AN ABSTRACT OF THE THESIS OF

<u>Jenda A. Johnson</u> for the degree of <u>Master of Science</u> in <u>Geology</u> presented on <u>June 9, 1995.</u> Title: <u>Geologic Evolution of the Duck Creek Butte Eruptive Center</u>, <u>High Lava Plains</u>, southeastern Oregon.

Abstract approved: ______ Redacted for Privacy ______ Anita L. Grunder

Mixing during synextensional magmatism of a layered magma chamber, followed by prolonged fractionation during tectonic quiescence, is recorded in the stratigraphy, geochemistry, geochronology, and structural history of the Duck Creek Butte eruptive center (DBEC). DBEC, located in the Basin and Range province of southeastern Oregon is the easternmost center in a west-northwest-trending, northwest-younging sequence of silicic vents. DBEC was studied by a combination of detailed geologic mapping (400 km²), 37 chemical analyses, mineral chemistry, three new ⁴⁰Ar/³⁹Ar ages, and Sr and Nd isotope data.

The DBEC sequence is dominated by rhyodacite and rhyolite but includes andesite, basaltic andesite, and basalt. Effusive volume decreases with time, and the compositional range becomes more restricted and more mafic. The earliest volcanic activity is recorded in more than 6 km³ of pyroclastic and effusive lava flows of porphyritic rhyodacite (10.38±0.04 Ma; ⁴⁰Ar/³⁹Ar, biotite) during movement along the faults related to uplift of the Steens Mountain fault block. The lava flowed over existing fault escarpments and was later truncated by these same faults. Late flows of rhyodacite contain quenched andesite inclusions that were entrained during evacuation of the magma chamber. Eruption of dacite with up to 30 percent quenched basaltic andesite inclusions ensued, possibly as the result of synmagmatic faulting. Andesite with mixing textures, associated with basaltic andesite and basalt, marks the end of DBEC activity along the fault system. Silicic magmatism migrated 2 to 4 km northwest to Indian Creek Buttes, where high-silica rhyolitic magma fractionated during tectonic quiescence, and then erupted (10.32 \pm 0.01 Ma; 40 Ar/ 39 Ar, sanidine).

The oldest rock in the area is the 16.2 Ma Steens Basalt. It is conformably overlain by tuffaceous sedimentary strata and 12-11 Ma basalt, basaltic andesite, and andesite. The older strata are overlain conformably to slightly unconformably by the DBEC sequence.

Post-DBEC rocks were deposited chiefly in drainages and west-northwest-trending fault-bounded valleys. The 9.7-Ma Devine Canyon Ash-flow Tuff and underlying tuffaceous sedimentary strata are found throughout southeastern Oregon. Following a protracted hiatus, a primitive high-alumina olivine tholeiite erupted adjacent to DBEC (1.38±0.01 Ma; ⁴⁰Ar/³⁹Ar, whole rock). No further volcanic activity is recorded. Quaternary sediment covers much of the area.

Movement along north-northeast- and west-northwest-striking normal faults and synchronous volcanic activity at DBEC near the northern terminus of the Steens Mountain escarpment is constrained between 10.4 and 1.4 Ma. Contemporaneous lavas are affected by at least three periods of faulting. Regionally extensive east-west-directed extension was active prior to and during eruption of the 10.4-Ma rhyodacite, indicated by truncated plunging flow folds. West-northwest-striking faults, which are parallel to the Brothers fault zone, were active in the period between emplacement of the 10.32-Ma rhyolite and the 9.7-Ma Devine Canyon Ash-flow Tuff. The 1.4-Ma olivine basalt filled a northwest-trending valley and subsequently was offset by north-striking normal faults. No further movement is recorded by Quaternary sedimentary units.

Compositional and textural evidence suggests that DBEC rocks result from several mechanisms including crustal melting, fractionation, magma mixing, and filter pressing.

Rhyolite and rhyodacite apparently were derived by crustal melting and fractionation, respectively, during tectonic quiescence. Successive tapping during tectonism caused mixing with underlying, more-mafic magma at a rate faster than silicic magma could be regenerated. Textural evidence and linear element-element arrays indicate that the dacite and andesite were derived mainly by magma mixing. Basalt and basaltic andesite of DBEC resulted from fractional crystallization of a primitive basalt.

Geologic Evolution of the Duck Creek Butte Eruptive Center, High Lava Plains, Southeastern Oregon

by

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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

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Jenda A. Johnson, Author

This thesis is dedicated to David R. Sherrod, husband, friend, mentor, critic

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- Plate 2. Description of map units and cross section of the Duck Creek Butte eruptive center.

(plates are in rear pocket)

GEOLOGIC EVOLUTION OF THE DUCK CREEK BUTTE ERUPTIVE CENTER, HIGH LAVA PLAINS, SOUTHEASTERN OREGON

CHAPTER 1: INTRODUCTION

1.1 Geologic Setting

Silicic centers in southeastern Oregon have been recognized for more than 30 years (Walker and Repenning, 1965; Greene and others, 1972; Walker and others, 1974; Walker, 1977), and yet the geology and petrology of individual centers are poorly known. Late Tertiary magmatism has been described as a bimodal association of basalt and rhyolite. wherein intermediate rocks are virtually absent (for example, Christiansen and McKee, 1978; Draper, 1991). Although the northern Basin and Range province is bimodal. individual eruptive centers possess a variety of compositions from basalt to rhyolite (for example, Juniper Ridge, MacLean, 1994; Duck Creek Butte, this study; Frederick Butte, J.A. Johnson, unpub. mapping). Duck Creek Butte eruptive center (DBEC; Figure 11) is composed of a sequence of locally erupted lava flows, dikes, and pyroclastic-flow deposits that vary from basalt to rhyolite in composition. Duck Creek Butte and adjacent Indian Creek Buttes are among the easternmost vents in a west-northwest-trending sequence of silicic vents in southeastern Oregon that are progressively younger to the west (Figure 1-2) (MacLeod and others, 1976). DBEC flows were emplaced between 10.5 and 10.3 Ma. A 1.4-Ma primitive olivine basalt vented adjacent to DBEC following a 9-m.y. hiatus in volcanic activity.

The purpose of this study is to understand the geologic evolution of the Duck Creek Butte eruptive center and its relation to the regional geologic setting. This work contributes to a larger project that is examining the 10- to 5-Ma segment of westward-younging silicic volcanism along the High Lava Plains (Figure 1-2) (A.L. Grunder, Oregon State



Figure 1-1: Location map and geographic names. (A) Southeastern Oregon, (B) Duck Creek Butte study area.



Figure 1-2: Map showing isochrons separating silicic domes in 1-m.y. increments along the High Lava Plains of Oregon and Snake River Plain of Idaho indicating opposing age progressions (MacLeod and others, 1976; Anderson and others, 1975).

NV = Newberry volcano; YS = Yellowstone; * = study area.

University, and students M.J. Streck, 1994; J.W. MacLean, 1994; B.T. Jordan, in progress). The broader goal is to develop a petrogenetic model for the region and to determine, in part, if the High Lava Plains trend is a mirror image to the eastward-younging Snake River Plain-Yellowstone hotspot trend. In order to understand the mechanisms that might create the diverging trends, more must be known about the age, distribution, origin, and structural setting of magmatism in the region.

The Duck Creek Butte eruptive center is situated approximately at the junction of three physiographic provinces: the High Lava Plains, the northern Basin and Range, and the Owyhee Upland (Dicken, 1950) (Figure 1-3). The High Lava Plains province encompasses Miocene to Quaternary volcanic rocks. Volcanism changed from dominantly basaltic to mainly silicic about 11 Ma. Basalt again became dominant after 5 Ma and does not appear to have an age progression.









Figure 1-3: (A.) Physiographic provinces of Oregon. (B) Enlargement of High Lava Plains. Long-dashed oblong indicates approximate track of northwest-trending age progression of silicic vents.

The High Lava Plains province is bounded on the north by the Blue Mountains province, which is composed of Mesozoic and Paleozoic marine strata, volcanic island-arc sequences, ophiolite assemblages, and granitic plutons, as well as Tertiary volcanic and sedimentary rocks. The Blue Mountains province is characterized by regional uplift and is bounded on the south by the linear structures of the Brothers fault zone that at least locally exhibit transcurrent movement and may represent transform zones (Walker and Robinson, 1990). The High Lava Plains province is bounded on the west by the Cascade Range, a Cenozoic volcanic arc related to subduction of the Juan de Fuca plate beneath the North American plate. To the south, the High Lava Plains province borders the Basin and Range province, which includes most of south Oregon east of the Cascades. The northwestern Basin and Range is characterized by a series of north-trending horsts and grabens that form the major mountain ranges such as Steens Mountain. The Owyhee Upland, which lies to the east of the High Lava Plains, comprises lava flows and sedimentary rocks that are more deeply dissected than the High Lava Plains. Quaternary basalt in the southern part of the Owyhee Upland lacks the north-striking faults that characterize the Basin and Range (Walker and MacLeod, 1991).

The DBEC study area is located in Malheur and Harney Counties, southeastern Oregon. It encompasses over 300 km² within all or part of five $7^{1}/_{2}$ -minute quadrangles: Duck Creek Butte, Dowell Butte, Venator Reservoir, Stockade Mountain, and Folly Farm (Plate 1). The closest settlement is Burns Junction, 55 km southeast. Elevation ranges from 1,220 m in the Barren Valley to 1,879 m atop Duck Creek Butte. The study area is located in the high desert and receives an average of 15 cm precipitation yearly, chiefly during the winter. Vegetation includes juniper, sage, and grasses.

Most land in the area is under the jurisdiction of the Bureau of Land Management. It is leased to cattle and sheep ranchers and is fenced for grazing. Private holdings include several farms in the Barren Valley and land adjacent to springs. The area is accessible by dirt roads from Highway 78 and from the Crowley road (Figure 1-1).

1.2 Methods of Study

Field work at the Duck Creek Butte eruptive center was begun during the summer of 1992 and completed during the summer of 1994. Geology was mapped on 1:24,000-scale topographic maps. Aerial photographs were used to interpret the extent of faults. Petrographic examination of 76 thin sections was performed to determine modes and textures of the volcanic rocks.

Major and some trace element chemical analyses were obtained using X-ray fluorescence spectroscopy (XRF) on fused glass beads. Fourteen samples were analyzed by X-RAL Laboratories, Vancouver, British Columbia. An additional 23 analyses were obtained using an automated Rigaku 3370 spectrometer at the GeoAnalytical Laboratory, Washington State University, Pullman, Washington. Correction factors for data from X-RAL, based on comparative replicate analyses from Stanford University, were applied for minor systematic differences in MnO (-0.015 weight percent), MgO (-0.07 for MgO <0.2 percent), P₂O₅ (-0.02 for P₂O₅ <0.1 percent), and Rb (-7 ppm). Na₂O and Cr concentrations from instrumental neutron activation analysis, where available, are used in place of XRF results. Trace element analyses for 20 samples were determined by instrumental neutron activation analysis (INAA) using the 1-MW Triga reactor at the Oregon State University Radiation Center following the procedure outlined in Laul (1979).

Prior to analysis, rock samples were cleaned of all weathered surfaces. Wherever possible glass was collected. All other samples were selected on the basis of both least amount of phenocrysts and least evidence for magmatic inclusions and mixing. All samples were broken in a standard alumina ceramic jaw crusher. Samples to be analyzed by XRF were ground to a fine powder in a tungsten-carbide shatterbox; INAA samples were ground in an alumina ceramic shatterbox. Three age determinations were done by Alan Deino at the Berkeley Geochronology Laboratory, Berkeley (CA) using the single-crystal and whole-rock laser-fusion ⁴⁰Ar/³⁹Ar method.

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Microprobe analyses of feldspar, olivine, pyroxene, biotite, and hornblende were done at Oregon State University using a fully automated Cameca SX-50 microprobe with wavelength-dispersive spectrometers. Strontium and neodymium isotope ratios for whole rock samples were obtained using a Finigan 261 mass spectrometer in the laboratory of Chris Hawkesworth at the Open University, Milton Keynes, Great Britain.

CHAPTER 2: STRATIGRAPHY

2.1 Introduction

Rocks exposed at the Duck Creek Butte eruptive center can be divided roughly into three stratigraphic groups: (1) basalt, andesite, and ash-fall tuff that predate DBEC, (2) DBEC series rocks, and (3) overlying ash-flow tuff, basalt, and sedimentary deposits (Figures 2-1 and 2-2, Plate 1). Detailed petrographic descriptions are in Appendix 2. Rock nomenclature is modified from LeBas and others (1986) (see Figure 4-3).

2.2 Rocks that predate the Duck Creek Butte eruptive center

Volcanic and volcaniclastic rocks older than DBEC are found throughout the study area. Correlation between rocks northeast of DBEC and south and west of DBEC is not always clear, and not all of the flow units found in the unit of basalt and andesite (Tba) were separated. Figure 2-3, however, indicates correlations defined by this study.

2.2.1 Steens Basalt (Ts)

Lava flows of aphanitic to coarsely porphyritic Steens Basalt form the oldest stratigraphic unit in the map area. The Steens Basalt is exposed extensively throughout much of southeastern Oregon (Fuller, 1931; Walker, 1960; Walker and Repenning, 1965; Greene and others, 1972; Carlson and Hart, 1983a; Hart and Carlson, 1985). It underlies an area estimated between 25,000 and 35,000 km² (Fig. 2-4). Flows extend from DBEC southward 120 km to the Pueblo Mountains (Avent, 1965; Minor, 1986) and 190 km southwest to Abert Rim (Carlson and Hart, 1983b); the southern and eastern extents are poorly defined. The northernmost exposure is west of Dowell Reservoir, on the basis of

CORRELATION OF MAP UNITS



Figure 2-1: Correlation chart for rock units described in text.





Figure 2-2: Simplified geologic map of the Duck Creek Butte Study Area



Figure 2-3: Correlation of map units on the south and northeast margins of flows of the rhyodacite of Duck Creek Butte.



Figure 2-4: Map showing approximate extent of Steens Basalt and Columbia River Basalt group (from Carlson and Hart, 1983 and Mankinen and others, 1985). Diagonal pattern in field of Steens Basalt denotes inferred range of Steens Basalt based on lithologic and/or chemical similarity to Steens Basalt.

basalt detritus in a landslide deposit. Beyond that the basalt is buried beneath younger strata to the north.

The Steens Basalt comprises medium- to dark-gray, diktytaxitic olivine basalt and basaltic andesite. It varies from aphanitic to coarsely porphyritic. Flows in the Duck Creek Butte study area range in thickness from 1 to 10 m and average 2 m thick. Total thickness is unknown because the base is unexposed; the unit is at least 200 m thick where exposed in a fault scarp near the south edge of the map area and at least 150 m thick along the Post Mountain escarpment at the northwest margin of the map area.

Maximum thickness of the unit is approximately 920 m where it is exposed in the Steens Mountain escarpment, 60 km south of the study area (measurement by me near the type section, and determined from geologic map of Minor and others, 1987b). There, the base is exposed and the top is capped by basaltic andesite (Appendix 4). At least 80, and possibly more than 100, individual flows form the Steens Basalt. Vents for the Steens Basalt are found in vertical dikes spectacularly exposed in the Steens Mountain escarpment (Fuller, 1931; Minor and others, 1987b and c). Steens Mountain represents the remains of a shield volcano that may have been 160-200 km in diameter with a total volume of about 12,000 km³ (Mankinen and others, 1985). No vents were found in the map area.

The Steens Basalt is middle Miocene in age. Recent work by Swisher and others (1990) yielded ages of 16.58±0.05 Ma and 16.59±0.02 Ma, determined using ⁴⁰Ar/³⁹Ar laser fusion of coarse plagioclase crystals from flows 1 and 31, respectively, at the type section (flows numbered consecutively upsection). Previously determined K-Ar ages from flows near DBEC range from 17.2 to 14.8 Ma (Hart and Carlson, 1985) but may include younger, petrographically similar basalt that is isotopically distinct from the Steens Basalt. The Steens Basalt is contemporaneous with much of the Columbia River Basalt Group of northeastern Oregon and eastern Washington (Walker, 1969; Hart and others, 1989).

2.2.2 Older tuff and tuffaceous sedimentary rocks (Tots)

A 1-m-thick, very fine-grained, well-sorted ash deposit is exposed in a road cut and on a hilltop near the southeast margin of the study area, $E^{1}/_{2}$ sec. 23, T. 28 S., R. 37 E. The rock has a white chalk-like appearance except where baked by an overlying basaltic andesite flow. Owing to limited exposure, it is generally included with the sedimentary rock and lava that form the basalt and andesite unit (Tba), but it is shown separately in two locations where it is well exposed.

This ash may be the distal air-fall equivalent of the tuff of Oregon Canyon (Rytuba and McKee, 1984) on the basis of its position directly above the Steens Basalt. It is difficult to correlate chemically owing to interlaboratory variation, differing analytical methods, and the tendency of all rhyolite in the province to be mildly peralkaline (Table 2-1). The tuff of

Map unit Analytical method	Tots XRF	Tots INAA	Tuff of Oregon Canyon Emission spectrography
Major-element analyses (wt.	percent)	normalized to	100 percent volatile free
SiO2	75.4		77.50
Al ₂ O ₃	10.15		11.50
TiO ₂	0.23		0.18
FeO*	4.45	4.39	1.90
MnO	0.07		0.02
CaO	0.21		0.06
MgO	0.00		0.10
K ₂ O	4.61		4.75
Na ₂ O	4.87	4.71	4.00
P205	0.01		0.01
prenormalization total	100.51		99.88
Trace-element and	alyses (pa	rts per million	
Ba	45	182	29
Fib	212	209	310
Sr	8		13
Zr	† 813		1100
Y	†156		130
Nb	†42		23
Pb	21		28

Table 2-1: Chemical analyses of Tertiary ash deposit (Tots) and the Tuff of Oregon
Canyon (Rytuba and McKee, 1984).

† denotes values >120 percent above calibrated range

Oregon Canyon is an ash-flow tuff erupted ~16.1 Ma from the McDermitt caldera complex, located about 100 km to the south (Rytuba and McKee, 1984), and is interbedded with basaltic andesite lava flows near the top of the Steens Basalt (Sherrod and others, 1989; Turrin and others, 1989).

In the northeast corner of the map area (sec. 15, T. 27 S., R. 38 E.), a well-bedded sedimentary deposit is the oldest unit exposed in the stream beds of Sutton, Soldier, and Stockade Creeks. Where best exposed the unit consists (from base upward) of 0.5 m of conglomeratic sandstone, 2 m of well-sorted sandstone, a 3-cm lens of crystal-rich sandstone, and at least 2 m of tan and white fallout tuff. The fallout tuff is even thicker, at least 9 m thick, where exposed in a steep stream bank at the confluence of the three creeks. The tuff may be a thicker exposure of the older tuff and tuffaceous sedimentary rocks (Tots) described in paragraphs 1 and 2 of this section, but no analysis was obtained.

2.2.3 Porphyritic basalt (Tb)

Fine-grained porphyritic diktytaxitic basalt, which resembles some lava flows of the Steens Basalt, is exposed discontinuously in the map area. I separate it from the Steens Basalt because it is distinctly fresher looking than any of the Steens Basalt and, in one location, float of the older tuff and tuffaceous sedimentary rocks (Tots) weathers out beneath it. The two basalts are commonly separated by a slope-forming unit with no outcrop, interpreted to represent intervening poorly indurated sedimentary strata. Although the porphyritic basalt represents a single flow that is generally less than 3 meters thick, the unit appears thicker in Plate 1 where it includes the slope-forming sedimentary unit. The basalt is medium gray and contains small phenocrysts of plagioclase (5 to 10 percent, to 4 mm in length) and microphenocrysts of olivine (1 percent, to 0.5 mm in diameter).

Similar basalt found 15 km to the west-northwest and 15-20 km southeast of the map area was termed "Steens-like" basalt by Carlson and Hart (1985), who noted that it is chemically similar but isotopically more evolved than Steens Basalt. The so-called Steenslike samples yielded ages ranging from 11.2 to 11.7 Ma (Hart and Mertzman, 1982) and thus clearly are significantly younger than Steens Basalt. Hart and Carlson (1985) suggested that this pulse of volcanism represented continued, but much diminished, magmatism of the Steens Basalt magmatic episode. I interpret this basalt to have resulted from a separate magmatic event on the basis of its substantially younger age and isotopic differences (see Sec. 5.3.1).

2.2.4 Basalt and andesite (Tba)

Very fine grained, aphyric to finely porphyritic basalt, basaltic andesite, and andesite form the youngest unit emplaced throughout the region prior to the growth of the Duck Creek Butte eruptive center. Although the unit varies from basalt to andesite in composition (51-60 percent SiO₂), the rocks are typically similar in appearance and are difficult to distinguish from one another and from fine-grained flows of the Steens Basalt. The basalt and andesite were not divided by composition as part of my mapping. Chemical analyses, however, indicate basalt is more abundant in the southern part of the map area and basaltic andesite and andesite are dominant north of DBEC.

On the northern margin of DBEC, a widespread thick sequence of basaltic andesite consists of multiple flows in excess of 100 m thick. There the basaltic andesite overlies the porphyritic basalt (Tb) and is overlain by the rhyodacite of Duck Pond Ridge (Tdrd). Outcrop extends from south of the map area where the unit of basalt and andesite (Tba) occurs as flows less than 15 m thick to beyond the northeast corner of the map area where the unit thickens and becomes more abundant.

The basaltic andesite lava typically varies from fine-grained and sparsely porphyritic to very fine grained and aphyric with abundant clay alteration. Fine-grained rocks contain plagioclase, clinopyroxene, Fe-Ti oxides, \pm olivine, \pm sideromelane. No petrographic thin-section analysis was performed on the basalts or andesites. The unit varies from medium gray with yellow streaks to medium dark gray. Although most of the unit is composed of

laterally continuous thin flows, near-vent accumulations of moderate reddish-orange to very-dark-red contorted flows and scoria are found where exposed by erosion in drainages.

I correlate these flows stratigraphically with basaltic andesite and andesite that are commonly found overlying the Steens Basalt elsewhere in the region (for example, Fuller, 1931; Minor, 1986; Sherrod and others, 1989; Turrin and others, 1989). South of Steens Mountain thick sequences of andesite flows appear to be contemporaneous with eruption of late flows of Steens Basalt (Mankinen and others, 1985). The map unit includes poorly exposed slope-forming deposits composed of unconsolidated to poorly consolidated sedimentary strata that include the tuff of Oregon Canyon.

2.2.5 Basalt of Stockade Creek (Tbs)

A distinctive basalt is exposed in the stream beds of Soldier, Stockade, and Sutton Creeks. Weathered outcrops have a distinctive black mottled snakeskin-like appearance that is attributed to ophitic pyroxene grains confined to areas separated by an intersertal or intergranular matrix (ophimottling as described by Avent, 1965, p. 24). Plagioclase, which is commonly up to 1.5 cm in length, varies in abundance from 2 to 25 volume percent but mostly forms about 5 percent of mode. In the less porphyritic samples, plagioclase megacrysts ranging in size from 4 to 9 cm are locally abundant. Although this basalt is similar in appearance to some lava flows of Steens Basalt (for example, flows I have found 350 m above the base of the sequence at its type section), it is distinguished from the Steens Basalt samples by its substantially higher Ba and lower Cu, V, and Ni concentrations. (Compare sample JJ94-163 in Table 4-7 with samples JS94-33, -34, -39 in Appendix 4.) This basalt weathers to buff-colored rounded outcrops with parallel, decimeter-scale partings. A brecciated flow top found in the northwest fork of Sutton Creek is highly vesiculated and weathers to gravel peppered with clear or yellowed plagioclase crystal fragments smaller than 5 mm. The basalt of Stockade Creek is about 7 m thick where it overlies the unit of older tuff and tuffaceous sedimentary rocks (Tots). Elsewhere the unit is at least 30 m thick, but the base is not exposed.

2.2.6 Lithic tuff of Soldier Creek (Tlt)

An unwelded to moderately welded, pumice- and lithic-rich tuff forms gentle slopes above the basalt of Sutton Creek in the Soldier, Stockade, and Sutton Creek drainages. Pumiceous lapilli (or fiamme where welded) range in abundance from 30 to 50 percent. Lithic fragments, including andesite, basalt, and gabbro, form 3-20 percent of the rock. The tuff also contains 3 to 5 percent clear crystals. The tuff is exposed as large flat boulders that vary in color from tan to pale orange to purplish gray. Maximum thickness is approximately 10 m.

2.2.7 Andesite breccia dikes of Dick Creek (Tad)

Brecciated andesite dikes stand out in bold relief on the canyon walls of Dick Creek. They are found only in this location and extend discontinuously for 1 km to the northwest. The dikes weather boldly, forming ribs as high as 6 m, and range from 1 to 4 m in width and 3 to 10 m in length. The dikes are composed of angular blocks of aphanitic to sparsely porphyritic andesite in an altered andesite matrix. The clasts are medium- to dark-gray with grayish-red streaking where fresh and weather grayish- or dark-reddish brown.

2.2.8 Rhyolite of Dowell Butte (Tr)

Dowell Butte is a domal mass of heterogeneous high-silica rhyolite flows surrounded by Quaternary sediment in the valley east of Duck Creek Butte. I assign it an age older than the Duck Creek Butte eruptive center on the assumption that it conforms to the trend of westward-younging silicic volcanism, but I lack any stratigraphic relation to support this supposition. Dowell Butte is undated by isotopic methods. The rhyolite is very light gray to pinkish gray and with 8-10 percent microphenocrysts in a partially devitrified glassy groundmass. Minerals include alkali feldspar, quartz, sericite, and hornblende. This rock is similar in hand sample and composition to the rhyolite of Indian Creek Buttes but is petrographically distinct in that it has bent, strained, and fractured crystals and contains 0.5-1 percent feathery sericite (muscovite?) that is preferentially aligned along flow lines. The strained crystals may have resulted from deformation during flow.

2.3 Duck Creek Butte eruptive center series

Duck Creek Butte eruptive center (DBEC) stratigraphic series includes volcanic and volcaniclastic rocks that range in composition from basalt to rhyolite. Eruptive units were emplaced between approximately 10.4 and 10.3 Ma on the basis of ⁴⁰Ar/³⁹Ar ages from the rhyodacite of Duck Creek Butte and the rhyolite of Indian Creek Buttes (Table 2-2). Not all stratigraphic relations can be resolved completely, but generalized stratigraphic relations are depicted in Figure 2-5. The sequence is dominated by rhyodacite and rhyolite (Fig. 2-6) with substantially lesser volumes of intermediate and mafic rocks.

2.3.1 Rhyodacite of Duck Creek Butte (Tdrd and Tdrdp)

The rhyodacite of Duck Creek Butte comprises distinctive biotite- and plagioclase-rich lava flows (Tdrd) that were erupted from multiple vents near the Duck Pond Ridge escarpment. Basal pyroclastic deposits (Tdrdp) are rarely exposed. The rhyodacite of Duck Creek Butte forms the most voluminous locally erupted unit in the map area (Fig. 2-6); it extends 18 km north-south and 10 km east-west. The eastern extent is uncertain due to faulting and subsequent burial by Quaternary lake-bed and alluvial deposits and basalt flows. Flows range in thickness from approximately 3 to more than 10 m. Talus obscures most contacts. A 180-m-thick exposure of the unit, found in a northwest-trending fault

 Table 2-2:
 40Ar/39Ar analytical data for Duck Creek Butte eruptive center.

Sample No.	Map Unit	Geologic Unit	Material Dated	⁴⁰ Ar/ ³⁹ Ar Age
JJ92-1	Tr ₁	Rhyodacite of Duck Creek Butte	Biotite-1 Biotite-2 Plagioclase	10.37±0.02 10.42±0.02 10.93±0.02†
JJ92-5	Tr ₃	Rhyolite of Indian Creek Buttes	Sanidine	10.32±0.01
JJ92-20	Qb ₂	Basalt of Duck Creek Flat	Whole Rock	1.36±0.04

[†] Note: New plagioclase age for Tr_1 was received too late for inclusion in text. Preliminary analytical runs on the plagioclase lacked consistent precision of the biotite ages. See Appendix 8 for detailed ${}^{40}Ar/{}^{39}Ar$ data received after thesis was completed. Analytical precision is also reported in Appendix 8.


Figure 2-5: Schematic drawing of a hypothetical cross section through the DBEC study area. Depicts stratigraphic relations between volcanic and volcaniclastic rocks at separate geographic locations. Does not represent actual cross section, structural relationships, or thicknesses.



Figure 2-6: Histogram showing volume of lavas at DBEC, grouped by composition. Quaternary basalt measured separately from basalt in DBEC series. No pre-DBEC rocks included.

scarp (sec. 7, T. 28 S., R. 38 E.), represents a minimum thickness because the base is not exposed and the upper part has been eroded.

The chief identifying characteristic of the lava is the presence of 7 to 12 percent phenocrysts including plagioclase (5-8 percent, up to 4 mm in length), biotite (1-2 percent, up to 2 mm across), and clinopyroxene (0.5-1 percent, up to 0.7 mm in length). Also found are Fe-Ti oxides, orthopyroxene, and amphibole. Individual flows are distinguished from each other chiefly by textural changes from the vitric, brecciated base, upward through stony, devitrified central zones to an upper vitrophyre. Collective field evidence suggests that an idealized exposure might consist of a pyroclastic surge deposit, a blockand-ash flow, a lower brecciated zone, a lower vitrophyre, an inner stony devitrified zone, an upper vitrophyre, and a capping pumiceous carapace. No more than two zones are exposed in any location, but all elements have been identified. The various lithologic types are described next.

- Pyroclastic deposits (Tdrdp): Two small outcrops of tuffaceous strata are exposed near the perimeter of Indian Creek Buttes. A 1-m-high ledge is exposed on the southeast flank of Indian Creek Buttes. Bedding planes are defined by well-sorted, clast-free ash and fine lapilli layers alternating with poorly sorted thicker beds containing 1-2 percent black silicic scoria to 3 cm in diameter, 2 percent angular chips of black rhyodacite, and about 1 percent clear crystals. A poorly sorted block-and-ash flow deposit, 3 to 4 m thick, is exposed in a single outcrop interbedded between the basalt and andesite (Tba) and rhyodacite lava flows (SW¹/4 sec. 13, T. 28 S., R. 37 E.). It is composed of matrix-supported angular clasts of the glassy rhyodacite to 25 cm, subangular tan purice as large as 25 cm in diameter, and subordinate smaller subrounded vesicular basalt clasts as large as 10 cm in diameter that were probably incorporated in the flow during transport across the ground.
- *Brecciated lower zones.* Four exposures of the basal brecciated zone were found; elsewhere the basal breccia zone is probably present beneath talus. Three of the

outcrop locations in the eastern part of the map area are composed of clast-supported breccia, with angular rhyodacite clasts as large as 1 m in a compositionally similar, altered matrix. A matrix-supported breccia with angular clasts that range from 2-10 cm across is found in a separate outcrop near the southern margin of the rhyodacite flows.

- *Vitrophyre*. The rhyodacite of Duck Creek Butte most commonly occurs as glassy porphyritic lava. Glassy zones have weakly developed perlitic texture owing to incipient hydration. The phenocrysts stand out in sharp contrast to the glass.
- Devitrified zone. The glassy zone grades abruptly upward to devitrified rhyodacite across a 10-cm interval. The pale-red to medium-light-gray, streaked stony devitrified rock has abundant spherulitic alteration. Devitrified flows above Duck Pond Ridge have finely spaced contorted and parallel flow foliations that are interpreted to be near-vent flows. An unusually spherulite-rich exposure is found 750 m west-northwest of Dowell Reservoir. There, reddish-brown to grayish-red spherulites, 8 mm in diameter, weather out of the gray stony devitrified rock in bold relief mimicking the appearance of lithophysae. Where spherulitic devitrification is pervasive, the biotite and clinopyroxene phenocrysts have been destroyed.
- *Pumiceous carapace*. An upper pumiceous zone is only preserved in topographically low areas or where protected by capping flows of the basalt of Duck Pond Ridge. The rock is highly inflated with a web-like texture and weathers to round boulders as large as 40 cm. It is chiefly light tan but varies from light gray to light orange.

Two ⁴⁰Ar/³⁹Ar ages of 10.38±0.04 Ma and 10.42±0.02 were obtained from biotite separated from the glassy part of the rhyodacite lava (Table 2-2). Previously published K-Ar ages of 10.0±0.4 and 9.8±0.6 Ma were obtained from biotite and plagioclase, respectively (Walker, 1974; recalculated by Fiebelkorn and others, 1982). The rhyodacite of Duck Creek Butte concordantly overlies basalt and andesite (Tba). The rhyodacite is overlain by the inclusion-rich dacite (Tdid) in its central part, by undated flows of the andesite of Duck Creek (Tda₂) on the south, by the basalt of Duck Pond Ridge (Tdb₁) and by the finely porphyritic basalt (Tdb₂).

