - 379	2.80 ± 0.40	92.00 ± 5.00	14.00 ± 6.00	15.20 ± 1.80	0.59 ± 0.11
1270 - 1280	385 - 388	0.09 ± 0.02	91.80 ± 1.70	46.00 ± 0.80	---	---
1290 - 1300	391 - 394	0.04 ± 0.01	5.80 ± 0.40	2.80 ± 0.40	N.D.	N.D.
1340 - 1350	406 - 409	N.D.	N.D.	12.50 ± 1.80	0.59 ± 0.13	N.D.
1390 - 1400	421 - 424	0.53 ± 0.13	31.00 ± 1.70	8.00 ± 2.00	1.30 ± 0.30	N.D.
1460 - 1470	442 - 445	N.D.	2.30 ± 0.60	5.60 ± 0.80	N.D.	N.D.
1500 - 1510	454 - 457	N.D.	42.00 ± 1.70	12.00 ± 2.00	1.40 ± 0.20	0.12 ± 0.04
1580 - 1590	479 - 482	0.43 ± 0.15	N.D.	4.60 ± 1.80	N.D.	N.D.
1660 - 1670	503 - 507	N.D.	81.50 ± 1.20	14.20 ± 1.80	N.D.	N.D.
1700 - 1710	515 - 518	N.D.	129.00 ± 3.00	12.00 ± 3.00	2.60 ± 0.40	N.D.
1780 - 1790	539 - 542	0.90 ± 0.20	670.00 ± 8.00	72.00 ± 10.00	4.20 ± 0.50	0.26 ± 0.06
1850 - 1860	560 - 563	0.09 ± 0.03	198.00 ± 2.00	22.00 ± 3.00	N.D.	N.D.
1890 - 1900	573 - 576	0.16 ± 0.05	314.00 ± 3.00	26.00 ± 3.00	N.D.	0.15 ± 0.03
1900 - 1910	575 - 578	0.09 ± 0.01	151.90 ± 1.60	8.20 ± 1.00	N.D.	0.03 ± 0.01
1920 - 1930	582 - 585	0.59 ± 0.09	443.00 ± 9.00	29.00 ± 4.00	---	---

Trace element concentrations for pyrite separates
from Phillips hole 4.

TABLE VIII

<u>Depth Interval</u>		<u>Au</u> (ppm)	<u>As</u> (ppm)	<u>Sb</u> (ppm)
<u>ft.</u>	<u>m.</u>			
1120 - 1130	341 - 344	0.02 ± 0.01	ND	7.20 ± 1.00
1590 - 1600	485 - 488	0.10 ± 0.02	67.60 ± 1.70	0.94 ± 0.18
1680 - 1690	512 - 515	ND	ND	0.90 ± 0.20

Trace element concentrations for pyrite
separates from Phillips hole 1.

Figure 26. Trace element concentrations for pyrite separates from Phillips hole 4 compared with downhole lithologies.

lowest concentrations are at the upper and lower contacts of the basalt, and highest concentrations are within the unit's interior. Sb was not detected in pyrite samples from the upper contact but was detected in the interior of the basalt, and its concentration increases slightly toward the lower contact. Concentrations of As and Sb in pyrite samples show a distinct increase from the deeper basalt unit down. Zn and Br concentrations are near or below detection limits near the bottom of the hole.

A separate trace element analysis was performed on late stage red (ferruginous?) quartz-plus-pyrite veinlets which cross cut porous white pitted host rock at a depth of 570 m. There is no apparent association of Au, As, Sb, Zn, or Br with the quartz-pyrite veins.

In addition to its presence in quartz veinlets, pyrite also occurs as finely disseminated euhedral crystals, in approximately equal abundance of cubes and pyritohedrons, within the pitted white porous host. Cubes and pyritohedrons were separated from the same sample bag (640-643 m) and analyzed separately for trace elements. Au, As and Sb concentrations for the two different morphologies are shown in Figure 27.

Discussion

Phillips holes 1 and 4 show a similar relation of essentially unaltered units overlying hydrothermally altered units (Figure 10). This relation indicates that the

Figure 27. Au, Sb, As concentrations for pyrite cubes and pyritohedrons from the same depth interval (1910 ft.)

alteration system evidenced in the subsurface predates the unaltered volcanic units which overlies these altered rocks. Since volcanism appears to have been related to more westerly trending structures rather than to the northwest trending faults along which surface alteration was localized, it is likely that earlier subsurface alteration was also related to this westerly trend.

Subsurface alteration recorded in Phillips stratigraphic test holes is characterized by abundant disseminated pyrite and locally abundant carbonate, while cinnabar and alunite are essentially absent. Paragenesis of subsurface alteration is not clear. It can be said that main stage alteration in the south was smectite-chlorite-carbonate-pyrite-quartz, while late stage alteration, deeper in the system, was quartz plus pyrite veining. In the north the system was depositing opal-CT.

