U.S. DEPARTMENT OF THE INTERIOR
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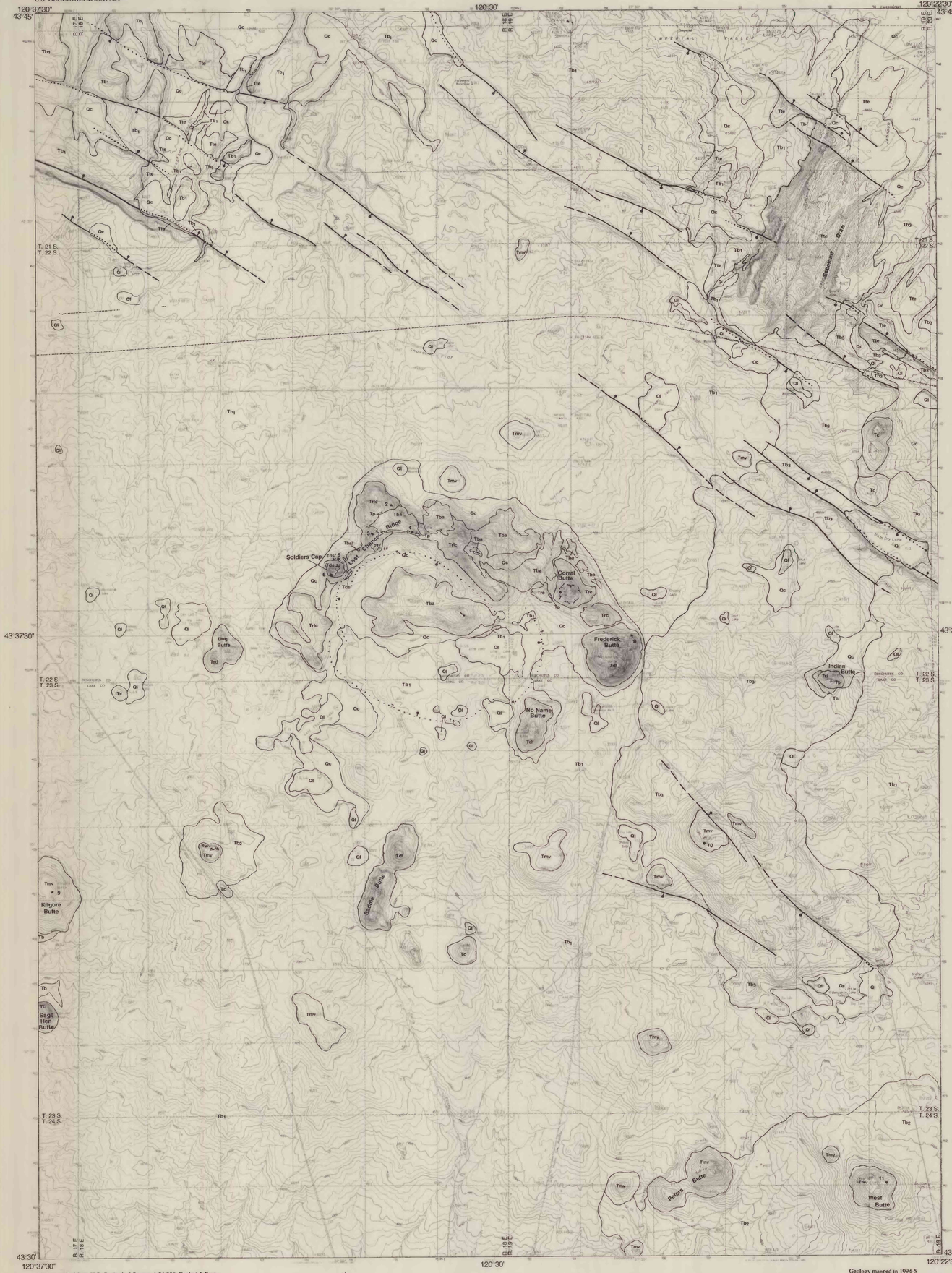


Base compiled from U.S. Geological Survey, 1:24,000: Frederick Butte, Imperial Valley South, Last Chance Ridge, and Soldiers Cap, 1983

