

Cedar Butte and Cogenetic Quaternary Rhyolite Domes of the Eastern Snake River Plain

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INTRODUCTION

The Eastern Snake River Plain (ESRP) is well known for voluminous Quaternary eruptions of olivine tholeiite basalt lavas and subordinate evolved mafic lavas (e.g., at Craters of the Moon) from Pliocene through Holocene time (e.g., Kuntz et al., 1992; Hackett and Smith, 1993; Leeman, 1982a; Hughes et al., 1997). Interlayered with, and intruding the basalts are topographically and petrologically distinctive high-silica rhyolite domes, lava flows, pyroclastic deposits, plug-like cryptodomes and laccoliths (Spear and King, 1982; Leeman, 1982b; McCurry et al., 1997). These include one of the largest Quaternary rhyolite domes in the world, Big Southern Butte (Spear, 1979; Kuntz and Kork, 1978).

Quaternary rhyolites are diachronous with and petrologically and geochemically distinguished from voluminous Tertiary rhyolite ignimbrites and lavas that underlie Quaternary basalts in the same area (e.g., Leeman, 1982a; Morgan et al., 1984; Hughes et al., 1997; Spear, 1979). Most are located on a northeast-trending, curvilinear topographic high, the axial volcanic zone (AVZ; Hackett and Smith, 1992), near the center of the ESRP (Fig. 1). Similar Quaternary rhyolite domes occur 130 km to the southeast, in the middle of the Blackfoot volcanic field (Fiesinger et al., 1982), and may also form the cores of laccoliths (i.e. Ferry Butte; Blackfoot Dome) along the southern margin of the ESRP near Blackfoot, Idaho (Hauser, 1992). Taken together, these rocks define a broad southeast-trending zone of widely distributed rhyolite volcanoes and hypabyssal intrusions, extending from the center of the ESRP, across the southern margin of the plain, into the middle of the Blackfoot volcanic field (Fig. 1).

This field trip focuses on field, petrological and geochemical features of Quaternary rhyolites and spatially and temporally as-

sociated, more mafic rocks along the AVZ (Fig. 1). First we will examine the easternmost of several prominent, large rhyolite domes (East Butte), and then examine rhyolitic and consanguineous intermediate and mafic rocks at Cedar Butte volcano (Fig. 2). Points of discussion are to include:

1. How and why are the Quaternary rhyolites distinguished in their geochemical and petrological characteristics from their slightly older, late Tertiary counterparts?
2. Are the rhyolites and coeval basalts compositionally bimodal, or do intermediate composition rocks occur as well?
3. What is the origin of the rhyolites? Are the rhyolites crustal melts, or are they the products of extreme fractionation of a mantle-derived parent?
4. Why do the rhyolites have the spatial distribution they do? Why don't similar rhyolites occur along other parts of the Yellowstone-Snake River Plain volcanic track?

FIELD TRIP GUIDE

Begin at Cavanaugh's Hotel, Exit 71 on Interstate Highway I-15, in Pocatello, ID. Proceed 22 miles north on I-15 to Blackfoot. Take the Highway 26 exit north towards Arco and the Idaho National Engineering and Environmental Laboratory (INEEL). Continue north for 35 miles to the intersection with Highway 20. Note young-looking basalt in road-cuts 5.3 to 6.2 miles north of the I-15 intersection; this is a distal lobe of the voluminous 5.2 ka Hells Half Acre lava flow (Kuntz et al., 1992; Karlo, 1977). At the Highway 20 intersection turn right (east) toward Idaho Falls; 9.2 miles east of the intersection you will note a large sign on the south side of Highway 20 describing the geology of "Three Buttes." Another 3.3 miles east you will pass the exit to "Argonne

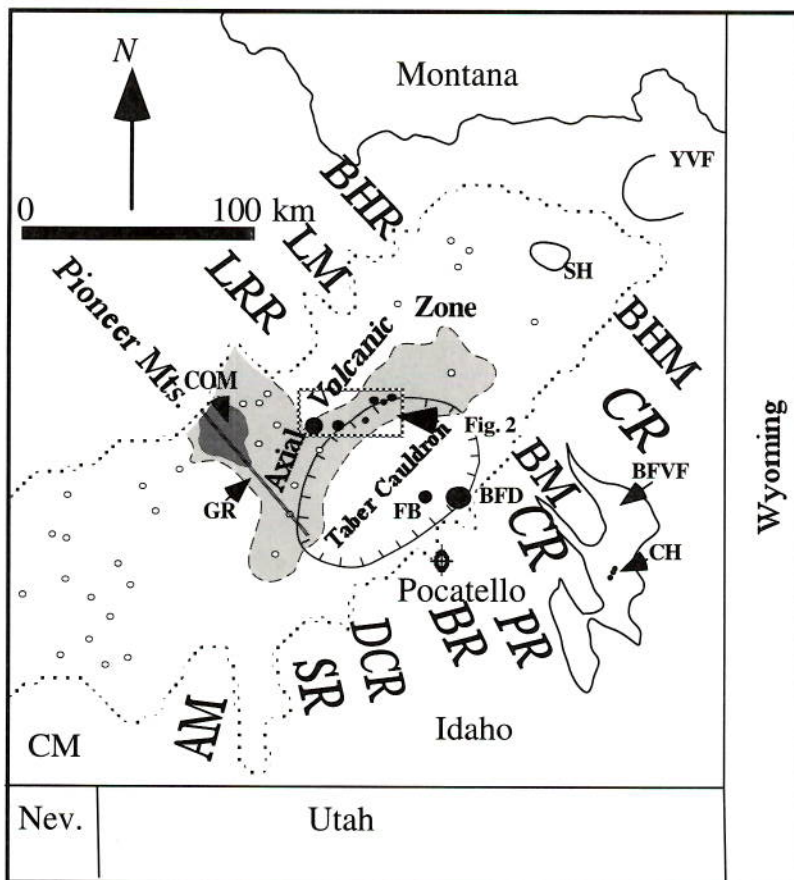


Figure 1. Location map and geologic setting of the Eastern Snake River Plain. Light shaded area represents a broad, gentle topographic high which straddles part of the Great Rift (GR), and axial portions of the ESRP. The axial part of the high is referred to by Hackett and Smith (1992) as the "Axial Volcanic Zone". Broad stippled line = outline of the eastern Snake River Plain; open circles = large basaltic shields; filled circles = rhyolite domes, flows, and laccoliths. Ranges peripheral to the plain are: LRR, Lost River Range; LM, Lemhi Mountains; BHR, Beaverhead Mountains; CM, Cassia Mountains; AM, Albion Mountains; SR, Sublett Range; DCR, Deep Creek Range; BR, Bannock Range; PR, Pocatello Range; CR, Chesterfield Range; BM, Blackfoot Mountains; CR, Caribou Range; BHM, Big Hole Mountains. Other abbreviations: FB, Ferry Butte; BFD, Blackfoot Dome; SH, Sand Hills; YVF, Yellowstone Volcanic Field. Taber Calderon is an inferred caldera associated with the eruption of the 10.2 Ma Arbon Valley Tuff (Kuntz et al., 1992; Kellogg et al., 1994).

National Laboratory West" (towards the north of the highway). Continue for another 0.9 miles to the east and look along the right (south) side of Highway 20 for a subtle intersection with a gravel road. Reset your odometer to zero.

NOTE: As soon as you turn off Highway 20 you are on restricted INEEL property. You must have proper identification and prior clearance from the INEEL in order to proceed.