Eruption of the rhyodacite was coeval with movement along the Duck Pond Ridge fault (see Structure, Sec. 3.3). This finding elucidates timing of faulting along the Steens Mountain fault system (Johnson and Deino, 1994).

2.3.2 Inclusion-rich dacite (Tdid)

The sparsely porphyritic inclusion-rich dacite forms lava flows that are easily recognized in the field because they contain 5 to 25 percent by volume of ubiquitous basaltic andesite magmatic inclusions that weather out in bold relief (Fig. 2-7) or, where less abundant, appear as small round dusty-gray spots. The dacite lava flows are distributed across 8 km from south-southwest of Duck Creek Butte to Dick Creek on the north. The elongate shape of the flows suggests that the dacite flowed northward through topographic lows in the rhyodacite of Duck Creek Butte (Tdrd).

The inclusion-rich dacite overlies the rhyodacite of Duck Creek Butte in all locations except on the northeast and the northwest where it overlies the basalt and andesite (Tba). The dacite is overlain by the Devine Canyon Ash-flow Tuff (Ttd) and the Tertiary sediment beneath the tuff (Tyts) near the northern margin of the dacite.

The unit averages 15 m in thickness. Its maximum thickness of 60 m occurs in the eastern cliffs of Duck Creek Butte, where the probable vent site is located. Individual thin flows can be distinguished at the top of Duck Creek Butte. Elsewhere, however, the unit is a single massive homogeneous flow.

The dacite matrix is aphanitic and contains 3-5 percent microphenocrysts of plagioclase, Fe-Ti oxides, orthopyroxene>clinopyroxene. In contrast, the basaltic andesite inclusions, which range from 2 mm to 7 cm in diameter, are fine grained, intersertal, and vesicular. The inclusions are composed of 20-40 percent glass, 40-50 percent plagioclase (up to 0.8 mm in length), 20 percent orthopyroxene and clinopyroxene (up to 0.5 mm in length), 5



Figure 2-7: Photograph of basaltic andesite inclusions weathering out of inclusion- rich dacite.



Figure 2-8: Petrographic thin section of contact between dacite host and quenched basaltic andesite inclusion in the inclusion-rich dacite (Tdid). (A) photograph of thin section; (B) drawing of quenched contact. White areas are vesicles, which are concentrated in the quenched glassy rim of the inclusion and become smaller and less abundant toward the core of the inclusion. Horizontal-ruled areas are plagioclase and pyroxene phenocrysts in the dacite.

percent Fe-Ti oxides (0.05-1 mm), 3 percent apatite (up to 0.1 mm in diameter), and rare olivine. Vesicles vary from 20 percent irregular-shaped voids as long as 2 mm in the glassy rim, to less than 3 percent chiefly smaller than 0.5 mm in the core. The inclusions have quench textures, indicating that the basaltic andesite was injected into the cooler dacite magma (Fig. 2-8 and Appendix 2).

2.3.3 Olivine-bearing basaltic andesite (Tdba₁)

A dark-gray, vesicular, sparsely porphyritic basaltic andesite forms a hill southwest of the rhyodacite of Duck Creek Butte. The basaltic andesite has an incipiently altered glassy groundmass and contains 15 percent phenocrysts of plagioclase (10 percent up to 4 mm in length) and microphenocrysts of olivine (3 percent, up to 0.5 mm across) and Fe-Ti oxides (2 percent, up to 0.5 mm). The unit is in contact only with the rhyodacite of Duck Creek Butte. Contacts are concealed by a mantle of talus so the relative ages of the two units may not be determined. Topographic relations on the map might suggest that the rhyodacite of Duck Creek Butte overlies the olivine-bearing basaltic andesite, but I infer that the basaltic andesite vented from the conical hill (spot elevation 5066, sec. 10, T. 28 S., R. 37 E.), flowed around a lobe of the rhyodacite, and therefore is the younger unit.

2.3.4 Basaltic andesite dike (Tdba₂)

A dike of glassy basaltic andesite cuts the rhyodacite of Duck Creek Butte (sec. 35, T. 27 S., R. 37 E.). The outcrop is approximately 20 m long, 5 m wide, and 1-3 m high. An upper reddish oxidized carapace looks like spatter, suggesting that the dike vented at its present exposed elevation. In contrast to the compositionally similar olivine-bearing basaltic andesite (Tdba₁), it contains a microscopic disequilibrium assemblage of plagioclase (An₂₀-An₃₀ by Michel-Levy method), clinopyroxene, Fe-Ti oxides, orthopyroxene, biotite, and trace amounts of olivine in a light- and dark-brown banded

glassy matrix. The disequilibrium mineralogy resulted from assimilation of a small amount of melt similar to the rhyodacite of Duck Creek Butte.

2.3.5 Basalt of Duck Pond Ridge (Tdb₁)

The basalt of Duck Pond Ridge is a coarsely plagioclase-phyric intergranular olivine basalt. It lies directly upon the rhyodacite of Duck Creek Butte. Small cobbles of baked, fine-grained sedimentary rock were found as float from an animal burrow beneath the basalt but could not be found in outcrop. On the basis of field relations between the basalt and the rhyodacite, an intervening sedimentary unit would be either very thin or discontinuous. The 3-km-long flow generally ranges from 2 to 7 m thick. The inferred vent is near the topographically highest location on the unit where it forms a massive, faulttruncated 18-m-high cliff. The basalt is similar in hand specimen to the coarsely porphyritic flows of the Steens Basalt. Phenocrysts include plagioclase (20-25 percent as large as 3 cm) and olivine (7-10 percent, up to 0.6 mm in diameter).

2.3.6 Fine-grained basalt (Tdb₂)

Platy to massive flows of dark-gray, fine-grained, ophitic, porphyritic basalt cap a prominent hill approximately 0.5 km northwest of Dowell Reservoir and extend for 2.5 km to the northeast. Phenocrysts include plagioclase (8-9 percent, 5 mm) and olivine (1-2 percent, 3 mm). In contrast, the basalt of Duck Pond Ridge, Tdb₁, contains numerous blocky coarse plagioclase phenocrysts and differs compositionally (see Sec. 5.3.2). The fine-grained basalt directly overlies the rhyodacite of Duck Creek Butte (Tdrd) and the unit of basalt and andesite (Tba). It is difficult to determine the number or thickness of individual flows, but the maximum thickness of the unit is 60-65 m where it may have accumulated in a topographic depression.

2.3.7 Andesite of Duck Creek Spring (Tda₁)

An elongate flat-topped sequence of two or three flows of dark-gray, very fine grained andesite is exposed beneath the rhyolite of Indian Creek Buttes at its south, southeast, and northwest margins. Where fully exposed on the south, the andesite exhibits a glassy base, a horizontally to vertically flow-jointed cliff-forming face, and an upper spheroidally weathered zone. Maximum thickness is 20 m. Phenocrysts (2-3 percent) of plagioclase, olivine, and clinopyroxene are 1 to 2 mm in diameter. On the southeast of Indian Creek Buttes, a single flow of pilotaxitic andesite overlies the pyroclastic surge deposit of the rhyodacite of Duck Creek Butte (Tdrdp).

2.3.8 Andesite of Duck Creek (Tda₂)

Porphyritic andesite is exposed as dikes, near-vent accumulations of scoriaceous lapilli and bombs, and small-volume flows adjacent to and south of Duck Creek. The unit was presumably vented from hill 5052 (NE 1/4 sec. 22, T. 28 S., R. 37 E.) on the basis of vertical flow jointing observed there. This hill also is the topographically highest point on the flow. The maximum thickness of the unit is 30 m at this location. The andesite flowed both northwest and southeast.

The southeastern lobe of lava flowed down a preexisting drainage in the approximate location of Duck Creek to its terminus near the mouth of Duck Creek. A prominent exposure farther up the canyon (NE 1/4 sec. 23, T. 28 S., R. 37 E.) has vertical flow foliations and platy contacts with the older rocks suggesting that it is a thick dike. The relationship with other flows in the creek, however, indicate that it instead represents thicker deposition of lava confined in a steep drainage that has been subsequently exposed by erosion.

The rock is distinguished from the andesite of Duck Creek Spring by having 5-9 percent phenocrysts of subhedral to anhedral fresh plagioclase commonly 1 cm (rarely to 3

cm) in diameter, and 1 percent rusty speckles of iddingsitized olivine from 0.5 to 1 mm in diameter in a charcoal-gray aphanitic groundmass.

2.3.9 Basaltic andesite of Brokendown Waterhole (Tdba₃)

The basaltic andesite of Brokendown Waterhole is an extensive series of lava flows located at the north margin of the rhyolite of Indian Creek Buttes. The basaltic andesite is dark gray, fine grained, and vesicular. Single 2- to 4-m-thick lava flows extend north where they ramped onto and around the south-southeast-dipping strata of the Steens Basalt (Ts) and the unit of basalt and andesite (Tba). These lavas also flowed over a northwest-trending escarpment. Minimum areal coverage is 7 km² with an average thickness of 20 m. The groundmass comprises plagioclase (50-55 percent, up to 1 mm in length), clinopyroxene (12-15 percent, up to 0.2 mm in length), olivine (4-6 percent, up to 0.3 mm in diameter), Fe-Ti oxides (4 percent, up to 0.5 mm), and clay-altered glass (20-25 percent).

2.3.10 Rhyolite of Indian Creek Buttes (Tdr₁)

Indian Creek Buttes is constructed entirely of sparsely porphyritic to aphyric homogeneous flows of high-silica rhyolite. The rhyolite of Indian Creek Buttes overlies the Steens Basalt with angular unconformity on the west margin of the buttes and conformably overlies the andesite of Duck Creek Spring (Tda₁) near Duck Creek Spring at the southeast margin.

The rhyolite of Indian Creek Buttes is the second most voluminous locally erupted unit in the map area (Fig. 2-6). Maximum total thickness is 135 m at the buttes, which form a dome complex roughly 5 km in diameter. Maximum thickness of individual flows is about 60 m. The rhyolite erupted from multiple vents. One probable vent site is located in a canyon 0.5 km northwest of Duck Creek Spring. There the rhyolite forms a 10-m-high contorted knob with abundant kink folds. Phenocrysts, found chiefly in the capping flows, include gray or pink quartz (≤ 1 percent, up to 1 mm in diameter), sanidine (Or₃₄Ab₆₅ to Or₆₇Ab₃₂, ≤ 1 percent, up to 3 mm in length), and hornblende (rare, up to 3 mm in length). The rhyolite of Indian Creek Buttes has low total phenocryst content (less than 2 percent) and lacks biotite and plagioclase, in contrast to the rhyodacite of Duck Creek Butte (Tdrd).

Contacts between devitrified, glassy, and poorly developed vapor-phase zones are obscured by talus. No basal or upper breccia or pumiceous carapace was found. The lithologic rock types within the unit are as follows:

- Devitrified zone: Most of the rhyolite exposed at Indian Creek Buttes is devitrified and contains as much as 90 percent spherulitic alteration. Hand samples have a sugary texture and are speckled with pale-pink spherulites. The rock is very light gray to light brownish gray; weathered surfaces range from light brownish gray to dark reddish brown. Rocks with complete spherulitic overgrowth have secondary silica filling the voids.
- Vapor phase zone: The ridge above the southwest margin of the flows has a 3-m-thick zone characterized by 30 percent round gas pockets from 5 to 8 mm in diameter with flow banding wrapping around the vesicles. The rock is devitrified with spherulitic alteration and has secondary silica in the voids. There is no petrographic evidence for lithophysae.
- *Glassy zone*: Subrounded to rounded weathered obsidian as much as 10 cm in diameter is found in the talus slopes at discrete horizons beneath outcrop of devitrified rhyolite and mark probable locations of now-perlitic glassy zones. The rock varies from black obsidian to streaked black and dark-gray incipiently hydrated glass. Light-gray perlitic zones are exposed only in road cuts. Blackish-red glass is found infrequently as bands in devitrified rock.

Sanidine from Indian Creek Buttes lava yielded a ⁴⁰Ar/³⁹Ar age of 10.32±0.01 Ma (Table 2-1). This rhyolite is similar in chemical composition and hand sample lithology to the slightly more evolved rhyolite of Dowell Butte.

2.3.11 Rhyolite of Big Gulch (Tdr₂)

Two hills and a flattish poorly exposed area of stony, devitrified, aphyric flow-banded rhyolite are found at the west margin of the study area. This rhyolite is similar in composition to the rhyolite of Indian Creek Buttes, Tdr_1 (Table 4-7) but is of uncertain correlation and therefore is not mapped separately. Isotopic age constraints are lacking; for the purposes of this study I will assume that the rhyolite of Big Gulch conforms to the westward-younging trend and therefore is slightly younger than the rhyolite of Indian Creek Buttes. Contact relations with the Steens Basalt are confusing, as the rhyolite is topographically lower than the basalt. Three interpretations are possible: (1) the rhyolite of Big Gulch forms a thick dome deposited adjacent to the topographically higher, already-faulted Steens basalt, (2) the rhyolite is faulted down with respect to the Steens Basalt, or (3) the rhyolite is older than the Steens Basalt. Mapping of this unit was completed late in the study, and therefore the unit will not be described in further detail in this study.

2.4 Younger units

2.4.1 Younger tuffaceous sedimentary strata (Tyts)

Poorly indurated tuffaceous rocks, exposed only in stream-cut walls (SE $^{1}/_{4}$ sec. 18, T. 27 S., R. 38 E. and SE $^{1}/_{4}$ sec. 12, T. 28 S., R. 37 E.) and road cuts (S $^{1}/_{2}$ sec. 16, T. 27 S., R. 38 E.) overlie the inclusion-rich dacite (Tdid) and are overlain by the Devine Canyon Ash-flow Tuff (Ttd). The thickness of the sedimentary rocks ranges from less than 2 m to more than 15 m; variation in thickness over lateral distances of a few hundred meters may

reflect irregular topographic surfaces that existed during deposition. The unit is composed of poorly indurated sedimentary deposits including ash and sandstone.

2.4.2 Devine Canyon Ash-flow Tuff (Ttd)

The Devine Canyon Ash-flow Tuff is a distinctive crystal-rich tuff. The unit has a maximum preserved thickness of 30 m near its type locality, 13 km north of Burns (Greene, 1973; Walker, 1979). Maximum thickness in the map area is about 4 m, though actual thickness is difficult to determine because the tuff mantles canyon walls. The nonwelded to poorly welded uppermost part of the unit has been removed by erosion. The Devine Canyon Ash-flow Tuff was formally named by Walker (1979) for its type locality about 13 km north of Burns, Oregon.



Figure 2-9: Map showing approximate original extent and source of Devine Canyon Ash-flow Tuff (from Walker, 1979).

Characteristically, the unit is greenish gray, massive, porphyritic densely welded ashflow tuff. In a few exposures other parts are exposed, such as basal fallout tephra (as thick as 3 m), poorly welded basal tuff, and rarely, a capping moderately welded zone where not stripped by erosion. The tuff originally covered more than 18,600 km² of southeastern Oregon (Fig. 2-9) and had a volume of approximately 195 km³ (Greene, 1973). The Devine Canyon Ash-flow Tuff probably erupted from a vent near the vicinity of Burns, as interpreted from isopachs (Greene, 1973).

Potassium-argon ages on sanidine range from 8.7 to 10.3 Ma (Fiebelkorn and others, 1982). A 40 Ar/ 39 Ar single-crystal age of 9.68±0.03 Ma was obtained from sanidine in the tuff (A.L. Deino and A.L. Grunder, unpub. data, 1993).

The Devine Canyon Ash-flow Tuff probably was largely confined to topographically low areas when emplaced. Most of the movement on northwest-striking faults was completed prior to emplacement of the unit in fault-bounded valleys, such as the Duck Creek drainage, where the tuff is preserved (see discussion in Section 3-4). The tuff conformably overlies the younger tuffaceous sedimentary strata (Tyts) in most locations in the study area. It directly overlies the inclusion-rich dacite (Tdid) in Dick Creek where it may have been deposited in a paleochannel.

2.4.3 Quaternary basalt.

Three separable basalt units filled the fault-bounded valley of Duck Creek Flat and Duck Creek. A fourth unit covers part of Barren Valley. Each of the basalts is medium dark gray, fine grained, diktytaxitic, and has an ophitic groundmass. Compositionally the basalts are similar (for example, high Mg and Cr and low Ti and K; Table 4-7).

2.4.3.1 Glomerophyric basalt (Qb₁)

The oldest of these basalts (Qb_1) is characterized by the presence of glomerocrysts composed of olivine and plagioclase and of phenocrysts of about 2 percent each of olivine

and plagioclase. The basalt is exposed in the south half of Duck Creek Flat and extends west for approximately 4 km (Plate 1). Minimum thickness of the unit ranges from 2 to 6 m on the basis of stream-cut exposures and topographic expression; the base of the unit is not exposed.

2.4.3.2 Basalt of Duck Creek Flat (Qb₂)

A younger, olivine-phyric basalt (Qb₂) probably was erupted from a vent located near the high point where the main access road crosses Duck Creek Flat. There, the vesicular basalt has abundant wavy flow features evident in morphology, color changes, and bands of vesicles. The lava flowed down Duck Creek for 2.5 km. The upper surface of the drainage-filling distal flow has well-preserved pahoehoe features as well as columnar jointing. A natural arch roughly 5 m wide by 4 m high and 1.5 m long near the terminus of this flow suggests the remnant of a lava tube that may have channeled lava farther down stream. The unit covers about 4 km² with at least two flows that have a combined thickness ranging from 5 to 30 m. It differs from the underlying glomerophyric basalt in that it lacks plagioclase phenocrysts. A whole-rock sample of the basalt of Duck Creek Flat yielded a 40 Ar/³⁹Ar age of 1.36±0.04 Ma (Table 2-1) (A.L. Deino, unpub. data; Johnson and Deino, 1994). Possesses reverse-polarity thermal remanent magnetization.

2.4.3.3 Basalt of Cord (Qb₃)

Flows of the basalt of Cord are distinguished in the field from the basalt of Duck Creek Flat by having coarser groundmass plagioclase. Lava from this unit flowed around kipukas of the Devine Canyon Ash-flow Tuff and over the escarpment formed by the Duck Pond Ridge fault onto the floor of the Barren Valley (Fig. 2-10), where it is buried by alluvium and lake deposits. Possesses reverse-polarity thermal remanent magnetization.



Figure 2-10: Photographs of basalt flows over escarpment. A.) Aerial oblique view of basalt flow over the Holei Pali (fault scarp), Hawaii Volcanoes National Park, Hawaii. B.) Photograph of the basalt of Cord that forms dark flat feature where it flowed over the Duck Pond Ridge fault scarp.

2.4.3.4 Basalt of Barren Valley (Qb₄)

Much of Barren Valley is floored by medium-gray fine-grained porphyritic basalt. The basalt, which is vesicular and diktytaxitic, entered the valley from the southeast. Chemical analysis of the basalt (sample number CH83-57B, data from W.K. Hart, written commun., 1993) indicates a fairly primitive, high-Mg, high-alumina olivine tholeiite that is chemically similar to the basalt of Duck Creek Flat (Qb_2) and the basalt of Cord (Qb_3). No age was obtained for this unit. The basalt possesses normal-polarity thermal remanent magnetization, therefore the age is younger than 0.78 Ma. An overlying, compositionally similar basalt analyzed 22 km southeast of DBEC yielded a K-Ar whole-rock age of 0.43±0.09 Ma (Hart and Mertzman, 1982).

2.4.4 Landslide deposits (Qls)

Five landslide deposits were mapped. Four are sizable deposits that formed along topographically steep areas of the Duck Pond Ridge escarpment. Unlike many parts of Oregon, where landslides occur where competent rocks overlie incompetent rocks, these landslides appear to be slope collapse entirely in relatively competent lava flows. The fifth is a trifling deposit at the confluence of Sutton, Soldier, and Stockade Creeks.

2.4.5 Lake deposits (QI)

Lacustrine deposits composed of silt, sand, and rounded pebbles were formed by a pluvial lake that occupied the now-dry Turnbull Lakebed in Barren Valley during the Pleistocene (Snyder and others, 1964). Paleolakes were common throughout much of the western United States during the last glaciation between 29 to 11 ka (Freidel and McDowell, 1992). Although several terraces formed by high lake stands are found in the topographic depression that forms most of the south half of the Folly Farm 7¹/₂ minute quadrangle, no wave-cut terraces were found on the perimeter of Barren Valley. Most of

the area mapped as lake deposits is tilled agricultural land. Thickness of sediment fill in the valley is unknown.

2.4.6 Alluvium (Qa)

Deposits mapped as alluvium consist of unconsolidated sediment formed in many environments. Much of the unit is colluvium and talus that blanket the lower slopes of bedrock hills. Moderately to well-sorted sand and gravel are found along stream beds. Much of the alluvium mapped in Barren Valley may be remnants of the Pleistocene lake deposits (Ql) now covered by grasses and wind-blown sand.

Well-indurated white diatomite is found in a 2-m-thick stream-cut exposure 0.5 km west of the west edge of the map area near Big Gulch (sec. 11, T. 28 S., R. 36 E.). Diatomite is found only at this location and probably represents a small impounded body of water adjacent to Big Gulch.

CHAPTER 3: STRUCTURE

3.1 Introduction

The structural history of the map area has three main aspects: (1) the relationship between local and regional patterns of deformation, (2) the timing of faulting episodes, and (3) the relationship between faulting and magmatism at this location.

High-angle normal faults form the dominant structural pattern of DBEC. Faults can be grouped broadly into two sets according to orientation: north- to northeast-striking faults, which parallel the Basin and Range horst and graben fabric, and northwest-striking faults, which parallel the Brothers fault zone pattern (Fig. 3-1).

Basin and Range faulting, which forms the dramatic topography of southeastern Oregon such as Steens Mountain, occurred in response to east-west-directed extension that began in mid-Eocene time (Stewart, 1978; Zoback, 1989; Li and others, 1990). Duck Pond Ridge lies on strike with, and likely is a continuation of the Steens Mountain escarpment. Offset increases along the Steens Mountain escarpment from less than 300 m at Duck Pond Ridge to more than 2 km at Steens Mountain. This northward-diminishing offset is consistent with other Basin-Range faults in southern Oregon, which diminish as they reach the High Lava Plains (my measurements of dip separation on faults mapped by Walker and others, 1967, Greene and others, 1972, and Walker and Repenning, 1965).

East-west-directed extension near the map area was occurring by ~16 Ma as indicated by orientation of approximately north-striking Steens Basalt feeder dikes at Steens Mountain. Indeed, decreasing tilt upward in volcanic strata that underlie the Steens Basalt at Steens Mountain suggests faulting and tilting as early as 18 Ma (Langer, 1991). Relatively uninterrupted extension and tilting between mid-Miocene and Holocene time was proposed by Minor (1986) for the Trout Creek Mountains, 120 km south of DBEC. Evidence that east-west extension may persist to the present includes north-striking faults



Figure 3-1: (A) Generalized fault map showing amount of stratigraphic separation on prominent faults in the study area. Line weight indicates relative amount of offset; (B) Inset of major northeast-striking Basin-Range faults and northwest-striking faults of Brothers fault zone. (C) Heat flow map of northwest United States (Blackwell, 1978). Dark shading indicates areas of high heat flow; gray area of low heat flow in eastern Idaho is caused by the Snake Plain aquifer.

found in the basalt of Barren Valley (Qb₄) (Greene and others, 1972; Walker and MacLeod, 1991), as well as in Quaternary alluvium along Steens Mountain (Walker and Repenning, 1965; Hemphill-Haley and Carver, 1988).

The northwest-striking faults that form the Brothers fault zone have been interpreted as a right-lateral strike-slip zone separating more highly extended crust on the south and lessextended crust to the north (Lawrence, 1976). These faults have generally less than 50 m of stratigraphic displacement, and show no clear evidence for strike-slip displacement (MacLean, 1994; Clayton, 1989).

At DBEC the relationship between north-northeast- and northwest-trending fault systems is unclear. The northwest-striking faults appear to be cut by, as well as cut, the north-northeast-striking faults. Both styles of faulting were present from pre-DBEC time into the Pleistocene. Northwest-striking faults are more closely spaced and have less than 120 m of dip separation. In contrast, the broadly spaced northeast-striking faults are dominated by the Duck Pond Ridge fault, which has more than 250 m of displacement.

3.2 Terminology

Slip indicates direction of motion or relative displacement of formerly adjacent points on opposite sides of a fault. Separation is the distance, or offset, separating stratigraphic units on both sides of the fault. In the map area, no indicators such as piercing points or slickensides were found to constrain slip. Owing to poor exposure, timing of motion on most faults is poorly constrained. Where the base of a stratigraphic unit is unexposed I estimate the amount of separation on the basis of topographic relief, which is a minimum value because of preferential erosion on the upthrown side and burial of stratigraphic units on the downthrown side.

3.3 Pre-eruptive and syneruptive faults

Evidence for timing of faulting along the Duck Pond Ridge-Steens Mountain escarpment can be constrained by lava flows at DBEC. The rhyodacite of Duck Creek Butte (Tdrd) flowed over an escarpment in Steens Basalt and the overlying basalt and andesite; the fault existed by 10.4 Ma when the rhyodacite flowed over the fault and formed the east-sloping flow lobe that protrudes into Barren Valley. I interpret the rhyodacite to have flowed downhill over an escarpment that was at least 30 m high. Although the basal contact is covered by talus, and offset cannot be determined, I think that the lower flows may have been faulted prior to the emplacement of the upper flows for the following reasons. Now-truncated plunging flow folds in the upper flows of the rhyodacite trend S20°E and plunge 15-26° over the edge of the escarpment (Fig. 3-2), indicating the rhyodacite flowed to the southeast over a precipice that may have been a scarp in the lower flows of the rhyodacite. These flow folds were truncated by continued movement along the fault and have ~100 m of additional offset indicating most of the offset occurred after 10.4 Ma. The basalt of Duck Pond Ridge (Tdb₁) is also offset by this fault, which indicates later movement.

An exposure of the andesite of Duck Creek (Tda₂) at the outlet of Duck Creek appears to be in its original depositional location about 5 m above the Barren Valley floor. I interpret this to indicate that movement along the Duck Pond Ridge fault was largely completed, and evidence for any additional movement is buried beneath Quaternary alluvium and lake-bed deposits. Minimum offset of the Duck Pond Ridge fault is 250 m on the basis of topographic relief.

Another example of faulting that may have preceded or been coeval with the DBEC lava flows is indicated by the unfaulted basaltic andesite of Brokendown Waterhole (Tdba₃). Flows of this unit were obstructed by a fault block of Steens Basalt and the older basalt and andesite (Ts and Tba respectively; hill 5425, sections 8 and 17, T. 27 S., R. 37 E.). The block, formed by two northwest-striking faults, is tilted south-southeast, in contrast to other fault blocks in that area that are untilted or dip to the west, such as Post Mountain. Two other exposures of Steens Basalt 3.5 and 4.2 km due south of hill 5425 dip to the east-southeast beneath the rhyolite of Indian Creek Buttes (Tdr₁). Although the lava flows are concordant where the rhyolite ramps onto the dipping basalt strata, the contact is interpreted as an angular unconformity.

The basaltic andesite of Brokendown Waterhole (Tdba₃) flowed north, banked onto the lower slopes of hill 5425, and flowed over the northwest-trending escarpment east of the hill to its terminus at Brokendown Waterhole. A northeast-striking fault displaces the basaltic andesite approximately 5-10 m down to the east.

3.4 Post-DBEC structural history

Movement along northwest-striking faults continued after deposition of the rhyolite of Indian Creek Buttes. Evidence for this is found in three faults near the west margin of the buttes. The center fault transects the rhyolite west of hill 5766 ($N^1/4$ sec. 32, T. 27 S., R. 37 E.) and forms the steep slope along the southwest margin of Indian Creek Buttes. The westernmost fault displaced the rhyolite down to the southwest as much as 90 m. These faults may extend down Duck Creek but are buried beneath colluvium and alluvium (Qa) and the basalt of Duck Creek Flat (Qb₂). Ramped and contorted flow lobes of the rhyolite and talus-covered contacts make fault traces difficult to locate precisely.

Remnants of the Devine Canyon Ash-flow Tuff (Ttd) are typically preserved as northwest-trending elongate outcrops. These remnants indicate a structural grain highlighted by thicker deposition of the tuff in the topographically lower areas of the northwest-trending fault-bounded valleys. From this evidence I infer that northwesttrending faults existed prior to the emplacement of the Devine Canyon Ash-flow Tuff



Figure 3-2: Photographs of flow lobe of the rhyodacite of Duck Creek Butte and plunging flow lobes in the rhyodacite. A) Aerial oblique view of the flow lobe of rhyodacite that flowed over the Duck Pond Ridge escarpment into Barren Valley. B) Plunging folds in the rhyodacite along Duck Pond Ridge escarpment.

about 9.7 Ma. Alternatively, the present exposures of tuff might represent thicker deposition in stream channels incised in a northwest-dipping fault block. The tuff is found the length of Baker Pass, the southwesternmost drainage in the study area. The Baker Pass trough is a narrow linear graben that drains in opposite directions from its summit near the turnoff to Duck Creek Butte on Highway 78. The Baker Pass exposures, and similar outcrop relations in another west-trending graben south of the map area, suggest that the tuff was entirely constrained along a preexisting graben.

An exposure of the Devine Canyon Ash-flow Tuff at the north end of Post Mountain is undeformed by the northwest-striking fault that formed Post Mountain, indicating that the tuff was deposited after the fault-bounded valley on the east side of Post Mountain had formed. Similarly, an outcrop of Devine Canyon Ash-flow Tuff northwest of the rhyolite of Big Gulch (Tdr₂) also blankets a northwest-striking fault.

Quaternary faulting is indicated by deformation of the Quaternary basalt lava flows. A fault offsets the basalt of Duck Creek Flat (Qb₂) about 30 m east-side-down at the basalt lava's terminus in Duck Creek. The basalt of Cord (Qb₃) is cut by a north-northwest-striking fault with at least 5 m of offset; alluvium mantles the downthrown side. No lineaments are preserved in the tilled Quaternary lake bed deposits of Barren Valley.

CHAPTER 4: GEOCHEMISTRY

4.1 Mineral Chemistry

4.1.1 Introduction

The following samples were selected for chemical analysis of phenocrysts by microprobe, on the basis of whole-rock composition, to represent the major petrologic

groups of the 10.5- to 10.3Ma DBEC rock series:

Table 4-1: Samples for microprobe analysis. Refer to Appendix 2 for detailed petrographic descriptions. pl=plagioclase, san=sanidine, cpx=clinopyroxene, opx=orthopyroxene, ol=olivine, Fe-Ti=Fe-Ti oxides, hb=hornblende, bi=biotite, qtz=quartz, ap=apatite *Italics* = trace phase

Sample	Мар	Sample descriptor	Abbreviated phenocryst
No.	Unit		mineralogy
JJ92-99	Tdb ₂	Fine-grained basalt	pl>>cpx>Fe-Ti>ol
JJ93-130	Tdb1	Basalt of Duck Pond Ridge	pl>>ol>Fe-Ti> <i>cpx</i>
JJ92-51	Tdid	Basaltic-andesite inclusion in dacite	pl>opx>cpx>Fe-Ti>ap
JJ92-102	Tdid	Inclusion-rich dacite	pl>Fe-Ti>opx>cpx>>hb, <i>bi, qtz, ol</i>
JJ92-1	Tdrd	Rhyodacite of Duck Creek Butte	pl>bi>cpx>opx>Fe-Ti>am
JJ92-5	Tdr ₁	Rhyolite of Indian Creek Buttes	san>pl>qtz>hb
			ſ

The bulk of the volcanic rocks at DBEC contain phenocrysts of plagioclase, clinopyroxene, olivine, Fe-Ti oxides, and biotite, with lesser amounts of orthopyroxene, sanidine or alkali feldspar, amphibole, and apatite. Selected feldspars, pyroxenes, olivine, biotite, and amphibole were analyzed by microprobe. Representative analyses for each mineral group are presented in Tables 4-2 through 4-6 (see Appendix 3 for complete analyses).

4.1.2 Feldspar

Plagioclase is ubiquitous in DBEC rocks with the exception of the rhyolite of Indian Creek Buttes, Tdr₁, which contains only alkali feldspar (Table 4-2, Fig. 4-1). Plagioclase ranges from oligoclase in Tdrd to bytownite in Tdb₂. Overall, plagioclase becomes more An rich from rhyodacite to basalt. Variation in core compositions between minerals within the same rock sample result both from slight compositional variation as well as the fact that the polished sections do not necessarily slice through the center of the crystal.

Phenocryst phases in Tdb₁ are exclusively normally zoned labradorite (An₅₁ to An₆₅) (Fig. 4-1). Intergranular groundmass crystals are andesine with a very slight compositional range (An₄₃ to An₄₅). Plagioclase in Tdb₂ exhibits both normal and reverse zoning and ranges between andesine and bytownite (An₄₅ to An₇₂). Groundmass laths in Tdb₂ are labradorite.