Lambert Conformal Conic projection

UTM GRID AND 1980 MAGNETIC NORTH DECLINATION AT CENTER OF SHEET

The scale of this map is 1:40,000

1 KILOMETER
1 MILE
1000 0 1000 2000 3000 4000 5000 6000 7000 FEET

CONTOUR INTERVAL 10 FEET
SUPPLEMENTARY CONTOUR INTERVAL 5 FEET

OREGON
QUADRANGLE LOCATION

# GEOLOGIC MAP OF THE FREDERICK BUTTE VOLCANIC CENTER, DESCHUTES AND LAKE COUNTIES, SOUTH-CENTRAL OREGON

By

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Geology mapped in 1994-5
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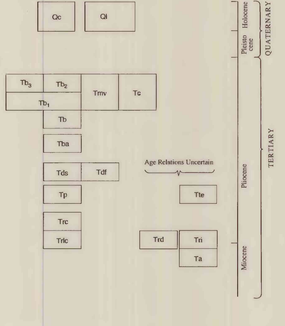
## CORRELATION OF MAP UNITS




## DESCRIPTION OF MAP UNITS

**Qc** **Colluvium and alluvium (Holocene and Pleistocene)**—Undifferentiated subangular to angular sand and gravel forms thin mantle on slopes and drainages

**Qt** **Lake deposits (Holocene and Pleistocene)**—Unconsolidated silt, sand, and gravel deposited in ephemeral lake beds

**Basalt (Pliocene)**—Medium-gray vesicular to massive lava flows. Ranges from moderately porphyritic to aphyric. Divided into:

**$Tb_3$** **Porphyritic basalt**—Fine-grained to very fine-grained dikty taxitic olivine basalt. Erupted from small shield volcano about 60 m high in southeast part of map area (sec. 16, T. 23 S., R. 19 E.) and flowed mostly to north. Covers about 65 $km^2$ in map area, but the flow extends northeast beyond map area. Flows average 4 m thick. Phenocrysts include euhedral plagioclase, 1–4 mm, 15–20 percent; and olivine, 1 mm, 3–7 percent. Groundmass, which is chiefly intergranular to subophitic or intersertal near vent, comprises plagioclase, clinopyroxene, and Fe-Ti oxides. Contains about 50.2 percent $SiO_2$ (No. 10, figs. 1 and 2; table 1). Normal-polarity magnetization. $^{40}Ar/^{39}Ar$ whole-rock age is 4.19 ± 0.42 Ma (R.A. Duncan, unpub. data)

**$Tb_2$** **Fine-grained basalt**—Consists of medium-gray aphyric to slightly porphyritic finely vesicular lava flows. Erupted from prominent shield volcanoes at Peters, West, Kilgore, and Trail Buttes. Covers about 30 $km^2$ in map area, but much of unit extends beyond map area. Most flows contain olivine phenocrysts ≤ 2 mm, about 1 percent. Capping flows at West Butte, however, have sparse phenocrysts of plagioclase as large as 5 mm. Kilgore and West Buttes lava contain about 49.7 and 48.5 percent $SiO_2$ respectively (Nos. 9 and 11, figs. 1 and 2; table 1). Flows from West Butte possess normal-polarity thermal remanent magnetization

**$Tb_1$** **Olivine basalt**—Vesicular to massive, fine- to very fine-grained dikty taxitic olivine-basalt lava flows. Some flows are moderately porphyritic, with 1–2 percent subhedral olivine, 1–2 mm; and 1–2 percent subhedral plagioclase, 1–3 mm. Ophitic groundmass is composed of plagioclase, clinopyroxene, olivine, and Fe-Ti oxides. Covers most of map area surrounding the Frederick Butte eruptive center, at least 300 $km^2$. Similar in composition to the porphyritic and fine-grained basalt (No. 1, figs. 1 and 2; table 1). Attempts to measure remanent magnetization at five sites were not definitive owing to conflicting results. Considered younger than the dacite of Frederick Butte because no dark, coarse dacitic pumice (unit Tp) is found overlying it. Overlies tuff of Espeland Draw (unit Tte)

**Tc** **Cinder vent deposits (Pliocene)**—Basaltic agglomerate, cinder, scoria, and spatter that form cones and irregular piles. Ranges from medium gray to brick red. Marks vents for basalt lava flows (unit $Tb_1$)

**Tmv** **Mafic vent structures (Pliocene)**—Locally vented lava flows that form small, steep-sided shield volcanoes. Marks vents for porphyritic, fine-grained, and olivine basalt units ($Tb_1$, $Tb_2$, and $Tb_3$)

**Tb** **Quenched basalt (Pliocene)**—Grayish-black to black glassy aphyric basalt lava. Top of flow is exposed between Kilgore and Sage Hen Buttes (sec. 25, T. 23 S., R. 17 E.)