Proceed south past intimidating-looking signs stating "Dangerous Road Ahead, Unauthorized persons are trespassers." At 1.4 miles there is a fork in the road, bear left. At 4.0 miles you will begin the ascent of a steep, rugged road (4-wheel-drive is

recommended) up the east flank of East Butte. Continue for another 1.2 miles until you have reached the southern (highest) peak on East Butte. Note that near the summit the road divides into two; take the left (southern) branch to a small parking area near some large antennas.

STOP 1. Overview of the "Axial Volcanic Zone".

- Compare and contrast Quaternary rhyolites of the ESRP with Tertiary rhyolites occurring in the same area.
- Geology of East Butte and Unnamed Butte

The axial volcanic zone (AVZ; Hackett and Smith, 1992), is a broad, roughly linear topographic high extending 150 km down the center of the ESRP. The high is constructional rather than structural in origin, having been produced by an unusually high concentration of basaltic vents (Kuntz et al., 1992). Figure 1 illustrates the shape of the topographic high interpreted from a GIS digital terrain elevation map. Note that the high is actually slightly curvilinear, and circumscribes the northwest part of the inferred Miocene Taber and southern parts of inferred calderas of the Heise Volcanic Field Caldera (Kuntz et al., 1992; Morgan et al., 1984). Kuntz et al. (1992) suggest that volcanic vents along the high resulted from preferred emplacement along some of the caldera boundary faults and north-west-trending rifts zones.

Dominating the southwest view from field trip Stop #1, along the AVZ, is Big Southern Butte, an enormous, high-silica-rhyolite cumulodome which formed at 300 ka (Spear, 1979; Spear and King, 1982; Kuntz et al., 1992). This dome rises 760 meters above its surroundings, and extends another 900 meters into the subsurface (Fishel, 1993). The dome evolved from a rhyolite sill, which was emplaced near the Quaternary basalt-Tertiary rhyolite contact. Continued injection of viscous rhyolite magma into the sill caused it to expand into a laccolith, and then ruptured the roof rocks, producing the present dome. Darkish-colored rocks on the north flank are remnants of the basalt cap.

Other prominent buttes to the southwest include Cedar Butte and Middle Butte. Cedar Butte, in front of and slightly to the left of Big Southern Butte (as viewed from Stop 1), is a broad shield, capped by a large tephra cone.

Flows, tephra and hypabyssal rocks range from basaltic trachyandesite to rhyolite in composition.

Middle Butte, six kilometers to the west, is capped by south-tilted (by 10°), olivine tholeiite lava flows (Spear, 1979). The flows are unusually old, compared to their surroundings (Fig. 2). Kuntz and Dalrymple (1979) and Spear (1979) both infer that the basalt cap has been uplifted by intrusion of a shallow, plug-like mass of rhyolite. Kuntz and Dalrymple (1979) refer to unpublished gravity and magnetic data by Don Maybe (USGS), that indicates the core of Middle Butte consists of rock that is less dense and less magnetic than basalt.

The subtle "mound" located ~1 km southwest of the base of East Butte is another rhyolite dome referred here to as "Unnamed

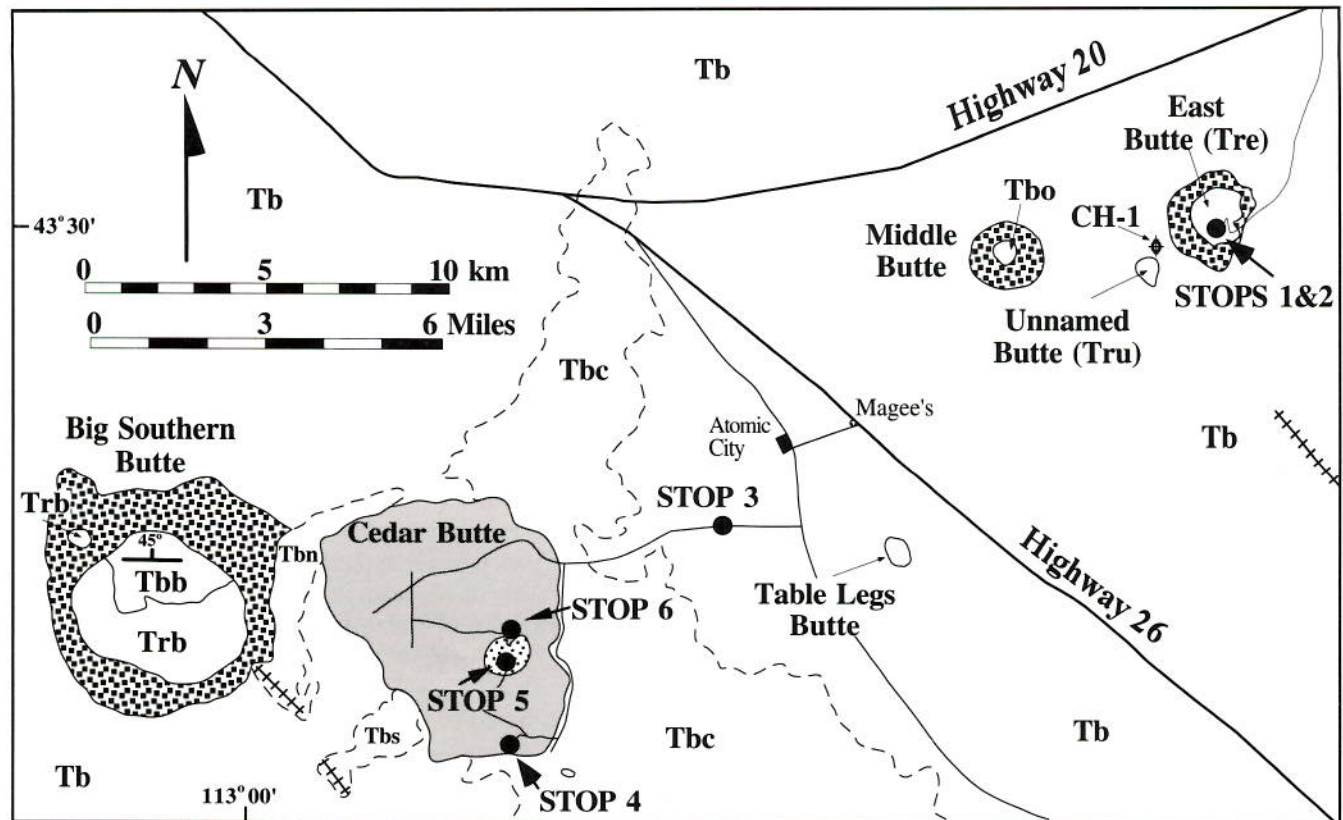


Figure 2. Simplified geologic map of salient geologic features near field trip stops (modified after Kuntz et al., 1994). Coarse stipple = debris fans surrounding East, Middle and Big Southern Buttes; light shade = Cedar Butte shield (400 ka); light stipple = tephra cone; Tbo = middle Quaternary (1.1 Ma) basalt capping Middle Butte; Tb = late Quaternary (mostly 100 to 350 ka) basaltic lava flows; Tbc = Quaternary lava flows uplifted along the north flank of Big Southern Butte; Trb = rhyolite of Big Southern Butte (294 ka); Tru = Unnamed Butte rhyolite (1.4 Ma); CH-1 = INEEL Corehole #1; Tre = East Butte rhyolite (0.58 Ma); track symbol = linear vent zones for some basaltic eruptions; dashed lines outline the margins of the Cerro Grande (Tbc; 13.4 ka), North Robbers (Tbn; 12.0 ka) and South Robbers (Tbs) basalt flows; other thin lines illustrate field-trip-related graded gravel and unimproved dirt roads.