Plagioclase in the basaltic-andesite inclusion from unit Tdid has a small compositional range from andesine to labradorite (An_{37} to An_{54}) and the single rim-core analysis revealed reverse zonation. Plagioclase phenocrysts in the dacite host are similar to the plagioclase in the inclusion (and may indeed be xenocrysts from the mafic injection) but have a slightly narrower compositional range (An_{39} to An_{50}). Plagioclase in Tdrd is chiefly reversely zoned but also exhibits normal zoning. Multiple-point traverses across oscillatory-zoned crystals were not performed. Composition ranges from oligoclase to andesine (An_{27} to An_{48}).

Sanidine (Or_{43} to Or_{67}) and anorthoclase (Or_{34} to Or_{37}) are found only in the rhyolite of Indian Creek Buttes (Tdr_1 , JJ92-5). All samples showed a slightly more sodic rim relative to core composition.

4.1.3 Pyroxene

Clinopyroxene crystals range from En_{50} to En_{60} (enstatite) for basalt to dacite (Table 4– 3, Fig. 4-2). In Tdrd, clinopyroxene is slightly more enriched in iron (En_{32-38}).



Figure 4-1: Feldspar compositions plotted on the feldspar ternary. Inset (upper right) shows fields for alkali feldspar and plagioclase. Or = orthoclase; Ab = albite; An = anorthite. Rim and core compositions for orthoclase feldspar are designated by 'r' and 'c', respectively, and are connected by dashed line.

			RHYC	DLITE		
Sample No. Map unit	JJ92-5 Tdr1	JJ92-5 Tdr1	JJ92-5 Tdr1	JJ92-5 Tdr1	JJ92-5 Tdr1	JJ92-5 Tdr1
	(c	r)	(c	r)	С	С
SiO ₂	65.1	65.79	64.25	65.51	65.03	65.85
Al ₂ O ₃	19.17	19.19	19.18	19.53	19.27	19.47
CaO	0.17	0.2	0.19	0.29	0.36	0.32
Na ₂ O	3.58	4.81	3.57	7.21	5.91	6.91
K ₂ O	11.35	9.42	11.36	5.65	7.94	6.18
MgO	0.01	0.01	0	0.01	0	0
FeO	0.06	0.09	0.05	0.09	0.15	0.13
BaO	<u>0.24</u>	<u>0.23</u>	<u>0.22</u>	<u>0.16</u>	<u>0.4</u>	<u>0.42</u>
	99.68	99.74	98.82	98.45	99.06	99.28
An	1	1	1	1	2	2
Ab	32	43	32	65	52	61
Or	67	56	67	34	46	37
plag. comp.	sanidine	sanidine	sanidine	anorthoclase	sanidine	sanidine

TABLE 4-2:	Representative	microprobe	analyses of	of feldspar
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	RHYODACITE								
Sample No. Map unit	JJ92-1 Tdrd	JJ92-1 Tdrd	JJ92-1 Tdrd	JJ92-1 Tdrd	JJ92-1 Tdrd				
_	С	(c			r)				
SiO ₂	61.26	58.30	59.80	56.33	57.57				
Al ₂ O ₃	24.17	25.83	25.27	27.92	26.39				
CaO	5.42	7.63	6.59	9.82	8.84				
Na ₂ O	7.45	6.38	6.99	5.5	5.92				
K ₂ O	1.18	0.79	1.02	0.47	0.61				
MgO	0.01	0.01	0.00	0.04	0.02				
FeO	0.1	0.20	0.18	0.32	0.44				
BaO	<u>0.02</u>	<u>0.02</u>	<u>0.04</u>	<u>0.08</u>	<u>0.09</u>				
	99.61	99.16	99.89	100.48	99.88				
An	27	38	32	48	43				
Ab	66	57	62	49	53				
Or	7	5	6	3	4				
plag. comp.	oligoclase	andesine	andesine	andesine	andesine				

Complete analyses in Appendix 3. c = core; (c---r) = core to rim; gm = groundmass crystalBeam comditions: beam current, 30 na; accelerating voltage, 15 kv; beam diameter, 5 microns; countingtime 10 sec. for all elements except for Ba (20 sec). Analytical precision based on repeat analyses ofstandards is better than 1 percent for SiO2, Al2O3, K2O (sanidine) and CaO (labradorite), better than 5percent for Na2O, K2O (oligoclase), CaO (oligoclase), and BaO (sanidine). All others are at or belowdetection limit.Ternary feldspar compositions: Ab = albite (NaAlSi3O8); Or = orthoclase (KAlSi3O8O;An = anorthite (CaAl2Si2O8)

TABLE 4-2 (Continued)

				BAS	ALT			
Sample No	. JJ92-99	JJ92-99	JJ92-99	JJ92-99	JJ92-99	JJ93-130	JJ93-130	JJ93-130
Map unit	Tdb ₂	Tdb ₁	Tdb ₁	Tdb ₁				
	(c	r)	gm	(c	r)	с	с	C
SiO ₂	51.35	50.37	53.01	49.96	53.43	56.33	51.67	55.02
Al ₂ O ₃	30.22	30.89	27.49	31.5	28.6	26.56	30.07	27.97
CaO	13.3	14.29	11.91	14.6	11.57	9.38	13.17	10.84
Na ₂ O	3.82	3.17	4.3	3.14	4.65	5.81	3.87	5.26
K ₂ O	0.25	0.27	0.44	0.21	0.4	0.5	0.2	0.47
MgO	0.12	0.11	0.51	0.12	0.1	0.05	0.09	0.08
FeO	0.55	0.73	1.13	0.48	0.88	1.19	0.65	0.71
BaO	<u>0.03</u>	<u>0.04</u>	0.02	0.01	0.01	0.03	0.01	0.09
	99.64	99.87	98.81	100.02	99.64	99.85	99.73	100.44
An	65	70	59	71	57	45	65	51
Ab	34	28	38	28	41	52	34	46
Or	1	2	3	1	2	3	1	3
plag. comp	. labradorit	bytownite	labradorit	bytownite	labradorite	andesine	labradorite	labradorite
	e		e					

INCLUSION-RICH DACITE (Inclusion and attached dacite from sample JJ92-51)

Sample No.	JJ92-51	JJ92-51	JJ92-51	JJ92-51	JJ92-51
Map unit	Tdid	Tdid	Tdid	Tdid	Tdid
	С	С	С	(c	r)
SiO ₂	55.66	56.93	54.76	55.85	53.42
Al ₂ O ₃	27.36	26.97	28.11	26.54	24.74
CaO	10.35	9.03	10.68	9.30	12.37
Na ₂ O	5.28	5.68	5.23	5.71	5.16
K ₂ O	0.61	0.76	0.61	0.63	0.83
MgO	0.07	0.05	0.06	0.10	0.07
FeO	0.65	0.50	0.77	1.21	0.71
BaO	<u>0.04</u>	<u>0.09</u>	<u>0.03</u>	<u>0.06</u>	<u>0.10</u>
	100.02	100.01	100.25	99.4	97.4
An	50	45	51	45	54
Ab	46	51	45	51	41
Or	4	4	4	4	4
plag. comp.	andesine	andesine	labradorite	andesine	labradorite

Complete analyses in Appendix 3. c = core; (c---r) = core to rim; gm = groundmass crystalBeam comditions: beam current, 30 na; accelerating voltage, 15 kv; beam diameter, 5 microns; countingtime 10 sec. for all elements except for Ba (20 sec). Analytical precision based on repeat analyses ofstandards is better than 1 percent for SiO2, Al2O3, K2O (sanidine) and CaO (labradorite), better than 5percent for Na2O, K2O (oligoclase), CaO (oligoclase), and BaO (sanidine). All others are at or belowdetection limit.Ternary feldspar compositions: Ab = albite (NaAlSi3O8); Or = orthoclase (KAlSi3O8O;An = anorthite (CaAl2Si2O8)



Figure 4-2: Pyroxene and olivine compositions. (A) Pyroxene quadrilateral. (B) Olivine compositions.

Sample No.	JJ92-51 J	JJ92-51	JJ92-51.	JJ92-51	JJ92-51.	JJ93-130	JJ93-130	JJ92-99	JJ92-99	JJ92-1	JJ92-1	JJ92-1	JJ92-1
Map unit	Tdid-i	Tdid-i	Tdid-i	Tdid-h	Tdid-h	Tdb1	Tdb1	Tdb2	Tdb2	Tdrd	Tdrd	Tdrd	Tdrd
SiO ₂	50.59	50.22	49.71	50.36	51.79	51.76	49.95	50.23	52.36	50.68	51.41	51.42	51.43
TiO ₂	1.41	1.47	1.12	1.05	0.46	1.28	1.07	1.49	1.04	0.12	0.11	0.43	0.12
Al ₂ O ₃	4.08	4.05	3.16	3.09	1.42	2.05	1.72	3.45	1.45	0.58	0.72	1.69	0.89
FeO	12.89	11.34	12.43	10.96	22.03	10.95	10.59	9.78	11.77	30.63	27.42	11.99	15.30
MnO	0.34	0.31	0.41	0.34	0.56	0.33	0.35	0.19	0.38	1.55	0.97	0.42	0.92
MgO	15.71	14.76	14.81	14.83	21.67	14.36	14.24	14.26	14.99	14.34	16.91	13.20	10.56
CaO	15.90	17.97	17.34	18.73	2.04	20.38	19.62	20.40	18.55	1.35	1.37	19.30	20.12
Na ₂ O	0.41	0.37	0.34	0.39	0.02	0.38	0.61	0.37	0.36	0.03	0.05	0.37	0.36
Cr ₂ O ₃	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>0.00</u>	<u>0.04</u>	<u>0.00</u>	<u>0.04</u>	0.15	<u>0.00</u>	0.00	0.02	0.00	0.00
	101.33	100.49	99.32	99.75	100.03	101.49	98.19	100.32	100.90	99.28	98.98	98.82	99.70
Wo	36	41	39	42	4	45	44	46	41	3	3	43	44
En	35	33	33	33	47	31	32	32	33	31	37	30	23
Fs	29	26	28	25	48	24	24	22	26	66	60	27	33

TABLE 4-3: Representative microprobe analyses of pyroxene.

Complete analyses are found in Appendix 3. Beam conditions: beam current, 50 na; accelerating voltage, 15 kv; beam diameter, 1 micron; than 1 percent for SiO₂, Al₂O₃, MgO, and CaO; better than 5 percent for TiO₂ and Na₂O; 5 to 15 percent for FeO, MnO, and Cr₂O₃. Pyroxene compositions: Wo = wollastonite (Ca2Si2O6); En = enstatite (Mg2Si2O6); Fs = ferrosilite (Fe2Si2O6)

Orthopyroxene is found only in the dacite (Tdid) and the rhyodacite (Tdrd) and occurs as hypersthene and ferrohypersthene, respectively. No pyroxene was found in Tdr_1 .

Tdb₁ has sparse, tiny intergranular augite that averages W044En32Fs24 with slight variation. The ophitic augite of Tdb₂ ranges from Wo₄₁En₃₃Fs₂₆ to Wo₅₀En₂₆Fs₂₄, with a systematically higher calcium (Wo) component when measured adjacent to plagioclase versus adjacent to olivine or iron oxides. The basaltic-andesite inclusion of Tdid has only clinopyroxene with a small range of compositions in the augite field (Fig. 4-2a), typically about Wo₄₀En₃₂Fs₂₉. It is subhedral and unzoned. The dacite host has both clinopyroxene and orthopyroxene, and shows the widest range of calcium content within the augite field (Wo₂₄-Wo₄₂). In general, the cores of the augite in the dacite are similar to those of the basaltic-andesite inclusion (Wo₃₆-Wo₄₂) with the exception of a Wo-depleted rim on a crystal in the dacite (Wo_{24}). Crystals vary from subhedral to euhedral. Orthopyroxene ranges from hypersthene (En₅₆) to low-iron ferrohypersthene (En₄₇), and varies from euhedral laths to anhedral subround remnants. If I assume that the two pyroxenes formed in equilibrium with the dacite, then temperatures between 900 and 1,000°C are calculated by using the pyroxene compositions and the projection method of Lindsley (1983); however, mineral relations are not clear owing to uncertainties introduced during magmatic mixing.

Unit Tdrd has both ferrohypersthene and ferrohedenbergite phenocrysts. The crystals are most commonly subhedral to anhedral and are unzoned, though both a normally zoned, subhedral and a reversely zoned, anhedral ferrohypersthene were found. A single anhedral augite phenocryst probably represents a phase in disequilibrium with the melt, because $Wo_{44}En_{23}Fs_{33}$ is the most common clinopyroxene in the rhyodacite. Using the two-pyroxene thermometer of Lindsley (1983), and assuming partial requilibration on cooling, a minimum temperature of formation of ~700°C is estimated. The estimated temperature may be in error owing to compositional variation reflecting analytical or calibration errors, or due to mixed mineralogy caused by hybridization of magmas.

4.1.4 Olivine

Olivine in both basalts (Tdb₁, Tdb₂) is homogeneous with a range in composition from Fo_{65} to Fo_{53} (Fig. 4-2b; Table 4-4). Phenocryst phases in both lavas are normally zoned. Groundmass crystals in Tdb₂ are typically more iron rich (Fo₅₃) than the phenocrysts. Groundmass olivine was not found in Tdb₁. Although olivine was found in thin-section analysis of the Tdid basaltic-andesite inclusion and in one thin section of the dacite host, none was found in the polished section. An olivine separate from Qb₂ was considerably more magnesian, Fo_{86} , than the DBEC basalts olivine.

4.1.5 Biotite

Biotite was found only in Tdrd and is commonly euhedral (Table 4-6).

4.1.6 Amphibole

Amphibole is present in Tdrd, but was not found on the polished section prepared for microprobe analysis. Amphibole in Tdr_1 is hornblende. It is remarkably uniform in composition both between and within individual crystals, suggesting equilibrium crystallization (Table 4-6).

4.1.7 Ilmenite

A single groundmass phenocryst of ilmenite was microprobed using the pyroxene standard and is presented in Table 4-5.

4.1.8 Chrome spinel

A single cryptocrystalline chrome spinel inclusion was found in an olivine separate from the basalt of Duck Creek Flat (Table 4-5)

Sample No.	JJ93-130	JJ93-130	JJ93-130	JJ92-99	JJ92-99	JJ92-99	JJ92-20
Map unit	Tdb1	Tdb1	Tdb1	Tdb2	Tdb2	Tdb2	Qb2
	c	r	typ	c	r	typ	typ
SiO2	36.17	34.83	35.10	36.05	35.35	34.47	40.9
TiO2	0.03	0.07	0.06	0.01	0.08	0.09	0.01
A12O3	0.00	0.00	0.00	0.00	0.00	0.00	0.07
FeO	30.90	37.89	36.33	31.32	36.21	39.69	14.03
MnO	0.37	0.64	0.54	0.40	0.46	0.56	0.19
MgO	32.63	26.21	27.87	31.45	26.36	24.62	47.67
CaO	0.18	0.11	0.15	0.15	0.14	0.07	0.28
NiO	0.07	0.03	0.06	0.05	0.05	0.06	0.01
ZnO	<u>0.01</u>	<u>0.03</u>	0.00	<u>0.05</u>	<u>0.06</u>	<u>0.03</u>	
	100.36	99.81	100.11	99.48	98.71	99.59	103.16
Fo	65	55	58	64	56	53	86

Table 4-4: Representative microprobe analyses of olivine.

Table	4-5:	Microprobe	analyses	of	ilmenite	and	chrome	spinel.
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Ilmenite		Chrome-spinel inclusion in olivir					
Sample No.	JJ93-130						
Map unit	Tdb1		Qb2				
SiO2	0.12	SiO2	0.16				
TiO2	20.84	TiO2	0.26				
A12O3	1.62	A12O3	47.79				
FeO	70.94	FeO	17.52				
MnO	0.61	MnO	0.17				
MgO	1.88	MgO	17.99				
CaO2	0.10	CaO	0.00				
Na2O	0.03	Cr	<u>14.35</u>				
Cr2O3	<u>0.00</u>						
	96.14		98.24				

Complete analyses are found in Appendix 3. Beam conditions: beam current, 50 na; accelerating voltage, 15 kv; beam diameter, 1 micron; counting time, 10 sec. for all elements. Analytical precision based on repeat analyses of olivine standard is better than 1% for SiO2, MgO (Mg-rich olivine), FeO, and MnO (Fe-rich olivine), and 5 to 15 % for MgO(Fe-rich olivine), and MnO (Mg-rich olivine). Values for Al2O3, CaO, NiO, ZnO, Cr2O5 are at or below detection limits.

Olivine composition: Fo = forsterite (Mg2SiO4).

c = core; r = rim; typ = typical crystal composition.
BIOTITE		
Sample #	JJ92-1	JJ92-1
map unit	Tdrd	Tdrd
SiO2	36.50	38.02
TiO2	5.66	5.31
Al2O3	13.22	12.60
FeO	19.78	20.44
MnO	0.08	0.16
MgO	11.46	10.97
CaO	0.00	0.04
Na2O	0.56	0.56
K2O	8.81	8.44
Cr2O3	0.05	0.00
Ox%(Zn)	<u>0.03</u>	0.03
	96.15	96.57
F	0.76	0.60
Cl	0.08	0.07

Table 4-6: Representative analyses of biotite and amphibole.

AMPHIBOLE	2		
Sample #	JJ92-5	JJ92-5	JJ92-5
map unit	Tdr1	Tdr1	Tdr1
SiO2	42.63	43.68	44.24
TiO2	2.16	1.80	1.59
Al2O3	8.55	8.47	8.25
FeO	27.50	23.90	23.55
MnO	0.51	0.51	0.50
MgO	5.16	7.49	7.63
CaO	9.99	10.37	10.19
Na2O	1.83	1.76	1.80
K2O	1.06	0.95	0.91
Cr2O3	<u>0.05</u>	0.00	0.02
	99.44	98.93	98.68
Cl	0.20	0.14	0.14
F	0.54	0.60	0.51

Complete analyses are found in Appendix 3. Beam conditions: beam current, 50 na; accelerating voltage, 15 kv; beam diameter, 1 micron; counting time, 10 sec. for all elements except TiO2 (20 sec.). Analytical precision based on repeat analyses.

4.2 Whole-Rock Composition

4.2.1 Classification

Bulk chemical composition for rocks sampled in the DBEC study area ranges from high-magnesia basalt to high-silica rhyolite (Fig. 4-3; Tables 4-7 through 4-9). Classification for the series of rocks is based on SiO₂ concentration: basalt (48-52 weight percent), basaltic andesite (52-57 percent), andesite (57-63 percent), dacite (63-68 percent), rhyodacite (68-72 percent) and rhyolite (>72 percent). On the total alkali versus silica diagram of LeBas and others (1986) the intermediate (>52, <63 percent SiO₂) samples of the DBEC series plot on and slightly above the trachybasalt to trachydacite boundary (Fig. 4-3). Although these samples are properly trachytic in composition owing to elevated total alkalies, they shall be referred to without the "trachy" designation herein. Major and trace elements are presented in Figures 4-4 and 4-5. All basaltic andesite and andesite is classified as "potassic" on the basis of Na₂O - 2 < K₂O (Le Maitre, 1989). K₂O and Na₂O vary smoothly with SiO₂, indicating that there has been little alteration of the original magmatic composition. All rocks are hypersthene normative and metaluminous (Shand, 1951), with the exception of the slightly peraluminous aphyric obsidian from the rhyolite of Indian Creek Buttes (Tdr₁, JJ92-5). CIPW norms are presented in Appendix 7.

4.2.2 Older basalts and andesites and Quaternary basalt

Steens Basalt in the map area (Ts, FF94-49: Table 4-8) is classified as a tholeiitic basalt by the system of Irvine and Baragar, (1971; Fig. 4-6A). At the type section, 60 km south of DBEC, the basalt varies from calc-alkaline at the base to tholeiitic near the top of the section (Fig. 4-6B and Appendix 4). Variations in many major and trace elements (for example, Al, Mg, K, Ba) between flows correlate with modal abundance of plagioclase and olivine. Although these variations have long been recognized (Gunn and Watkins, 1970), compositional change from base to top has been largely ignored. Fifty samples from the



Figure 4-3: Chemical analyses of rocks in the Duck Creek Butte study area plotted on total alkali-silica classification diagram, modified from Le Bas and others (1986) to include a field for rhyodacite indicated by dashed lines. Data from Tables 4-6 through 4-8. "Trachy" designation is not used in the text.

	R	hyolite	2		R	<u>hyodac</u>	<u>ite</u>	
	JJ92-4	JJ92-5	JJ94-158	JN94-16	JJ92-1	JJ92-7	JJ92-88	JJ92-101
Map Unit	Tdr ₁	Tdr ₁	Tdr ₂	Tdr ₂	Tdrd	Tdrd	Tdrd	Tdrd
Lithology	0	L	Ō	Ō		L	L	L
SiO ₂	76.35	76.00	76.04	75.03	70.19	70.26	70.08	69.47
TiO ₂	0.11	0.12	0.08	13.98	0.55	0.53	0.55	0.56
Al ₂ O ₃	12.79	13.03	13.00	0.06	14.51	14.61	14.53	14.99
FeO*	1.18	1.29	1.14	0.85	3.15	3.02	3.01	2.96
MnO	0.04	0.04	0.04	0.07	0.07	0.07	0.07	0.08
MgO	0.04	0.10	0.00	1.10	0.80	0.67	0.67	0.66
CaU No O	0.66	0.66	0.76	0.00	2.18	1.98	2.06	1.92
	5.74	5.37	4.00	4.55	3.39	3./0	3.75	4.06
	5.07	5.15	4.93	4.34	4./9	4.95	5.15	5.13
F205	100	100	100	0.02	0.18	0.15	0.15	0.18
VDF anal	100		100	100	100	100	100	100
Dh	170	<u>146</u>	171	0	116	100	126	107
Ra	216	237	1/1	9	1630	1660	1000	127
Sr	51	18	29	6	283	250	272	296
Zr	156	149	139	4	242	278	273	233
Nb	34	49	34	508	22	33	17	26
Y	67	50	51	141	30	33	36	15
Pb			23	84				
Zn			49	83				
Ga			18	27				
V C::			0	17				
			5	19				
Cr	4 30	4 56	14	36	637	13	41	55
Sc	4.55	4.50	1	23	0.57	43	41	55
INAA			-					
Cs	4.24	4.06			3.28			
U	5.08	6.18			4.62			
Th	12.92	12.62			10.37			
Hſ	4.93	4.72			5.48			
Ta	2.13	1.99			1.20			
SD	nd	0.70			0.65			
AS	2.50	2.74			1.50			
Co	0.34	2.75			0.15			
La	33.35	34.03			34.15			
Če	68.86	73.24			62.11			
Nd	30.70	32.59			26.46			
Sm	7.06	7.24			5.24			
Eu	0.36	0.37			1.16			
Tb	1.25	1.17			0.77			
Y Ð	4.71	5.31			3.33			
LU W	0.72	0.70			0.44			
<u></u>	1.80	2.30			1.60			

TABLE 4-7: Whole-rock compositions of DBEC samples (includes Quaternary basalt).

 \dagger = exceeds standard. *italics in XRF* = *INAA data* Major element data normalized to 100%; prenormalized data is in Appendix 6. FeO* = total iron as FeO. JJ92 XRF data are from XRAL, British Columbia; JJ93, -94, -95 and FF XRF data are from Washington State University, Pullman WA. Key to Lithology: L = lava; O = obsidian; Qi = quenched inclusion; D = dike; UT & WT = unwelded & welded tuff

	Dacite	<u>Andesite</u>					
	JJ92-102	JJ92-27	JJ93-41	JJ93-126	JJ93-140	JJ94-1iA	JJ94-1iB
Map Unit	Tdid	Tda ₁	Tda ₁	Tda ₂	Tda ₂	Tdrd	Tdrd
Lithology	L	L	Ĺ	Ĺ	Ĺ	Oi	Oi
SiO ₂	66.27	59.61	61.42	60.76	60.13	60.28	60.02
TiO ₂	0.87	1.44	1.32	1.17	1.13	1.53	1.44
Al ₂ O ₃	14.78	15.08	15.81	15.74	15.80	15.78	15.62
FeO*	5.30	7.90	6.13	6.93	7.16	8.93	8.43
MnO	0.12	0.14	0.13	0.14	0.13	0.13	0.18
MgO	1.06	3.03	2.53	2.64	3.05	1.22	1.40
CaO	3.12	5.52	5.27	5.46	5.69	4.59	4.72
Na ₂ O	4.06	3.71	3.83	3.91	3.76	3.97	4.35
K ₂ O	4.09	3.14	3.24	2.94	2.85	2.77	2.96
P_2O_5	0.33	0.44	0.32	0.33	0.30	0.80	0.88
	100	100	100	100	100	100	100
XRF analys	ses (ppm)	8					
Rb	100	67	67	68	63	61	63
Ba	1530	1260	1727	1159	1132	1931	1453
Sr	287	278	256	259	266	380	353
Zr	296	366	367	327	323	316	324
Nb	38	38	29	26	26	34	32
Y	26	54	†48	†45	†47	48	57
Рь			10	9	7	9	9
Zn			105	96	90	128	146
Ga			20	18	21	19	21
V C			123	128	117	39	17
			27	38	23	17	5
	2 07	45.262	42	34	34	4	2
Sc.	2.97	45.502	/0	10	/3.30	3	2
INAA (nm)			23	19	24	22	22
Cs	2.90	1.55	1 64	1 66	1 36		
U	4.50	3.20	3.92	2.67	2 47		
Ťh	9.11	5.95	6.90	5.80	5.80	4.00	7.00
Hf	6.08	7.40	10.20	8.31	8.51		
Та	2.95	2.59	1.75	1.42	1.43		
Sb	0.56	0.54	0.18	0.23	0.19		
As	2.20	2.10	5.10	4.20	3.90		
Sc	9.94	18.55	20.20	19.40	20.10		
Co	23.98	36.21	24.90	19.80	19.70		
La	42.74	37.12	41.00	35.90	39.00	39.00	48.00
Ce	82.62	73.48	85.30	72.20	74.90	86.00	99.00
Nd	38.33	35.54	37.70	35.70	38.20		
Sm	7.69	7.96	8.58	7.61	8.58		
Eu	1.96	2.18	2.39	1.99	2.17		
10 V.5	1.11	1.35	1.36	1.18	1.30		
I U I n	4.70	4.70	4.88	4.49	4.80		
W	143 30		0.74	0.09	0.73		
**	143.30	110.00	1.70	1.70	2.30		

 \dagger = exceeds standard. *italics in XRF* = *INAA data* Major element data normalized to 100 percent; prenormalized data is in Appendix 6. FeO* = total iron as FeO. JJ92 XRF data are from XRAL, British Columbia; JJ93, -94, -95 and FF XRF data are from Washington State University, Pullman WA. Key to Lithology: L = lava; O = obsidian; Qi = quenched inclusion; D = dike; UT & WT = unwelded & welded tuff

	Basaltic Andesite					<u>alt</u>		
	JJ92-6	JJ92-38 J	J92-51 J	IJ92-62	JJ92-99	JJ93-130	JJ93-20	JJ94-15 1
Map Unit	Tdba ₁	Tdba ₂	Tdid	Tdba ₃	Tdb ₂	Tdb ₁	Ob,	Oba
Lithology	Ĺ	Đ	Qi	Ĺ	L L	Ĺ	Ĺ	Ĺ
SiO ₂	52.66	53.43	54.81	54.98	50.86	48.83	48.72	49.43
TiO ₂	2.11	2.09	2.49	2.11	1.74	2.56	0.92	1.13
Al ₂ O ₃	16.05	15.88	14.27	14.60	16.95	15.88	16.23	16.96
FeO*	10.92	10.81	10.90	10.60	10.32	13.04	9.97	9.48
MnO	0.18	0.18	0.21	0.18	0.17	0.21	0.18	0.17
MgO	4.26	4.22	3.33	4.05	5.55	5.45	10.03	8.36
	7.23	7.11	7.00	6.46	8.84	9.05	11.06	11.16
Na ₂ O	3.09	3.42	3.18	4.10	3.58	3.41	2.53	2.82
R ₂ U	2.10	2.14	2.43	2.42	1.28	0.87	0.26	0.35
$P_{2}O_{5}$	0.74	0.73	1.39	0.50	0.70	0.69	0.10	0.14
	100	100	100	100	100	100	100	100
XRF analy	ses (ppi	<u>n)</u>						
Rb	37	33	39	50	22	11	4	6
Ba	914	904	1770	1200	760	548	91	137
5r 7-	390	591	353	255	584	324	207	240
Lr Nh	207	208	256	328	151	262	65	78
V	44	27	50	49	40	24	10	8
Pb	51	29	20	40	19	760	19	20
Zn		82	147	124	113	+140	67	68
Ga			1	127		25	14	17
V						255	230	254
Cu						64	69	53
Ni	54.59	17.00	21.00	65.00	112.00	48	189	123
Cr	20.33	4	4.9	82	98.69	46	399	257
Sc						34	41	36
Cs	0.70	2.97	1.23	1.13	0.18	0.23	0.15	
UTh	2.10	2.10	1.76	1.95	.2.70	1.80	1.90	
	1.04	9.70	4.70	4.00	1.26	0.81	0.30	
Ta	0.86	1 61	0.20 2 / 1	0.10	3.90	0.83	1.48	
Sb	0.45	0.20	2.71	0.30	1.07	0.15	0.24	
As	2.40	1.00	0.90	2.20	3.00	1.40	3.00	
Sc	19.48	9.82	22.30	23.50	23.30	29.80	34.20	
Co	29.31	4.12	39.70	29.70	54.40	42.30	53.30	
La	27.81	45.00	49.10	39.60	31.70	30.50	4.43	
Ce	60.28	85.20	93.20	85.40	62.00	63.60	9.20	
Nd	34.00	37.70	54.70	43.00	29.40	39.50	7.20	
Sm E	7.42	7.86	12.10	9.34	6.80	9.92	2.17	
150 Th	2.09	2.03	3.57	2.80	2.12	3.06	0.87	
ru Vh	3 10	1.19	1.94	1.44	1.03	1.73	0.47	
La	0.40	4.20	0.81	4.95	2.39	5.14	2.01	
w	2.80	3.30	72.50	1.80	71.70	5.40	1.20	

 TABLE 4-7
 (DBEC continued)

 \dagger = exceeds standard. *italics in XRF* = *INAA data* Major element data normalized to 100 percent; prenormalized data is in Appendix 6. FeO* = total iron as FeO. JJ92 XRF data are from XRAL, British Columbia; JJ93, -94, -95 and FF XRF data are from Washington State University, Pullman WA. Key to Lithology: L = lava; O = obsidian; Qi = quenched inclusion; D = dike; UT & WT = unwelded & welded tuff

Pre-DBEC basalt and andesite									
	JJ93-19	JJ92-59	JJ93-133	JJ93-134	JJ93-147	JJ94-161	JJ94-163		
Map Unit	Tba	Ts?	Tba	Tas	Tad	Tba	Tbs		
Lithology	L	L	L	L	L	L	L		
SiO ₂	56.16	51.28	56.52	61.86	59.28	55.05	49.93		
TiO ₂	2.00	2.57	2.01	1.06	2.33	2.13	2.49		
Al_2O_3	13.85	15.25	14.58	16.56	14.11	15.49	15.53		
FeO*	11.06	12.16	9.48	5.56	10.14	10.57	12.24		
MnO	0.17	0.18	0.15	0.11	0.15	0.19	0.17		
MgO	3.95	4.96	4.11	2.24	1.93	3.18	5.63		
CaO	7.46	8.75	7.99	5.28	5.34	6.33	8.80		
Na ₂ O	3.25	3.21	3.41	4.00	3.91	3.81	3.22		
K ₂ O	1.78	1.24	1.45	2.97	2.25	2.52	1.23		
P ₂ O ₅	0.31	0.40	0.30	0.36	0.56	0.73	0.76		
	100	100	100	100	100	100	100		
XRF analyse	es (ppm)								
Rb	49	27	37	49	56	52	17		
Ba	652	492	608	1087	757	1053	769		
Sr	346	379	371	476	285	417	385		
Zr	189	190	171	212	274	243	202		
N b	15	30	13	15	22	22	17		
Y Dh	35	31	32	26	†53	40	37		
F D 7 m	J 111		4	11	+122	10	121		
	24		20	80 17	1132	120	131		
V	285		300	133	180	220	20		
Ċu	62		64	27	17	23	20		
NI	11	74.27	17	6	0	0	42		
Cr	14	63.301	24	3	1	4	69		
Sc	39		32	18	30	24	29		
INAA									
Cs	1.61	1.08		0.85					
U	2.18	1.90		1.45					
Th	5.50	2.80		3.90					
Hf	5.18	4.47		5.22					
18	0.98	1.50		0.80					
S D	0.22	0.55		0.20					
AS	1.80	28.10		3.30					
	29.70	51 50		13.40					
La	22 50	10 78		20 60					
Ce	48.60	39.79		58.00					
Nd	26.20	24.88		27.10					
Sm	6.43	6.60		5.43					
Eu	1.87	2.05		1.48					
ТЬ	1.03	1.19		0.74					
Yb	3.15	3.37		2.60					
Lu	0.46	0.43		0.39					
W	2.10	74.01	. =.=	3.30					

TABLE 4-8: Whole-rock composition of pre-DBEC basalt and andesite

 \dagger = exceeds standard. *italics in XRF* = *INAA data* .Major element data normalized to 100 percent; prenormalized data is in Appendix 6. FeO* = total iron as FeO. JJ92 XRF data are from XRAL, British Columbia; JJ93, -94, -95 and FF XRF data are from Washington State University, Pullman WA. Key to Lithology: L = lava; O = obsidian; Qi = quenched inclusion; D = dike; UT & WT = unwelded & welded tuff

TABLE 4-8 (Continued)

TABLE 4-9: Miscellaneous rhyolite and tuff

	Basalt and	andesite (
	FF94-23 F	F94-36 F	F94-49	JJ92-90	JJ93-123	JJ93-124	
Map Unit	ТЬ	Tba	Tba	Τs	Tr	Tots	Ttd
Lithology	L	L	L	L		UT	WT
SiO ₂	50.37	50.66	59.46	49.28	76.52	76.21	75.40
TiO ₂	2.05	1.94	2.01	1.95	0.06	0.20	0.23
Al ₂ O ₃	16.48	15.69	13.70	17.16	13.00	11.15	10.15
FeO*	11.01	12.01	10.27	12.05	0.81	2.67	4.45
MnO	0.17	0.17	0.15	0.18	0.05	0.05	0.07
MgO	5.63	6.07	2.33	5.80	0.03	0.00	0.00
CaO	10.36	9.39	5.63	8.98	0.72	0.30	0.21
Na ₂ O	3.07	3.24	3.78	3.46	4.24	4.07	4.87
K ₂ O	0.61	0.58	2.36	0.84	4.56	5.32	4.61
P_2O_5	0.24	0.26	0.32	0.30	0.02	0.02	0.01
	100	100	100	100	100	100	100
XRF analy	ses (ppm)				•		
Rb	12	10	68	14	235	128	212
Ba	213	398	892	327	48	29	45
Sr	388	447	307	494	10	6	8
Zr	140	137	243	136	106	†938	†813
Nb	10	15	17	8	45	†87	†42
Y	31	26	41	29	70	†149	†1 5 6
РЬ	3	2	12	4		26	21
Zn	96	108	121	104		†223	†262
Ga	24	22	20	22		†28	†30
V C	319	256	291	291		0	0
	95	0	14	175		12	5
	177	11	U	105	3.000	18	21
Sc	33	30	28	28	5.900	3	3
INAA	55	50	20	20		U	U
Cs					7 67		5 20
Ŭ					11.09		9.85
Th					17.85		23.30
Hf					4.57		25.90
Ta					4.13		2.72
Sb					0.94		0.78
As					4.27		2.90
Sc					0.95		1.38
Co					8.51		0.40
La					11.92		89.40
Ce					33.25		214.00
Nd					20.39		102.00
5 m F.,					6.61		25.00
ец Ть							2.23
I U Vh					1.44		4.41
I D					/.34		15.80
W					0.94		2.29
					/1.55		2.50

 \dagger = exceeds standard. *italics in XRF* = *INAA data*. Major element data normalized to 100%; prenormalized data is in Appendix 6. FeO* = total iron as FeO. JJ92 XRF data are from XRAL, British Columbia; JJ93, -94, -95 and FF XRF data are from Washington State University, Pullman WA. Key to Lithology: L = lava; O = obsidian; Qi = quenched inclusion; D = dike; UT & WT = unwelded & welded tuff



Figure 4-4: Silica versus major element variation diagrams. MnO and P_2O_5 diagrams are continued on next page. Data from Tables 4-7 through 4-9.