**Tba** **Basaltic andesite (Pliocene)**—Light- to medium-gray porphyritic basaltic andesite lava flows commonly with reddish iron-oxide staining around small vesicles. Erupted from dikes along Last Chance Ridge and on northeast and west flanks of Frederick Butte eruptive center. Flows drape north- and northeast-facing slopes of Last Chance Ridge. Also erupted from vent complex in the central depression of the eruptive center. Flows range from 2 to 8 m thick and have a maximum composite thickness of 45 m, but base is not exposed. Contains phenocrysts of subhedral to anhedral plagioclase, seriate to 3 mm long, 2–8 percent; anhedral clinopyroxene to 2 mm across, less than 1 percent; and sparse olivine, less than 0.5 mm across. Glassy to very fine-grained pilotaxitic groundmass has abundant finely disseminated Fe-Ti oxides. Fine-grained inclusions less than 1 cm across are composed of plagioclase, Fe-Ti oxides, and clinopyroxene. Compositionally the basaltic andesite is the least evolved member of rocks erupted at the Frederick Butte eruptive center (Nos. 3 and 4, figs. 1, 2, and 3; table 1). Overlies rhyolite of Last Chance Ridge (Trc) and may overlie pumice-fall deposits (Tp). Interpreted to be youngest lava flow of the Frederick Butte eruptive center. Magnetic polarity not measured

**Tds** **Dacite of Soldiers Cap (Pliocene)**—Glassy to devitrified porphyritic dacite lava. Unit is 40 m thick and varies from highly altered to stony devitrified platy rocks in the upper part of the unit, to a lower, 15–20-m-thick section composed of discontinuous irregular layers of pumiceous and glassy agglomerate. Lower agglomerate preceded but was quickly followed by lava flows. Phenocrysts and microphenocrysts include subhedral and embayed to euhedral reversely and normally zoned plagioclase commonly with sieve texture, 0.5–2 mm in length, 7–10 percent; anhedral clinopyroxene, 0.5–1 mm across, commonly with high-relief inclusions, including Fe-Ti oxides; subhedral to euhedral orthopyroxene, 0.3–0.5 mm, 1–2 percent; and Fe-Ti oxides, 0.3–0.5 mm; 1–2 percent. Also contains less than 1 percent magmatic inclusions 1–2 mm in diameter composed of fine-grained plagioclase. The dacite of Soldiers Cap is compositionally and mineralogically similar to the dacite of Frederick Butte (No. 6, figs. 1, 2, and 3; table 1). Trace-element models suggest that the dacite may be derived from the basaltic andesite (Tba) and the rhyolite of Last Chance Ridge (Trc) (figs. 3 and 4). Pale-gray pumice clasts weathering out beneath the north side of Soldiers Cap are rhyolitic in composition (No. 5, figs. 1 and 2; table 1). If these are erosional clasts from the basal agglomerate, the initial eruption of the dacite was of mixed-magma composition; alternatively they may have been related to late eruption of either the rhyolite of Last Chance Ridge or the rhyolite of Dog Butte. This pumice is not part of the pumice-fall deposits (Tp). The dacite of Soldiers Cap overlies the rhyolite of Last Chance Ridge

**Tdf** **Dacite of Frederick Butte (Pliocene)**—Medium-gray to light-orange-gray porphyritic dacite lava. Flows average 4 m thick with combined thickness of over 160 m at Frederick Butte; base is not exposed. Rock varies from incipiently devitrified glassy flows to stony devitrified platy flows. Phenocrysts and microphenocrysts include seriate plagioclase, to 5 mm in length (largest crystals, 3–5 mm, are anhedral to subhedral, reversely and normally zoned, and commonly contain clinopyroxene and melt inclusions dispersed throughout, or confined to discrete zones near the margins), 7–15 percent; clinopyroxene 0.1–0.25 mm (uncommon larger crystals to 1 mm are attached to plagioclase as glomerocrysts), 3–5 percent; Fe-Ti oxides to 0.2 mm, 1–2 percent; and sparse orthopyroxene, 0.3–0.5 mm. The dacite of Soldiers Cap is compositionally and mineralogically similar to the dacite of Frederick Butte (No. 10, figs. 1, 2, 3, and 4; table 1). Overlies the rhyolite of Corral Butte. A K-Ar age of 4.0 ± 0.4 Ma was obtained from plagioclase from the dacite (Walker, 1974; recalculated by Fiebelkorn and others, 1982). May be as much as 0.5 million years older on basis of recent analyses of previously dated rocks on the High Lava Plains by $^{40}Ar/^{39}Ar$ method (A. L. Grunder, oral commun.)