Butte" (Fig. 2; Kuntz et al., 1994). The small topographic size of the 1.4 Ma dome belies its true size. A cored well drilled northeast of Unnamed Butte (CH-1; Fig. 3) penetrated over 1000 feet of the rhyolite, suggesting that it is comparable in size to East Butte, but has been largely buried by younger basalt flows (Kuntz, 1978). Recent detailed geochemical work on lava flows overlain by the dome indicates that they are highly evolved geochemically (McCurry, unpublished data). The flows vary systematically downward in composition from rhyolite to mafic trachyandesite, between 1200 and 1900 feet (Fig. 3). Chemical covariations are strikingly similar to those observed at Cedar Butte (McCurry et al., unpublished data).

Kuntz and Dalrymple (1979) and Spear (1979) both studied the geology and petrology of East Butte. Spear (1979) indicates that most foliations are inclined away from the center of the dome, suggesting that the dome is primarily endogenous in origin. Kuntz and Dalrymple (1979) disagree, indicating that most of the flow banding is actually inward-dipping, like the lower half of an elongated onion. They suggest that the original magma was too viscous to flow, and instead rose as inclined concentric sheets.

Kuntz and Dalrymple (1979) point out that a distinctive irregularity (notch) in the southeast side of East Butte lies next to a major vent for a basaltic volcano. Fragments of the distinctive,

plagioclase-phyric basalt occur within the rhyolite (field trip Stop 2). They suggest that the rhyolite magma may have intruded into a fracture which was obstructed in that area by basaltic lava.

Proceed back down East Butte the same way you came up; park in a pull-out 0.8 miles down from the summit, at the lowest large switch-back (i.e. nearest the base of the butte).

STOP 2. Examine rhyolite and mafic enclaves of East Butte.

This road-cut exposes part of the interior of the East Butte dome. Note the strong, south-dipping layering, defined by a combination of flow-banding and weakly developed lithophysal zones. Also note the presence of common, but volumetrically minor mafic enclaves. Enclaves in this outcrop are angular to rounded in shape and vary from under a centimeter to 8 cm across. Most of the enclaves are strongly porphyritic, containing distinctive, large (to 1 cm) plagioclase laths in a dark gray, aphanitic, dense to moderately vesicular matrix. An analysis of one of the enclaves by Kuntz and Dalrymple (1979) indicates that the enclaves are basaltic trachyandesite (i.e. alkali-rich) in composition, rather than olivine tholeiite basalt.

Kuntz and Dalrymple (1979) and Spear (1979) both note a lithologic similarity between these enclaves and the large basaltic volcano adjacent to the notch on the southeast side of East

Butte. Spear (1979) also notes disequilibrium phenocryst assemblages and textures in similar enclaves elsewhere in the dome. He interpreted the enclaves as "hybrid inclusions" produced by mixing of partially crystallized mafic magma with the host rhyolite. However, most of the enclaves vary from angular to subangular, and have sharp, unchilled contacts with the rhyolite, suggesting they were rigid (i.e. largely crystallized) prior to being incorporated into the rhyolite.

The following is a petrographic description of rhyolite from this location: Strongly porphyritic, consisting of euhedral to subhedral, randomly oriented phenocrysts of sanidine (15% to 3 mm), quartz (5% to 1 mm), ferroaugite (1% to 0.8 mm), opaques (minor to 0.2 mm) and trace microphenocrysts of apatite and zircon, in a fine-grained, dense, weakly pilotaxitic felsic matrix. Sparse, small, irregular lithophysal cavities are infilled by vapor-phase tridymite and alkali-feldspar. Many clinopyroxene grains are partially altered to dusty opaques, particularly around their margins. Many phenocrysts occur in glomeroporphyritic clots. Some large sanidine grains have well-developed, intracrystalline, granophyric textures. Zircon-like grains (possibly monazite) have a somewhat unusual blocky habit. Spear (1979) notes the presence of minor fayalite and aenigmatite (?) [possibly chevkinite?] in other samples from East Butte. Kuntz and Dalrymple (1979) also note the presence of minor amounts of oxidized biotite(?) and sphene (titanite).

Return to Highway 20. Turn west (left) on Highway 20 and return to the Highway 26 exit. Turn left (south) on Highway 26 and proceed 7 miles south. Turn right off the highway, next to Magee's, onto the road to Atomic City. Zero your odometer mileage. Drive west on the road to a T-intersection. There is a Texaco station, a post office, and a small hotel to the right, in Atomic City. Turn left, to the south (i.e. away from Atomic City) on the

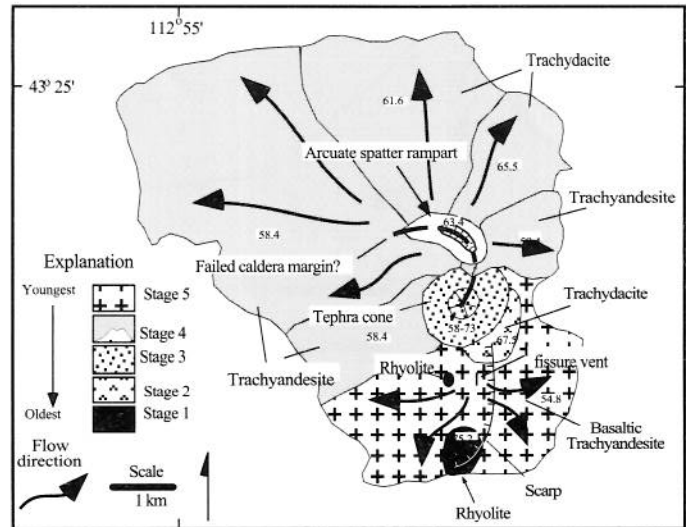


Figure 4. Diagrammatic illustration of the major geologic units of Cedar Butte volcano. Stages are discussed in the text. Flow directions are inferred from stretched vesicle lineations and flow folds orientations (modified from Hayden, 1992).

unlabeled paved road. Drive 1.4 miles to the end of the pavement, and take a right on a graded gravel road; note Big Southern Butte in the distance. Stop at a small rise at mile 2.65 for an overview of the geology of Cedar Butte.