Figure 4-4 (continued from previous page).



Figure 4-5: Silica versus trace element variation diagrams. Symbols as in Figure 4-4.



Figure 4-5 (continued from previous page).



Figure 4-6: (A) AFM diagram indicating the fields of tholeiitic and calcalkaline basalts (Irvine and Baragar, 1971). Includes only samples from study area; (B) Alkalies versus silica diagram indicating fields of tholeiitic and calc-alkaline basalts (MacDonald and Katsura, 1964). Most middle- and upper-Steens Basalt samples exceed 5 percent Na₂O+K₂O, and therefore are not plotted on this diagram.

lower, middle, and upper parts of the Steens Basalt sequence near the type section (Appendix 4) show a continuum with increasing K₂O and decreasing Mg from base to top (Fig. 4-7). Variation in the sequence is also seen in decreasing Cr and increasing FeO/MgO, P_2O_5/TiO_2 and Zr/Nb vs. Zr upsection (Figs. 4-8 and 5-1). The lower flows show a remarkable trace-element homogeneity whereas the upper flows have increasing compositional scatter (Fig. 5-1).

On the basis of major- and trace-element compositions, the porphyritic basalt (Tb, FF94-23) is compositionally similar to the Steens Basalt (Fig. 5-1), which is consistent with its correlation with the "Steens-like" or "Steens Mountain type" basalt southeast of DBEC defined by Carlson and Hart (1987). The basalt of Stockade Creek (Tbs, JJ94-163) is also compositionally similar to some of the Steens Basalt flows (see Appendix 4, samples JS94-33, -34, and -39) but lacks the characteristic Cu, V, and Ni enrichment and has substantially higher Ba than the Steens Basalt. South of DBEC, both the porphyritic basalt (Tb) and the unit of basalt and andesite (Tba) are tholeiitic and have higher Sc and Ca and lower Ba, Rb, Nb, Zr, K₂O, and P₂O₅ than the DBEC series (Figs. 4-4, 4-5, and 5-1). Northeast of DBEC, however, the pre-DBEC andesite (JJ93-134, JJ94-161) is similar in major- and trace-element composition to the DBEC series.

The basalt of Duck Creek Flat (Qb₂, JJ92-20) is an olivine-normative high-alumina tholeiite with a primitive MORB*-type signature. The basalt is characterized by low SiO₂, K₂O, Na₂O, TiO₂, Zr, Nb, and Y, and high CaO, MgO, Cr, CaO/Al₂O₃, and CaO/FeO. It has a relatively flat REE** pattern (Fig. 4-9D) typical of MORB (Basaltic Volcanism Study Project, 1981). A spider diagram for other elements shows enriched large-ion-lithophile elements and depleted high-field-strength elements relative to MORB (Fig. 4-10). Qb₂ has ⁸⁷Sr/⁸⁶Sr and ¹⁴³Nd/¹⁴⁴Nd ratios of 0.70508 and 0.512717, respectively (Appendix 5). The

* Mid-Ocean Ridge Basalt

^{**} REE: Rare-earth elements, include LREE, light rare-earth elements, and HREE, heavy-rare earth elements.



Figure 4-7: MgO-TiO₂-K₂O ternary plot showing the fields for basalt and basaltic andesite at DBEC. Shown shaded are fields of high-alumina olivine tholeiite (HAOT), transitional tholeiite (LKLT = low K, low Ti), alkali olivine basalt, and Steens Basalt (from Hart and others, 1984). Dashed fields of Steens Basalt from this study indicate stratigraphic location, data from Appendix 4.



Figure 4-8: Major-element ratios showing the change in composition from base to top of the Steens Basalt sequence near the type section at Steens Mountain.



Figure 4-9: Rare-earth element diagrams for rocks of DBEC. REE values are normalized to C1 chondrite values (Anders and Ebihara, 1982). (A) Rhyolite and rhyodacite; (B) andesite; (C) basaltic andesite; (D) basalt.

basalt of Cord (Qb₃) is more evolved than Qb₂, as indicated by having lower Mg and higher alkalis, Al₂O₃, Rb, Sr, Ba, and Zr.

4.2.3 DBEC series

Magma that erupted between 10.38 and 10.32 Ma from DBEC forms a coherent suite of rocks that ranges from 48.8 to 76.3 percent SiO₂ (Table 4-7; Fig. 4-3). Within the DBEC suite, major and minor elements form nearly linear arrays on silica variation diagrams (Figs. 4-4 and 4-5). CaO, MgO, and MnO decrease and Na₂O and K₂O increase systematically with increasing SiO₂ content. Intermediate-composition lavas are high in K₂O (Gill, 1981). Rare-earth-element patterns for the DBEC series samples are generally similar to each other (Fig. 4-9). There is no systematic relationship between silica content and REE enrichment. All rocks are depleted in high-field-strength elements and enriched in large-ion-lithophile elements relative to MORB (Fig. 4-10).

Basalts : Tdb₁ (JJ92-130) and Tdb₂ (JJ92-99) can be termed tholeiitic and calcalkaline, respectively (Fig. 4-6). They can also be described high-potash, high-titania tholeiite (HKHT, Tdb₁) and alkali olivine basalt (Tdb₂) by the criteria of Hart and others (1984) (Fig. 4-7). Tdb₁ has higher Fe, Ti, Zr, Y, and Hf and lower K, Sr, Ba, Rb, Cr, Th, Ta, and LREE/HREE than Tdb₂.

Basaltic andesites : The basaltic andesites are high-potash (Gill, 1981), calc-alkaline rocks (Irvine and Baragar, 1971). Trace-element enrichments mimic those of the basalts (Fig. 4-10). Tdba₂ (JJ92-38) has lower Sc, Co, Nb, and Cr and higher Cs, Th, LREE, and HREE relative to Tdba₁ and Tdba₃ (Table 4-7). A tholeiitic basaltic-andesite inclusion (JJ92-51) found in Tdid (JJ92-102) is enriched in P, Ti, Mn, Ba, Y, Nb, and REE relative to all other basaltic andesites. Perhaps loss of the outer glassy rim of the inclusions during sample preparation creates an analysis of only the



Figure 4-10: Spider diagrams of DBEC elements. (A) rhyolite to dacite; (B) andesite; (C) basaltic andesite; (D) basalt. Normalization factors from Pearce (1983).

filter-pressed cumulate that forms the core (see Section 5.4.2.4, petrogenesis of the basaltic andesite inclusion).

Andesite: The most remarkable feature of the four andesites (JJ92-27, -41, JJ93-126, -140) is their major- and trace-element similarity (Fig. 4-10). With respect to the rest of the suite, they represent a continuum between the evolved basalts and Tdrd, with the exception of possessing higher Zr and Y, lower Sr, and high Cr for their SiO₂ content. The andesite inclusions in the rhyodacite (JJ94-1iA, -1iB) have higher TiO₂, Fe₂O₃, P₂O₅, Ba, and Sr, and lower MgO, Cu, and Ni than the andesite flows.

Dacite: The composition of the dacite is fairly consistently on a mixing line between the rhyodacite and Tdba₁ (JJ92-6) for both major and trace elements (Figs. 4-4, 4-5, 5-2). Although care was taken to remove all inclusions, some undetected mafic inclusions may skew the analysis slightly.

Rhyodacite: Analyses from different flow lobes from separate vents of the rhyodacite of Duck Pond Ridge (Tdrd; JJ92-1, -7, -88, -101) show little variation in majorelement composition. Trace-element variations and modal abundance of different mineralogic phases vary.

Rhyolite: A silica gap between 70.3 and 76 percent SiO₂ highlights the difference between the rhyodacite and the relatively aphyric rhyolite (Tdr₁; JJ92-4, -5). Samples from the upper and lower flows straddle the dividing line between the peraluminous and metaluminous fields of Shand (1951) and are similar to other high-silica metaluminous rhyolites (for example, Hildreth, 1979; Metz and Mahood, 1991). They are enriched in Rb, Zr, Y, and Nb and depleted in Fe, Ti, Ca, Mg, Ba, Sr, Sc, and La with respect to the less-evolved rhyodacite. They also exhibit a flatter, slightly less LREE-enriched pattern and strong negative Eu anomaly typical of metaluminous highsilica rhyolite (Fig. 4-9).

4.2.4 Miscellaneous rhyolites

Dowell Butte (Tr, JJ92-90) and the rhyolite of Big Gulch (Tdr₂, JJ94-158 and JN94-16) have compositions similar to the rhyolite of Indian Creek Buttes. Dowell Butte may be more evolved as inferred from lower Ba, Sr, and Zr and higher Rb. The Devine Canyon Ash-flow Tuff (JJ92-123) is not related to the rest of the suite. These rocks were not used in modeling the evolution of DBEC and therefore are not discussed further.

4.2.5 Discussion

Minor silica gaps spanning 55 and 59 percent SiO_2 and 62-66 percent SiO_2 may be a function of incomplete sampling of multiple flow units. Alternatively, the gaps may represent a real break in the continuum due to hybridization of mafic magmas with smaller amounts of silicic magma. In this case, it is possible for complete mixing of the liquid phases to take place. Petrographic, textural, and mineralogic evidence for disequilibrium is common in the intermediate-composition rocks that otherwise appear homogeneous in hand specimen and within flows. In an opposite case, if a small volume of mafic magma were injected into a silicic magma chamber, the hotter mafic melt would cool before hybridization was complete, forming immiscible blobs (Sparks and Marshall, 1985), such as seen in the inclusion-rich dacite (Tdid) and late flows of the rhyodacite of Duck Pond Ridge (Tdrd).

At high concentrations of SiO₂ the leveling off of K₂O may reflect fractionation of potassium feldspar and biotite from the less silicic melts. The scatter in FeO for the basalts may reflect either a component of Fe enrichment during differentiation of a tholeiitic magma or source heterogeneity. The Al₂O₃ content, which does not correlate with SiO₂, shows a pronounced low between 54 and 59 percent SiO₂ but otherwise decreases with increasing SiO₂. An inverse relationship for the same samples is reflected in TiO₂ and may represent a Ti-Al substitution. The large scatter in TiO_2 may also reflect the appearance of Fe-Ti oxides, which is controlled by oxygen fugacity and/or source heterogeneity.

It is common for MnO, TiO₂, and P_2O_5 (as well as Zn and Zr) to increase between basalt and basaltic-andesite composition due to fractional crystallization of olivine, plagioclase, and augite. Phosphorous and Zr maxima at intermediate compositions are well documented in the Thingmuli and Skaergaard rocks (Carmichael and others, 1974).

Compatible elements (Sr, Cr, Sc, Co) decrease and incompatible elements (Rb, Ba, Th, Hf, Ta, V, Cs) generally increase with increasing silica content. The scatter in Sr composition reflects plagioclase and apatite accumulation in porphyritic samples. The positive initial slope in Zr is due to incompatibility of the element with minerals fractionating in the mafic liquids. With increasing SiO₂ content, zircon becomes a stable phase on the liquidus and can be removed in a fractionating crystalline assemblage. Elevated Nb indicates source enrichment.

4.3 Strontium and Neodymium Isotopes

Strontium and neodymium isotopic analyses for five samples from the DBEC series and one Quaternary basalt were received late in the study (Appendix 5). Rocks selected for isotopic analysis include:

- the oldest and youngest mafic units, the basalt of Duck Pond Ridge (Tdb₁) and the basalt of Duck Creek Flat (Qb₂), respectively. These samples were selected to determine isotopic composition within the same eruptive center over time;
- (2) the inclusion-rich dacite and the basaltic andesite inclusion. This co-eruptive pair was selected to determine if isotopic ratios reflected similar sources; and
- (3) the rhyolite of Indian Creek Buttes and the rhyodacite of Duck Creek Butte. Isotopic composition of these silicic rocks will be used to test the relationship between them and the composition of the crust from which they may have been derived.

CHAPTER 5: PETROGENESIS

5.1 Introduction

Chemical, petrographic, and mineralogic evidence indicates that all of the units at the Duck Creek Butte eruptive center formed under open-system conditions. Although magma mixing appears to be the dominant mechanism, complex models involving more than one source and/or secondary modification are necessary to account for differences in traceelement concentrations. Contributing petrologic processes include Rayleigh fractionation, boundary-layer fractionation, magma mingling, zone melting, and filter pressing.

Numeric modeling of both Rayleigh and boundary-layer fractionation for major and trace elements evolution, as well as phase equilibria of the basalts was accomplished using MIXNFRAC and BLF computer models (Nielsen, 1989; Nielsen and DeLong, 1992). Additional mathematical programs include: mass balance calculations for least-squares fractionation and mixing (XLFRAC, Stormer and Nicholls, 1978); equations for assimilation and fractional crystallization for trace elements (DePaolo, 1981); the general equations for Rayleigh fractional crystallization and batch melting of trace elements (for example, Cox and others, 1979, Chapter 14); and a trace-element-ratio model for magma mixing to qualify end members for intermediate compositions (Langmuir and others, 1978).

The petrogenetic models are based on simplistic assumptions with respect to parental melt and daughter magma composition, crustal composition, pressure, temperature, partition coefficients, oxygen fugacity, and volatile content. They can, however, serve to elucidate basic principles, as well as show which mechanisms are possible and which were most likely operating in the system.

5.2 Terminology

Magma mixing is the mixing of two or more magmas, regardless of origin, to form a single homogeneous hybrid that may or may not reach equilibrium. I distinguish mixing as a batch process from assimilation. Assimilation is the continuous digestion of magma derived from the wall rock during heating. During partial assimilation, low-melting-temperature and incompatible elements are preferentially enriched in the melt. Magma mingling is the incorporation of two or more melts of contrasting viscosity or miscibility that form quenched inclusions (Bacon, 1986). Zone melting refers to a differentiation process wherein an ascending body of hot magma partially melts and assimilates the overlying crustal material while simultaneously fractionating liquidus minerals (Cox and others, 1979). Boundary-layer fractionation of a magma chamber combines crystallization with mixing of the interstitial liquids formed during crystallization at the margin of the magma with the main magma (Nielsen and DeLong, 1992). Fractional crystallization is the separation of precipitating crystals from the melt.

5.3 Basalt Petrogenesis

Basalt exposed in the study area includes the Steens Basalt (Ts), the porphyritic basalt (Tb), basalt of Duck Creek Butte eruptive center (Tdb₁ and Tdb₂), and the Quaternary basalt (Qb₁, Qb₂, and Qb₃). The most primitive basalt is the basalt of Duck Creek Flat (Qb₂), which therefore was used as a potential parent for DBEC basalt. Despite the large age difference between this basalt and the DBEC basalts, similarity in trace elements (Fig. 4-10) suggests a general similarity of basalt input over time. Although there is some compositional diversity among the basalts in the study area, they probably represent a small

portion of the potential basaltic magmas that were injected during the evolution of the magmatic center.

5.3.1 Steens and Steens-like basalt

The Steens Basalt and porphyritic basalt are treated here because they provide insight into mantle and crustal sources near DBEC. An experimental study of plagioclase-hosted melt inclusions in the Steens Basalt suggest that the phenocrysts grew in a fairly shallow (1-3 kbar), well-mixed, evolved magma chamber that could have originated by crustal assimilation and fractionation of plagioclase and olivine from a mantle-derived primary basalt (Johnson and others, 1995). High Fe and incompatible element concentrations with low Mg and compatible element concentrations indicate fractionation and some assimilation, whereas ${}^{87}Sr/{}^{86}Sr$ and ϵ_{Nd} analyses (Fig. A5-1, Appendix 5) of the Steens Basalt indicate a depleted mantle source (Carlson and Hart, 1983b). Carlson and Hart (1983b) and Hart and Carlson (1987a) propose that the parental Steens Basalt was subjected to extensive crustal contamination by a crustal material that was predominantly Cenozoic in age and consisted only of the extrusive rocks and their reworked products that were produced as a magmatic arc migrated across southern Oregon and northern Nevada. This mafic crustal material was only slightly more isotopically evolved than the primary magmas themselves. Recent sampling of the Steens Basalt at the type section (Appendix 4) indicates a compositional change up section, including higher P2O5/TiO2, K2O, and Zr/Nb (Fig. 5-1) and lower MgO. It is unclear which basalt Carlson and Hart sampled (that is, whether it was the least evolved or not) and whether there are isotopic differences between the base and the top of the complete Steens Basalt section.

Following a ≈ 4 m.y. lull, small-volume flows of basalt (Tb) that are compositionally similar to the Steens Basalt flowed disconformably over the surface of the undeformed older basalt along the northern flank of the Steens Basalt shield. It is suggested that these flows represent a younger pulse of magmatism genetically related to the bulk of the Steens

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Basalt (Hart and Mertzman, 1982; Hart and others, 1984). Higher ${}^{87}Sr/{}^{86}Sr$ and lower \mathcal{E}_{Nd} values (Appendix 5) obtained for these basalts, however, indicate either derivation from an enriched mantle source (Carlson, 1984) or contamination by a more evolved crustal source (Carlson and Hart, 1983a).

5.3.2 DBEC basalt

The basalt of Duck Pond Ridge (Tdb_1) and the fine-grained basalt (Tdb_2) difer from the bulk of the Steens Basalt lavas in that they contain higher P₂O₅ and Nb and lower Cu (Table 4-7 and Appendix 4). They are similar in many major and many trace elements to select flows in the upper part of the Steens Basalt sequence at its type section.

In the study area the Tdb₁ and Tdb₂ are considerably more evolved than Qb₂. The systematic increase in most incompatible elements in Tdb₁ and Tdb₂ suggests that they were derived by crystal fractionation from a primitive basalt (Fig. 4-5). Elevated Ti, Fe, and V implies fractional crystallization, in contrast to crustal assimilation which would result in a decrease in these elements (Marsh, 1989). In addition, the ternary diagram of Grove and others (1982) indicates a fractionation trend from a primitive parent similar to Qb₂ (Fig. 5-2).

The basalt of Duck Creek Flat (Qb_2) is the most primitive basalt in the area, therefore was used as a potential parental magma. Simple Rayleigh fractionation, however, cannot produce the DBEC basalts because incompatible trace-element calculations yield widely varying results that require up to 85 percent fractionation of Qb₂ to produce the evolved basalts. Low CaO/FeO and Sc depletions in Tdb₁ and Tdb₂ relative to Qb₂ strongly suggests a crystal fractionation process, in particular one that includes the removal of clinopyroxene. High Sr values in Tdb₂ also requires the significant removal of clinopyroxene from a basalt similar to Qb₂. No clinopyroxene phenocrysts, however, were found in any of the basalts. In addition, the relatively high Cr, Ni, and Co contents would require spinel, or at least orthopyroxene as a liquidus phase, but they also are absent



Zr/Nb

E. Zr/Nb vs. Ce/Y. Indicator of degree of partial melting.

from the modal assemblage. (A single microscopic chrome spinel inclusion in olivine was found in the basalt of Duck Creek Flat.). Hence a boundary-layer fractionation model was tested using BLF (Nielsen and DeLong, 1992). Although boundary-layer fractionation can account for some of the chemical variation between Qb₂ and DBEC basalts (Fig. 5-3), it cannot account for the elevated Ti, P₂O₅, Sr, Ba, Nb, Hf, and REE characteristic of the basalt of Duck Pond Ridge (Tdb₁) or the fine-grained basalt (Tdb₂).

Tdb₁ and Qb₂ are similar in trace-element ratios, such as Ti/Y and Y/Nb (Figs. 5-1), possibly indicating similar mantle sources. Tdb₂, on the other hand, has trace element ratios that differ from Tdb_1 and Qb_2 indicating possible contributions from several processes including derivation from a different source than Tdb₁ and Qb₂ (for example, Zr/Nb, Fig. 5-1B), smaller degrees of partial melting (Ce/Y, Fig. 5-1E), or lesser amounts of crustal assimilant (indicated by lower K/Rb). Compared to Tdb₁, Tdb₂ has both higher compatible-element concentrations (Cr, Ni, Co, Table 4-7) with respect to Rb/Sr, indicating a more primitive composition, and higher less-incompatible elements (Sr, Rb, K, Th, Ba, Ta, and Nb) indicating a more evolved composition. These can be resolved by invoking different sources. Alternatively, magma recharge or extensive boundary-layer fractionation could also be reconciled with the observed chemistry. Grove and others (1982) reported a Sr enrichment at Medicine Lake and noted that models that successfully reproduce major and most trace elements cannot account for the elevated Sr content. They attribute the variability in high-alumina basalt Sr contents in part to source region characteristics plus AFC and magma mixing. Strontium is one of the most difficult elements to explain due to variability in both crustal concentration and partition coefficients (Marsh, 1989).

5.3.3 Quaternary high-alumina olivine tholeiite

Compositionally similar primitive high-alumina olivine tholeiites (HAOT) are found scattered across the High Lava Plains with no obvious temporal pattern (Fig. 5-4).



Figure 5-2: Projection on olivine-diopside-quartz ternary from plagioclase. Mineral components and projection scheme are defined in Grove and others (1982). FeO/Fe₂O₃ ratio reset by method of Sack (1980). Anhydrous low-pressure phase boundaries are shown as dashed lines.



Figure 5-3: Variation diagrams showing the fractionation paths of the basalt of Duck Creek Flat using Rayleigh (MIXNFRAC) and boundary-layer fractionation (BLF) models (Nielsen, 1990; Nielsen and DeLong, 1992). Rayleigh trend is short dashed; BLF trend is long dashed. Bold + = Quaternary basalt; light + = DBEC.

Primitive HAOTs are characterized by $Al_2O_3>16$ weight percent, MgO>8.9 percent, CaO/Al₂O₃ ~0.7, P₂O₅ ~0.1 percent, TiO₂ <1.0 percent, Zr ~50 ppm, Cr \geq 200 ppm. Although HAOTs in general range in age from 16 Ma in the Steens Basalts to ~6 ka near Newberry volcano (MacLeod and Sherrod, 1992), the primitive tholeiites along the High Lava Plains appear to have erupted exclusively during Pliocene and Pleistocene time.

The basalt of Duck Creek Flat (Qb₂) is a primitive HAOT and has a trace-element pattern characteristic of both continental and ocean-island basalt (Pearce, 1983). This pattern is indicated by greatest enrichment in the most incompatible elements, Ba, Th, Ta, and Nb, and no enrichment in the least incompatible elements, Y and Yb, relative to midocean ridge basalt (Fig. 4-10). Trace-element enrichments have been interpreted to reflect minor contamination with a crustal component of oceanic origin ranging from oceanic basalt to pelagic sediments (McKee and others, 1983; Mullen, 1983; Hart and others, 1984; Draper, 1991; Bailey and Conrey, 1992). The back-arc basin signature has contributed to the hypothesis that volcanism in southeastern Oregon may be related to the subduction of



Figure 5-4: Map showing distribution of Pliocene and Pleistocene high-alumina olivine tholeiite in High Lava Plains (modified from Walker, 1973).

the Juan de Fuca Plate beneath the North American plate with ensuing arc-related volcanism behind the Cascades arc. Chemical and isotopic similarity of the southeastern Oregon HAOTs, regardless of time and space, suggests that a compositionally monotonous mantle source underlies the area (Bailey and Conrey, 1992). The HAOTs probably resulted from direct mantle melting with little crustal residence time in small widely dispersed magma chambers (Hart and others, 1984; Draper, 1991).

The composition of Qb₂ mimics the trends at Devil's Garden, northern California/south-central Oregon (Fig. 5-5) (McKee and others, 1983). It matches, within analytical error, the lowest abundances obtained at Devil's Garden for Sr and Ba, and the highest obtained for K and Rb. Values for major elements, Cr, Ni, and Ba/Sr are similar. McKee and others (1983) argue for a source consistent with origin by 20 percent melting of an anhydrous mantle peridotite. They emphasize that the basalt represents an uncontaminated primary melt of a mantle depleted in K, Rb, and Cs, but not in Ba and Sr. Higher K and Rb at DBEC could be due to source heterogeneity.

In spite of close similarities between the Devils Garden basalts and primitive basalts in the study area, I argue that the lava in the study area represents a primary melt that was contaminated by a small degree of crustal melting. Rb/Sr and Sm/Nd ratios (0.0194 and 0.301, respectively) are similar to the mantle signature (Pearce, 1983). Qb₂ is relatively little fractionated, as indicated by high Mg, Cr, Ni, and Ca contents and low K/Zr and K/Ti ratios. The relative enrichment in large-ion lithophile (LIL) elements relative to high-fieldstrength (HFS) elements (Fig. 4-10D) is best explained by assimilation or mixing with silicic melts that originated through partial melting of a crustal source with a large sedimentary contribution (Bailey and Conrey, 1992). In addition, the slightly elevated ⁸⁷Sr/⁸⁶Sr value for Qb₂ relative to Tdb₁ suggests contamination. Digestion of a small increment of an enriched metagraywacke or similar biotite-bearing protolith by dehydration melting would provide the necessary enrichments. The ease of contaminating primitive tholeiites is due to an increased liquidus temperature and decreased incompatible-element concentration (Bailey and Conrey, 1992). Whole-rock phase relations calculated using MIXNFRAC (Nielsen, 1990) indicate a high liquidus temperature of 1,240°C with the appearance of Fo_{86.6} olivine. Microprobe analysis of olivine yielded values of Fo₈₆.



Figure 5-5: Spider diagram showing comparison between the basalt of Duck Creek Flat (Qb₂, JJ92-20) and Devils Garden basalt. Data from McKee and others (1983) except JJ92-20 (this study).

5.4 Petrogenesis of basaltic andesite, and esite, and dacite

5.4.1 Introduction

The broad range of compositions from basaltic andesite to dacite is considered together because, in general, they form a continuum. Although they are chemically fairly uniform, most samples contain disequilibrium phenocryst assemblages derived from basaltic and rhyolitic magmas like those in extrusive units in the area.

Intermediate-composition lavas across the Oregon plateau have gone relatively unrecognized, and their importance in the petrologic framework needs to be ascertained. Recent detailed and reconnaissance field work of at least four separate volcanic centers along the High Lava Plains indicates that andesite and dacite are more common than previously recorded. Petrographic and geochemical analyses of intermediate rocks from Duck Creek Butte eruptive center, Frederick Butte (Johnson, unpub. data), Juniper Ridge (MacLean, 1994), Newberry volcano (MacLeod and Sherrod, 1988; Linneman, 1990; Linneman and Myers, 1990; MacLeod and Sherrod, 1992; MacLeod and others, 1995), and the Rattlesnake Ash-flow Tuff (Streck, 1994) indicate that mixing appears to be the dominant process in the formation of intermediate lava, but that other processes, including crustal assimilation, crystal fractionation, magma recharge (MacLean, 1994; Grunder and others, 1994; Grunder and others, 1995), and filter pressing, are required to explain details of variable chemical composition.

With the exception of a small-volume glassy vent and the quenched basaltic andesite inclusions in the dacite, the basaltic andesites and andesites are relegated to the perimeter of DBEC. This "shadow effect" is evidently common in small-volume silicic centers (Wiebe, 1993b). Wiebe (1993b) attributes the spatial correlation to ponding of multiple intrusions of basalt beneath a less dense silicic cap, allowing denser mafic liquids to reach the surface only around the periphery of a central silicic magma reservoir (also, Hildreth and others, 1991). Andesitic magma began erupting before initiation of silicic volcanism (unit Tba) and continued after emplacement of the inclusion-rich dacite but was inactive during and after emplacement of the rhyolite of Indian Creek Buttes. Andesite inclusions are also present in the rhyodacite of Duck Creek Butte (Tdrd). The mixed-composition lavas appear to be related to active tectonism during which time both movement along faults and coincident influx of fresh basalt provided the magmatic and convective input necessary to produce the hybrids (see Chapter 6).

Petrogenetic models for the origin of intermediate composition magma falls into four categories:

- (1) fractionation of basalt to basaltic andesite coupled with assimilation of a traceelement enriched crustal component,
- (2) mixing of basalt with rhyodacite,
- (3) mixing of basaltic andesite with rhyodacite or dacite,
- (4) magma mingling and filter-pressing owing to devolatilization during quenching of basaltic-andesite cumulate blobs within cooler dacite.

5.4.2 Basaltic Andesites

The three basaltic andesite flows and the basaltic andesite inclusion have similar major element patterns but show trace-element variability. They are also texturally and mineralogically distinct from each other. Their relationship to the basalt flows is reflected in similar patterns on trace-element spider diagrams (Fig. 4-10). Mass balance calculations using the basalt and mineral analyses suggest that fractionation of reasonable quantities of olivine + plagioclase \pm clinopyroxene \pm Fe-Ti oxides will account for most of the major element variations. However, discrepancies in calculated versus observed trace-element concentrations require other processes to account for various enrichments and depletions.

5.4.2.1 Olivine-bearing basaltic andesite

The olivine-bearing basaltic andesite (Tdba₁) has 15 percent phenocrysts of plagioclase, olivine, and Fe-Ti oxides in an intersertal groundmass with plagioclase and unidentified mafic phases. There is no petrographic evidence for magma mixing, and the phenocrysts appear to be in equilibrium.

Attempts to model fractional crystallization of the basalts $(Qb_2, Tdb_1, and Tdb_2)$ is precluded by poor incompatible element fits. Mixing and fractional-crystallization models are required to enrich Sr, Th, and Nb to levels unattained by simple fractionation.