**Tp** **Pumice-fall deposits (Pliocene)**—Concentrations of pumice lapilli that vary from light yellowish brown to dark yellowish brown on the weathered surface, and a dark yellowish brown on fresh internal surface are found in protected areas above the rhyolites of Last Chance Ridge, Corral Butte, and Indian Butte. Pumice is not found on the basaltic andesite (Tba) but is found around the base of that unit. The roughly equant clasts are 2–7 cm in diameter and contain up to 3 percent plagioclase as large as 5 mm and sparse green clinopyroxene as large as 1 mm. May be related to the eruption of the tuff of Espeland Draw. No chemical analyses were performed on the pumice. Pale pumice clasts found on north side of Soldiers Cap are not part of this unit

**Tte** **Tuff of Espeland Draw (Pliocene)**—Massive pumice-, lithic- and crystal-rich ash-flow tuff. Varies from pale-grayish orange pumice-rich unwelded, to purplish-gray moderately welded. Maximum thickness in the map area is 30 m; base not exposed. The moderately welded zone exposed in the northeast corner of the map area has glassy to very fine grained lithic fragments that average 2 cm in diameter but are as large as 15 cm, up to 10 percent; flamme as long as 40 cm, flattened 4:1; and subhedral to euhedral plagioclase up to 4 mm in length, 4–5 percent. An unwelded zone exposed in the northwest corner of the map area has dark brown and tan pumice to 3 cm in diameter, 15–20 percent; lithics to 1 cm across, 3–5 percent; and plagioclase to 5 mm, 2–3 percent. A thin section of the moderately welded tuff collected 5 km north of the map area showed a depletion in lithics, pumice, and phenocrysts relative to the rock in Espeland Draw. The groundmass is incipiently devitrified brown glass shards. Lithic fragments include ophitic to intersertal fine-grained porphyritic basalt, angular fragments to 3 mm across, 3 percent; and irregularly shaped chips of very fine grained quartz with diffuse grain boundaries and 1–3 percent brown glass, up to 2 mm across, less than 1 percent. Phenocrysts and microphenocrysts include subhedral to anhedral plagioclase, 0.5–3 mm long, 4–5 percent; subhedral olivine, <1 mm, 0.5 percent; green subhedral clinopyroxene, to 0.7 mm, 0.5 percent; anhedral Fe-Ti oxides, to 0.5 mm, 0.5 percent. Chemical analyses from pumice collected 5 km north of the map area indicate that both dacite and low-silica rhyolite compositions are present (fig.1; table 2; M.J. Streck, unpub. data, 1993). Trace-element analyses (figs. 3 and 4) indicate that the tuff may be related to rhyolite pumice and dacite flows from the Frederick Butte complex as suggested by Walker and Nolf (1981). The unit laps onto older extrusive and intrusive rocks of Hampton Buttes north of the map area. The tuff of Espeland Draw was referred to as the "ash-flow tuff near Hampton Butte" (Walker, 1970; MacLeod and others, 1976; Walker and Nolf, 1981) and informally as the Hampton Tuff or tuff of Buckaroo Lake (MacLean, 1994). Informal mapping of outcrop of the tuff by M. J. Streck (fig. 5; oral commun., 1995) indicates the tuff covered at least 1,200 $km^2$; however lateral extent of the tuff is obscured by regionally extensive capping olivine basalt flows. Plagioclase collected from the tuff near Hampton Buttes yielded a K-Ar age of about 3.7 ± 0.6 Ma (Walker, 1974; recalculated by Fiebelkorn and others, 1982)

**Trc** **Rhyolite of Corral Butte (Pliocene)**—Pale-gray porphyritic rhyolite lava. Weathers tan to pale reddish gray and mottled with 5–7 percent rusty specks. Flows that form Corral Butte are platy and dip uniformly toward center of the hill where the unit is about 150 m thick. Contains subhedral to euhedral sodic feldspar phenocrysts 1–2 mm across, 3–4 percent; and sparse olivine microphenocrysts. Microcrystalline to glassy groundmass is composed of subparallel laths of plagioclase and finely disseminated Fe-Ti oxides. Outcrop adjacent to Corral Butte on southeast side is more altered and has sugary stony appearance. Glass collected near the base of Corral Butte (No. 7, fig. 1, 2, and 3; table 1) indicates a slightly less evolved rhyolite than the rhyolite of Last Chance Ridge. Unit is older than the dacite of Frederick Butte