The older alteration assemblage in hole 4 is not characteristically produced by low pH fluids. This assemblage may have been developed by low-temperature, near-neutral pH waters. Minerals comprising the assemblage also suggest that alteration may have been developed at or below the water table (Fournier, 1983). If the top of the older system developed near the paleosurface as seems likely from observed stratigraphic relations, this is suggestive that the water table may have been closer to the surface during the time which the older hydrothermal system was developed.

From observed mineral assemblages in the subsurface, it is a reasonable assumption that temperatures of deposition were within the range of those temperatures inferred for surface alteration. Quartz, chlorite, pyrite, and carbonate can all form within the inferred temperature range for surface alteration. The opal-CT hole 2 suggests that this portion of the system may have been above the water table and subjected to more acidic alteration conditions.

The association of Hg, Au, As and Sb in epithermal hydrothermal systems, both active and fossil, has been amply demonstrated by other studies (e.g. White and Heropoulos, 1983; Keith, 1983; Berger, 1983). Other elements which were not analyzed for in this study, but may also be associated, include Tl, Te, Se, Bi and B (White and Heropoulos, 1983). No arsenic minerals occurring as separate phases were identified at Glass Buttes.

Seward's (1973) experimental studies indicate that considerable amounts of Au may be transported in solutions in the near-neutral pH region where the $\text{Au}(\text{HS})_2$ complex predominates over other Au-thio complexes. The As-Sb association detected at Glass Buttes is compatible with Seward's suggestion that arsenothio and antemonothio complexes may also be significant transporters of Au in some hydrothermal solutions. Therefore, the presence of Au, As and Sb in association with the pyrite in Phillips hole 4 may be indications of transport by thio complexes in

hydrothermal solutions of near neutral pH . The alteration mineral assemblage associated with the subsurface hydrothermal system is chemically compatible with near neutral pH.

THE HYDROTHERMAL SYSTEMS

The two hydrothermal systems (Figure 28) which are interpreted to have been active at Glass Buttes at different times have a number of characteristics which can be compared and contrasted:

1.) The systems were active at different times, but both were responsible for near-surface alteration at the times they were active.

2.) Even though the two systems have markedly different alteration assemblages associated with them, they are both within the same range of epithermal temperatures judging from their respective mineral assemblages.

3.) Based upon mineral assemblages, the two alteration systems differ in pH of altering fluids. The older system was likely dominated by near-neutral waters, whereas for the younger system, the solutions were more acid.

4.) It is also suggested, based upon mineral assemblages, that alteration observed for the older system was more likely close to, or beneath the water table. Surface alteration associated with the younger system was likely developed above the water table. Water table levels in central Oregon may have been progressively depressed since five million years ago as the Cascade Range increased in elevation to the west. If this were the case, the

Figure 28. Cross section of the Glass Buttes complex showing inferred distribution of alteration. Dot-dashed lines represent paleosurface.

apparent westward recession, progressively deeper, of limits of surface alteration, heat flow anomaly, and high resistivity may be linked to the westward propagation of silicic volcanism, during which water table levels may have declined over time.

5.) Based on the presence of abundant auriferous, finely disseminated pyrite grains associated with the older system, it appears that structural control was not a significant factor in localization of alteration and mineralization. The younger system was clearly controlled by structures.

6.) Both systems likely had a volcanic heat source, and both systems were likely dominated by convecting meteoric waters.

The younger hydrothermal system, represented by surface alteration, can be modeled as having been active as northwest trending faults developed. The faults served to localize alteration. All breccias observed in the study area are fault breccias. No breccias interpreted to be of hydrothermal origin were identified. The lack of hydrothermal breccias is related to the apparent lack of focus for the younger system. Instead of the system being plugged, which would cause overpressures to build and eventual fracturing, pressure release and boiling of hydrothermal fluids, the system apparently 'leaked' during its life without ever sealing itself. This would perhaps explain why mercury mineralization is low-grade. The lack

of overpressure as a mineralization focal mechanism prevented higher mercury concentrations (and likely precious metal concentrations deeper in the system) from developing. Subsurface alteration is not structurally controlled, and disseminated auriferous pyrite developed in permeable tuff units. These units occur at considerable depth, however, and Au mineralization is low grade. From present data, Glass Buttes does not appear to be a promising prospect for precious metals.