The best fit is provided by 30 to 40 percent fractionation of plagioclase, clinopyroxene and olivine from Tdb₂, but low resultant P, Mn, Sr, Ti, and Sc, and high Rb, K, Ca, and Al suggest less fractionation and some incompatible element-enriching assimilation. High Sr values require a Sr-enriched parental basalt such as the Tdb₂ basalt, but other trace elements better fit a model that uses Tdb₁ as the mafic end-member. Zone melting by an ascending magma similar to Tdb₁ could also produce this melt by partial melting of crustal rocks (for example, metagraywacke), thus enriching the melt in K, Rb, Cs, Ba, Sr, Th, and Nb. Simultaneous fractionation of plagioclase with small amounts of ilmenite (Ti, Ta, Hf, Zr, and Sc) and apatite (P, Y, REE) would produce the necessary trace element depletions.

I prefer a mixing-fractional crystallization model which combines mixing 80 percent basalt, similar to Tdb₁, with 20 percent rhyodacite (Tdrd) in concert with about 3-4 percent fractionation of plagioclase + ilmenite \pm olivine \pm apatite, plus the addition of a crustal component contributing excess Sr, Th, and Nb.

5.4.2.2 Basaltic-andesite dike

A small-volume basaltic-andesite dike (Tdba₂) that erupted through flows of the rhyodacite of Duck Creek Butte (Tdrd) is nearly chemically identical, within analytical error, to the olivine-bearing basaltic andesite (Tdba₁) for most major and trace elements

with the exception of having lower Sc and Cr, and higher Cs, Th, LREE, and HREE. Petrographic analysis of Tdba₂ reveals a distinctly different mineralogy than Tdba₁. There are no phenocryst phases present that would be in equilibrium with a basaltic melt. Instead, the observed assemblage of Tdba₂ comprises sodic plagioclase, clinopyroxene, Fe-Ti oxides, orthopyroxene, and biotite in a dark- and light-brown swirled glass matrix. Presumably the banding in the glass represents partially mixed mafic and silicic melts. A single fine-grained glomerocryst of olivine and plagioclase was found in thin section. A physical model for this lava suggests an aphyric basaltic magma mixed with low-silica rhyolitic melt and erupted prior to subliquidus cooling of the basalt or resorption of the felsic phenocrysts. Decompression associated with the rapid rise of magma can generate magma that is above its liquidus (Philpotts, 1990). Alternatively, assimilation of K- and H₂O-rich contaminant may also contribute by lowering the liquidus as long as the percent of assimilation is low.

Figure 5-2 indicates that a mix of 75 percent basalt of Cord (Qb₃) and 25 percent rhyodacite (Tdrd) yields a plausible mix model for Tdba₂. Additional fractionation of pyroxene from the basaltic melt would account for the depletions in Sc and Cr.

5.4.2.3 Basaltic andesite of Brokendown Reservoir

Tdba₃ has the same general trace-element profile as the other basaltic andesites but doesn't conform well to mixing of any of the flows at DBEC. The aphyric fine-grained flows appear to have had plagioclase, clinopyroxene, olivine, and Fe-Ti oxides on the liquidus just prior to eruption. No petrographic evidence for mixing was found.

Through comparison to Grove and others (1982; Fig. 5-2) assimilation of a rhyolitic melt by Tdb_1 or Tdb_2 in conjunction with fractionation of plagioclase and olivine is indicated. Simple fractionation from any of the basalts provides poor trace element fits.
5.4.2.4 Basaltic-andesite inclusion

The quenched basaltic andesite inclusions in the inclusion-rich dacite, Tdid, represent classic magma mingling of a rapidly crystallizing quenched basaltic magma in a cooler silicic melt. The inclusions are anomalous because they possess P_2O_5 , Ba, and trace-element enrichments consistent with plagioclase, apatite, and ilmenite accumulation relative to the other flows of DBEC.

The concentration of vesicles towards the glassy rim (Fig. 2-8) in concert with the observed mineralogy suggests that a cumulate origin could be accomplished by a filter pressing process (Bacon and Metz, 1984; Sisson and Bacon, 1994). During crystallization and devolatilization of the entrained mafic magma, forced expulsion of intercumulate liquid may have resulted in small enclaves that display a textural and compositional cumulate signature. The selective exchange of elements that possess high diffusion rates could selectively enrich the mafic portion of the system. Chemical diffusion between comingled basaltic and silicic melts can produce enrichments in Fe, P, Mn, Rb, and REE and depletion in Na in the mafic melt until equilibrium is reached (Watson, 1982). The inclusions lack evidence for vapor-phase transport from the dacite to the enclave.

Clues to possible magmatic mechanisms can be found in the inferred crystallization sequence. Subhedral to euhedral clinopyroxene and Fe-Ti oxides were the first phases to crystallize, as evidenced by their common presence as inclusions in plagioclase. This reversal in the crystallization order relative to plagioclase may be due to high water content, high P₂O₅, and rapid cooling rates, all of which lower the plagioclase crystallization temperature relative to other phases (Eggler and Burnham, 1973; Grove and Bence, 1979).

Prior to eruption, a double-diffusive interface may have formed when a pulse of volatile-rich basaltic magma was injected into the base of the dacitic magma chamber (see Dacite, Section 5.4.4). Heat exchange can drive convection in both layers forming a sharp interface between them (Sparks and others, 1977). Sudden convective overturning of the

volatile-rich mafic layer into the overlying cooler dacite layer may have triggered an eruption due to rapid quenching, crystallization, and exsolution of volatiles.

Alternatively, the ubiquitous presence of small inclusions may have resulted from the forceful injection of a primitive-composition basaltic dike into the dacite. Mechanical and thermal properties of the compositionally contrasting melts may have prevented hybridization, and the predominantly silicic chamber, which was below the solidus of the basalt, rapidly quenched the entrained basalt (Bacon, 1986). Additional convection in the chamber then resulted from superheating and decreased viscosity of the dacite due to heating. Concurrent movement along the fault may have facilitated convection. Textural evidence in the dacite indicates rapid expulsion of the magma before mineral equilibrium could be established.

5.4.3 Andesites

In contrast to the compositionally diverse basaltic andesites, the andesites form a chemically cohesive group (Fig. 4-10) that erupted from separate locations around the southern and eastern perimeter of the rhyodacite of Duck Creek Butte. Mineralogy of the andesites is similar; all have sieved and zoned (normal, reverse, and oscillatory) plagioclase, altered olivine, clinopyroxene, and Fe-Ti oxides. Tda₂ differs from Tda₁ in that it contains 5 to 9 percent equant plagioclase grains as long as 3 cm in length. No microprobe analyses of minerals from the andesites were obtained.

Linear element-element diagrams (Figs. 4-4 and 4-5) and abundant textural evidence support derivation by mixing of two or more magmas. However, some fractionation is consistent with enrichments in Zr, although elevated Cr concentrations imply that fractionation of pyroxene or spinel was not extensive.

Trace-element ratio diagrams based on the calculations of Langmuir and others (1978) (Fig. 5-6), indicate a good fit between rhyodacite (Tdrd) or dacite (Tdid) and basaltic andesite (Tdba₁), or rhyodacite and basalt to produce the andesites. However, simple



Figure 5-6: La/Sc versus SiO₂/Rb ratio-ratio diagram with companion plots for the DBEC series rocks. Dashed line indicates mix between the basalt of Duck Pond Ridge (Tdb₁) and the rhyodacite of Duck Creek Butte (Tdrd). The same relationship holds for the olivine-bearing basaltic andesite (Tdba₁) and the rhyodacite. The upper companion plot does not include the rhyolite of Indian Creek Buttes (Tdr₁), and the lower plot does not include the basalt of Duck Creek Flat (Qb₂).

mixing of Tdba₁ and Tdrd to produce any of the andesites using XLFRAC (Stormer and Nichols, 1978) yielded high Σr^2 values in spite of evident linear relationships.

The best sum of the square of the residuals (Σr^2) is obtained by mixing Tdrd with two or more basaltic compositions. A simple mix of Tdrd and a single basalt did not satisfy trace element requirements. Mixing a mafic end member with the rhyolite (Tdr₁) provided consistently poor fits. The following mixes provide low Σr^2 values and calculated trace element abundances (with the exception of Sr, calculated too high, and Zr, too low) within analytical error to produce Tda₂ (JJ93-140):

(1) 55 percent Tdrd + 9 percent Qb₂+ 36 percent Tdb₁: $\Sigma r^2 = 0.43$;

(2) 49 percent Tdrd + 10 percent Tdb₁ + 41 percent Tdb₂: $\Sigma r^2 = 0.12$.

Similar models performed on Tda₁ had the lowest Σr^2 value (0.36) when mixing 51 percent Tdba₁ (JJ92-6)+ 49 percent Tdid dacite.

This type of end-member mixing between evolved basalt and rhyodacite or basaltic andesite and dacite is common in producing andesites and dacites (Grunder and others, 1995). The occurrence of subequal proportions of mixing end members is commonly modeled (for example, Feeley and Grunder, 1991) and probably reflects the limiting condition that \geq 50 percent of the mafic end member is required to effect mixing (Sparks and Marshall, 1985).

5.4.4 Dacite

The inclusion-rich dacite, Tdid, contains ubiquitous quenched magmatic inclusions (see Section 5.4.2.4) and a complicated phenocryst assemblage which includes anhedral feldspar, Fe-Ti oxides, orthopyroxene, clinopyroxene, \pm biotite, \pm quartz, \pm olivine in varying proportions. Fine-grained clinopyroxene overgrowth on some Fe-Ti oxides and glass-inclusion-rich rims on anhedral feldspar indicate disequilibrium conditions prior to eruption.



Figure 5-7: Trace element concentrations in Tdid (inclution-rich dacite) compared to a 3:1 mix of Tdrd (rhyodacite of Duck Creek Butte) and Tdba₁ (olivine-bearing basaltic andesite).

The dacite cannot be derived from the andesite by simple crystal fractionation. Dacite, the logical precursor of rhyodacite in crystal fractionation, can more easily be derived from Tdrd rather than the reverse on a mathematical basis. Figure 5-7 shows that a 3:1 mix of Tdrd with Tdba₁ produces a good fit for most trace elements. This is also supported by linear element-element variation diagrams (Figs. 4-4 and 4-5) and the trace-element-ratio mix model in Figure 56. Experimental work by Kouchi and Sunagawa (1983) indicates that, even under uniform high temperature, small quantities of basaltic magma form inclusions when incorporated into a silicic melt. Basalt, on the other hand dissolves the dacite to form hybrid andesites which can be incorporated more easily into a silicic melt. The inherent question then is: under what conditions can a larger volume of silicic magma mix with a smaller volume of mafic magma and not quench it?

Mixing of disparate melts can be accomplished in a "wet" system (Fig. 5-8). Physical impediments to hybridization of magmas with significantly different properties can be lessened by: (1) incorporation of H_2O into mafic melt with coincident fractionation of magnetite which decreases the density; (2) assimilation of alkalis to decrease viscosity of silicic or hybrid melts; (3) step-wise mixing of a hybrid intermediate boundary layer; (4) maintaining a high temperature, and commensurably lower viscosity, of the silicic melt; (5) steady supply of high temperature basaltic liquids into the base of the chamber to promote robust convection (Huppert and Sparks, 1988). Under these conditions the mafic melt, which has both a higher convective velocity than the silicic (due to both lower viscosity and a higher coefficient of thermal expansion) as well as a higher chemical diffusion rate, can entrain the silicic magma in small increments and produce a homogenized layer at its upper boundary (Koyaguchi, 1986). With limited mafic injection, the hybrid can evolve to a significant volume with mechanical and thermal properties similar to those of the silicic melt. Under the boundary conditions, the chemically and thermally similar silicic and intermediate magmas are able to mix essentially in a liquid state in a wide range of mixing ratios.



Figure 5-8: Cartoon illustrating a "wet" magma system. Differentiated basalt magmas (incipient hybrids) in a wet basalt are lower in density than parental basalts due to early fractionation of magnetite. At elevated temperatures, evolved convecting magmas form a hybrid interface and, through a step-wise evolution, can produce a variety of hybrid magmas. Injection of basalt into the base of the chamber provides heat necessary for homogenization. (R.M. Conrey, written commun., 1994).

5.5 Petrogenesis of rhyodacite and rhyolite

5.5.1 Introduction

Duck Creek Butte is dominated by the rhyodacite of Duck Creek Butte (Tdrd) and the rhyolite of Indian Creek Buttes, which represent about 90 percent of the erupted volume of DBEC. The rhyodacite of Duck Creek Butte is interpreted to be derived largely from opensystem processes including partial crustal melt, magma mixing, and fractional crystallization. The rhyolite of Indian Creek Buttes (Tdr₁) is derived by partial crustal melt, similar to that of the rhyodacite of Duck Creek Butte with a much higher contribution from crystal fractionation in a relatively closed system.

Attempts to rigorously apply melt and fractionation models are limited by (1) unknown crustal lithology, (2) large variations in partition coefficients for individual minerals due to solid solution as well as evolving liquid composition, and (3) lack of phenocrysts in the rhyolite to determine phases removed.

5.5.2 Rhyodacite of Duck Creek Butte

The rhyodacite of Duck Creek Butte (Tdrd) covers most of the study area with laterally extensive flows that erupted from multiple vents located near, or parallel to, the Duck Pond Ridge fault scarp. Although the flows of rhyodacite are fairly homogeneous with respect to major elements, trace element concentrations vary widely. The variation is attributed to local concentrations of different minerals and mineral assemblages.

The rhyodacite did not evolve by crystal fractionation from the inclusion-rich dacite (Tdid) but by a more complex path derived by crustal melting, magma mixing, and fractionation of mineral phases. Although fractionation of 16 percent plagioclase, ilmenite, clinopyroxene, apatite, and orthopyroxene from inclusion-rich dacite (Tdid) can produce rhyolite (XLFRAC; Stormer and Nicholls, 1978), trace element concentrations, calculated using bulk partition coefficients consistent with the mineral assemblage, predict much

lower values of incompatible elements than observed. In addition, the concentration of chromium in the rhyodacite is too high to have resulted from crystal fractionation.

Petrographic evidence for a convecting, periodically recharged magma chamber includes complexly zoned plagioclase phenocrysts that may reflect attempts at equilibration during relatively brief contact with changing magmatic fluids (See Fig. 5-8 and Sec. 5.4.4 on "wet" system). The diverse phenocryst assemblage comprising plagioclase, biotite, clinopyroxene, orthopyroxene, hornblende, Fe-Ti oxides, quartz, and unidentified trace phases suggests mixed silicic melts. The wide range of plagioclase core and rim compositions (An₂₇ to An₆₂ and An₂₉ to An₆₅, respectively) argues for the periodic injection of mafic to silicic magmas, common in large silicic systems (Weibe, 1993a, b). Most plagioclase is subhedral to anhedral, resorbed and sieve textured. Sieve texture is common in rocks of hybrid origin.

Evidence for a mafic basal layer and possibly an intermediate hybrid layer in the magma chamber is found in small round very fine grained andesite inclusions that are compositionally similar to the DBEC andesites. These sparse inclusions, found in one of the upper flows, were probably entrained by convection during overturning following eruption of early flows of the rhyodacite.

The potential source rocks for partial melting in the DBEC area include metamorphosed volcanic and related sedimentary rocks. Dehydration melting of metamorphosed basalt and andesite under low pressure and moderate temperature provides a fairly good model for a derivation of the rhyodacite of Duck Creek Butte, with the exception of having lower potassium and higher sodium (Beard and Lofgren, 1991). Alkali concentrations, however, are sensitive to small variations in the melting protolith. The nearest exposures of basement rocks are Jurassic-Triassic volcanic and volcanically derived sedimentary rocks exposed 100 km north and south-southwest of the study area; Triassic-Paleozoic rocks of ophiolite suites are found 135 km north-northeast of the study area (Walker and MacLeod, 1991). Andesitic to basaltic metagraywacke is also found as xenoliths in the Rattlesnake Ash-flow

Tuff that erupted 90 km west of DBEC (Martin Streck, oral commun., 1995). Hence a mafic to intermediate-composition crustal protolith is reasonable.

Experimental results on fluid-absent partial melting of metagraywackes indicate that the residual feldspar is strongly enriched in orthoclase component, which would not explain the high-potassium suite at DBEC (Vielzeuf and Montel, 1994). High degrees of partial melting of a graywacke produce a sodium-rich melt. Therefore, presence of pelite, which would yield a more potassium-rich liquid on melting (for example, Beard and Lofgren, 1991), as sandwiched layers within the crust may be indicated (Hall, 1987).

Another potential source for the rhyodacite is vapor-absent melting of a biotite- and amphibole-bearing tonalitic gneiss (Skjerlie and Johnston, 1992). Elements that would be enriched during low degrees of partial melting include Rb, Cs, Mn, Sc, Hf, Nb, Ta, Th, and Yb.

To fabricate the trace element abundances in a hypothetical protolith, I used a batch melt equation as a crude approximation (Wood and Fraser, 1976). Partition coefficients are from Arth (1976) and Nash and Crecraft (1985). Proportions of solid phases that would be in equilibrium with the rhyodacite at 20 percent melting (at 975°C, 10 kbar) were taken from the experimental work of Skjerlie and Johnston (1992). I then manipulated the traceelement concentrations for a hypothetical crustal composition. The resulting values (Fig. 5-9) are consistent with those expected for an evolved mafic protolith. This model is a crude test because partition coefficients are poorly known and the model parameters will change during the evolution of the melt. In assuming a closed system, the batch-melt model ignores contributing processes such as mixing, recharge, and fractional crystallization.

The rhyodacite of Duck Creek Butte has ⁸⁷Sr/⁸⁶Sr of 0.70490 (Appendix 5), which may reflect contamination by small amounts of an isotopically more primitive Sr-rich mafic melt. The original silicic melt that evolved to the rhyodacite likely had an original ⁸⁷Sr/⁸⁶Sr value equal to, or slightly lower than, that of the rhyolite of Indian Creek Buttes (Tdr₁; ⁸⁷Sr/⁸⁶Sr of 0.70741). The assumption that the rhyodacite evolved from a crustal melt



Figure 5-9: Trace-element spider diagram using hypothetical protolith to create the element concentrations in the rhyodacite of Duck Creek Butte. The batch melt equation is from Wood and Fraser (1976).

similar to the rhyolite implies that spatial proximity indicates similar protoliths. DePaolo's (1981) model for isotope ratios and trace element concentrations indicates that the incorporation of a small amount (~1 percent) of hypothetical primitive melt with an ⁸⁷Sr/⁸⁶Sr value of 0.704 into a Sr-depleted rhyolite with a 0.70741 ratio yields the 0.70496 value for Tdrd when coupled with 10 percent fractional crystallization. The ease of contaminating a Sr-poor magma during the magmatic stage makes the interpretation less straightforward than in more mafic rocks (Mahood and Halliday, 1988).

The rhyodacite resulted from complex interactions involving zone melting during extension and change in crustal thickness. As hot mantle-derived basalt is injected into the thinning crust as sills and dikes, initiation of partial melting is facilitated by progressive heating of the crust, release of volatiles, and decreased pressure. Continued heat input aids both greater degrees of melting and the bouyant rise of multiple pods of silicic melt. If a primitive basaltic magma with a liquidus temperature of $1,230^{\circ}$ C (as calculated for Qb₂), intrudes an already heated (~500°C) H₂O-rich crust at a shallow depth (5-10 km), dehydration and decompression melting can produce a partial melt equal to the volume of the intruded mafic melt (Weibe, 1993b). The heat content of a large body of basaltic magma is sufficient to cause this volume of silicic melt to form if little heat is lost.

5.5.3 Rhyolite of Indian Creek Buttes

The rhyolite of Indian Creek Buttes (Tdr₁) erupted from multiple vents located west of vents and flows of the rhyodacite of Duck Creek Butte. The model I present is a high-level stratified magma body that evolved by crystal fractionation from a rhyodacite that was produced by crustal melting and hybridization of coalescing silicic magmas. Field relations indicate that a more-evolved upper part of the chamber erupted first as aphyric to very-sparsely porphyritic flows that were quenched to glass. Enrichment in phenocrysts on capping flows may reflect tapping of a magma chamber in which crystal settling or a volatile gradient have led to increasing phenocryst abundance downward (Hildreth, 1981).

Trace-element systematics, as well as phenocryst assemblages, are consistent with fractional crystallization of a melt similar in composition to the rhyodacite of Duck Pond Ridge as the dominant controlling process in producing the rhyolite of Indian Creek Buttes. Other processes are assumed to be minor because trends in element concentrations are closely matched by fractionation models. Extremely low concentrations of Sr and Ba rule out an origin by single-stage melting of any crustal lithology. Strong depletions in Eu, Sr, Ba, Zr, and Sc, in concert with moderate enrichments in Rb, Th, U, MREE, HREE, Nb, Y, and Ta, argue for derivation from a melt similar to the rhyodacite of Duck Creek Butte (Tdrd) by crystal fractionation (Fig. 4-5, Table 4-7). All models show that removal of observed phenocryst phases from the rhyodacite (Tdrd) can adequately account for most of the element variations. Trace phases, which were not observed but may be present, may account for other differences; for example, fractionation of monazite and allanite could account for lower LREE concentration (Miller and Mittlefehldt, 1982).

Least-squares method for modeling of major elements to determine approximate proportions of fractionating phases was performed using XLFRAC (Stormer and Nichols, 1978). Variations in trace elements were calculated by a Rayleigh fractionation equation (Cox and others, 1979). Bulk partition coefficients were determined using mineral distribution coefficients of Mahood and Hildreth (1983), Nash and Crecraft (1985), and Arth (1976).

An adequate fractionating assemblage as indicated by low residuals ($\Sigma r^2 = 0.11$) can produce the trends between Tdrd and Tdr₁ (JJ92-5). This assemblage comprises 13.6 percent plagioclase, 5.4 percent biotite, 2.7 percent amphibole, 0.6 percent apatite, and 0.4 percent ilmenite. Although the model uses no more than five minerals, the addition of approximately 1 percent each of clinopyroxene and orthopyroxene in place of a portion of that assigned to amphibole would match the observed modal assemblage. Potassium feldspar, though absent in Tdrd, likely became a fractionating phase as the melt evolved. Additional fractionation produced the more evolved Tdr_1 (JJ92-4), but lack of phenocrysts and changes in partition coefficients make determination less tenable.

Trace element ratios also indicate that plagioclase and biotite played major roles in the fractionating assemblage. Strong increase in K/Ba indicates fractionation of biotite and potassium feldspar; increase in Rb/Sr by plagioclase removal is slightly tempered by removal of biotite; K/Rb depletion reflects potassium feldspar removal; no change in Sr/Ba indicates that plagioclase fractionation is balanced by biotite and potassium feldspar fractionation.

Previously discussed AFC models for the origin of the suite of rocks erupted at DBEC indicate a Ba-enriched biotite-bearing mafic protolith. Small degrees of partial melting of such a rock would produce large concentrations of K, Ba, Nb, and Y. To produce the large volume of low-Sr, low-Ba magma seen at Indian Creek Buttes by low degrees of partial melting requires simultaneous fractionation of large volumes of feldspar-, clinopyroxene-, and biotite-rich cumulates larger than the erupted volume.

The interpretation of Sr-isotopic compositions of rhyolites is less straight forward than in more mafic rocks, owing to the ease of contamination of Sr-poor magmas during magmatic and post-magmatic processes. ⁸⁷Sr/⁸⁶Sr value of 0.70741 for the rhyolite (Appendix 5) suggests origin by anatexis of isotopically evolved crust rather than fractionation of a mafic melt. High Rb/Sr values in a magma chamber can bring about measurable variations in the ⁸⁷Sr/⁸⁶Sr ratio by *in situ* decay of ⁸⁷Rb resulting in increased ⁸⁷Sr/⁸⁶Sr (Christensen and DePaolo, 1987; Mahood and Halliday, 1988). Subsequent closed-system fractionation accounts for the trace-element concentrations. Although the Srisotopic ratio of Tdrd is too low to be directly parental to Tdr₁, it provides an adequate major- and trace-element model parent based on the assumption that the original crustal melt parental to Tdrd was probably higher in initial ⁸⁷Sr/⁸⁶Sr, and open-system contamination by mafic melts served to lower the ratio.

CHAPTER 6: DISCUSSION AND CONCLUSIONS

The discussion of the Duck Creek Butte eruptive center focuses on two aspects: (1) the relationship between compositional and textural trends and the tectonomagmatic evolution of DBEC, and (2) the northwest-younging trend of silicic vents and late-stage primitive basalt erupted along the High Lava Plains.

6.1 Tectonomagmatic summary of DBEC

The abundance of rhyodacite and dacite and the preponderance of mixed textures in lavas of DBEC is in contrast to the high-silica rhyolite typical of other silicic eruptive centers of the High Lava Plains and indicates that it had a different history. DBEC also differs in that it lies astride a long-lived fault. The following scenario accounts for the regional and local tectonic setting of DBEC and places the petrologic constraints in a physical context.

Early magmatism prior to the development of DBEC consisted of basalt and basaltic andesite derived by fractional crystallization and mixing of small proportions of crustal melt. Following a brief lull in magmatic activity, DBEC produced a suite of magmas that varies in composition from rhyodacite to basaltic andesite. Each compositional type is characterized by abundant evidence for mixing. This suite records the eruptive decay of a magmatic system disrupted by faulting. Following a period of tectonic quiescence the rhyolite of Indian Creek Buttes, derived by fractional crystallization of a crustal melt, erupted from vents west of the rhyodacite of Duck Creek Butte. The principal petrologic sequence of events is depicted in Figure 6-1 and 6-2 and includes the following points.

 Crustal thinning and faulting by Basin-and-Range extension facilitated the ascent of relatively unfractionated basalt (Tb) in the vicinity of DBEC between 12 and 11 Ma.



Figure 6-1: Cartoon of the tectonomagmatic evolution of the Duck Creek Butte eruptive center. Numbers refer to descriptions in the text.



Figure 6-2: Graph of time versus SiO_2 . Shaded circles indicate compositions of rock types observed at DBEC; open circles indicate compositions inferred to have been present; asterisk indicates presence as quenched inclusions. Numbers in parentheses refer to panel numbers in Fig. 6-1.

Injection of basaltic sills and dikes into crustal rocks resulted in small degrees of crustal melting and the formation of pods of silicic melt (Fig. 6.1, panel 1).

(2) With continued thermal input, silicic magma pods coalesced to form a large, wellmixed magma chamber that evolved to a doubly convecting layered chamber capped by the rhyodacite of Duck Creek Butte (Tdrd) (panel 2). Most of the lava is chemically homogeneous plagioclase-biotite-clinopyroxene rhyodacite. Minor phenocrysts of orthopyroxene and amphibole indicate some variations in water content or temperature differences in the chamber. Generation of a well-mixed upper silicic chamber implies coalescencing pods of crustal melts during tectonic quiescence. A layered chamber with mafic underpinnings is inferred because hybrid andesite was entrained as inclusions; the inclusions probably represent an intermediate layer that was a mixture of rhyodacite and basaltic andesite. A basaltic andesite derived from assimilation and fractional crystallization likely formed the hotter convecting basal layer (panel 2). Continued basal injection of mafic magmas supplied heat to the convecting chamber.

(3) Eruption of the rhyodacite of Duck Creek Butte (Tdrd) was initiated by an explosive phase and resulted in the emplacement of block-and-ash deposits to the east, and finer, well-sorted deposits to the west. More than 6 km³ of rhyodacite lava flows followed (panel 3). Distribution of vents imply the chamber was at least 5 by 3 km across. Weakness along faults provided a conduit for eruption, allowing the magma to escape without freezing. Rapid drawdown entrained sparse blobs of andesite, which occur mainly in late-erupted lavas inferred to originate from deeper in the chamber. Although syneruptive faulting cannot be proven, I infer that tectonic activity facilitated rapid drawdown and near-complete evacuation of the chamber because subsequent volumes of silicic magma are very small. In addition, field evidence indicates that movement along the Duck Pond Ridge fault both predated and postdated eruption of the rhyodacite.

- (4) Eruption was followed by convective mixing of much of the residual rhyodacite melt with the hybrid andesite intermediate layer to form the inclusion-rich dacite (Tdid), which erupted as lavas (panel 4). Mixing may have been facilitated by movement along the Duck Pond Ridge fault following evacuation of the rhyodacite.
- (5) The initial small volume of dacite lava has few mafic magmatic inclusions, but as many as 30 percent quenched basaltic andesite inclusions are evenly distributed in later dacite lavas. The size and distribution of the entrained inclusions indicate strong convection that was driven by increased mafic input. Alternatively, faulting may have driven rapid eruption which then caused entrainment. The inclusions represent basalt that was filter pressed during quenching (see Sec. 5.4.2.4). The mingled magma was evacuated from the chamber before equilibration overgrowths formed on minerals in the dacite. Following the evacuation of the dacite, only a small amount of silicic magma remained, as indicated by the change in composition of erupted magma.
- (6) Reduced size of the silicic magma chamber is indicated by the eruption of basalts near the previous silicic vents. The basalt of Duck Pond Ridge (Tdb₁) erupted near the central vent of the rhyodacite of Duck Creek Butte. Lack of mineralogic evidence for contamination by the rhyodacite indicates that the basalt dike bypassed the diminished magma chamber. To the east 3¹/₄ km, a virtually aphyric basaltic andesite mixed with a small proportion of biotite-bearing rhyodacite and formed the basaltic andesite dike (Tdba₂). Although the dike cuts flows of the rhyodacite of Duck Creek Butte, it likely erupted near the shadow zone of the silicic magma chamber, assimilating only a small amount of rhyodacite. Near the northeastern vent of the rhyodacite of Duck Pond Ridge, a chemically distinct high-potash low-titania fine-grained basalt (Tdb₂) was the last eruptive unit in the northern part of DBEC. Movement along the Duck Pond Ridge fault truncates both Tdb₁ and Tdb₂.
- (7) Mixing of the residual dacite with basaltic andesite yielded andesites of Duck Creek Spring (Tda₁) and Duck Creek (Tda₂). The andesites can be obtained by a 3:1 mix of

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olivine-bearing basaltic andesite (Tdba₁) and the rhyodacite of Duck Creek Butte (Tdrd) (Fig. 5-7). Although the two andesites are compositionally identical, they are mineralogically distinct in that the andesite of Duck Creek has very coarse (up to 3 cm in length) blocky plagioclase, suggesting the andesites were possibly sequentially tapped from a cooling mixed chamber representing the final stage of magmatism at DBEC.

(8) The locus of magmatism then migrated northwestward to Indian Creek Buttes. The basaltic andesite of Brokendown Waterhole (Tdba₃), which is compositionally similar to the other basaltic andesites, erupted from a vent west of Duck Butte. The eruption locale indicates that it is not related to the plumbing of Duck Creek Butte, but may be a precursor to the development of Indian Creek Buttes proper. This is inferred by lack of evidence for contamination of the mafic magma with high-silica rhyolite. The emplacement of the rhyolite of Indian Creek Buttes may have followed quickly or lagged by as much as 0.2 m.y. on the basis of a 10.38±0.04-Ma biotite age from the rhyodacite of Duck Creek Butte and a sanidine age of 10.32±0.04 Ma from the rhyolite of Indian Creek Buttes (Table 2-1). The shift in the predominance of partial melting of the crust to crystal fractionation in developing the high-silica rhyolite chamber suggests tectonic quiescence. Continued basaltic underplating maintained a high temperature, which served to prevent the system from freezing during crystallization. The rhyolite of Indian Creek Buttes erupted through centrally located vents in two stages that represent the eruption of a weakly stratified rhyolitic chamber composed of an aphyric highly evolved layer overlying a sparsely porphyritic layer. Any injections of hot basaltic magma presumably remained ponded beneath the silicic chamber, owing to compositional and thermal contrasts.

In summary, Duck Creek Butte eruptive center initially produced abundant intermediate and mixed magmas, presumably as a consequence of synmagmatic faulting. Structural disruption and frequent eruption prevented development of a high-silica rhyolite. Indian Creek Buttes, in contrast, is extremely differentiated suggesting quiescent conditions.

Following a 9-m.y. hiatus in extrusive magmatic activity, primitive Quaternary basalt erupted in Duck Creek Flat and Duck Creek. Compositionally similar basalt erupted across the High Lava Plains with no obvious temporal pattern. Although the basalt of Duck Creek Flat has an isotopic signature distinct from DBEC rocks (Appendix 5), it possesses traceelement enrichment similar to, but more depleted than, the DBEC series rocks (Fig. 4-10).

6.2 Age Progression

The High Lava Plains and Brothers fault zone have a complex tectonic and magmatic history. On the basis of my work at Duck Creek Butte eruptive center, Frederick Butte, and the Malheur Cave area (Fig. 1-2), and on structural and magmatic patterns of the region (Walker and others, 1967; Walker, 1969; Greene and others, 1972; MacLeod and others, 1976; MacLeod and Sherrod, 1988; Walker and MacLeod, 1991; MacLeod and Sherrod, 1992; MacLean, 1994; Streck, 1994), I here develop the argument that the High Lava Plains represents a propagating transform boundary that developed in the past 12 million years, and that silicic volcanism is related to migration at the tip of this system. On the basis of observations at DBEC and across the High Lava Plains, the following aspects are noted:

- (1) Largely unfractionated basalt (Tb) erupted between 12 and 11 Ma, prior to the development of DBEC. Compositional changes in basalt at this time (Carlson and Hart, 1985) may mark the transition from Basin-Range extension to an incipient extension-related transform system.
- (2) Unit Tb gives way to evolved basaltic andesites and andesites (Tba) not later than 10.5 Ma.