**Trd** **Rhyolite of Dog Butte (Pliocene)**—Devitrified stony aphyric platy rhyolite that varies in color from pale tannish gray to pinkish gray. Steep-sided outcrop is more than 45 m thick; base not exposed

**Trfc** **Rhyolite of Last Chance Ridge (Pliocene or Miocene)**—Sparsely to moderately porphyritic rhyolite lava with sugary to dusty luster. Although much of the rhyolite is mantled by talus, the unit is probably more than 100 m thick, forming the arcuate Last Chance Ridge; base is not exposed. Phenocrysts include subhedral to euhedral sodic feldspar, 1–2 mm, 1–3 percent; and rare pink quartz to 1 mm. Varies from perlitic with 5–50 percent spherulitic alteration to cryptocrystalline devitrified stony flows. Spherulites commonly stand out in relief and have reddish-brown shells that constitutes 10–25 percent of the radius; envelope grades abruptly to pale-gray radial center. Some flows contain thin flow layering with lithophysae 0.5–2 cm across rounded to partially flattened parallel to flow layers, with secondary quartz in the voids. Pebbles of obsidian collected from a discrete horizon in the unit have 77 percent $SiO_2$ (No. 2, figs. 1, 2, and 3; table 1). Overlain by the dacite of Soldier Cap and the basaltic andesite

**Tri** **Rhyolite of Indian Butte (Pliocene or Miocene)**—Pale-gray to pinkish-gray devitrified porphyritic rhyolite lava weathers tan to reddish orange. Unit is about 40 m thick and covers less than 0.1 $km^2$. Contains plagioclase to 4 mm, 3–5 percent; sparse clinopyroxene, 1 mm; and secondary rusty metallic speckles to 1 mm across. Overlies the andesite (Ta) and is overlain by the pumice-fall deposit (Tp)

**Ta** **Andesite (Pliocene or Miocene)**—Platy lava flows of sparsely porphyritic very fine-grained dark-gray andesite with centimeter-scale partings are exposed beneath the west margin of Indian Butte. Unit is more than 4 m thick; base is not exposed. Contains phenocrysts of plagioclase, 0.5–2 mm long, 1–2 percent; and sparse orthopyroxene, to 1.5 mm long. Abundant scoria mantles the lower part of the south-facing slope of Indian Butte and may be a related, poorly exposed cinder cone

Contact Approximately located

Fault Approximately located, dotted where concealed. Ball and bar on downthrown side

2 * Rock sample locality Refer to table 1 for analytical data; figure 2 for location

Strike and dip of layering in lava flows; orientation of platy flows

Vent location for unit Tbs

Pumice boundary Pumice lapilli up to 2 cm in diameter mantles unconsolidated soil north of latitude 43°42'30" (See Geologic Summary)

## GEOLOGIC SUMMARY

The Frederick Butte eruptive center lies in south-central Oregon along the northwest margin of the Basin and Range Province on the High Lava Plains (fig. 5). The High Lava Plains consists of middle Miocene to Holocene volcanic rocks confined to a 250-km-long by 50-km-wide tract in southeastern Oregon (Walker, 1969). The region is characterized by silicic vents that are progressively younger to the northwest (MacLeod and others, 1976) that provide a mirror image to the eastward-youngingg Snake River Plain-Yellowstone hotspot trend. The 4-Ma dacite of Frederick Butte lies in the western quarter of this chain of silicic vents, which range in age from 10.4 Ma at Duck Creek Butte (Johnson, 1995), 200 km east-southeast of Frederick Butte, to 0.6 Ma at Newberry volcano (MacLeod and Sherrod, 1992) 60 km west-northwest. Like those on the Snake River Plain, the High Lava Plains silicic centers are surrounded by younger basalt flows similar to those that occur throughout the region.

Bedrock in the map area consists entirely of locally erupted Miocene and Pliocene volcanic rocks that range in composition from basalt to rhyolite (Walker and others, 1967; Walker and MacLeod, 1991). Unconsolidated Quaternary sedimentary and volcaniclastic deposits blanket slopes and topographically low areas.

The Frederick Butte eruptive center is a semicircular structure composed of rhyolite, dacite, and basaltic andesite lava flows. The oldest flows consist of thick sequences of high-silica rhyolite of unknown age that may originally have formed a subcircular domal mass.