STOP 3. Overview of Cedar Butte

- Shield
- Tephra cone
- Arcuate vent zone
- Rhyolite lava flows

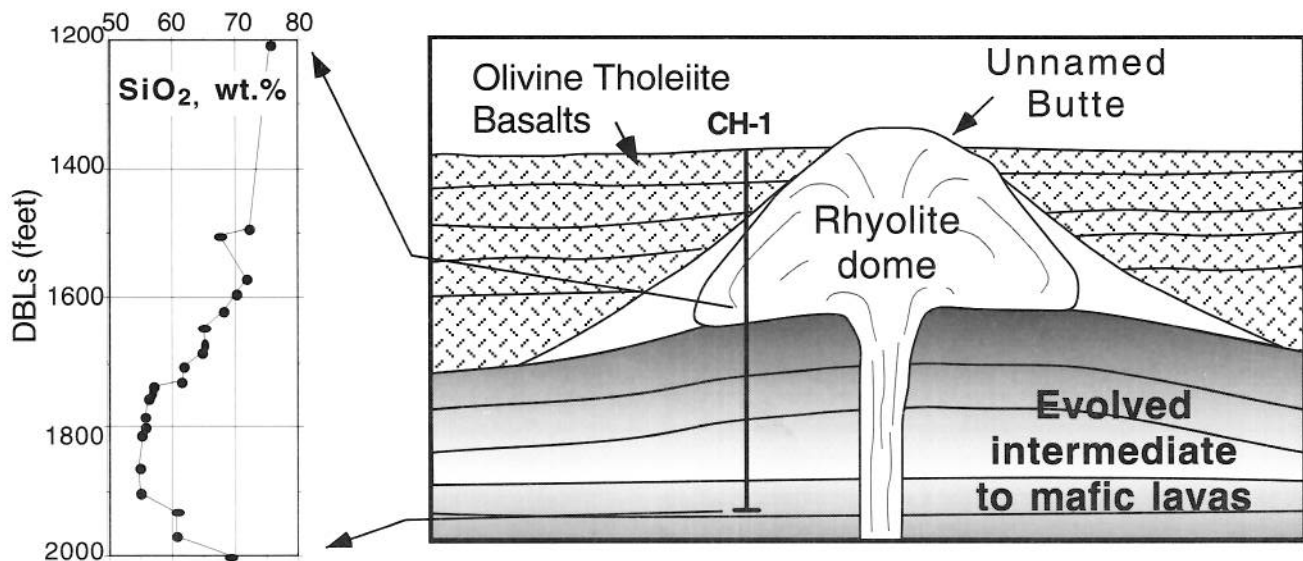


Figure 3. A diagrammatic, northeast (left) – southwest directed cross-section of Unnamed Butte. CH-1 is a cored borehole (Kuntz and Dalrymple, 1979; McCurry, unpublished data). Silica contents are graphed to the left of the sketch, for samples collected from near the base of the dome.

GEOLOGY AND PETROLOGY OF CEDAR BUTTE VOLCANO

Cedar Butte is a ~400 ka (Kuntz et al., 1994) polygenetic volcanic center located near the intersection of two major structural lineaments, the Arco Rift Zone and ESRP axial volcanic zone (Fig. 1). The volcano consists of a broad shield, ~4 by 9 km across and 120 meters high, a prominent ~1-km-long curvilinear spatter rampart, and a large, 100-meter-high compound tephra cone (Fig. 4). Vents and dikes are north-northeast to northwest trending and are concentrated near the center of the shield.

This seemingly modest-sized shield is slightly elongate to the northwest, covering an area of ~31 km², with a minimum volume of erupted material of 9.2 km³ (Hayden, 1992). Much of the volcano is buried by later Pleistocene to Holocene lavas. Lava flows which may have been derived from Cedar Butte have been identified from cores and borehole logs near the INEEL (Hayden, 1992; Spear, 1979; Steve Anderson, U.S. Geological Survey, personal communication, 1994), and are also present in an uplifted block of basalt on the east side of Big Southern Butte (Fishel, 1993). These observations suggest the volcano originally extended ~20 km across its base. Cedar Butte volcano may therefore have had a total volume of well over 10 km³ - comparable to that of the largest, compositionally similar, "evolved" center exposed on the Snake River Plain, Craters of the Moon volcanic center (Kuntz, et al., 1986).

Cedar Butte evolved through five major stages of activity (Fig. 4).

Stage 1

Effusion of a roughly north-trending high-silica rhyolite lava flow ~3 km long, 1 km wide and at least 70 meters thick (volume ~0.2 km³). The flow is mantled by blocky and pumiceous breccia. Phenocrysts are sparse (<1% total volume) and consist of sanidine > fayalite > quartz > Fe-Ti oxides and accessory zircon and apatite.

The southern toe and eastern margin of the flow are relatively steep, giving Cedar Butte an unusual step-like morphology on those sides. In previous mapping of the region (Kuntz and Kork, 1978; Kuntz et al. 1992, 1994; Spear, 1979) the east side of the butte was mapped as a north-trending fault scarp; one of very few faults on the ESRP. However, we reinterpret this scarp as a steep flow lobe margin of the underlying rhyolite. Although the rhyolite is mostly covered by a thin veneer of younger basaltic trachyandesite flows, it is exposed through nearby "windows" not covered by subsequent lava flows (Hayden, 1992). Some of the younger flows erupted from vents on top of the rhyolite; in these areas the later lavas are contaminated with xenoliths and xenocrysts of the rhyolite (near "fissure vent" on Fig. 4). Excellent exposures of these flows along the scarp demonstrate that they flowed over the scarp, rather than being cut by it. Therefore faulting either predates the younger flow, or, we believe more likely, the scarp was produced by edge of the underlying rhyolite flow.

Stage 2

The apparent passive effusion of the stage 1 rhyolite flow was followed by more explosive eruption of trachydacite lava. Ex-

plosive fountaining is suggested by the flows' generally distinctive clastogenetic textures. Orientations of stretched vesicles, glass ribbon bomb orientations, and rheomorphic fold axes indicate the lava erupted from a vent that is now buried under the stage-3 tephra cone. The lava is sparsely porphyritic; phenocryst abundances and assemblage resemble those of the preceding rhyolite.

Stage 3

Stage 3 is distinguished by the construction of a large tephra cone. The cone is one of the largest Quaternary tephra cones on the ESRP. It has a relief of ~100 meters, is 1.2 km across, and is deeply eroded, suggesting it was originally even larger. A large breach on the north side of the cone appears to be erosional rather than volcanic in origin.

In contrast to other large tephra cones on the SRP (Womer, et al., 1982; Hackett and Morgan, 1988; McCurry et al., 1997), Cedar Butte is distinguished by an absence of evidence for meteoric water involvement. Eruptions appear to have been dominantly strombolian in nature, having produced thick layers of moderately to poorly bedded and moderately to poorly sorted scoria bombs, pumice, and spatter. Most exposures are of moderately welded agglutinate. Small lava flows also issued from the sides of the cone.

The cone-forming eruptions produced a spectrum of magma types (trachyandesite - trachydacite - rhyolite), as well as pyroclasts containing intermingled glasses of contrasting compositions. In our preliminary work we did not observe a correlation between stratigraphy and composition, at least on the scale of 5-10 meters of stratigraphic section. However exposures are very limited, so we can not rule out larger scale patterns which would indicate a correlation between time and chemical composition of the erupted materials.

Spear (1979) suggests that the large tephra cone was the last phase in formation of Cedar Butte. However, good exposures on the north flank of the cone indicate that flows to the north pinch out rapidly south against the cone, rather than project beneath the cone.

A spectacular system of north-northeast-trending compositionally-bimodal dikes cuts through the extreme northern flank of the tephra cone (Fig. 4). These are described in the discussion for field trip Stop 6.

Stage 4

After tephra cone formation ceased (stage 3), effusive activity shifted north. Subsequent eruptions were voluminous and took place from a north to northwest curvilinear fissure system at least several hundred meters to perhaps 1-km long, producing a prominent arcuate spatter rampart (Fig. 4). When combined, dikes, tephra cone, and arcuate vent zone define a near-circular 150° arc with a radius of curvature of ~0.8 km (bold dashed line on Fig. 4).