Near-surface clay-rich vein material within major fault zones is not characteristic of the acidic alteration indicated by other surface alteration minerals. Trace element concentrations and spatial and paragenetic relations suggest that the brown clay-rich vein material was deposited under conditions of rather abrupt change in the chemico-physical environment. It is suggested here that the fault zones, which could act to localize downflow of groundwater, may have mixed with thermal fluids to decrease temperature and acidity, causing precipitation of the clay-rich material along major fault zones. The episodic character of hydrothermal activity would allow periodic downflow of surface waters during lulls in upflow of thermal fluids. The pervasive leaching of glass would continue while thermal pulses were active, but as pulses waned intermittently, lower temperature 'quenching' could occur within the fault zones, resulting in the precipitation of clay-rich veins.

SUMMARY AND CONCLUSIONS

Silicic volcanic units mapped at Glass Buttes are exogenous domes which exhibit a recurrent stratigraphy, from interior to exterior, of core obsidian, gray glass, carapace obsidian, and brown glass breccia. Exogenous domes and flows also exist within the complex (Berri, 1982; Cummings, 1984). Figure 28 is a highly schematic cross section which relates major lithologic units, structure, and alteration. The following sequence of development, over time, of the Glass Buttes volcanics and associated hydrothermal systems is compatible with the data from this study:

- 1.) Silicic volcanism began at Glass Buttes before five million years ago. Silicic volcanism may have initiated at the eastern end of the complex and propagated westward. Basaltic volcanism within and surrounding the complex was coeval with, and postdates silicic volcanism. A hydrothermal system was associated with early volcanism, and is interpreted to have been low temperature, near neutral pH, with alteration developed at or below the water table.

- 2.) Silicic and basaltic volcanism continued, and covered the waning or dead hydrothermal system.

- 3.) After silicic volcanism at the eastern end of the complex ceased, initiation of northwest trending faulting

was accompanied by hydrothermal activity which produced the present surface alteration. This system was low temperature (probably less than 150 degrees C) and produced acidic alteration, probably above the water table. Clay-rich vein material in major fault zones may represent periodic flow of surface waters down fault zones causing precipitation of the clays along with elements leached from glass in proximity to the faults. The hydrothermal system was leaky, and never focused significant mineralization.

4.) Plateau basalts overlapped the complex as the surface hydrothermal system waned.

5.) Faulting continued along northwest trends.

Pyrite associated with the older alteration system contains low-level Au mineralization along with elevated concentrations of As and Sb. Drill holes may have penetrated only high levels of the older system due to subsequent volcanic activity covering, and subsequent faulting and downdropping, of the altered units. Mapping of surface alteration revealed highest temperatures localized along major northwest trending faults, with a crudely systematic change to lower temperature alteration mineralogy away from faults.

Trace element studies of progressively altered rocks afforded inferences regarding relative mobilities of a number of trace elements under hydrothermal conditions responsible for the development of surface alteration. Hf and Ta displayed lowest mobilities, while Sc and La

exhibited highest mobilities under surface alteration conditions.

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APPENDIX A

Chemical concentrations in selected samples
at Glass Buttes.

Sample #	SiO ₂	Al ₂ O ₃	TiO ₂	Fe ₂ O ₃	FeO	MnO	CaO	MgO	K ₂ O	Na ₂ O	P ₂ O ₅
35.	98.55	0.88	0.04	0.04	0.04	0.00	0.03	0.02	0.08	0.30	0.02
36.	80.06	13.81	0.05	0.10	0.11	0.01	0.04	0.04	4.01	1.76	0.02
37.	78.21	13.53	0.06	0.11	0.13	0.05	0.32	0.05	4.76	2.77	0.02
38.	78.17	13.59	0.05	0.10	0.12	0.04	0.80	0.03	4.19	2.84	0.06
39.	77.89	13.43	0.05	0.12	0.13	0.03	0.29	0.05	4.56	3.44	0.01
40.	79.11	15.50	0.05	0.11	0.12	0.01	0.04	0.03	4.30	0.72	0.02
41.	78.83	13.29	0.05	0.37	0.43	0.01	0.09	0.04	4.52	2.35	0.01
42.	78.81	13.24	0.05	0.10	0.11	0.01	0.25	0.04	4.33	3.03	0.03
43.	95.99	2.88	0.12	0.09	0.10	0.03	0.03	0.03	0.25	0.48	0.02
44.	49.92	16.83	1.61	5.12	5.87	0.18	9.15	6.93	0.48	3.53	0.37
45.	80.23	13.49	0.06	0.11	0.12	0.02	0.08	0.04	3.67	2.17	0.03
46.	77.10	13.51	0.07	0.11	0.13	0.04	0.49	0.05	4.87	3.62	0.02

Values given in weight per cent.

APPENDIX A, cont.