Caldera collapse of the central portion of the eruptive center (fig. 6) is tentatively interpreted to have occured during, or closely following, the violent eruption that created the tuff of Espeland Draw. Speculation on this source area for the tuff is based on the semicircular constructional edifice, thinning of the tuff away from Frederick Butte, and compositional similarity of pumice from the tuff to the dacite and rhyolite lavas (figs. 1, 3, and 4). Timing is inferred on the basis of typical caldera models. Pliocene to Holocene volcanic and sedimentary deposits obscure most field relations.

Thick porphyritic dacite lava flows of Frederick Butte and Soldiers Cap may have may have been emplaced along ring fractures following collapse of the caldera, possibly forming a broad multidomed complex that included Soldiers Cap, Frederick Butte, No Name Butte, and Saddle Butte.

The tuff of Espeland Draw (Tte) possesses a similar K-Ar age (3.7 ± 0.6 Ma), within error, to the dacite of Frederick Butte (4.0 ± 0.4 Ma) (Fiebelkorn and others, 1982). Recent $^{40}Ar/^{39}Ar$ ages obtained from silicic rocks along the High Lava Plains indicate that absolute ages could be as much as 0.5 m.y. older than previous K-Ar ages (A. L. Grunder, oral commun., 1994). Major- and trace-element analyses of the dacite of Frederick Butte and Soldiers Cap, and a rhyolite pumice from beneath the dacite of Soldiers Cap, are similar to dacite and rhyolite pumice collected from the tuff (figs. 1 and 3; tables 1 and 2). Trace-element ratio diagrams based on the calculations of Langmuir and others (1978) indicate a relatively good fit between rhyolite (Trfc and Tc) and basaltic andesite (Tba) to produce the dacite (Tdf and Tds) of the Frederick Butte eruptive center (fig. 4). Chemical differences between the lava and pumice can be explained by the fact that the dacite lava is porphyritic and the pumice is chiefly glass. The mineralogy of the dacitic units and the tuff is also similar.

Following collapse of the caldera, basaltic andesite lava erupted both in the depression and from ring dikes on Last Chance Ridge to flow down the north slope of Last Chance Ridge. This marked the end of volcanic activity associated with the silicic eruptive center.

Within 0.5 m.y., regionally extensive vent- and fissure-fed olivine basalt flooded the area, leaving the silicic centers as discrete steptoes (kipukas). These relatively homogeneous primitive lavas, characterized by $Al_2O_3$>16 weight percent, MgO>8.9 percent, $CaO/Al_2O_3$ ~0.7, and Cr ≥ 200 ppm are present throughout southeastern Oregon with no obvious age progression (Hart and Mertzman, 1982; Hart and others, 1984; MacLeod and Sherrod, 1992; Johnson, 1995).

Topographically low areas in the northern part of the map area are discontinuously mantled with millimeter- to centimeter-sized pinkish-gray to very light gray pumice clasts on yellowish-gray unconsolidated soil north of latitude 43°42'30". The map area lies on the ~25-cm-isopach trajectory for pumice fall from Newberry volcano (Walker and MacLeod, 1991) that is estimated to be about 1,600 $^{14}C$ yr B.P. (Spaker and others, 1978). Some of the pumice may also have been derived from eruptions of Mt. Mazama that formed Crater Lake (7.6 ka, Bacon, 1983).

## STRUCTURAL SETTING

The dominant structural feature of the north half of the map area is the northwest-striking Brothers fault zone (fig. 5). These en echelon normal faults, which offset Miocene and Pliocene basalt, do not offset any Quaternary lava flows from Newberry volcano (MacLeod and Sherrod, 1992). The fault zone, which is slightly oblique relative to the more westerly trend of silicic vents, separates more highly extended crust to the south from less-extended crust to the north (Walker, 1974; Lawrence, 1976). The faults are interpreted to represent a transform boundary that terminates Basin and Range extension against the Blue Mountains (Lawrence, 1976; Walker and Robinson, 1990). Extensive Pliocene basalt flows may bury older faults of the Basin and Range Province.

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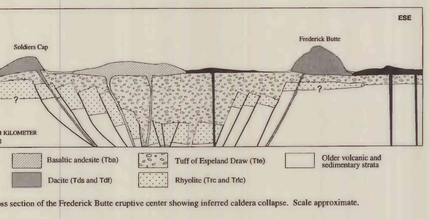


**Figure 5:** Physiographic provinces of Oregon with inset of High Lava Plains. Long-dashed oblong indicates approximate track of northwest-trending age progression of silicic vents (modified from MacLeod and others, 1976).