- (3) About 10.4 Ma the rhyodacite of Duck Pond Ridge erupts explosively, followed by the emplacement of over 6 km³ of lava flows. Subsequent eruptions discharge subordinate mixed dacites, andesites and fractionated basalts. Less than 0.1 m.y. later, silicic magmatism propagates a short distance westward resulting in the deposition of the rhyolite of Indian Creek Buttes.
- (4) Following a 9-m.y. lull, the primitive high-Mg, low-Ti Quaternary basalt of Duck Creek Flat erupts.
- (5) Along the High Lava Plains, a linear series of silicic vents shows a systematic age progression westward from 10.4 Ma at DBEC to 0.6 Ma at Newberry volcano (MacLeod and others, 1976). The High Lava Plains silicic trend began its migration away from the inferred location of the Snake River Plain-Yellowstone hot spot at about 11 Ma.
- (6) And, steep northwest-striking faults, parallel to the younging direction, are broadly distributed similar to that of a propagating continental rift (Benes and others, 1994). Inflation during thermal uplift during an extended period of magmatic input, and subsidence related to cooling and deflation during waning stages of magmatism may have contributed to the widely dispersed northwest-striking small-offset faults.

Between 17 and 15 Ma widespread basaltic volcanism in southeastern Washington, eastern Oregon, western Idaho, and north-central Nevada resulted from approximately eastwest directed extensional tectonics (Fig. 6-3) (Stewart, 1978; Zoback, 1989; Li and others, 1990). This volcanism in southeastern Oregon deposited 12,000-15,000 km³ of Steens Basalt over a surface of little topographic expression (Mankinen and others, 1985; Carlson and Hart, 1983b). To the north on the Columbia Plateau, a major magmatic event is preserved in the voluminous Columbia River Basalt Group (Fig. 6-3), which includes over 174,000 km³ of basalt erupted from multiple vent locations during less than 2 m.y. (Tolan and others, 1989).





The theory that a mantle plume resided near the tri-state region of Oregon, Idaho and Nevada at ~17 Ma is generally accepted. Interpretations on the origin of the plume include the emergence of a hot spot at that location or the re-emergence of an Eocene fore-arc hot spot that was prevented from ascending by the subducting Farallon plate (Duncan, 1982; Brandon and Goles, 1988; Humphries and others, 1992; Geist and Richards, 1993). By one theory, the mantle plume may have been diverted 200 km to the north, producing the main sequence of Columbia River Basalt flows before its traverse beneath the Snake River Plain (Hooper and Hawkesworth, 1993; and Camp, 1995). Simultaneously, propagating Basin-and-Range extension northward into Oregon may have been facilitated by softening of the lithosphere by the plume. By ~11 Ma the eruption of voluminous basalt was replaced by isolated, fault-related fissures that produced less-fractionated high-alumina olivine tholeiites (McKee and others, 1983; Carlson and Hart, 1987).

About 11 Ma a transition to predominantly silicic volcanism began at the eastern end of the High Lava Plains. MacLeod and others (1976) noted two subparallel, 250-km-long, age-progressive belts of rhyolitic domes, flows, and ash-flow tuffs in southeastern Oregon. These belts, which trend roughly N 75° W, form a mirror image to the Snake River Plain-Yellowstone eastward-younging age trend (Figs. 1-2 and 6-3). A little-noted feature is that domes discrepant to the age progression crop out along the isochrons that represent the trend of age progression. Specifically, older (pre-11 Ma) domes crop out locally as far west as 119° 45' (Horsehead Mountain, A.L. Grunder, unpub. data), but domes younger than the age progression are uncommon. The belts of westward-younging domes are roughly perpendicular to the Steens Mountain escarpment and subparallel to faults of the Brothers fault zone.

Theories regarding the age trend along the High Lava Plains remain in dispute. Walker (1969) introduced the anomalous trend by noting that many of the northeast-trending graben-forming structures in southeastern Oregon terminate at the Brothers fault zone and suggested that the normal faults of the zone and the volcanic vents along it "represent the

surface manifestations of deformation on a large, deeply buried structure, the exact nature of which is not known." Christiansen and McKee (1978) attributed the younging age trend in southeastern Oregon to progressive heating and ductile deformation of the lithosphere due to mantle upwelling in the central part of the Great Basin, with brittle deformation, maximum extension, and volcanism migrating toward the edges of the province. The northern-boundary transverse structures of the Brothers fault zone are interpreted to compensate for Basin-Range extension along the High Lava Plains where it abuts the nonextending terrane of the Blue Mountains province to the north (Lawrence, 1976; Walker and Nolf, 1981). Hart and Carlson (1987a) attributed the distribution of volcanism to crustal rifting in a back-arc environment related to the subduction of the Juan de Fuca plate beneath the North American plate. In order to address both the rhyolitic age progression and the absence of a similar mafic progression, Draper (1991) proposed that a trailing edge of the Snake River Plain hot mantle "blob" migrated westward, progressively melting the crust producing rhyolitic material. He suggested that as extension in the region increased along the Brothers fault zone, smaller volumes of primitive basalt saw shorter crustal residence, and the volume of rhyolitic material erupted decreased.

These theories do not, however, address (1) the lack of evidence for strike-slip displacement on the Brothers fault zone, or (2) the copious Quaternary mafic volcanism with no temporal trend scattered throughout the area.

I tentatively suggest that the High Lava Plains northwest-younging age trend can be accommodated in a magmatic/tectonic model that employs a "leaky" transform system that emanates from the major north-south-trending Steens Mountain escarpment. The age progression is consistent with the time-dependent evolution of a propagating transform. Propagation is an essentially passive response to plate driving forces whose origins may be remote from the axis (Christie and Sinton, 1986). In southeastern Oregon the kinematics of plate movement and adjustment with respect to the Basin and Range, Cascade Range, Blue Mountains, Idaho Batholith, and Snake River Plain is poorly understood. It is possible that the High Lava Plains region represents a transition from "passive" lithospheric stretching of an oblique transform related to east-west extension to an "active", magmatically driven extensional propagating continental rift. The younging trend appears to have begun near the Duck Creek Butte eruptive center, which straddles the Steens Mountain escarpment at its northern end. Duck Creek Butte lies 100-150 km from the inferred position of the Yellowstone hot-spot plume at ~11 Ma. The thermal/magmatic energy of the spreading plume head (Draper, 1991) may have facilitated melting and elevation of the crust along a tectonically weakened boundary beneath the High Lava Plains away from the hot spot at Duck Creek Butte.

Benes and others (1994) note that continental rifting proceeds as distributed deformation whereby extension is being proportioned among all faults by means of a "book shelf" mechanism, versus the concentration of faulting adjacent to the central axis region of oceanic rifts. The broadly distributed faults of the Brothers fault zone may reflect a similar process.

To support evidence for a propagating transform at DBEC, the following compositional and temporal variations can be found in a petrogenetic model based on a propagating rift (Christie and Sinton, 1986). The points are numbered to match the descriptions of DBEC listed in the first part of this section and depicted in Figure 6-4:

- Largely unfractionated lava is erupted near the active tip because the heat budget does not allow adequate residence time for magma at shallow depths to evolve.
- (2) A diverse population of mixed magma compositions erupts 5 and 20 km from the tip.
- (3) About 20 to 30 km behind the tip both maximum degree of fractionation and maximum compositional diversity yields highly differentiated silicic magma.
- (4) Basalt decreases toward normal MORB range (MgO >9 percent, FeO ~9 percent, TiO₂
 ~0.9 percent) approximately 100 km behind the propagating rift tip.
- (5) Discrete, widely separated pods of rhyolite show a younging age progression toward the tip of the propagating rift, and may migrate away from a hot spot.

(6) Normal faulting parallel to the rift is ubiquitous, with a more widely dispersed pattern of faulting in continental rifts (Benes and others, 1994).

The relationship between northwest-striking normal faults, regional tectonic regimes, and Quaternary basaltic volcanism is unclear. The rapid rise to the surface of fairly primitive "depleted mantle"-derived basalt, such as the basalt of Duck Creek Flat, was tied to short residence times (Draper, 1991) in response to extension-related crustal thinning and presence of shallow asthenospheric mantle beneath the High Lava Plains following propagation of the Duck Creek Butte-Newberry volcano silicic trend. I propose that the normal faults may result in part from buckling during cooling of the inflated crust.



Figure 6-4: Compositional characteristics of a propagating oceanic rift over distance (Christie & Sinton, 1986) compared to compositional changes through time at DBEC.

6.3 Conclusion

In conclusion, I propose two dominant mechanisms contribute to the character of the Duck Creek Butte eruptive center:

The formation of magmas at Duck Creek Butte eruptive center is attributed to a combination of processes including partial crustal melting during injection of mantlederived magmas into the crust, active faulting, convection, mixing, mingling, and fractional crystallization. Active tectonic processes during extension may have facilitated the mixing and eruption of the hybrid magmas, whereas periods of tectonic quiescence may have allowed homogenization and fractionation to occur. The basis for this model is chemical and isotopic evidence that reflects crustal contamination, mixing, and fractional crystallization and textural evidence which strongly indicates mixing and convective circulation. Compositional changes found in the DBEC series suggest the evolution of a mutually convecting layered magma chamber that is periodically disrupted. Field evidence for coeval faulting and magmatism supports this hypothesis.

Existing models that attempt to explain the westward-younging trend of silicic vents across the High Lava Plains are incomplete because they do not fully account for the following: (1) the age progression is not a broad swath but represents two discrete parallel belts; (2) individual silicic centers range in composition from basalt to high-silica rhyolite; (3) late-stage primitive Quaternary high-alumina olivine tholeiites have no age progression. A model that includes a propagating transform fault, produced by intricately linked tectonic forces including Basin-Range extension, hot spots, and distant back-arc effects, can explain many features found within the study area and across the High Lava Plains. Although much yet remains unanswered, classical geological investigations using additional field work and geochemistry will be valuable in testing the model.

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APPENDICES

APPENDIX 1: Map locations and additional procedures performed on rocks that were analyzed by XRF. See also Figure A1-1 on next page for sample locations. Does not include locations for additional thin section analysis. XRF = X-ray fluorescence, INAA = Instrumental neutron activation analysis, TS = petrographic thin section.

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Sample	Мар	XRF	INAA	Micro	Age	Iso	topes		La	ongitu	de				
	Unit			probe		Sr	Nid	TS	doar	min			Latit	lde	
JJ92-1	Tdrd	*	*	*	*	*	*	*	118º	<u>11111</u> 10	Sec	; T			Sec
													43	10	10
JJ92-4	Tdr1	*	*			*		*	118°	11	35"	\vdash	43°	10	41"
JJ92-5	Tdr1	*	*	*	*			*	118°	10	54"		43°	10	38"
JJ92-6	Tdba ₁	*	*					*	118°	9'	35"		43°	91	59"
JJ92-7	Tdrd	*	_					*	118°	9	10"		43°	9'	44"
JJ92-19	Tba	*	*					*	118°	8'	47"		43°	81	45"
JJ92-20	Qb2	*	*		*	*	*	*	118°	8	52"		43°	81	41"
JJ92-27	Tdb1	*	*					*	118°	10	5"		43°	10	11"
JJ92-38	Tdba ₂	*	*					*	118°	8'	27"		43°	10	44'
JJ92-41	Tda ₁	*	*					*	118°	8	55"		43°	11	44"
JJ92-51	Tdid	*	*	*		*	*	*	118°	81	14"		43°	10	9"
JJ92-59	Ts?	*	*					*	1180	12	1 "		43°	12	41"
JJ92-62	Tdba ₃	*	*					*	118°	12	13"		43°	12	5"
JJ92-88	Tdrd	*						*	118°	7	12"		43°	9	0"
JJ92-90	Tr	*	*					*	118°	0	58"		43°	11	6"
JJ92-99	Tdb ₂	*	*	*				*	118°	3'	31"		43°	13	25"
JJ92-101	Tdrd	*						*	118°	7	17"		43°	14	11"
JJ92-102	Tdid	*	*			*	*	*	118°	7	14"		43°	12	12"
JJ93-123	Ttd	*						*	118°	7	49"		43°	7	2"
JJ93-124	Tots	*	*					*	118°	71	57"		43°	71	2 "
JJ93-126	Tda ₂	*	*					*	118°	81	5"		43°	7	3 "
JJ93-130	Tdb ₁	*	*	*		*		*	118°	6	6"		43°	10	35"
JJ93-134	Tas	*	*					*	118°	3	37"		43°	12	47"
JJ93-140	Tda ₂	*	*					*	118°	- 91	11"	_	43°	7	22"
JJ93-147	Tad	*						*	118°	3	41"		43°	12	9"
JJ94-151	Qb3	*						*	118°	7	36"		43°	7	3"
JJ93-158	Tdr2	*						*	118°	14	31"		43°	9	35"
JJ93-161	Tas	*						*	118°	2	6"		43°	12	59"
JJ93-163	Tbs	*						*	118°	2	1 "		43°	14	4"
									_	-+	_	┫			
FF94-23	Tb	*							118°	10	37"	1	43°	5	21"
FF94-36	Tba	*			T				118°	13	24"	1	43°	6	50"
FF94-39	Tba	*			T				118°	12	2"	1	43°	8	24"
FF94-49	Ts	*							118°	14	40"	1	43°	- 4	53"
JN94-16	Tdr ₂	*							118°				43°		
												-			



Figure A1-1: Sample locations for chemical analyses listed in Tables 4-7 through 4-9.

Appendix 2: Petrography and mineralogy

Samples are first separated into two broad groups: older units and locally erupted units, which include DBEC series and Quaternary basalt. The locally erupted units then are separated on the basis of silica content into basalt-to-rhyolite categories and are arranged within those categories in stratigraphic order from oldest to youngest. Sample number in parentheses refers to chemical analyses (Tables 4-7 through 4-9). All sample locations are listed in Appendix 1; chemical analyses are noted on the sample location map (Fig. A-1) and on Plate 1. Sample numbers for petrographic analyses that have no accompanying chemistry are not listed.

4.1 OLDER UNITS

Steens Basalt (Ts, JJ92-59): Steens basalt in the study area is a medium- to medium-dark gray, diktytaxitic olivine-bearing basalt that varies from aphanitic to coarsely porphyritic. A key marker unit has 25 to 30 percent crudely aligned plagioclase to 2 cm in length. In general, the modal assemblage consists of plagioclase (35 to 70 percent), ophitic to subophitic clinopyroxene (15 to 30 percent), olivine (10 percent), FeTi oxides (4 to 6 percent), and cryptocrystalline groundmass (0 to 15 percent). Textures include porphyritic, diktytaxitic, ophitic, subophitic, intergranular, and seriate. Rare small glomerocrysts of plagioclase and olivine are present. Plagioclase is tabular, euhedral to subhedral, displays both albite and Carlsbad twinning, and ranges from 1-20 mm in length. Olivine varies from subhedral to anhedral, shows incipient to complete alteration to iddingsite. and ranges from 0.25 to 2 mm across. Clinopyroxene is present chiefly as intergranular or subophitic to ophitic late-stage crystallization, though some phenocrysts as large as 0.5 mm are present. Fe-Ti oxides are anhedral to subhedral and range from 0.25 to 0.5 mm across.

Older tuff and tuffaceous sedimentary rocks (Tots, JJ93-124) A 3-4 m thick exposure of moderately indurated white ash was collected in a road cut. It is composed chiefly cryptocrystalline glass-dust matrix with approximately 5 percent incipiently devitrified glass shards to 0.25 mm in length. It also contains 0.5 percent crystals of anhedral alkali feldspar (0.25 mm), anhedral quartz (0.15 mm), and green clinopyroxene (0.05 mm).

Basalt of Stockade Creek (Tbs, JJ94-163) The basalt of Stockade Creek is very fine-grained, holocrystalline, intersertal to intergranular to subophitic to ophitic, with random arrangement of groundmass. **Plagioclase** megacrysts, as long as 9 cm, are locally abundant, but are chiefly less than 1.5 cm in length. The megacrysts are subhedral and normally zoned. The **groundmass** comprises plagioclase (60-70 percent), clinopyroxene (15-20 percent) FeTi oxides (4-8 percent) and glass (5-20 percent). No olivine was found.

Porphyritic basalt (Tb, FF94-23) The holocrystalline fine-grained porphyritic basalt has 2 to 5 percent phenocrysts of subhedral **plagioclase** (1-3 mm; anhedral olivine inclusions present in larger crystals) and anhedral

olivine (0.5-0.7 mm with >50 percent iddingsite alteration). The intergranular **groundmass** is comprises 55-65 percent plagioclase, 20-30 percent olivine, 10-20 percent clinopyroxene, and 2 percent FeTi oxides (late stage dendritic).

Lithic Tuff (Tlt) The moderately welded rock contains 3-20 percent cryptocrystalline to fine-grained andesitic lithic fragments, in glassy to cryptocrystalline groundmass. Sparse spherulites are found in the center of glassy areas. Subangular lithics fragments as large as 0.5 cm include the following assemblages: (1) very fine grained pilotaxitic plagioclase-rich andesite (?) with FeTi oxides as the only mafic phase, (2) fine grained intersertal plagioclase with FeTi oxides, (3) fine-grained intergranular plagioclase, clinopyroxene, FeTi oxides, with ~2 percent spongy plagioclase phenocrysts, (4) holocrystalline medium grained plagioclase plus olivine. A rare 7-cm across lithic fragment has a glassy to cryptocrystalline matrix with >5 percent crystal fragments of mottled euhedral to subhedral plagioclase to 2 mm in length, euhedral to anhedral zoned clinopyroxene to 1.5 mm in length, FeTi oxides, and sparse orthopyroxene.

Basaltic andesites (Tba, JJ93-19, JJ93-133) The basaltic andesites are all intergranular and fine- to very-fine grained and have "fuzzy" indistinct grain boundaries and/or abundant clay alteration. Groundmass phases include plagioclase (35 to 70 percent), clinopyroxene (20 to 40 percent), FeTi oxides (5 to 12 percent), olivine (0 to 2 percent), glass (0 to 3 percent), and unidentifiable clays (5 to 25 percent). The basaltic andesites are generally aphanitic, but can also be sparsely porphyritic with about 1 percent plagioclase phenocrysts to 3 mm and rare glomerocrysts of plagioclase and olivine. In Dick Creek (JJ93-134) the flows are very-finegrained (all crystals are smaller than 0.1 mm); groundmass varies from pilotaxitic to randomly oriented crystals, and comprises 70-80 percent plagioclase, 3-5 percent FeTi oxides, 5-10 percent intergranular clinopyroxene, and 3 percent sideromelane. The phenocrysts make up 3-5 percent of the volume and include euhedral to subhedral plagioclase (0.25-2 mm) that shows normal, oscillatory, and reverse zoning, less than 0.5 percent anhedral FeTi oxides (0.3 mm), and few small glomerocrysts of plagioclase and clinopyroxene.

Andesite dikes of Dick Creek (Tad, JJ93-147) Petrographic analysis of a clast shows a cryptocrystalline groundmass with 4 percent FeTi oxides, 1 percent subhedral to euhedral plagioclase (0.5-2 mm, probably andesine), less than 1 percent anhedral clinopyroxene (0.1-0.2 mm), and trace anhedral quartz (0.25 mm). The matrix is similar to the clast in mineralogy, but has about 50 percent green and brown glass.

Rhyolite of Dowell Butte (Tr_1 , JJ92-90) The rhyolite is very light gray to pinkish gray, and is finely porphyritic with 8-10 percent phenocrysts in a clear vitric matrix. Phenocrysts comprise 6-8 percent bent, strained, and fractured euhedral to subhedral **alkali feldspar** (0.1-0.75 mm) with ubiquitous undulatory extinction. Feathery sericite (1 percent) preferentially follows flow lines. There are fewer than 0.5 percent anhedral, embayed, strained quartz, and less than 0.25 percent hornblende.

4.2 DUCK BUTTE ERUPTIVE CENTER UNITS

Basalt

Basalt of Duck Pond Ridge (Tdb₁, JJ93-130) is a medium-dark gray, porphyritic, holocrystalline, intergranular basalt with 25-30 percent phenocrysts of plagioclase, olivine, and FeTi oxides. Coarse-grained, angular, subhedral to euhedral, blocky anhedral seriate **plagioclase** phenocrysts (20-25 percent) occur as 2 dominant populations: 2 to 20 mm (rarely to 3 cm), and 1 mm. Plagioclase composition ranges from An₅₁ to An₆₁. A few plagioclase crystals poikilitically enclose olivine and FeTi oxides. Anhedral to subhedral equant **olivine** (7 to 10 percent), ranges from 0.1 to 0.6 mm, has Mg content ranging from Fo₅₃ to Fo₆₅, and shows 40 to 90 percent alteration to iddingsite. The fine-grained intergranular **groundmass** comprises 65-70 percent plagioclase (An₄₂₋₄₅), 20-25 percent mafics which are chiefly olivine with 5-20 percent alteration to iddingsite, sparse clinopyroxene (identified in thin section but not found during microprobe analysis), and 10 to 12 percent FeTi oxides. Two percent round to oval **vesicles**, 0.5 to 5 mm in diameter, are widely separated.

Fine-grained basalt (Tdb₂, JJ92-99) is a medium dark gray, intergranular and ophitic to subophitic, porphyritic, sparsely vesicular basalt with approximately 10 percent phenocrysts of plagioclase and olivine in a fine-grained groundmass. Anhedral to subhedral **plagioclase** crystals (8-9 percent) to 0.5 cm in length, exhibit Carlsbad, albite, and pericline twins all with varying degrees of oscillatory zoning between An₄₅ and An₇₂; a few crystals poikilitically enclose olivine. Clots of sector-zoned plagioclase are common. Anhedral iddingsitized (3 to 5 percent altered) **olivine** (Fo₅₃₋₆₅) to 3 mm in diameter form 1-2 percent of the volume. The **groundmass** is composed of an interlocking matrix of approximately 70 percent euhedral to subhedral tabular plagioclase (An₃₅₋₅₅ by Michel-Levy method; 0.1-0.4 mm in length), 15 percent ophitic to subophitic clinopyroxene (0.5-1 mm), 10 percent anhedral, equant, intergranular iddingsitized (0 to 90 percent altered) olivine (0.1-0.2 mm), and 5 percent euhedral to subhedral FeTi oxides (0.1-0.2 mm).

Glomerophyric basalt (Qb₁) Qb₁ is vesicular, very fine grained, porphyritic, diktytaxitic, and ophitic to subophitic. Grayish red oxidation surrounds the vesicles. It has 2-3 percent glomerocrysts, to 1 cm, composed of olivine and subordinate plagioclase, as well as ~2 percent each of **plagioclase** laths (to 3 mm) and **olivine** (to 2 mm) as phenocryst phases. Modal analysis of the **groundmass** includes approximately 55-60 percent plagioclase laths to 3 mm, 20-25 percent ophitic clinopyroxene, 8-12 percent olivine (includes 2 percent phenocrysts and 6-10 percent intersertal grains), 5-8 percent FeTi oxides, and 10-15 percent vesicles. Several 1 mm diameter quartz xenocrysts were found in hand sample (JJ93-146), but none were found in thin section.

Basalt of Duck Creek Flat (Qb₂, JJ93-20) Qb₂ is a diktytaxitic, ophitic, porphyritic basalt with 2 to 3 percent phenocrysts of olivine. **Olivine**, to 2 mm, is subhedral to euhedral with iddingsite alteration around the edges. **Plagioclase** is not a phenocryst phase in Qb₂. The very fine-grained **groundmass** is comprised of subhedral to euhedral plagioclase laths

(50-55 percent; compositions, determined by the Michel-Lévy method, range from An52-58); ophitic clinopyroxene (25-30 percent) enclosing both plagioclase and olivine; intergranular olivine (8-11 percent) to 2 mm in diameter which is almost completely altered to iddingsite; subhedral FeTi oxides (3-9 percent) occur as equant grains to ____ mm, and are found partially enclosing (ophitic) plagioclase implying late-stage mineralization. Vesicles (10-15 percent) are round, to ____ mm in diameter, with plagioclase laths intruding the voids (diktytaxitic). A rarely exposed basal flow has ____ times more FeTi oxides than the upper flow, otherwise they are texturally and mineralogically similar.

Basalt of Cord (Qb₃, JJ94-151) Qb₃ is similar in modal composition to Qb₁. Phenocrysts include 1 percent each of **plagioclase** to 2 mm in length and **olivine** to 0.6 mm in diameter. It differs from Qb₁ by lack of glomerocrysts and coarser groundmass.glomerocrysts.

Basaltic Andesite

Olivine-bearing basaltic andesite (Tdba₁, JJ92-6) has an incipientlyaltered, brownish-black glassy groundmass with clear microlites, and 15 percent phenocrysts. Phenocrysts include 10 percent euhedral to subhedral plagioclase (0.1-4 mm; many with abundant black cryptocrystalline inclusions), 3 percent euhedral olivine (0.1-1.0 mm), and 2 percent FeTi oxides (0.1-0.2 mm).

Basaltic andesite dike (Tdba₂ JJ92-38) Petrographic analysis of the dike of basaltic andesite that cuts the low-silica rhyolite reveals a dark brown glass with incipient devitrification confined to flow lines. The rock has ~5 percent subhedral to euhedral plagioclase ($\sim An_{20}$) 0.1 to 1 mm in length (many have either sieve texture or clinopyroxene inclusions), 3-4 percent anhedral clinopyroxene, 2 percent FeTi oxides, and less than 0.5 percent orthopyroxene. A single glomerocryst of olivine and plagioclase was seen in thin section, and a single xenocryst of biotite.

Basaltic andesite of Brokendown Waterhole (Tdba₃, JJ92-62) The upper basaltic-andesite flow that caps a thick package of andesite flows (-62) is composed of approximately 50-55 percent plagioclase laths (to 0.5 mm in length), 12-15 percent intersertal clinopyroxene (\pm orthopyroxene?) (to 0.15 mm across), 4-6 percent olivine (to 0.25 mm in diameter), 4 percent FeTi oxides, plus a 20-25 percent grainy cryptocrystalline material (clayaltered glass?). Sparse, small glomerocrysts of plagioclase and olivine are found in thin section.

Andesite

Andesite of Duck Creek Spring (Tda₁, JJ92-27, JJ92-41) The basal andesite that forms the flow lobe to the southwest of Indian Creek Buttes (JJ92-27) has a very fine-grained groundmass with approximately 2-3 percent phenocrysts of plagioclase and olivine. The plagioclase and olivine phenocrysts appear chiefly as sparse glomerocrysts. The subhedral to euhedral **plagioclase** is 0.5 to 2 mm in length, has both albite and Carlsbad/pericline twins, and exhibits some overgrowths and/or sieve textures indicative of disequilibrium conditions. The anhedral **olivine** (0.5 mm) has approximately 5 percent iddingsite alteration. The **groundmass** is composed of 65-70 percent plagioclase, 20 percent clinopyroxene (\pm opx?), 7 percent FeTi oxides, and 3-8 percent clay alteration. Sparse, small olivinerich glomerocrysts are evident only in thin section. The basal flow of this southeastern lobe has 3-7 percent phenocrysts of plagioclase (to 1 cm) and clinopyroxene (to 1 mm) in a groundmass of plagioclase, clinopyroxene, and intersertal glass.

The eastern flow (-41) has a microcrystalline pilotaxitic groundmass that appears to be chiefly plagioclase and clay-altered glass. Phenocrysts (4-5 modal percent) include euhedral to subhedral oscillatory plagioclase (1-7 mm with abundant sieve textures, $\sim 1\%$ anhedral olivine (0.1-0.3 mm), and sparse clinopyroxene. Glomerocrysts of plagioclase and iddingsitized olivine are common.

Andesite of Duck Creek (Tda2, JJ93-126, -140): These include porphyritic and glomeroporphyritic trachyandesite flows and dikes with 5 to 10 percent phenocrysts of plagioclase and olivine. Plagioclase (5-9 percent) occurs as subhedral to euhedral albitic laths as long as 1 cm in length , and as blocky, equant anhedral to subhedral crystals to 2.5 mm across. The blocky grains display Carlsbad, albite, or no twinning, and are commonly zoned (both normal and reverse) or have sieve textures in the cores. Olivine $(\leq 1 \text{ percent}; 0.1-0.5 \text{ mm})$ is subhedral to euhedral. Individual phenocrysts are almost completely altered to iddingsite and/or sideromelane, whereas the olivine that occurs with plagioclase as sparse glomerocrysts is 20 to 50 percent altered to iddingsite. The groundmass varies from cryptocrystalline to very fine grained, and is comprises randomly oriented interlocking euhedral plagioclase (60 to 80 percent), intergranular anhedral clinopyroxene (10 to 35 percent), FeTi oxides (2 to 4 percent), brown glass (0-3 percent), and up to 15 percent miscellaneous non identifiable cryptocrystalline "dust". Magmatic inclusions were found in thin-section analysis from both sample locations. The inclusions are 2.5 mm in diameter and are composed of 40 percent brown glass, 40 percent euhedral plagioclase laths (0.1 to 0.3 mm), 5 percent equant euhedral FeTi oxides (0.025 to 0.05 mm) with rare dendritic needles (0.1 mm), and 5 percent anhedral to subhedral clinopyroxene (0.05 to 0.1 mm).

Dacite

Inclusion-rich dacite (Tdid: JJ92-102; basaltic andesite inclusion is JJ92-51): The dacite is medium-dark to dark gray and is characterized by 3-30 percent magmatic inclusions which range from 0.2 to 5 cm in diameter. It is sparsely porphyritic, with 3-5 percent phenocrysts of feldspar > FeTi oxides > orthopyroxene > clinopyroxene > quartz, and has an aphanitic groundmass. Rare hornblende and olivine were seen in only one thin section. (Phenocrysts >0.1 mm may be xenoliths from the basaltic andesite melt) Feldspar (1-3 percent) phenocrysts to 1 mm anhedral with some resorption. Sieve-textured reaction rim or core common. Exhibits normal, oscillatory, and reversed zoning. FeTi oxides (0.2 to 1 percent) to 0.2 mm (mostly 0.03 mm) are finely disseminated. Orthopyroxene and clinopyroxene (0.5-1 percent, OPX>CPX; <0.5 mm) are anhedral. Quartz crystals (<1 percent; to 1 mm in diameter) are anhedral and resorbed. Overgrowth fabric on some of the feldspar and pyroxene indicates disequilibrium conditions. Groundmass is cryptocrystalline with random orientation of abundant feldspar (?) crystallites in a brown matrix.

The **basaltic andesite inclusions** are fine grained, intersertal, vesicular, sparsely porphyritic (2 percent), and commonly have glassy rims indicative of rapid quenching. Phenocrysts (in decreasing abundance) include anhedral plagioclase (An₄₈₋₅₁) to 0.8 mm in length, subhedral clinopyroxene laths to 0.5 mm in length, and rare fine-grained anhedral olivine (not found in microprobe analysis). The **groundmass** comprises 40-50 percent subhedral to euhedral plagioclase to 0.4 mm, 20-40 percent partially devitrified glass, 10-20 percent orthopyroxene > clinopyroxene to 0.3 mm, 5 percent dendritic>blocky FeTi oxides (blocky to 0.02 mm, dendritic to 0.6 mm indicative of quenching), and 3 percent clear euhedral apatite to 0.01 mm. Vesicles in a 3 cm inclusion varied from 20 percent of mode in the glassy rim to less than 5 percent in core.