Geometry of the curvilinear dike/fissure system resembles vent/dike systems which are influenced by interactions between local (i.e. volcano-related) and regional stress fields (e.g., Mueller and Pollard, 1977). However, at Cedar Butte, this would imply a regional extension directed perpendicular to the plain, an idea which is inconsistent with the orientations of northwest-trending

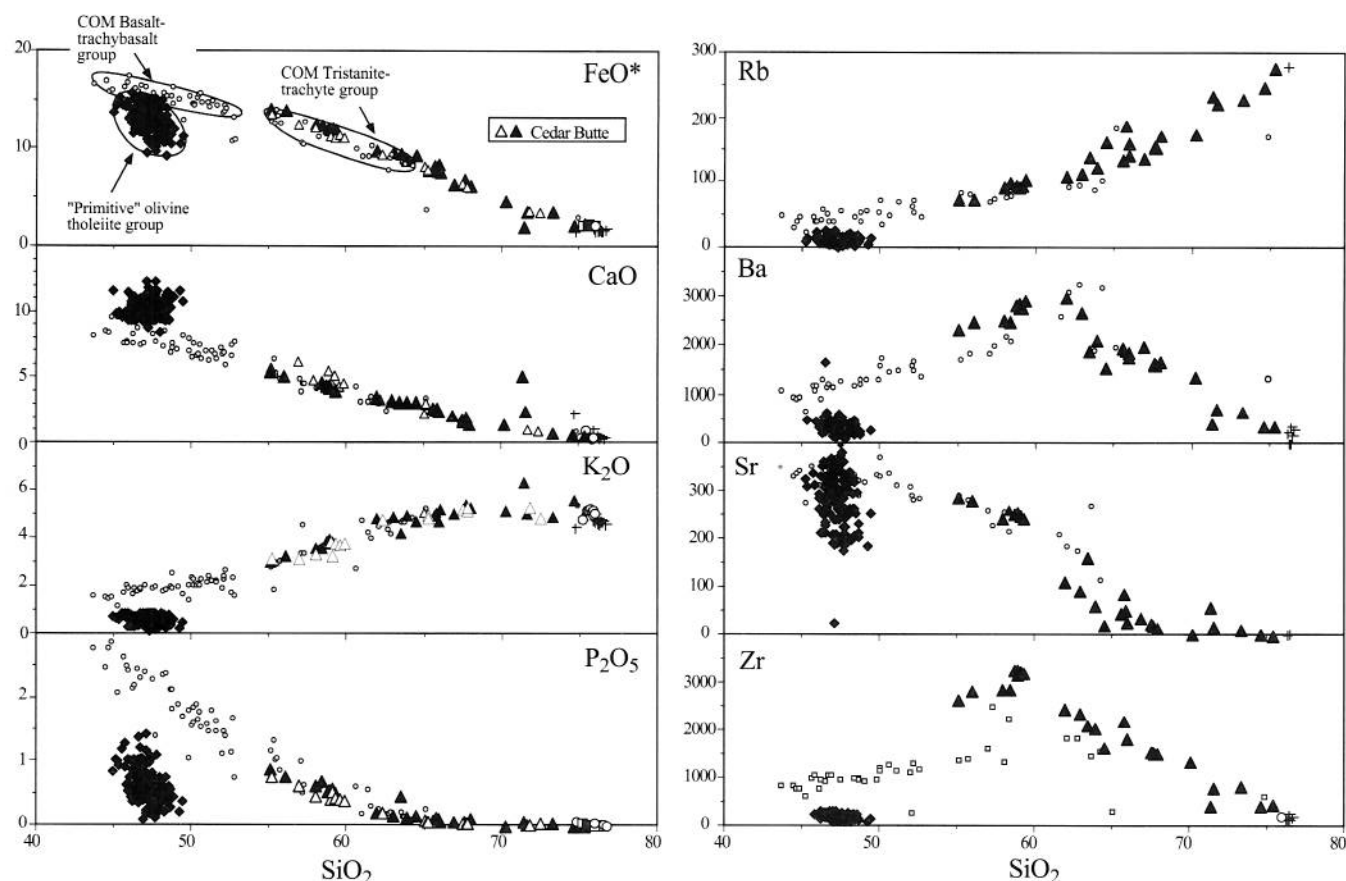


Figure 5. Representative whole-rock major and trace element analyses of Cedar Butte and related volcanic rocks; oxides normalized to 100% on an anhydrous basis (Hayden, 1992; McCurry, unpublished data). Symbols and sources of the data are as follows: large filled triangles = Cedar Butte; small open triangles = Cedar Butte (Spear, 1979); small diamonds - Snake River plain olivine tholeiite basalts (Kuntz et al., 1992; Spear, 1979; Fishel, 1993); small open circles - "evolved" volcanics of Craters of the Moon volcanic center (Kuntz et al., 1992; Leeman et al., 1976); plus symbol - Big Southern Butte rhyolite (Spear, 1979; unpublished data by McCurry and Mertzman); large open circle - East Butte rhyolite (Spear, 1979).

normal faults marginal to the plain. We speculate that the distinctive geometry of this system of vents resulted from incipient caldera formation above a shallow magma chamber (e.g., see discussions in Suppe, 1985, p. 223-228).

At least five distinct eruptions from the arcuate vent zone produced lavas ranging from trachyandesite to trachydacite in composition (Fig. 4). Although individual lava flows appear to be relatively homogeneous, some exhibit varying scales of magma mixing and hybridization (Fishel, 1992).

The lavas are typically sparsely porphyritic. Intermediate flows contain phenocrysts of plagioclase, olivine, ferroaugite, Fe-Ti oxides and accessory apatite. More felsic flows contain phenocrysts of plagioclase + anorthoclase + olivine + Fe-Ti oxides and accessory zircon and apatite. Accessory xenocrysts and wispy blebs of contrasting magma types (i.e. small-scale magma mixing) are fairly common but not abundant. In contrast to highly evolved lavas at Craters of the Moon (abbreviated COM; e.g. Stout et al., 1994) we found no accidental lithic fragments which might have been derived from disaggregated Precambrian basement.

Stage 5

The final eruption at Cedar Butte produced the least siliceous lava (54.8% SiO_2). The vent is a north-trending fissure just south of the tephra cone (Fig. 4). The eruption produced a relatively thin flow which mantles much of the southern third of Cedar Butte. Although similar in most respects to older trachyandesites at Cedar Butte, this flow contains scattered xenoliths and xenocrysts of "stage-1-type" rhyolite, consistent with our interpretation of a large subsurface extent for the rhyolite flow.

No significant erosion occurs between lava flows or pyroclastic units suggesting there was no major hiatus during formation of the volcanic center. Unfortunately, exposures are very limited due to weak erosional incision of the young rocks, and we have no basis for quantifying the time of evolution.

The five stages of Cedar Butte evolution record a systematic change over time from more siliceous to less siliceous eruptive products. This relationship between composition and time, combined with abundant evidence for magma mixing and partial hybridization at Cedar Butte, suggest that the lavas were erupted from a shallow, compositionally zoned magma chamber.

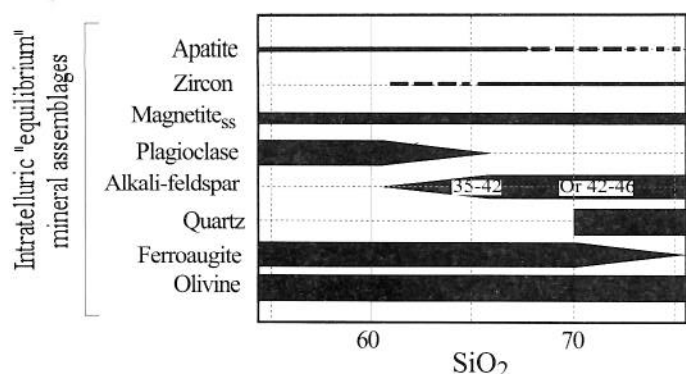


Figure 6. An interpretation of assemblages of minerals which, based upon their petrographic features, are believed to be intratelluric phases which were in equilibrium with the host magmas. Widths of bars indicate relative abundance. Numbers on bars indicate compositions of respective phases based upon electron microprobe analyses (Hayden, 1992).