<u>Sample #</u>	<u>Au</u>	<u>Ta</u>	<u>As</u>	<u>Sb</u>	<u>Sm</u>	<u>Sc</u>
1.	n.d.	0.33±.07	n.d.	n.d.	5.91±.07	33.3±.12
2.	n.d.	0.39±.07	n.d.	n.d.	9.73±.11	31.6±.14
3.	n.d.	1.47±.15	n.d.	n.d.	7.49±.09	42.48±.15
4.	n.d.	0.78±.14	n.d.	n.d.	4.84±.07	38.10±.60
5.	n.d.	1.39±.14	n.d.	n.d.	4.97±.04	22.60±.30

<u>Sample #</u>	<u>La</u>	<u>Lu</u>	<u>Yb</u>	<u>Th</u>	<u>Eu</u>	<u>FeO</u>
1.	11.4±.4	0.63±.09	3.0±.40	1.1±.20	1.74±.04	11.19±.10
2.	20.9±.6	1.03±.11	5.2±.40	1.8±.30	2.33±.05	11.29±.11
3.	14.3±.5	0.96±.11	5.3±.60	n.d.	2.22±.05	13.20±.12
4.	9.70±.7	0.67±.14	3.4±.70	n.d.	1.46±.06	10.50±.50
5.	15.6±.4	0.39±.08	2.9±.50	0.58±.09	1.83±.19	8.50±.30

Values given in parts per million, except for FeO, which represents total Fe, weight per cent.
n.d.= not detected.

APPENDIX A, cont.

<u>Sample #</u>	<u>Hf</u>	<u>Co</u>	<u>Cs</u>	<u>Ce</u>	<u>Cr</u>
1.	3.80±0.3	44.4±0.7	n.d.	n.d.	306.0±20.0
2.	6.60±0.3	33.4±0.6	n.d.	25.5±1.8	62.0±8.0
3.	5.30±0.4	48.4±0.7	n.d.	n.d.	340.0±20.0
4.	1.60±0.2	51.0±6.0	n.d.	n.d.	146.0±17.0
5.	1.83±0.19	39.0±3.0	n.d.	n.d.	165.0±12.0

Values given in parts per million.

n.d.= not detected.

APPENDIX B SAMPLE LOCATIONS

APPENDIX B, cont.

APPENDIX C
SURFACE SAMPLES

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<u>Sample #</u>	<u>Description</u>	<u>INAA</u>	<u>XRD</u>	<u>XRF</u>	<u>T.S.</u>
1	basalt	x		x	x
2	basalt	x			
3	basalt	x			x
4	basalt	x			x
5	basalt	x			
6	rhyolite glass			x	
7	rhyolite glass			x	
8	opal - CT			x	
9	opal - CT			x	
10	opal - CT			x	
11	opal - CT			x	
12	opal - CT			x	
13	opal - CT			x	
14	rhyolite glass	x			
15	opal - CT				
16	rhyolite glass			x	
17	rhyolite glass			x	
18	rhyolite glass			x	
21	milky opal - A	x	x		x
22	milky opal - A	x	x		
23	hyalite	x	x		
24	hyalite	x	x		
25	hyalite	x	x		
26	alpha quartz	x	x		x
27	alpha quartz	x	x		
28	alunite	x	x		
29	brown clay-rich material	x	x		
30	alunite		x		
31	alunite		x		
32	altered glass		x		
33	brown clay-rich material		x		

SURFACE SAMPLES

<u>Sample #</u>	<u>Description</u>	<u>INAA</u>	<u>XRD</u>	<u>XRF</u>	<u>T.S.</u>
34.	alunite		x		
35.	opal-CT		x	x	
36.	rhyolite glass		x	x	x
37.	rhyolite glass			x	
38.	altered glass	x		x	
39.	rhyolite glass			x	
40.	altered glass	x		x	x
41.	altered glass			x	
42.	ribbon alpha quartz	x	x	x	x
43.	opal-CT		x	x	
44.	plateau basalt			x	
45.	altered glass	x	x	x	x
46.	rhyolite glass			x	

SUBSURFACE SAMPLES

<u>Phillips holes</u>	<u>Description</u>	<u>INAA</u>	<u>XRD</u>	<u>XRF</u>	<u>T.S.</u>
1 - 40'	basalt	x	x		x
1 - 200'	hyalite		x		
1 - 1590'	alpha quartz		x		
1 - 1680'	alpha quartz		x		
2 - 1100'	glass		x		
2 - 1190'	opal - CT		x		
4 - 500'	basalt	x			x
4 - 580'	Amorphous SiO ₂		x		
4 - 580'	feldspar crystals		x		
4 - 720'	alpha quartz and feldspar		x		
4 - 880'	alpha quartz		x		
4 - 1270'	alpha quartz		x		
4 - 1910'	alpha quartz		x		
<u>Core</u>					
30'	alunite		x		
40'	opal - A		x		x
215'	alunite		x		x
220'	bleached glass				x
240'	breccia				x
275'	alunite		x		x