Rhyodacite

Rhyodacite of Duck Creek Butte (Tdrd, JJ92-1, JJ92-7, JJ92-88, JJ92-101) varies from incipiently hydrated (grayish black to dark reddish brown), to perlitic (light to medium gray), to stony, slightly phasealtered devitrified (light-gray sugary to brownish-gray stony), to a light-gray to gravish-orange pink pumiceous carapace. It is porphyritic with 7 to 12 percent phenocrysts of plagioclase > biotite > orthopyroxene > clinopyroxene > FeTi oxides > amphibole. Plagioclase (5-8 percent), to 4 mm in length, occurs as anhedral to subhedral simple to complicated phenocrysts. It occurs as zoned (normal and reversed), sieve textured, occasionally resorbed, and rarely as glomerocrysts. Chemical composition is oligoclase to andesine (Table 4-2). Orthopyroxene (0-1 percent), is 0.25 to 0.5 mm in length and is chiefly subhedral. Biotite (1-2 percent), is subhedral to euhedral, to 2 mm across. Green clinopyroxene (0.5 to 1 percent) is anhedral to euhedral, 0.05 to 0.7 mm, and exhibits simple twinning. Fe-Ti oxides (0.5 to 1 percent) are anhedral to euhedral, 0.1 to 0.25 mm equant grains. Amphibole (< 0.25 percent) is subhedral to euhedral to 0.8 mm. The groundmass ranges from almost completely glassy with abundant flow aligned microlites (acicular to 0.025 mm, blocky to 0.005 mm), to incipiently devitrified. Spherulitic alteration was found in only one location, where it was pervasive. Sparse glomerocrysts vary from microcrystalline to very fine grained (probably plagioclase & clinopyroxene). Cryptocrystalline to very fine-grained plagioclase-rich melt inclusions were also found A 20-cm clast of rhyolite from the surge deposit found beneath the rhyolite flows had 5-10 percent vesicles, and 7 percent phenocrysts comprises of 4 percent anhedral to subhedral plagioclase to 2 mm, 1-1.5 percent subhedral biotite to 0.5 mm, 1 percent anhedral orthopyroxene to 0.25 mm, 1 percent anhedral to euhedral FeTi oxides to 0.25 mm, <0.5 percent anhedral clinopyroxene to 0.25 mm. No amphibole was found, The clast had a glassy groundmass with incipient devitrification of the flow lines. An altered fine-grained inclusion in the rhyolite clast had 40-50 percent clear glass, 40-50 percent plagioclase, 8 percent FeTi oxides, 3 percent orthopyroxene, and 3 percent clay.

Rhyolite

Rhyolite of Indian Creek Buttes (Tdr₁, JJ92-5, JJ92-4): Sparsely phyric to aphyric rhyolite occurs chiefly as light gray to very-light gray partly devitrified. Textures that vary from perlitic to sugary to stony, with 0 to 90 percent spherulitic alteration; it also occurs as cobbles of black to black/reddish brown streaked obsidian. Groundmass is glassy to cryptocrystalline with parallel alignment of microlites along flow lines. Phenocrysts include ≤ 1 percent subhedral and embayed sanidine to 3 mm. Most are unzoned but they also show undulatory, or checkerboard (microcline) extinction, ≤ 1 percent 0.25 mm euhedral blocky plagioclase aligned parallel to flow lines, 0.5 percent anhedral and embayed quartz to 1 mm, and rare elongate subhedral hornblende to 3 mm. One sample from low in the section had >90 percent spherulitic alteration with coarser quartz filling the vugs (?) between the radial aggregates, plus approximately 2 percent speckling of very-fine-grained FeTi oxides, and 2 percent brown glass. The only xenolith found was a 15 cm diameter rounded xenolith comprises of 85 percent plagioclase, 8 percent FeTi oxides, 7 percent mafics. Alteration obscures precise identification, but the xenolith was probably plucked from the older basaltic andesite that overlies the Steens Basalt.

Appendix 3:	Microprobe	analyses	performed	for	this st	udy.

FELDS	PAR	Mineral	SiO ₂	Al ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	FeO	BaO	Total
JJ92-1	Tdrd	Plagiocl.	61.26	24.17	5.42	7.45	1.18	0.01	0.10	0.02	99.61
JJ92-1	Tdrd	Plagiocl.	60.66	24.53	5.83	7.41	1.08	0.00	0.21	0.02	99.74
JJ92-1	Tdrd	Plagiocl.	60.26	24.80	6.38	7.16	1.04	0.01	0.20	0.08	99.93
JJ92-1	Tdrd	Plagiocl.	60.52	24.73	5.97	7.24	1.23	0.02	0.20	0.03	99.94
JJ92-1	Tdrd	Plagiocl.	58.49	26.37	7.82	6.34	0.85	0.03	0.15	0.01	100.06
JJ92-1	Tdrd	Plagiocl.	59.19	25.56	7.10	6.88	0.95	0.02	0.23	0.04	99.97
JJ92-1	Tdrd	Plagiocl.	59.75	25.17	6.71	6.94	1.11	0.00	0.20	0.12	100.00
JJ92-1	Tdrd	Plagiocl.	59.37	25.09	6.87	6.64	0.88	0.04	0.41	0.04	99.34
JJ92-1	Tdrd	Plagiocl.	58.39	26.00	7.60	6.52	0.73	0.01	0.17	0.03	99.45
JJ92-1	Tdrd	Plagiocl.	59.67	25.74	7.18	6.76	0.92	0.00	0.23	0.00	100.50
JJ92-1	Tdrd	Plagiocl.	60.75	24.53	5.92	7.27	1.09	0.00	0.17	0.05	99.78
JJ92-1	Tdrd	Plagiocl.	60.74	24.62	5.95	7.26	1.14	0.00	0.16	0.04	99.91
JJ92-1	Tdrd	Plagiocl.	58.96	25.52	7.09	6.69	0.99	0.01	0.28	0.14	99.68
JJ92- 1	Tdrd	Plagiocl.	57.52	26.08	7.96	6.43	0.81	0.00	0.31	0.15	99.26
JJ92-1	Tdrd	Plagiocl.	60.25	24.92	6.28	7.01	1.25	0.01	0.23	0.18	100.13
JJ92-1	Tdrd	Plagiocl.	60.03	24.77	6.01	7.07	1.33	0.01	0.22	0.28	99.72
JJ92-1	Tdrd	Plagiocl.	60.65	25.07	6.40	7.10	0.99	0.02	0.25	0.02	100.50
JJ92-1	Tdrd	Plagiocl.	59.80	25.27	6.59	6.99	1.02	0.00	0.18	0.04	99.89
JJ92-1	Tdrd	Plagiocl.	63.36	22.85	6.42	5.98	1.01	0.06	0.56	0.12	100.36
JJ92-1	Tdrd	Plagiocl.	57.03	26.78	9.18	5.51	0.58	0.02	0.42	0.09	99.61
JJ92 -1	Tdrd	Plagiocl.	56.33	27.92	9.82	5.50	0.47	0.04	0.32	0.08	100.48
JJ92- 1	Tdrd	Plagiocl.	57.27	26.63	8.51	6.09	0.69	0.03	0.33	0.12	99.67
JJ92-1	Tdrd	Plagiocl.	57.57	26.39	8.84	5.92	0.61	0.02	0.44	0.09	99.88
JJ92-1	Tdrd	Plagiocl.	59.26	25.08	6.41	7.06	1.00	0.00	0.21	0.02	99.04
JJ92-1	Tdrd	Plagiocl.	58.65	25.15	6.74	6.77	0.86	0.02	0.14	0.02	98 35
JJ92-1	Tdrd	Plagiocl.	59.49	24.99	6.18	7.25	1.06	0.01	0.19	0.05	99.22
JJ92-1	Tdrd	Plagiocl.	59.72	24.83	6.23	6.98	1.12	0.00	0.15	0.06	99.00
JJ92- 1	Tdrd	Plagiocl.	59.94	24.42	5.99	7.21	1.19	0.01	0.17	0.07	99.00
JJ92-1	Tdrd	Plagiocl.	60.58	24.35	5.94	7.21	0.96	0.01	0.17	0.08	99.30
JJ92-1	Tdrd	Plagiocl.	65.03	20.66	5.60	5.54	1.31	0.05	0.64	0.08	98.91
JJ92-1	Tdrd	Plagiocl.	65.57	19.83	5.58	4.69	1.54	0.08	0.79	0.13	98 21
JJ92-1	Tdrd	Plagiocl.	59.15	25.13	6.63	6.92	1.07	0.01	0.28	0.10	99.20
JJ92-1	Tdrd	Plagiocl.	56.14	27.07	8.52	5.98	0.75	0.02	0.28	0.22	98.98
JJ92-1	Tdrd	Plagiocl.	60.79	23.90	5.26	7.38	1.44	0.02	0.24	0.10	99.13
JJ92- 1	Tdrd	Plagiocl.	59.09	24.91	6.42	7.15	1.01	0.01	0.20	0.04	98.83
JJ92-1	Tdrd	Plagiocl.	59.24	24.52	6.03	7.22	1.16	0.00	0.23	0.05	98.45
JJ92-1	Tdrd	Plagiocl.	59.38	24.49	6.18	7.11	1.26	0.01	0.21	0.09	98 73
JJ92-1	Tdrd	Plagiocl.	60.95	24.04	6.35	6.30	1.14	0.02	0.34	0.16	99 30
JJ92-5	Tdrl	Sanidine	62.67	19.45	0.79	5.77	7.11	0.02	0.17	0.40	96 38
JJ92-5	Tdr1	Sanidine	65.10	19.17	0.17	3.58	11.35	0.01	0.06	0.24	99.68
JJ92-5	Tdr1	Sanidine	65.12	19.26	0.22	3.63	11.29	0.01	0.12	0.27	99.92
JJ92-5	Tdr1	Sanidine	65.19	19.13	0.22	3.75	11.09	0.00	0.07	0.22	99.67
JJ92-5	Tdr1	Sanidine	65.79	19.19	0.20	4.81	9.42	0.01	0.09	0.23	99 74
JJ92-5	Tdr1	Sanidine	64.25	19.18	0.19	3.57	11.36	0.00	0.05	0.22	98.87
JJ92-5	Tdr1	Sanidine	65.51	19.53	0.29	7.21	5.65	0.01	0.09	0.16	98 45
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Appendix 3 (cont.):

		Mineral	SiO ₂	Al ₂ O3	CaO	Na ₂ O	K ₂ O	MgO	FeO	BaO	Total
JJ92-5	Tdr1	Sanidine	65.85	19.47	0.32	6.91	6.18	0.00	0.13	0.42	99.28
JJ92-99	Tdb2	Plagiocl.	51.35	30.22	13.30	3.82	0.25	0.12	0.55	0.03	99.64
JJ92-99	Tdb2	Plagiocl.	50.37	30.89	14.29	3.17	0.27	0.11	0.73	0.04	99.87
JJ92-99	Tdb2	Plagiocl.	53.21	28.91	11.74	4.58	0.38	0.10	0.77	0.00	99.69
JJ92-99	Tdb2	Plagiocl.	53.23	28.99	11.89	4.43	0.37	0.09	0.84	0.04	99.88
JJ92-99	Tdb2	Plagiocl.	56.47	26.69	9.21	5.39	1.26	0.06	0.79	0.09	99.96
JJ92-99	Tdb2	Plagiocl.	53.01	27.49	11.91	4.30	0.44	0.51	1.13	0.02	98.81
JJ92-99	Tdb2	Plagiocl.	49.96	31.50	14.60	3.14	0.21	0.12	0.48	0.01	100.02
JJ92-99	Tdb2	Plagiocl.	50.99	30.77	13.72	3.52	0.23	0.09	0.49	0.05	99.86
JJ92-99	Tdb2	Plagiocl.	49.74	31.50	14.59	3.02	0.20	0.11	0.49	0.00	99.65
JJ92-99	Tdb2	Plagiocl.	51.46	30.63	13.47	3.63	0.24	0.12	0.51	0.00	100.06
JJ92-99	Tdb2	Plagiocl.	53.43	28.60	11.57	4.65	0.40	0.10	0.88	0.01	99.64
JJ92-99	Tdb2	Plagiocl.	49.60	31.43	14.79	2.92	0.27	0.20	0.76	0.00	99.97
JJ92-99	Tdb2	Plagiocl.	51.07	30.83	13.72	3.34	0.26	0.08	0.73	0.01	100.04
JJ92-99	Tdb2	Plagiocl.	52.10	29.65	12.97	3.92	0.31	0.08	0.80	0.02	99.85
JJ92-99	Tdb2	Plagiocl.	50.86	30.37	13.73	3.43	0.29	0.12	0.52	0.01	99.33
JJ92-99	Tdb2	Plagiocl.	49.49	31.47	14.91	2.99	0.15	0.11	0.49	0.03	99.64
JJ92-99	Tdb2	Plagiocl.	51.85	29.82	13.16	3.93	0.30	0.11	0.76	0.01	99.94
JJ92-99	Tdb2	Plagiocl.	52.11	29.06	12.22	3.99	0.38	0.17	0.86	0.01	98.80
JJ92-99	Tdb2	Plagiocl.	51.85	29.69	12.90	3.80	0.31	0.12	1.08	0.03	99.78
JJ92-99	Tdb2	Plagiocl.	53.53	28.71	11.63	4.50	0.43	0.19	1.04	0.04	100.07
JJ93-130	Tdb1	Plagiocl.	53.09	28.62	11.70	4.53	0.42	0.19	1.05	0.01	99.61
JJ93-130	Tdb1	Plagiocl.	53.41	28.56	11.58	4.65	0.42	0.11	0.82	0.01	99.56
JJ93-130	Tdb1	Plagiocl.	52.57	28.43	11.51	4.62	0.43	0.09	0.88	0.02	98.55
JJ93-130	Tdb1	Plagiocl.	51.56	27.77	11.51	4.45	0.37	0.08	0.88	0.02	96.64
JJ93-130	Tdb1	Plagiocl.	50.21	27.18	11.14	4.43	0.41	0.09	0.87	0.07	94.40
JJ93-130	Tdb1	Plagiocl.	51.88	29.98	12.85	4.10	0.26	0.09	0.80	0.00	99.96
JJ93-130	Tdb1	Plagiocl.	51.51	30.13	13.29	3.87	0.19	0.07	0.56	0.04	99.66
JJ93-130	Tdb1	Plagiocl.	52.88	28.84	11.99	4.62	0.28	0.07	0.81	0.01	99.50
JJ93-130	Tdb1	Plagiocl.	51.01	30.14	13.46	3.73	0.22	0.06	0.77	0.00	99.39
JJ93-130	Tdb1	Plagiocl.	56.33	26.56	9.38	5.81	0.50	0.05	1.19	0.03	99.85
JJ93-130	Tdb1	Plagiocl.	51.67	30.07	13.17	3.87	0.20	0.09	0.65	0.01	99.73
JJ93-130	Tdb1	Plagiocl.	55.02	27.97	10.84	5.26	0.47	0.08	0.71	0.09	100.44
JJ93-130	Tdb1	Plagiocl.	51.66	30.08	13.10	4.03	0.14	0.09	0.59	0.02	99.71
JJ93-130	Tdb1	Plagiocl.	53.37	29.12	12.18	4.55	0.29	0.07	0.81	0.05	100.44
JJ93-130	Tdb1	Plagiocl.	52.15	29.77	12.95	4.13	0.18	0.10	0.54	0.01	99.83
JJ93-130	Tdb1	Plagiocl.	54.62	27.80	10.83	5.20	0.35	0.06	0.81	0.08	99.75
JJ93-130	Tdb1	Plagiocl.	56.77	26.90	9.02	5.99	0.78	0.04	1.06	0.07	100.63
Dacite	Tdid	Plagiocl.	55.66	27.36	10.35	5.28	0.61	0.07	0.65	0.04	100.02
Dacite	Tdid	Plagiocl.	56.01	27.34	10.04	5.23	0.73	0.08	0.70	0.08	100.21
Dacite	Tdid	Plagiocl.	55.71	27.67	10.02	5.22	0.68	0.03	0.55	0.06	99.94
Dacite	Tdid	Plagiocl.	60.38	21.91	7.00	4.34	2.52	0.51	2.07	0.04	98.77
inclusion	Tdid	Plagiocl.	54.76	28.11	10.68	5.23	0.61	0.06	0.77	0.03	100.25
inclusion	Tdid	Plagiocl.	58.58	25.22	7.42	6.25	1.19	0.01	0.59	0.21	99.47

Appendix 3 (cont.):

		Mineral	SiO ₂	Al ₂ O ₃	CaO	Na ₂ O	K ₂ O	MgO	FeO	BaO	Total
inclusion	Tdid	Plagiocl.	56.28	26.93	9.43	5.46	0.71	0.08	0.98	0.05	99.92
inclusion	Tdid	Plagiocl.	55.85	26.54	9.30	5.71	0.63	0.10	1.21	0.06	99.40
inclusion	Tdid	Plagiocl.	53.42	24.74	12.37	5.16	0.83	0.07	0.71	0.10	97.40
inclusion	Tdid	Plagiocl.	57.14	26.55	9.01	5.79	0.91	0.03	0.57	0.11	100.11
inclusion	Tdid	Plagiocl.	57.41	26.06	8.50	5.89	0.93	0.07	0.76	0.04	99.66
Dacite	Tdid	Plagiocl.	57.70	23.55	8.18	4.32	1.84	0.10	1.15	0.08	96.92
Dacite	Tdid	Plagiocl.	56.93	26.97	9.03	5.68	0.76	0.05	0.50	0.09	100.01
Dacite	Tdid	Plagiocl.	59.10	24.24	7.67	5.21	1.48	0.07	0.99	0.06	98.82
Dacite	Tdid	Plagiocl.	56.00	26.89	9.60	5.16	0.78	0.10	0.78	0.10	99.41

PYROX	ENE	Mineral:	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O
JJ92-99	Tdb2	ClinoPyx	50.23	1.49	3.45	9.78	0.19	14.26	20.40	0.37
JJ92-99	Tdb2	Orthopyx.	51.39	0.96	1.85	9.82	0.24	15.82	19.51	0.32
JJ92-99	Tdb2	ClinoPyx	50.16	1.27	2.86	9.38	0.19	13.63	20.06	0.37
JJ92-99	Tdb2	ClinoPyx	50.63	1.58	2.78	10.84	0.27	13.92	19.36	0.39
JJ92-99	Tdb2	ClinoPyx	52.36	1.04	1.45	11.77	0.38	14.99	18.55	0.36
JJ92-99	Tdb2	ClinoPyx	51.17	1.28	2.04	11.61	0.36	13.74	19.39	0.37
JJ92-99	Tdb2	ClinoPyx	57.98	0.61	11.64	7.59	0.21	7.82	12.53	3.10
JJ92-99	Tdb2	ClinoPyx	59.86	0.41	14.83	4.77	0.12	5.19	9.77	3.24
JJ92-1	Tdrd	Orthopyx.	50.97	0.15	0.64	29.78	0.95	15.11	1.51	0.01
JJ92-1	Tdrd	ClinoPyx	51.38	0.13	0.99	14.93	0.84	9.91	18.50	0.32
JJ92-1	Tdrd	ClinoPyx	52.09	0.11	0.74	14.91	0.85	11.13	20.00	0.26
JJ92-1	Tdrd	ClinoPyx	51.78	0.18	0.92	14.51	0.74	11.13	20.15	0.31
JJ92-1	Tdrd	Orthopyx.	49.93	0.15	0.58	29.07	1.41	16.84	1.41	0.06
JJ92-1	Tdrd	Orthopyx.	51.28	0.19	0.59	29.23	1.42	15.89	1.43	0.01
JJ92- 1	Tdrd	Orthopyx.	50.68	0.12	0.58	30.63	1.55	14.34	1.35	0.03
JJ92-1	Tdrd	Orthopyx.	50.65	0.13	0.57	30.06	1.40	14.88	1.45	0.01
JJ92-1	Tdrd	Orthopyx.	51.41	0.11	0.72	27.42	0.97	16.91	1.37	0.05
JJ92-1	Tdrd	Orthopyx.	50.41	0.10	0.81	28.68	1.40	13.28	1.30	0.06
JJ92-1	Tdrd	Orthopyx.	50.97	0.09	0.38	29.35	1.25	15.71	1.24	0.02
JJ92- 1	Tdrd	Orthopyx.	51.46	0.14	0.37	28.94	1.15	16.45	1.23	0.03
JJ92-1	Tdrd	Orthopyx.	51.42	0.10	0.43	28.03	0.96	16.29	1.20	0.05
JJ92-1	Tdrd	ClinoPyx	51.42	0.43	1.69	11.99	0.42	13.20	19. 30	0.37
JJ92-1	Tdrd	ClinoPyx	51.44	0.36	1.55	13.11	0.47	12.71	18.78	0.33
JJ92-1	Tdrd	ClinoPyx	51.43	0.12	0.89	15.30	0.92	10.56	20.12	0.36
JJ92-1	Tdrd	ClinoPyx	66.18	0.24	11.14	6.88	0.24	4.10	8.65	0.86
JJ92-1	Tdrd	ClinoPyx	51.54	0.12	0.82	14.95	0.92	10.30	20.42	0.32
JJ92-1	Tdrd	ClinoPyx	52.27	0.12	0.85	15.05	0.87	10.19	19.84	0.30
JJ92-1	Tdrd	Orthopyx.	51.37	0.06	0.36	30.70	1.35	15.20	1.16	0.00
JJ92-1	Tdrđ	Orthopyx.	51.44	0.09	0.40	30.61	1.53	14.99	1.19	0.02
JJ92-1	Tdrd	Orthopyx.	51.60	0.12	0.56	29.08	1.21	16.02	1.22	0.02
JJ92-1	Tdrd	Orthopyx.	51.28	0.16	0.52	29.01	1.12	15.75	1.23	0.01

Appendix 3 (cont.)

PYROXE	ENE	Mineral:	SiO ₂	TiO ₂	Al ₂ O ₃	FeO	MnO	MgO	CaO	Na ₂ O
inclusion	Tdid	ClinoPyx	51.98	0.75	2.04	12.94	0.53	14.13	18.38	0.31
inclusion	Tdid	ClinoPyx	48.77	2.07	5.80	12.87	0.36	13.07	16.89	0.45
inclusion	Tdid	ClinoPyx	50.59	1.41	4.08	12.89	0.34	15.71	15.90	0.41
inclusion	Tdid	ClinoPyx	50.69	1.47	4.13	11.75	0.29	14.59	17.92	0.43
inclusion	Tdid	ClinoPyx	50.22	1.47	4.05	11.34	0.31	14.76	17.97	0.37
inclusion	Tdid	Orthopyx.	50.74	0.66	2.68	20.26	0.49	22.50	2.20	0.06
dacite	Tdid	Orthopyx.	53.59	0.57	2.13	17.82	0.45	24.93	2.00	0.05
dacite	Tdid	ClinoPyx	49.71	1.12	3.16	12.43	0.41	14.81	17.34	0.34
dacite	Tdid	ClinoPyx	50.36	1.05	3.09	10.96	0.34	14.83	18.73	0.39
dacite	Tdid	ClinoPyx	52.09	0.51	1.55	19.06	0.51	23.90	1.98	0.04
dacite	Tdid	ClinoPyx	50.11	0.94	2.92	13.23	0.46	14.35	17.07	0.29
dacite	Tdid	Orthopyx.	51.79	0.46	1.42	22.03	0.56	21.67	2.04	0.02
dacite	Tdid	Orthopyx.	53.29	0.43	1.29	18.79	0.49	24.29	1.87	0.05
dacite	Tdid	ClinoPyx	51.76	1.28	2.05	10.95	0.33	14.36	20.38	0.38
JJ93-130	Tdb1	ClinoPyx	50.37	1.13	1.57	11.38	0.33	14.35	19.43	0.35
JJ93-130	Tdb1	ClinoPyx	49.95	1.07	1.72	10.59	0.35	14.24	19.62	0.61

JJ93-130 Tdb1 Ilmenite 0.12 20.84 1.62 70.94 0.61 1.88 0.1 0.03

OLIVINE	2	Mineral	SiO ₂	TiO ₂ A	1203	FeO	MnO	MgO	CaO	NiO	ZnO	Total
JJ93-130	Tdb1	Olivine	35.36	0.02	0.01 3	36.62	0.71	27.80	0.27	0.01	0.10	100.90
JJ93-130	Tdb1	Olivine	36.17	0.03	0.00 3	30.90	0.37	32.63	0.18	0.07	0.01	100.36
JJ93-130	Tdb1	Olivine	35.95	0.00	0.00 3	32.66	0.52	30.90	0.16	0.07	0.03	100.29
JJ93-130	Tdb1	Olivine	35.55	0.04	0.00 3	35.00	0.56	29.09	0.16	0.03	0.10	100.53
JJ93-130	Tdb1	Olivine	34.83	0.07	0.00 3	37.89	0.64	26.21	0.11	0.03	0.03	99.81
JJ93-130	Tdb1	Olivine	35.20	0.07	0.00 3	36.02	0.55	27.87	0.16	0.01	0.00	99.88
JJ93-130	Tdb1	Olivine	35.10	0.06	0.00 3	36.33	0.54	27.87	0.15	0.06	0.00	100.11
JJ93-130	Tdb1	Olivine	36.01	0.03	0.00 3	32.89	0.47	30.56	0.18	0.05	0.10	100.29
JJ93-130	Tdb1	Olivine	35.76	0.03	0.00 3	32.65	0.53	30.53	0.17	0.08	0.00	99.75
JJ93-130	Tdb1	Olivine	35.55	0.05	0.00 3	34.35	0.48	29.04	0.14	0.03	0.00	99.64
JJ93-130	Tdb1	Olivine	35.55	0.02	0.00 3	33.31	0.55	30.18	0.19	0.05	0.03	99.88
JJ93-130	Tdb1	Olivine	35.34	0.03	0.00 3	34.39	0.57	28.97	0.17	0.07	0.10	99.64
JJ93-130	Tdb1	Olivine	35.02	0.04	0.00 3	35.83	0.63	27.81	0.16	0.02	0.00	99.51
JJ93-130	Tdb1	Olivine	34.79	0.06	0.00 3	87.58	0.65	26.24	0.09	0.00	0.05	99.46
JJ93-130	Tdb1	Olivine	34.95	0.06	0.00 3	37.52	0.71	26.45	0.10	0.04	0.01	99.84
JJ93-130	Tdb1	Olivine	34.74	0.06	0.00 3	37.86	0.71	26.02	0.15	0.03	0.10	99.67
JJ93-130	Tdb1	Olivine	34.41	0.07	0.00 3	88.08	0.66	25.44	0.07	0.02	0.03	98.78
JJ92-99	Tdb2	Olivine	36.24	0.03	0.00 3	30.93	0.33	32.20	0.18	0.08	0.01	100.00
JJ92-99	Tdb2	Olivine	36.20	0.03	0.00 3	31.87	0.43	30.87	0.15	0.07	0.11	99.73
JJ92-99	Tdb2	Olivine	35.32	0.05	0.00 3	34.77	0.49	28.86	0.18	0.10	0.02	99.79
JJ92-99	Tdb2	Olivine	34.53	0.12	0.00 3	9.04	0.53	23.26	0.12	0.01	0.08	97.69
JJ92-99	Tdb2	Olivine	36.05	0.01	0.00 3	31.32	0.40	31.45	0.15	0.05	0.05	99.48
JJ92-99	Tdb2	Olivine	35.69	0.04	0.00 3	32.69	0.40	30.35	0.17	0.06	0.01	99.41
JJ92-99	Tdb2	Olivine	35.43	0.05	0.00 3	34.87	0.44	28.85	0.18	0.07	0.03	99.92

Appendix 3 (cont)

OLIVINE	C	Mineral	SiO ₂	TiO ₂ A	A12O3	FeO	MnO	MgO	CaO	NiO	ZnO	Total
JJ92-99	Tdb2	Olivine	35.35	0.08	0.00	36.21	0.46	26.36	0.14	0.05	0.06	98.71
JJ92-99	Tdb2	Olivine	34.47	0.09	0.00	39.69	0.56	24.62	0.07	0.06	0.03	99.59
JJ92-99	Tdb2	Olivine	34.32	0.05	0.00	38.56	0.58	25.58	0.16	0.05	0.03	99.33
JJ92-99	Tdb2	Olivine	36.16	0.02	0.00	31.22	0.41	31.69	0.15	0.11	0.09	99.85
JJ92-99	Tdb2	Olivine	35.58	0.01	0.00	32.99	0.48	30.04	0.15	0.04	0.06	99.35
JJ92-99	Tdb2	Olivine	34.99	0.09	0.00	34.54	0.42	28.88	0.06	0.06	0.00	99.04
JJ92-99	Tdb2	Olivine	35.54	0.04	0.00	34.32	0.46	29.40	0.23	0.04	0.02	100.05
JJ92-99	Tdb2	Olivine	35.46	0.02	0.00	35.12	0.48	28.98	0.19	0.08	0.08	100.41
JJ92-99	Tdb2	Olivine	34.81	0.05	0.00	37.64	0.48	26.22	0.15	0.00	0.00	99.35
JJ92-99	Tdb2	Olivine	34.51	0.11	0.00	38.85	0.59	24.85	0.14	0.03	0.10	99.18

AMPHI	BOLE	SiO ₂	TiO ₂	Al_2O_3	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr_2O_3	F	CI
JJ92-5	Tdr1 Amph.	42.00	2.15	8.61	28.22	0.52	4.55	9.97	1.90	1.04	0.01	0.53	0.22
JJ92-5	Tdr1 Amph.	41.76	2.18	8.65	28.04	0.54	4.31	10.01	1.88	1.05	0.04	0.38	0.21
JJ92-5	Tdr1 Amph.	41.76	2.17	8.80	27.93	0.51	4.59	9.94	1.89	1.05	0.00	0.34	0.22
JJ92-5	Tdr1 Amph.	42.05	2.17	8.71	27.77	0.53	4.41	10.07	1.78	1.08	0.02	0.45	0.23
JJ92-5	Tdr1 Amph.	41.91	2.15	8.58	27.76	0.55	4.64	9.92	1.82	1.09	0.02	0.42	0.20
JJ92-5	Tdr1 Amph.	41.83	2.16	8.73	27.47	0.51	4.48	9.95	1.83	1.09	0.05	0.33	0.22
JJ92-5	Tdr1 Amph.	43.68	1.80	8.47	23.90	0.51	7.49	10.37	1.76	0.95	0.00	0.60	0.14
JJ92-5	Tdr1 Amph.	44.24	1.59	8.25	23.55	0.50	7.63	10.19	1.80	0.91	0.02	0.51	0.14
JJ92-5	Tdr1 Amph.	43.97	1.35	8.12	24.10	0.51	7.43	10.14	1.81	0.92	0.00	0.63	0.15
JJ92-5	Tdr1 Amph.	43.81	1.73	8.21	24.42	0.52	7.11	10.32	1.81	0.94	0.00	0.49	0.16
JJ92-5	Tdr1 Amph.	43.28	1.78	8.45	24.46	0.50	6.86	10.28	1.80	1.01	0.00	0.38	0.18
JJ92-5	Tdr1 Amph.	43.98	1.67	7.83	23.69	0.53	7.81	10.21	1.73	0.91	0.02	0.50	0.13
JJ92-5	Tdr1 Amph.	44.05	1.62	8.15	24.00	0.54	7.71	10.36	1.79	0.89	0.01	0.36	0.13

BIOTITE			SiO ₂	TiO ₂	A12O3	FeO	MnO	MgO	CaO	Na ₂ O	K ₂ O	Cr_2O_3	F	CI
JJ92-1 T	drd B	Biot.	37.63	5.84	13.63	20.39	0.08	11.82	0.00	0.58	9.08	0.05	0.78	0.08
JJ92-1 T	drd B	liot.	37.26	5.81	13.78	20.56	0.16	11.89	0.00	0.58	9.19	0.00	0.66	0.08
JJ92-1 T	drd B	Biot.	39.10	5.46	12.96	21.02	0.16	11.28	0.04	0.58	8.68	0.00	0.62	0.07

APPENDIX 4: XRF analyses of Steens Basalt collected near type section at Steens Mountain. Lower, middle, and upper denote relative outcrop location for 3 groups of flows in the >900-m-thick section. Collected by P.R. Hooper, C.J. Hawkesworth, and me. Analyst: Diane Johnson, GeoAnalytical Lab, WSU, Pullman, WA.