Geochemistry

Major and Trace Element Chemistry

Cedar Butte is a moderately alkaline intermediate to silicic volcanic center (Hayden, 1992 and Spear, 1979). Major geochemical features are illustrated in several Harker diagrams (Fig. 5). In these figures SRP olivine tholeiite basalts and COM lavas are shown for reference.

Lavas and pyroclastic rocks span a nearly continuous spectrum of major-element composition from 55 to 75% silica. Major- and trace-element covariation plots (Fig. 5) exhibit smooth variations in chemistry which are most often linear (e.g., Ca and FeO*), but also include some moderate (e.g., K₂O, Rb) and pronounced changes in slope (Ba, Zr).

Salient aspects of Cedar Butte rock chemistries are as follows:

1. There is a pronounced compositional discordance between the most mafic Cedar Butte rocks and SRP olivine tholeiite basalts. This discordance is characteristic of other mafic to intermediate volcanic centers on the SRP, such as Craters of the Moon (e.g., Leeman, 1982b; Stout et al., 1994). Cedar Butte is missing the

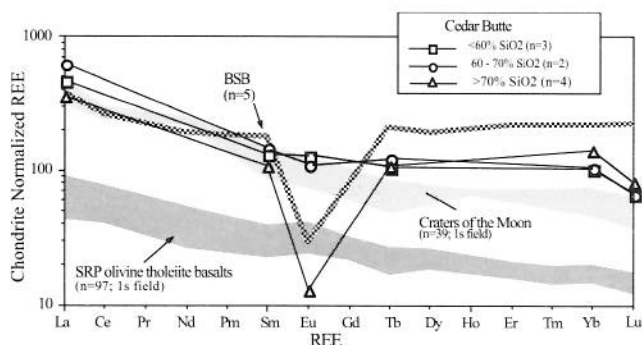


Figure 7. Chondrite normalized REE plots of rocks from Cedar Butte (McCurry, unpublished data), SRP olivine tholeiites (medium shade pattern), COM lavas (light shade) and Big Southern Butte rhyolite (dark shaded line). Data for COM lavas and olivine tholeiites are from Kuntz et al. (1992), Knobel et al. (1995), Fishel (1993) and Hughes (unpublished data). Data for Big Southern Butte are from Spear (1979) and Noble et al. (1979).

most mafic compositions observed at COM.

2. Cedar Butte rocks overlap in composition with other evolved volcanic systems on the ESRP (represented in Fig. 5 by COM). It seems remarkable that essentially all major chemical, petrologic and mineralogical features of Cedar Butte rocks overlap with COM rocks between 54 and 66% SiO₂, despite the difference in ages and locations of the two centers (e.g., Stout et al., 1994; Hayden, 1992). Clearly, the evolution of the two suites must be due to the same processes. There are some differences, perhaps best demonstrated in Figure 5 by an apparent discordance in Zr-contents of Cedar Butte and COM. Trends of Zr-contents of both volcanic systems seems to define straight lines; respective trends appear offset and of opposite slopes between ~57 and 65% silica. Over this range Zr-concentration increases from ~1,300 to 1,900 ppm in COM rocks, while declining from ~3200 to 1,900 ppm in Cedar Butte rocks.

3. Some changes in slopes defined by chemical variation trends correlate systematically with changes in phenocryst assemblage and abundance (as previously demonstrated for COM rocks). Most prominent among these are changes in trends of Rb, Ba, and K₂O. At a bulk silica content of ~60%, the Rb-trend increases in slope, whereas Ba changes from positive to negative slope with increasing silica. The changes correlate with the appearance of intratelluric alkali-feldspar (Fig. 6). Barium strongly partitions into alkali-feldspar, whereas Rb is mildly incompatible. Therefore it seems likely that fractionation of this phase produced the observed opposite behaviors of the two elements.

A second significant change in trend is demonstrated by a flattening of K₂O-silica slope at ~67% SiO₂ on the Harker diagrams. This roughly coincides with an increase in the abundance of alkali feldspar and decline, and eventual absence, with increasing silica, of plagioclase as an intratelluric phase.

The curved nature of some Cedar Butte covariation trends precludes simple two-component mixing as a major petrogenetic mechanism, although as previously stated, petrographic and field evidence for at least some magma mixing is strong. Stout et al. (1994), Reid (1995), Leeman et al. (1976) and Leeman (1982b) convincingly demonstrated that similar lavas at COM were largely the products of fractional crystallization. The basis of arguments they brought to bear at COM is essentially the same at Cedar Butte.

4. Perhaps the most significant feature of chemical data from Cedar Butte is that they appear to close a "compositional gap" (between ~66 and 74% SiO₂) between trachyandesite-dacite lava sequences and high-silica rhyolites of the ESRP. Rocks spanning this compositional range erupted during at least two stages of volcanic center evolution (stages 2 and 3). Samples which were analyzed are only sparsely porphyritic, and olivine and alkali-feldspar phenocryst compositions are intermediate between mafic and silicic extremes. Therefore it seems unlikely that the bulk rock chemistry is an artifact of crystal accumulation or magma mixing, and opens up the possibility that the most siliceous rocks are genetically related to the intermediate rocks (cf. Spear, 1979).

Hayden (1992) performed incremental mass balance calculations of fractional crystallization using observed compositions of phenocrysts, and produced a close match to the observed trends in bulk major element rock chemistry (Sr² < 0.5; Bryan et al.,

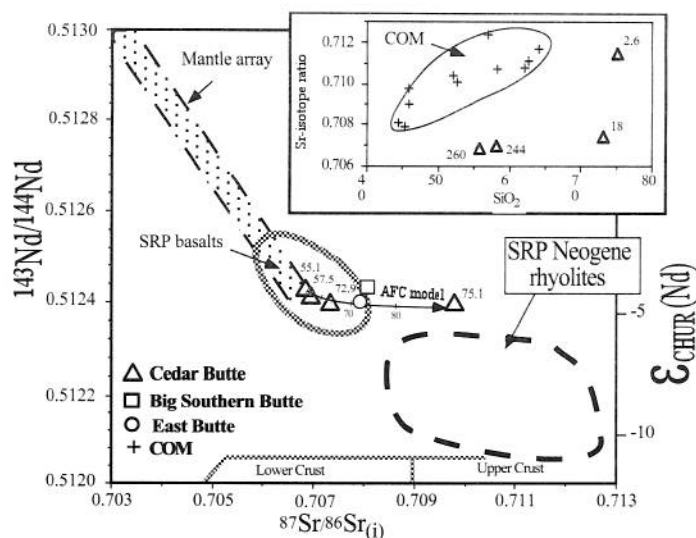


Figure 8. A plot of Nd- and Sr-isotope ratios for samples from Cedar Butte (McCurry, unpublished data); Cedar Butte (triangles), Big Southern Butte (open square) and East Butte (open circle). Numbers next to Cedar Butte samples are silica contents of the respective samples. Curved line represents an AFC model; numbers next to tick marks on the curve indicate percent fractionation of the trachyandesite parent magma (discussed in the text). Inset diagram illustrates relationships between Sr-isotopes and silica for COM (after Leeman et al., 1976) and samples from Cedar Butte. Numbers next to Cedar Butte samples are whole-rock Sr-concentrations. Fields for Neogene rhyolites and SRP basalts are based upon data from Menzies et al. (1983), Lum et al. (1989), and Hildreth et al. (1991).