**Figure 6:** Schematic WNW-ESE cross section of the Frederick Butte eruptive center showing inferred caldera collapse. Scale approximate.

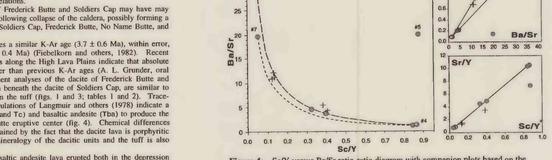


**Figure 2:** Map locations for XRF analyses in Table 1

**Table 1:** Chemical analyses from rocks and pumice in the map area. BL samples are of pumice from the tuff of Espeland Draw collected five kilometers north of the map area (M.L. Streck, unpub. data, 1993). Major-element analyses are normalized to 100 percent with all iron as $Fe^{2+}$. Original oxide totals shown.

| Map # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | Pumice from tuff of Espeland Draw | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Sample | FB94-63 | FB94-10 | FB96-81 | FB94-16 | FB94-12 | FB94-15 | FB94-19 | FB94-24 | FB96-80 | FB94-26 | FB94-52 | BL-46a | BL-46b | BL-46d | BL-46e | BL-46f |
| Map unit | $Tb_1$ | Trfc | Tba | Tba | Tte? | Tds | Trc | Tdf | Tmv | $Tb_3$ | $Tb_2$ | pumice | pumice | pumice | pumice | pumice |
| Major-element analyses, normalized water-free (weight percent) | | | | | | | | | | | | | | | | |
| $SiO_2$ | 49.27 | 77.05 | 55.35 | 55.28 | 74.59 | 66.28 | 74.45 | 67.74 | 49.58 | 50.19 | 48.64 | 65.96 | 67.45 | 72.49 | 72.74 | 72.78 |
| $Al_2O_3$ | 16.72 | 12.54 | 15.72 | 15.72 | 13.43 | 15.06 | 13.13 | 14.76 | 17.34 | 17.86 | 17.72 | 14.23 | 14.24 | 13.76 | 13.32 | 13.39 |
| $TiO_2$ | 1.41 | 0.11 | 1.66 | 1.66 | 0.22 | 0.83 | 0.19 | 0.75 | 1.31 | 0.99 | 0.78 | 0.57 | 0.53 | 0.27 | 0.25 | 0.27 |
| FeO* | 9.34 | 1.22 | 9.39 | 9.71 | 2.18 | 5.48 | 2.36 | 4.51 | 9.34 | 8.38 | 8.59 | 5.83 | 5.52 | 2.92 | 3.20 | 3.23 |
| MnO | 0.17 | 0.03 | 0.19 | 0.18 | 0.08 | 0.14 | 0.08 | 0.10 | 0.18 | 0.14 | 0.16 | 0.18 | 0.18 | 0.10 | 0.10 | 0.10 |
| CaO | 11.26 | 0.72 | 8.00 | 8.00 | 0.92 | 3.44 | 0.99 | 3.33 | 10.46 | 10.43 | 11.80 | 3.52 | 3.27 | 1.19 | 1.61 | 1.55 |
| MgO | 8.11 | 0.00 | 4.11 | 3.85 | 0.21 | 0.95 | 0.00 | 1.25 | 8.27 | 8.30 | 9.50 | 0.78 | 0.52 | 0.12 | 0.20 | 0.21 |
| $K_2O$ | 0.35 | 3.91 | 1.25 | 1.12 | 4.14 | 2.59 | 3.34 | 2.97 | 0.24 | 0.38 | 0.12 | 2.90 | 2.77 | 4.66 | 4.45 | 4.42 |
| $Na_2O$ | 3.10 | 4.41 | 3.78 | 3.92 | 4.18 | 4.96 | 5.46 | 4.39 | 3.09 | 3.12 | 2.60 | 4.32 | 4.15 | 3.32 | 3.86 | 3.86 |
| $P_2O_5$ | 0.28 | 0.01 | 0.55 | 0.57 | 0.05 | 0.26 | 0.01 | 0.21 | 0.20 | 0.21 | 0.08 | 0.17 | 0.20 | 0.13 | 0.25 | 0.16 |
| Original oxide total | 99.06 | 101.07 | 99.94 | 100.24 | 99.02 | 100.65 | 101.03 | 100.45 | 100.04 | 101.44 | 99.95 | 98.46 | 98.83 | 98.96 | 99.98 | 99.97 |
| Trace-element analyses (parts per million) | | | | | | | | | | | | | | | | |
| Ni | 139 | 8 | 1 | 8 | 10 | 2 | 11 | 10 | 124 | 164 | 150 | 9 | 6 | 11 | 9 | 12 |
| Cr | 191 | 2 | 1 | 32 | 0 | 0 | 0 | 9 | 145 | 236 | 69 | 9 | 2 | | 3 | 3 |
| Sc | 37 | 2 | 32 | 32 | 7 | 20 | 4 | 14 | 39 | 33 | 48 | 22 | 23 | 10 | 10 | 9 |
| V | 206 | 4 | 269 | 240 | 5 | 16 | 1 | 63 | 213 | 211 | 204 | 3 | 2 | 4 | 1 | 4 |
| Ba | 241 | 1053 | 564 | 496 | 1149 | 913 | 1161 | 897 | 201 | 206 | 97 | 986 | 1143 | 1164 | 1183 | 1165 |
| Rb | 3 | 96 | 19 | 20 | 77 | 58 | 94 | 71 | 2 | 5 | 2 | 55 | 59 | 69 | 70 | 70 |
| Sr | 279 | 35 | 388 | 392 | 58 | 242 | 59 | 192 | 257 | 397 | 166 | 226 | 211 | 96 | 105 | 106 |
| Zr | 108 | 143 | 155 | 160 | 305 | 255 | 365 | 225 | 94 | 90 | 56 | 314 | 327 | 461 | 433 | 438 |
| Y | 28 | 45 | 37 | 38 | 8 | 30 | 36 | 43 | 28 | 22 | 21 | 56 | 60 | 76 | 71 | 71 |
| Nb | 5.6 | 9.4 | 9.9 | 12 | 15 | 16.2 | 18.8 | 12.2 | 4.3 | 5.1 | 2.5 | 14.7 | 15.3 | 18.9 | 17.5 | 18.5 |
| Cu | 41 | 11 | 58 | 57 | 14 | 2 | 4 | 10 | 63 | 88 | 50 | 14 | 14 | 10 | 5 | 7 |
| Zn | 75 | 33 | 96 | 95 | 76 | 94 | 99 | 67 | 77 | 65 | 57 | 110 | 108 | 53 | 93 | 93 |
| Pb | 0 | 13 | 3 | 4 | 14 | 13 | 12 | 9 | 1 | 2 | 0 | 16 | 22 | 10 | 14 | 16 |
| La | 15 | 38 | 33 | 26 | 49 | 34 | 19 | 16 | 14 | 14 | 0 | 13 | 36 | 30 | 31 | 34 |
| Ce | 28 | 49 | 42 | 47 | 69 | 48 | 86 | 64 | 19 | 37 | 22 | 38 | 55 | 70 | 67 | 66 |
| Th | 2 | 8 | 3 | 1 | 8 | 6 | 9 | 0 | 2 | 0 | 0 | 5 | 6 | 7 | 6 | 8 |