Sample No.	SiO ₂	Al2O	TiO ₂	FeO*	MnO	CaO	MgO	K ₂ O	Na_2O	P_2O_5	Cr	Ba	Rb	Zr	Y	Nb
MF63	49.71	16.27	2.23	11.19	0.17	9.26	6.96	0.88	3.02	0.32	160	243	12	161	30	14
MF64	49.85	18.39	2.09	9.84	0.16	10.62	5.03	0.60	3.14	0.29	189	238	8	150	27	13
MF65	49.45	14.71	2.03	11.49	0.18	9.18	8.89	0.89	2.85	0.33	500	263	15	151	28	14
MF66	49.34	14.32	1.81	11.06	0.18	9.88	10.09	0.64	2.45	0.23	650	203	11	132	26	10
MF67	50.24	14.77	2.32	11.81	0.18	10.23	6.51	0.79	2.87	0.28	296	205	12	165	31	13
MF68	50.90	16.09	1.96	9.76	0.17	10.32	7.01	0.69	2.87	0.23	274	175	15	138	29	11
MF69	49.43	14.77	1.81	10.37	0.17	10.28	9.82	0.56	2.58	0.21	463	148	12	127	26	11
MF70	49.88	18.11	1.97	9.53	0.16	10.42	6.01	0.59	3.04	0.29	153	196	11	140	25	12
MF71A	49.01	15.51	2.24	11.66	0.19	10.16	7.31	0.69	2.94	0.30	238	238	10	148	30	11
MF71B	48.91	16.55	2.22	11.24	0.18	10.13	6.64	0.69	3.14	0.31	183	242	7	159	30	12
JS 1	50.26	17.75	2.00	9.73	0.12	9.99	6.11	0.77	2.99	0.28	146	211	13	143	26	11
JS 2	50.15	14.66	1.94	10.63	0.18	10.60	8.57	0.66	2.39	0.23	489	187	12	138	26	10
JS 3	50.78	16.16	1.98	9.94	0.17	10.33	6.93	0.68	2.78	0.24	278	189	12	140	28	11
JS 4	49.06	14.35	1.79	10.89	0.18	9.99	10.66	0.57	2.31	0.21	461	136	10	126	25	10
JS 5	49.40	16.84	1.92	10.38	0.17	10.78	7.12	0.50	2.67	0.22	292	167	8	138	26	11
JS 6	50.42	16.44	2.04	9.96	0.17	10.65	6.66	0.67	2.76	0.23	281	178	12	140	28	11
JS 8	49.97	14.76	2.24	11.20	0.18	10.83	7.43	0.61	2.52	0.27	330	148	11	154	30	12
JS 9	50.16	14.92	2.20	11.15	0.17	10.63	7.31	0.70	2.52	0.25	329	143	16	154	31	12
JS10	48.93	14.71	2.49	11.99	0.19	11.08	7.33	0.54	2.48	0.26	276	106	8	165	32	15
JS11	48.03	15.79	1.80	10.96	0.17	10.74	9.79	0.28	2.26	0.18	424	66	3	122	25	10
MIDDLE FLO	ows															
JS31	49.25	16.56	1.90	11.09	0.19	9.69	7.46	0.70	3.14	0.23	137	262	13	130	31	7
JS32	53.67	16.30	1.80	9.52	0.16	7.85	4.68	1.96	2.74	0.48	84	584	47	181	32	14
JS33	52.39	15.98	2.10	10.55	0.19	8.10	4.89	1.75	3.61	0.49	66	593	35	183	33	14
JS34	51.05	16.19	2.02	10.59	0.19	8.76	6.20	1.22	3.59	0.40	76	444	20	157	34	12
JS36	50.19	15.54	2.10	11.45	0.19	9.15	6.09	1.11	3.43	0.37	107	386	19	156	36	10
JS37	51.26	16.08	2.65	11.71	0.19	8.13	5.46	1.50	3.29	0.52	84	473	31	211	37	15
JS38	50.00	15.10	2.51	12.22	0.20	8.99	5.55	1.26	3.52	0.46	95	415	22	190	38	13
JS39	50.13	15.41	3.63	12.94	0.22	8.27	5.24	1.47	3.39	0.60	58	497	26	223	39	17
JS40	49.01	14.26	2.96	13.35	0.21	8.62	5.69	1.23	3.65	0.55	85	430	18	205	40	16
UPPER FLOW	WS															
JS50	49.76	14.89	2.85	13.02	0.21	8.79	5.31	3.60	3.57	0.49	64	456	14	191	50	14
JS51	49.12	16.10	2.32	12.73	0.19	8.89	5.82	3.59	3.56	0.40	45	369	16	191	51	10
JS52	49.96	14.37	3.20	13.95	0.22	7.80	4.31	3.83	3.82	0.68	13	619	28	251	52	19
JS53	50.19	17.15	2.56	11.22	0.19	8.61	4.62	1.23	3.82	0.49	48	447	18	187	53	13
JS54	48.75	16.37	2.40	12.03	0.20	9.12	6.40	0.96	3.47	0.42	135	366	11	166	54	12
JS55	50.03	18.25	2.20	10.38	0.16	9.26	4.76	0.96	3.66	0.40	69	369	11	158	55	10
JS56	53.14	15.62	2.60	10.91	0.18	7.10	3.86	2.12	3.85	0.66	9	745	38	245	56	19
JS57	53.62	15.12	2.37	11.27	0.18	6.94	4.21	2.18	3.71	0.49	13	600	43	231	57	16
JS58	49.86	16.82	2.07	12.09	0.18	8.27	5.78	1.13	3.53	0.38	76	409	18	158	58	11

APPENDIX 5: Strontium and neodymium isotope data

The following isotope data are part of a reconnaissance study and are discussed only briefly in the text: Additional analyses are being received as this thesis is being completed; therefore critical analysis of the data will be included in later publications. Variation diagrams are presented in Figure A5-1 (next page).

Map Unit	Sample Number	⁸⁷ Sr/ ⁸⁶ Sr	¹⁴³ Nd/ ¹⁴⁴ Nd	
Tdrd	JJ92-1	0.70490	0.512553	<u> </u>
Tdr ₁	JJ92-4	0.70741	n.d.	
Qb ₂	JJ93-20	0.70508	0.512717	
Tdid (incl.)	JJ92-5 1	0.70494	0.512534	
Tdid	JJ92- 102	0.70483	0.512552	
Tdb_1	JJ93-130	0.70481	n.d.	

Analytical data were obtained on a Finigan 261 mass spectrometer using standard chemical preparation techniques. The Sr-isotope data are normalized to a value of 0.71022 for the international standard NBS 987. Two standard deviations on the mean of repeated analyses of the standard are 0.000036. The Nd isotopes represent initial values and have not been renormalized to a particular standard. n.d. indicates isotope not determined. Analyses were performed at The Open University, Milton Keynes, United Kingdom, under the supervision of C.J. Hawkesworth.



Figure A5-1: (A) Strontium and neodymium isotopes for DBEC samples listed in Appendix 5; (B) Steens basalt, "Steens-type" basalt (Tb), and DBEC samples plotted on 87 Sr/ 86 St vs Σ_{Nd} diagram; (C) Abundance of Sr, Rb, Sm, and Nd for DBEC samples. Values from Table 4-7.

APPENDIX 6:	Unnormalized	XRF	data	for	samples	in	Tables	4-7-4	-9.
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Sample	XRF	Map 1	Litho	o SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	lotal
No.	Lab	Unit	Тур	e										
JJ92-1	XRAL	Tdrd	L	67.70	0.53	14.00	3.04	0.07	0.77	2.10	3.46	4.62	0.17	96.46
JJ95-1iA	WSU	Tdrd	Qi	59.28	1.51	15.52	8.78	0.13	1.20	4.51	3.90	2.72	0.79	98.33
JJ95-1iB	WSU	Tdrd	Qi	58.79	1.40	15.30	8.26	0.17	1.37	4.62	4.26	2.90	0.87	97.44
JJ92-4	XRAL	Tdr ₁	0	75.80	0.11	12.70	1.17	0.04	0.04	0.66	3.71	5.03	0.02	99.27
JJ92-6	XRAL	\mathbf{Tdba}_1	L	51.20	2.05	15.60	10.62	0.18	4.14	7.03	3.59	2.10	0.72	97.22
JJ92-5	XRAL	Tdr1	L	73.50	0.11	12.60	1.25	0.04	0.10	0.64	3.45	4.98	0.04	96.71
JJ92-7	XRAL	Tdrd	L	67.80	0.51	14.10	2.92	0.07	0.65	1.91	3.63	4.78	0.14	96.50
JJ92-19	WSU	Tba	L	56.11	2.00	13.84	11.05	0.17	3.95	7.45	3.25	1.78	0.31	99.91
JJ92-20	WSU	Qb2	L	47.68	0.90	15.88	9.76	0.18	9.82	10.82	2.48	0.25	0.10	97.86
JJ92-27	XRAL	Tdba 1	L	58.50	1.41	14.80	7.76	0.14	2.97	5.42	3.64	3.08	0.43	98.14
JJ92-38	XRAL	Tdba ₂	D	52.50	2.05	15.60	10.62	0.18	4.15	6.99	3.36	2.10	0.72	98.26
JJ92-41	WSU	Tda1	L	61.25	1.31	15.77	6.11	0.13	2.52	5.26	3.82	3.23	0.32	99.72
JJ92-51	XRAL	Tdid	Qi	53.40	2.43	13.90	10.62	0.21	3.24	6.82	3.09	2.37	1.35	97.43
JJ92-59	XRAL	Ts?	L	50.10	2.51	14.90	11.88	0.18	4.85	8.55	3.14	1.21	0.39	97.70
JJ92-62	XRAL	Tdba ₃	L	54.60	2.10	14.50	10.53	0.18	4.02	6.42	4.08	2.40	0.50	99.32
JJ92-88	XRAL	Tdrd	L	68.00	0.53	14.10	2.92	0.07	0.65	2.00	3.64	4.98	0.15	97.04
JJ92-90	XRAL	Tr	L	73.60	0.06	12.50	0.78	0.05	0.03	0.69	4.08	4.39	0.02	96.19
JJ92-99	XRAL	Tdb ₂	L	50.10	1.71	16.70	10.17	0.17	5.47	8.71	3.53	1.26	0.69	98.50
JJ92-101	XRAL	Tdrd	L	67.20	0.54	14.50	2.86	0.08	0.64	1.86	3.93	4.96	0.17	96.74
JJ92-102	XRAL	Tdid	L	65.00	0.85	14.50	5.20	0.12	1.04	3.06	3.98	4.01	0.32	98.08
JJ93-123	WSU	Ttd	UT	75.51	0.20	11.05	2.65	0.05	0.00	0.30	4.03	5.27	0.02	99.08
JJ93-124	WSU	Tots	WT	75.79	0.23	10.20	4.47	0.07	0.00	0.21	4.90	4.63	0.01	100.51
JJ93-126	WSU	Tda ₂	L	60.36	1.16	15.64	6.88	0.14	2.62	5.42	3.88	2.92	0.32	99.34
JJ93-140	WSU	Tda ₂	L	59.54	1.12	15.64	7.09	0.13	3.02	5.63	3.72	2.82	0.30	99.01
JJ93-130	WSU	Tdb ₁	L	48.76	2.56	15.86	13.02	0.21	5.44	9.04	3.41	0.87	0.69	99.86
JJ93-133	WSU	Tba	L	56.53	2.01	14.58	9.48	0.16	4.11	7.99	3.41	1.45	0.30	100.01
JJ93-134	WSU	Tba	L	61.93	1.06	16.58	5.57	0.11	2.24	5.29	4.00	2.97	0.37	100 12
JJ93-147	WSU	Tad	L	58.85	2.32	14.01	10.07	0.15	1.92	5.30	3.88	2.23	0.56	99.28
JJ94-151	WSU	Ob ₁	L	50.14	1.15	17.21	9.62	0.18	8.48	11.32	2.86	0.35	0.15	101 45
JJ94-158	WSU	Tdr ₂	L	77.24	0.08	13.21	1.16	0.04	0.00	0.77	4 06	5.01	0.01	101.45
JJ94-161	WSU	Thas	L	55.20	2.13	15.53	10.60	0.19	3 19	6 3 5	3.82	2 53	0.01	101.30
JJ94-163	WSU	Tbs	L	49.84	2.49	15.50	12.22	0.17	5.62	8.78	3.21	1.23	0.74	99.81
FF94-23	WSU	Tb	L	50.69	2.06	16.58	11.08	0.17	5.67	10.43	3.09	0.61	0.25	100 63
FF94-36	WSU	Tba	L	51.00	1.95	15.80	12.09	0.17	6.11	9.45	3.26	0.58	0.25	100.62
FF94-39	WSU	Tha	L	60.07	2.03	13.84	10.38	0.16	2.35	5.69	3.82	2.20	0 20 1	101.00
FF94-49	WSU	Ts	L	49.53	1.96	17.25	12.11	0.18	5.83	9.03	3.48	0.84	0.30	100.51
JN94-16	WSU	Tdr ₂	L	76.15	###	0.07	0.86	0.07	1.12	0.00	4.62	4.40	0.02 1	01.49

L = lava; Qi = quenched inclusion; O = obsidian; D = dike; UT = unwelded tuff; WT = welded tuffXRAL = XRAL Laboratories, British Columbia; WSU = GeoAnalytical Lab, Washington StateUniversity, Pullman Washington.

Sample #	Map Unit	Q	С	Or	Ab	An	Di	Hy	Ol	Mt	11	Ap
JJ92-1	Tdrd	23.4	0.0	27.3	29.3	9.0	0.2	5.0	0.0	1.0	1.0	0.4
JJ92-4	Tdr1	32.9	0.0	29.7	31.4	3.1	0.0	1.5	0.0	0.4	0.2	0.1
JJ92-5	Tdr1	32.3	0.5	29.4	29.2	2.9	0.0	1.7	0.0	0.4	0.2	0.1
JJ92-7	Tdird	22.5	0.0	28.3	30.7	8.1	0.4	4.4	0.0	0.9	1.0	0.3
JJ92-6	Tdba1	0.4	0.0	12.4	30.4	20.3	8.2	16.8	0.0	3.4	3.9	1.7
JJ93-19	Tba	8.0	0.0	10.5	27.5	17.9	14.1	14.0	0.0	3.6	3.8	0.7
JJ93-20	Qb2	0.0	0.0	1.5	21.0	31.5	17.4	6.6	15.1	3.2	1.7	0.2
JJ92-27	Tda1	9.1	0.0	18.2	30.8	15.0	7.6	11.5	0.0	2.5	2.7	1.0
JJ92-38	Tdba2	2.8	0.0	12.4	28.4	21.3	7.2	17.4	0.0	3.4	3.9	1.7
JJ92-41	Tda1	11.5	0.0	19.1	32.3	16.4	6.3	9.1	0.0	2.0	2.5	0.8
JJ92-51	Tdid-incl	7.9	0.0	14.0	26.1	17.1	6.6	14.8	0.0	3.4	4.6	3.2
JJ92-59	Ts?	1.2	0.0	7.2	26.6	23.0	13.9	16.6	0.0	3.8	4.8	0.9
JJ92-62	Tdba3	1.7	0.0	14.2	34.5	14.2	11.9	14.5	0.0	3.4	4.0	1.2
JJ92-88	Tdrd	21.9	0.0	29.4	30.8	7.4	1.3	4.0	0.0	0.9	1.0	0.4
JJ92-90	Tr	31.2	0.0	26.0	34.5	2.8	0.4	0.9	0.0	0.3	0.1	0.1
JJ92-99	Tdb2	0.0	0.0	7.5	29.9	26.0	10.4	10.9	6.0	3.3	3.3	1.6
JJ92-101	Tdrd	19.7	0.0	29.3	33.3	7.3	0.7	4.2	0.0	0.9	1.0	0.4
JJ92-102	Tdid	17.5	0.0	23.7	33.7	9.9	2.7	6.7	0.0	1.7	1.6	0.8
JJ93-126	Tda2	10.5	0.0	17.3	32.8	16.6	6.8	10.4	0.0	2.2	2.2	0.8
JJ93-130	Tdb1	0.0	0.0	5.1	28.9	25.4	12.3	10.6	7.2	4.2	4.9	1.6
JJ93-133	Tba	8.3	0.0	8.6	28.9	20.2	14.4	12.3	0.0	3.1	3.8	0.7
JJ93-134	Tas	12.3	0.0	17.6	33.8	18.5	4.4	9.0	0.0	1.8	2.0	0.9
JJ93-140	Tda2	9.8	0.0	16.7	31.5	17.7	6.9	11.6	0.0	2.3	2.1	0.7
JJ93-147	Tad	12.6	0.0	13.2	32.8	14.2	7.1	10.6	0.0	3.3	4.4	1.3

Appendix 7: CIPW normative minerals for select rocks of study area

Q = quartz; C = corundum; Or = Orthoclase; Ab = albite; An = anorthite; Di = diopside; Hy = hypersthene; Ol = olivine; Mt = magnetite; Il = ilmenite; Ap = apatite

Appendix 8: Complete ⁴⁰Ar/³⁹Ar analytical data.

The following tables were received after the thesis was prepared. Weighted mean ages may differ slightly from those in the thesis. The plagioclase age for the rhyodacite of Duck Creek Butte, JJ92-1, is presented here for the first time.

Lab ID#	Temp.	Ca/K	³⁶ Ar/ ³⁹ Ar	4	⁴⁰ Ar*/ ³⁹ Ar	% ⁴⁰ Ar*	Age (Ma)
	°C or Watts		%(-	³⁶ Ar/ ³⁹ Ar)	Ca		±lσ
<u></u>					<u> </u>	· · · · · · · · · · · · · · · · · · ·	
Sample JJ	93-20 (whole	e-rock bulk	incremental	heating,	furnace)		
8238-01A	600	25.5	17.9	0.0	34.23	0.6	86 ± 226
8238-01B	700	24.8	0.102	3.4	0.714	2.4	1.84 ± 0.52
8238-01C	800	21.7	0.0104	29.2	0.444	16.8	1.15 ± 0.07
8238-01D	875	13.3	0.0074	25.2	0.536	24.6	1.39 ± 0.07
8238-01E	1000	13.3	0.0093	20.0	0.614	21.7	1.58 ± 0.08
8238-01F	1100	17.8	0.0159	15.7	0.598	13.0	1.54 ± 0.15
8238-01G	1200	21.6	0.0239	12.6	0.558	8.2	1.44 ± 0.22
8238-01H	1400	221	0.0723	42.8	0.740	5.3	1.91 ± 0.45
8238-011	1650	228	0.238	13.4	0.606	0.9	1.56 ± 3.77
Sample 1192-5 (sanidine single-crystal laser-fusion)							
7494-01	t f	0 017	0.00005	4 5	1 734	99.2	10.37 ± 0.04
7494-02	t.1.	0.017	0.00009	2.5	1 719	98.5	10.28 ± 0.04
7494-02	t f	0.019	0.00030	0.8	1 733	95.2	10.20 ± 0.04 10.37 ± 0.05
7494-03	t f	0.016	0.00006	37	1 732	99.0	10.37 ± 0.03 10.36 + 0.04
7494-05	t.1. t f	0.017	0.00008	3.0	1 722	98.7	10.30 ± 0.01
7494-06	t f	0.016	0.00009	2.5	1.718	98.6	10.28 ± 0.04
7494-07	t.f	0.017	0.00006	3.9	1.726	99.1	10.33 ± 0.04
7494-08	t.r. tf	0.015	0.00008	2.6	1.711	98.7	10.24 ± 0.05
7494-09	t.r. tf	0.016	0.00008	2.8	1 715	98.7	10.26 ± 0.04
7494-10	t.f.	0.018	0.00004	6.2	1.736	99.4	10.39 ± 0.04
Sample II	92-1 aliquot	#1 (biotite)	bulk laser inc	remental	heating)		
8150 01 A		0.157		0.2	0.826	10.8	750 ± 0.43
8159-01A	0.0	0.137	0.01130	0.2	1.000	52.2	7.30 ± 0.43
8150 01C	0.8	0.120	0.00341	0.5	1.055	52.5	9.97 ± 0.21
8150-01D	1.5	0.074	0.00202	0.5	1.133	82.5	10.43 ± 0.10 10.40 ± 0.05
8159-01D	23	0.035	0.00068	0.5	1 147	85.2	10.40 ± 0.05
8150-01E	2.5	0.040	0.00063	1.5	1 141	86 1	10.35 ± 0.05
8159-01G	3.0	0.063	0.00047	1.8	1 148	89.5	10.33 ± 0.00 10.41 ± 0.05
8159-01U	3.5	0.005	0.00031	1.6	1 1 4 4	927	10.41 ± 0.05 10.38 ± 0.04
8159_01I	6.0	0.033	0.00034	1.0	1 1 5 2	94 4	10.36 ± 0.04 10.45 ± 0.04
8159-01J	8.6	0.069	0.01090	0.1	0.574	15.1	5.21 ± 0.27
Sample II	02 1 aliquot	#2					
Sample JJ	22-1 aliquor	π	0.00097	0.1	1 004	0 0 <i>(</i>	11.10 . 0.40
8159-02A	0.6	0.055	0.00987	0.1	1.224	29.6	11.10 ± 0.40
8159-02B	0.8	0.081	0.00259	0.4	1.212	61.4	10.99 ± 0.30
8159-02C	1.3	0.034	0.00155	0.3	1.105	/1.8	10.57 ± 0.12
8159-02D	1.9	0.016	0.00084	0.3	1.151	82.3	10.44 ± 0.05
8159-02E	2.3	0.020	0.00063	0.4	1.140	80.1	10.39 ± 0.05
8159-02F	2.0	0.048	0.00058	1.1	1.138	80.9	10.32 ± 0.05
8159-02G	5.0	0.055	0.00047	1.0	1.149	89.3	10.42 ± 0.06
8159-02H	3.3	0.033	0.00031	1.4	1.155	92.8	10.45 ± 0.05
8159-02I	0.0	0.034	0.00028	1.7	1.153	93.5	10.45 ± 0.04
8139-02J	8.0	0.040	0.00042	1.5	1.142	90.3	10.36 ± 0.13
			(cont'd.)			

Lab ID#	Temp.	Ca/K	³⁶ Ar/ ³⁹ Ar		⁴⁰ Ar*/ ³⁹ Ar	% ⁴⁰ Ar*	Age (Ma)
	°C or Watts		%(³⁶ Ar/ ³⁹ A	r) _{Ca}		±1σ
Comple II	[02 1 -1;		-1 411- 1)	
Sample JJ	192-1 anquot #	FI (plagio	clase bulk las	er increi	mental neaur	1g)	
7443-01A	1.0	3.71	0.0501	1.0	13.97	48.8	9.84 ± 0.25
7443-01B	3.0	5.98	0.0075	11.2	14.70	88.2	10.35 ± 0.08
7443-01C	6.0	6.16	0.0124	7.0	15.86	82.3	11.16 ± 0.08
7443-01D	7.6	5.90	0.0062	13.3	15.16	90.5	10.67 ± 0.07
7443-02A	1.0	3.52	0.0365	1.3	15.81	59.8	11.13 ± 0.38
7443-02B	3.0	4.87	0.0048	14.2	15.30	92.6	10.77 ± 0.05
7443-02C	6.0	5.01	0.0288	2.4	15.63	65.2	11.00 ± 0.09
7443-02D	7.6	5.39	0.0017	45.4	15.43	98.3	10.86 ± 0.10
7443-03A	1.0	2.66	0.0437	0.9	14.39	52.9	10.13 ± 0.16
7443-03B	3.0	6.00	0.0069	12.2	15.77	89.8	11.10 ± 0.08
7443-03C	6.0	6.12	0.0153	5.6	18.89	81.5	13.28 ± 0.08
7443-03D	7.6	6.17	0.0044	19.7	16.01	93.9	11.26 ± 0.17
7443-04A	1.0	3.23	0.0387	1.2	15.24	57.4	10.73 ± 0.20
7443-04B	3.0	5.40	0.0046	16.3	14.85	92.8	10.45 ± 0.06
7443-04C	5.0	5.66	0.0017	45.6	15.34	98.2	10.79 ± 0.07
7443-04D	7.6	5.15	0.0030	23.6	15.16	95.7	10.66 ± 0.10

Notes: Errors in age quoted for individual runs are 1σ analytical uncertainty. 't.f.' indicates total fusion. Weighted averages are calculated using the inverse variance as the weighting factor (Taylor, 1982), while errors in the weighted averages are 1σ standard error of the mean (Samson and Alexander, 1987). Ca/K is calculated from ${}^{37}\text{Ar}/{}^{39}\text{Ar}$ using a multiplier of 1.96. ${}^{40}\text{Ar}^*$ refers to radiogenic argon. $\lambda = 5.543 \times 10^{-10} \text{ y}^{-1}$. Isotopic interference corrections: $({}^{36}\text{Ar}/{}^{37}\text{Ar})_{\text{Ca}} = 2.74 \times 10^{-4} \pm 1 \times 10^{-6}$, $({}^{39}\text{Ar}/{}^{37}\text{Ar})_{\text{Ca}} = 7.02 \times 10^{-4} \pm 2 \times 10^{-6}$, $({}^{40}\text{Ar}/{}^{39}\text{Ar})_{\text{K}} = 7 \times 10^{-4} \pm 3 \times 10^{-4}$. For sample JJ93-20, J=0.001432 ± .000005; for sample JJ92-5, J = 0.003326 ± 0.000001; for sample JJ92-1 biotite, J = 0.005042 \pm 0.000015; for sample JJ92-1 plagioclase, J = 0.0003912 \pm 0.000001. Data for sample JJ93-20 were acquired at the New Mexico Bureau of Mines and Mineral Resources (Socorro); all other data were acquired at the Berkeley Geochronology Center (Berkeley). Irradiations were performed in the CLICIT facility of the Oregon State University TRIGA reactor.





Da Ta 1 7 -	Tdr1 To 2 Taba1	Tdid rd Tba	Tara Tara Tara Tara Tara Tara Tara Tara
Tyts	Younger tuffaceous sedimentary strata (Miocene)-Poorly	Tdb	Basalt of Duck Pond Ridge (Miocene)—Coarsely plagioclase-phyric [Following eight units
	indurated laminated to massive tuffaceous sedimentary rocks, including ash and sandstone form gentle slopes and are exposed only in stream-cut walls and road cuts. Thickness ranges from less than 2 m to more than 15 m		intergranular olivine basalt. Phenocrysts include plagioclase (20-25 percent as large as 3 cm) and microphenocrysts of olivine (7-10 percent, up to 0.6 mm in diameter). Thickness ranges from 2 to 7 m. Similar in hand specimen to the coarsely porphyritic flows of the Steens Basalt percent feat
[Foll	owing 12 units are part of Duck Creek Butte eruptive center] Rhyolite of Big Gulch (Miocene)—Stony, devitrified, aphyric flow- banded rhyolite similar in composition to the rhyolite of Indian Creek	Tdba2	Basaltic andesite dike (Miocene)—Glassy basaltic andesite contains a microscopic disequilibrium assemblage of plagioclase (oligoclase), clinopyroxene, Fc-Ti oxides, orthopyroxene, biotite, and trace amounts of olivine in a light- and dark-brown banded glassy matrix. Similar in composition to Tdba ₁ Tad Andesite breccia composed andesite in gray with g
	Buttes (Tdr ₁). Stratigraphic relations are difficult to determine owing to talus-covered contacts with Steens Basalt. Age relation to Steens Basalt assumes faulted contact. Alternatively, the rhyolite is older than 16 Ma and does not fit the younging silicic age progression	Tdba ₁	Olivine-bearing basaltic andesite (Miocene)—Dark-gray, vesicular, porphyritic lava flows. Characterized by incipiently altered glassy groundmass and contains 15 percent phenocrysts of plagioclase (1 to 4 mm long) and microphenocrysts of olivine (3 percent, up to 0.5 mm across) and Fe-Ti oxides (2 percent, up to 0.5 mm) The second secon
Tdr	Rhyolite of Indian Creek Buttes (Miocene)—Aphyric to sparsely porphyritic homogeneous flows of high-silica rhyolite. Includes devitrified, glassy, and poorly developed vapor-phase zones. Phenocrysts, found chiefly in the capping flows, include gray or pink quartz (≤1 percent, up to 1 mm in diameter), sanidine (≤1 percent, up to 3 mm long), and hornblende (rare, up to 3 mm long). Maximum thickness of individual flows is about 60 m; maximum total thickness is 135 m. Sanidine yielded a ⁴⁰ Ar/ ³⁹ Ar age of 10.32±0.04 Ma	Tdid	Inclusion-rich dacite (Miocene)—Sparsely porphyritic lava flows. Contains 5 to 25 percent quenched basaltic andesite magmatic inclusions. Dacitic matrix is aphanitic and contains 3-5 percent microphenocrysts of plagioclase, Fe-Ti oxides, orthopyroxene, and clinopyroxene. The basaltic andesite inclusions, which range from 2 mm to 7 cm in diameter, are fine grained, intersertal, and vesicular. The inclusions are composed of 20-40 percent glass, 40-50 percent plagioclase (up to 0.8 mm long), 20 percent orthopyroxene and clinopyroxene (up to 0.5 mm long), 5 percent Fe-Ti oxides (0.05-1TosBasalt to 5 percent basalt of Stocka porphyritic plagioclase
Tdba ₃	Basaltic andesite of Brokendown Waterhole (Miocene)—Dark- gray, fine-grained, vesicular lava flows. Comprises plagioclase (50- 55 percent, up to 1 mm long), clinopyroxene (12-15 percent, up to 0.2 mm long), olivine (4-6 percent, up to 0.3 mm in diameter), Fe-	Tdrd	mm), 3 percent apatite (up to 0.1 mm in diameter), and rare olivine. Vesicles are concentrated in the glassy rim. Thickness averages 15 m; maximum thickness is 60 m Rhvodacite of Duck Creek Butte (Miocene)—Biotite- and present are
Tdaa	Ti oxides (4 percent, up to 0.5 mm), and clay-altered glass (20-25 percent). Maximum thickness is 30 m composed of 2- to 4-m-thick lava flows Andesite of Duck Creek (Miocene)—Porphyritic lava flows. Contains		plagioclase-rich flows of glassy to stony lava. Rock comprises 7 to olivine and exposed sloped slope
	5-9 percent phenocrysts of subhedral to anhedral fresh plagioclase commonly 1 cm (rarely to 3 cm) long and 1 percent rusty speckles of iddingsitized olivine from 0.5 to 1 mm in diameter in a charcoal-gray aphanitic groundmass. Maximum thickness is 30 m		distinguished from each other chiefly by textural changes from the vitric, brecciated base, upward through stony, devitrified central zones to an upper vitrophyre. Flows range in thickness from approximately 3 to more than 10 m. Maximum estimated thickness mm in dia
Tda ₁	Andesite of Duck Creek Spring (Miocene)—Dark-gray, very fine grained lava flows. Contains 2-3 percent phenocrysts of plagioclase, olivine, and clinopyroxene 1 to 2 mm in diameter. Maximum thickness is 30 m		is 180 m, but base is not exposed and the upper part has been eroded. Biotite yielded a ⁴⁰ Ar/ ³⁹ Ar age of 10.38±0.04 Ma. Divided locally into: Tots Older tuff and Volcanich
Tdb ₂	Fine-grained basalt (Miocene)—Platy to massive flows of dark-gray, fine-grained, ophitic basalt. Phenocrysts include plagioclase (8-9 percent, 5 mm) and olivine (1-2 percent, 3 mm); groundmass comprises 70 percent plagioclase, 15 percent clinopyroxene, 10	Tarap	grained bedded ash and lapilli deposit (composed of 1-2 percent black silicic scoria to 3 cm in diameter, 2 percent angular chips of black rhyodacite, and about 1 percent clear crystals in an ash matrix) > 1m thick, and a poorly sorted, matrix-s ported block-and-ash flow thick is approached block of theorem in an ashy
	percent olivine, and 5 percent Fe-Ti oxides. Maximum thickness is 60 m		deposit is composed chiefly of blocks of thyodache fill an asity steens Basait (with thick



Description of map units and cross section of the Duck Creek Butte eruptive center

redate the Duck Creek Butte eruptive center]

A' FEET

I Butte (Miocene)—Very light gray to pinkish gray ous stony rhyolite lava with 8-10 percent crysts of alkali feldspar, quartz, and hornblende in a vitified glassy groundmass. Also contains less than 0.5 hery sericite (muscovite?) preferentially aligned along flow als are commonly bent, strained, and fractured

likes of Dick Creek (Miocene)—Brecciated dikes of angular blocks of aphanitic to sparsely porphyritic an altered andesite matrix. Clasts are medium- to darkayish-red streaking. Form ribs as high as 6 m and ranges m wide and 3 to 10 m long

dier Creek (Miocene)—Unwelded to moderately nice- and lithic-rich tuff. Varies from tan to pale-orange gray. Rock comprises 30 to 50 percent pumiceous lapilli where welded), 3-20 percent mafic lithic fragments, and 3 clear crystals. Maximum thickness is 10 m

de Creek (Miocene)—Distinctive black mottled basalt. Rock comprises 2 to 25 percent blocky phenocrysts (average 1.5 cm). In less porphyritic egacrysts ranging in size from 4 to 9 cm are locally About 7 m thick where it overlies older tuff and tuffaceous rocks (Tots). Elsewhere the unit is at least 30 m thick, exposed

ite (Miocene)—Very fine grained, aphyric to finely basalt, basaltic andesite, and andesite. Fine-grained rocks gioclase, clinopyroxene, and Fe-Ti oxides. Sporadically olivine and sideromelane. Uncommon small flows of plagioclase phyric basalt cap the unit. Includes poorly pe-forming deposits composed of unconsolidated to poorly ad sedimentary strata that include the tuff of Oregon

(Miocene)—Fine-grained, medium-gray, porphyritic, basalt with phenocrysts of plagioclase (5 to 10 percent, ong) and microphenocrysts of olivine (1 percent, to 0.5 neter). Although the porphyritic basalt represents a single s generally less than 3 meters thick, maximum thickness hudes underlying slope-forming sedimentary unit

tuffaceous sedimentary rocks (Miocene) stic sedimentary deposits. Generally included with the andesite unit (Tba), except for where it is well exposed. stal air-fall equivalent of the tuff of Oregon Canyon d McKee, 1984)

ocene)—Lava flows of medium- to dark-gray, aphanitic porphyritic olivine basalt and basaltic andesite. Varies nitic to coarsely porphyritic, laterally continuous lava age 2 m thick. Maximum exposed thickness is 200 m; exposed. Age is about 16.5 Ma on basis of ⁴⁰Ar/³⁹Ar ninations on plagioclase (Swisher and others, 1990)