1968). Spear (1979) performed similar calculations over a smaller silica range. He also presents chondrite-normalized REE data which support a fractional crystallization model. However he specifically excluded rhyolites from this model because: 1. the most silicic rocks have lower LREE concentrations than some intermediate rocks; 2. absence of a fractionating phase which could have produced the lower LREE ratios.

Our preliminary REE analytical work, illustrated in Figure 7, confirms the patterns of LREE and HREE shown by Spear. Note that Big Southern Butte (BSB), made of rhyolite even more evolved than the most silicic rhyolite at Cedar Butte, has even lower LREE/HREE ratios than rhyolites at Cedar Butte. However, fractionation of small amounts of chevkinite (a LREE-rich sorosilicate) may have produced the observed REE behavior (McCurry, unpublished data). We have recently confirmed the presence of chevkinite, by petrographic and electron-microprobe analyses of minerals in heavy mineral separates from Cedar Butte pumices and obsidian (McCurry, unpublished data).

Isotope Chemistry

Sr- and Nd-isotopes of four Cedar Butte samples are illustrated in Figure 8. Analyses are also shown of samples of high-silica rhyolites from East Butte and Big Southern Butte.

Samples from Cedar Butte range from 0.70684 to 0.70967 in initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio; ϵ_{Nd} varies from -4.14 to -4.70. Sr- and to a lesser extent, Nd-isotopes correlate systematically with silica content. Simple two-component mixing has already been excluded

on the basis of bulk major element chemistry and patterns of phenocryst assemblages and composition. A coupled assimilation and fractional crystallization (AFC) model illustrates one possible relationship (Fig. 8). The most mafic trachyandesite is assumed to represent the parent magma. Plagioclase+alkali feldspar, olivine, ferroaugite, Fe-Ti oxides and chevkinite are assumed to fractionate in weight proportions of 0.6, 0.15, 0.15, 0.10, and 3×10^{-5} , respectively, yielding estimated bulk distribution coefficients of $D_{\text{Sr}} = 4$ and $D_{\text{Nd}} = 1.1$ (McCurry, unpublished data). Assimilant chemical composition is from lower and upper crustal xenoliths in SRP lavas (Leeman et al., 1985). The long curved line represents the AFC model fractionation path. Small numbers indicate percentage crystallization of the parent magma.

The AFC model yields a successful match for observed Sr- and Nd-isotopes as well as Sr- and Nd-concentrations. It is highly sensitive to r (ratio of assimilation to crystallization). No successful models were produced using r 's of more than a few percent, primarily because of the extremely low Sr-concentration of the most evolved sample (2.6 ppm). This apparently rules out more than a few percent contribution from any reasonable crustal rock.

Sr-isotope, compositional and textural features of COM rocks suggest greater involvement of crustal material (e.g., Leeman et al., 1976; Stout et al., 1994). For example, whereas accidental crustal xenoliths are common in COM lavas, they are absent at Cedar Butte. In addition, COM Sr-isotopes increase from 0.7079 to 0.7117 between 45 and 63.5% silica, Cedar Butte Sr-isotope ratios increase from 0.7068 to 0.7097 between 55 to 75% silica. Differences in silica and Sr-isotope patterns of the two systems are illustrated in the inset to Figure 8.

One of the intriguing features of the isotopic data for high-silica rhyolites of the ESRP is that, with the exception of one sample from Cedar Butte, all overlap in Nd- and Sr- isotopes with SRP olivine tholeiite basalts and overlap with each other in major- and trace-element chemistry (Figs. 5, 7). This suggests that a repeating mechanism of formation is involved for the rhyolites, different than that which produced earlier Tertiary rhyolites in the same area (e.g. Leeman, 1982a,c). The isotopic data appear to preclude any mechanism involving major contribution to the rhyolites from lower or upper crustal geochemical reservoirs (Fig. 8), and provides strong evidence of a liquid-line-of-descent, by fractional crystallization, between olivine tholeiites – intermediate magma suites – and high silica rhyolites.

Conclusions

Previous work on evolved volcanic centers of the eastern Snake River Plain suggests that mafic-intermediate composition volcanic rocks evolved primarily by fractional crystallization and minor assimilation from a primitive olivine tholeiite parent (e.g., Thompson, 1972a,b, 1975; Leeman et al., 1976, 1982b; Stout et al., 1994; Kuntz et al., 1986; Reid, 1995). However high-silica rhyolite flows and hypabyssal intrusions, which overlap with the intermediate centers in space and time, have been placed into separate, and somewhat poorly defined categories (e.g., "residual melt", Spear, 1979; crustal melt, Leeman, 1982c).

We suggest that the rhyolites were produced by an extension of the same basic mechanism responsible for the other "evolved"

magmas on the plain, i.e. extreme polybaric fractional crystallization of SRP basalt. This idea has previously been ruled out on the grounds of paucity of intermediate composition rocks, discordances in isotopic compositions (Leeman, 1982c), and trace element patterns (Spear, 1979). Although these arguments clearly apply to older Tertiary rhyolites of the ESRP (Leeman, 1982c), they do not apply as well to the younger rhyolites (i.e. Cedar Butte, Big Southern Butte, East Butte, etc.). Cedar Butte is one place where an entire range (above 54% silica) of evolved magma compositions erupted. Most of the rhyolites overlap in Sr- and Nd-isotopes with SRP olivine tholeiites. Finally, discrepancies in LREE data may be accounted for by fractionation of trace amounts of chevkinite.

Formation of high-silica rhyolites in the ESRP by extreme fractionation of basaltic parents, has important implications for magma and energy supply rates into the crust in this region (cf. Kuntz, 1992), because of the large amount of basalt magma that is required to produce even small amounts of rhyolite daughter magma. Big Southern Butte alone has an exposed volume of 8 km³ (Kuntz et al., 1992) and may have a total volume of 10-20 km³ when subsurface volume is taken into account. This would imply existence of a large crustal parental basaltic magma reservoir perhaps ten to a hundred times that size. If located in the mid- to lower crust a chamber of that size might conceivably be still partially molten. This idea is consistent with recent geophysical work by Peng and Humphreys (1998), which documents a zone of lower crustal partial melt extending southeast from beneath Big Southern Butte to beneath the Blackfoot volcanic field. It is intriguing that the regional geophysical anomaly overlaps precisely the general region of Quaternary rhyolite volcanism in southeast Idaho (excluding Yellowstone).

Continue west on the gravel road. The road crosses a train-track at 5.5 miles. Note the distinctively young-looking Cerro Grande flow (13.4 ka; Kuntz et al., 1994) from 5.5 to 6.0 miles. This flow was derived from vents, just out of sight, to the southeast of Cedar Butte. Take a left on the dirt track heading south around the east flank of Cedar Butte. Zero your odometer. NOTE: roads on Cedar Butte are unimproved and can be treacherous; 4WD is strongly recommended!