Data are from Diane Johnson at the GeoAnalytical Lab at Washington State University, Pullman, WA.

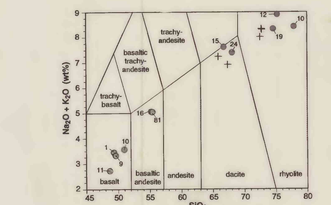


**Figure 1:** Chemical analyses of whole-rock and pumice samples plotted on a total alkali-silica classification diagram of Le Bas and Streckeisen (1991). Circles represent analyses from map area; crosses represent analyses of pumice from the tuff of Espeland Draw (unpub. data from M. L. Streck, 1993.)




**Figure 4:** Sc/Y versus Ba/Sr ratio-ratio diagram with companion plots based on the calculations of Langmuir and others (1978) for the Frederick Butte rhyolite, dacite, and basaltic andesite ( ), and pumice collected from the tuff of Espeland Draw ( ). Long dashed line indicates mix between basaltic andesite (4) and the rhyolite of Last Chance Ridge (2); short dashed line indicates mix between basaltic andesite (4) and the rhyolite of Corral Butte (7)

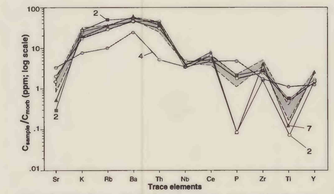


**Figure 3:** Spider diagram of the Frederick Butte rhyolite, dacite, and basaltic andesite (lines with circles) and pumice from the tuff of Espeland Draw (gray area enclosed in dashed line). Dacite of FB falls within pumice field. Number indicates map number. Normalization factors from Pearce (1983)