At 2.5 miles note the prominent scarp to the west (right side of road). Kuntz et al. (1992) interpreted this scarp as a NNW-trending fault scarp. However, more detailed mapping by Hayden (1992) suggests that the scarp is a depositional feature formed by the east flank of a thick rhyolite lava flow. The flow extends to the south for 2-3 kilometers from a vent which is now buried beneath the prominent tephra cone. The rhyolite flow has been veneered by thin mafic lava flows, some of which produced beautiful cascade-like features across the escarpment.

At 3.1 miles take a right onto the dirt track leading up onto the southeast flank of Cedar Butte. Turn right at the fork in the road at 3.2 miles. Turn left at the junction at 3.4 miles. Turn left at the next junction at 3.5 miles and drive to the end of the road (3.65 miles). Park vehicles in the grassy opening, preferably beneath a cool Cedar tree, and hike about a quarter mile to the toe of the rhyolite lava flow.

STOP 4. Quaternary high-silica rhyolite lava flow; discussion topics and objectives include:

- Define flow features; possible source of the flow.
- What are rhyolite lava flows doing on a SRP shield volcano?
- Is Cedar Butte an Archeological obsidian-source region?

Hike south from the parking area about a quarter mile, to the toe of the rhyolite flow. Along the way note the abundance of pumiceous rhyolite blocks; these are part of the upper pumice carapace of the flow. Near the cliffy area at the toe of the flow you will see devitrified and crystallized parts of the flow. There are numerous zones of autoclastic rhyolite in this area (i.e. monolithologic rhyolite fragments in a rhyolite matrix), produced by internal brittle deformation within the extremely viscous flow, and incorporation of rubble from the advancing toe of the flow during its emplacement. Thin, wispy zones of obsidian (an Archeological obsidian source?) occur in some areas, within otherwise crystallized or devitrified rhyolite. The rhyolite has a silica content of 75.2%, and is sparsely porphyritic, consisting of less than 1% phenocrysts of sanidine > fayalite > quartz > Fe-Ti oxides and accessory apatite and zircon.

This rhyolite flow is largely covered by a thin veneer of younger, more mafic flows. The original flow probably emanated from a vent located beneath the large tephra cone ~2 km to the north.

Zero your odometer mileage. Back-track to the last intersection (0.15 miles). Take a right and proceed to the next intersection at 0.25 miles. Take a left and drive north up the shield on a very rocky road for 0.5 to the next intersection. Take a right and follow the jeep-track leading to the south rim of the Cedar Butte tephra cone. Park on the rim of the cone.

STOP 5. Tephra cone; discussion topics and objectives:

- Explosive volcanism
- Magma mixing

This deeply dissected tephra cone consists of a remarkably wide variety of pyroclasts, ranging from trachyandesite to rhyolite in composition (Hayden, 1992; McCurry, unpublished data). The cone has been erosionally breached on the north side. It is

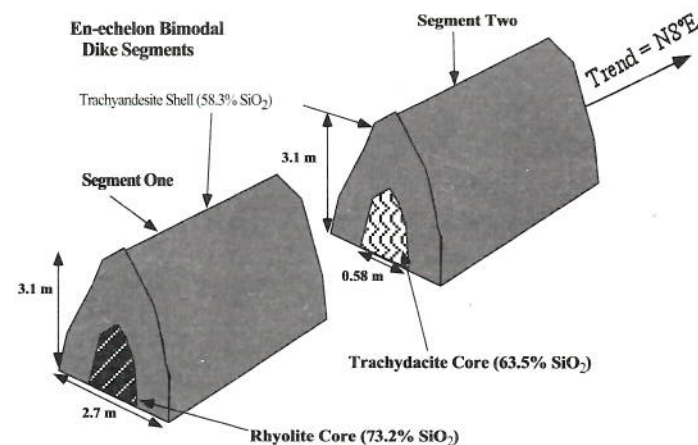


Figure 9. A diagrammatic depiction of dike segments which intrude into the north flank of a tephra cone on Cedar Butte. Silica contents are shown for samples collected from the margins and cores of the dike segments.

intruded by compositionally bimodal dikes on its north flank (field trip Stop 6). Resistant ridges around the rim of the cone consist of a variety of agglutinated spatter, and welded pumiceous pyroclasts. It is not difficult to find pumices consisting of intimately interbanded mafic and felsic components. Small, "rootless" mafic lava flows, probably produced by consolidated spatter, occur below the rim in some areas.

In contrast to many other large tephra cones across the Snake River Plain (Womer et al., 1982; Hackett and Morgan, 1988), the eruptions which produced the tephra at Cedar Butte appear to be entirely magmatic in origin, rather than hydromagmatic.

Proceed back down the south flank of the cone, back-tracking to the last intersection. Zero your odometer at the intersection. Turn left, and proceed south down the south side of the shield. At 0.5 miles note the track leading to the right; continue straight. At the next intersection (0.7 miles) bear left. Continue another 0.1 miles to the end of the track and then turn left onto the "larger" track heading north. Proceed north along this road, retracing your steps along the east flank of Cedar Butte, until you return to the graded gravel road at 3.9 miles. Again rezero your odometer. Turn left (west) on the graded gravel road.

Proceed for 2.3 miles to the west on the graded gravel roads, until you reach a dirt track paralleling prominent power lines. Turn left (south) for 1.1 miles on the power-line road. At this point, turn left (east) off the power-line road onto another track. At 0.7 miles down this road, bear left at the fork in the road. Continue for another 0.75 miles and park at the top of a steep section of road which leads down into the prominent gully incised into the north flank of the Cedar Butte tephra cone. Note prominent blade-like-exposures of mafic dikes ~10 meters east (left) of the road.

STOP 6. Polymodal dikes

- Dike and magma emplacement processes
- Implications for source magma reservoirs

Walk north to the prominent blade-like exposures of mafic dikes. Two of the three dikes exhibit spectacular features of bimodal magma interaction (Fig. 9). The dikes strike N 8° E and dip vertically, to steeply to the east. The overall morphology is wedge-shaped, tapering towards the top, suggesting that the original magma had not propagated to the surface at this location. Contacts with the host tephra are bulbous on a scale of 10's of cm to a meter. Contacts with the host-rock tephra (part of the prominent tephra cone located to the south) have produced a thin zone where the glassy tephra pyroclasts are fused into dense obsidian.

Both southerly dike segments have a layered structure consisting of a core of felsic composition and a rind of more mafic composition (Fig. 9). In the southerly dike the interior of the dike is rhyolitic in composition. This can be observed in a small addit on the east side of the dike. In the middle segment (which can be observed in cross-section, looking to the north), the core consists of trachydacite. In both cases the "rind" consists of trachyandesite. Contacts between the two lithologies varies from sharp to gradational over a few centimeters. In many places there are wispy blebs of one lithology within the other. Both features indicate the original magmas were at least partially molten when they were brought into contact. The dike lithologies overlap in composition

with the compositions of pyroclasts in the tephra cone to the south, suggesting that the dike is the northern continuation of vents which fed that tephra-cone-forming eruption.

Processes by which mafic magmas tend to migrate toward conduit walls, when in contact with more silicic magma, are referred to by Carrigan (1994) as "viscous segregation" and "encapsulation". Carrigan describes experimental and theoretical bases for the segregation process, indicating that it is primarily the result of the highly contrasting viscosities of magma types. More fluid mafic melts tend to migrate into the zones of high-shear (i.e. margin) within the conduits. Carrigan demonstrates that it is possible to produce such a dike geometry even though the original source reservoir was continuously zoned, with rhyolitic melts on the top - as seems likely beneath Cedar Butte.

The dikes are a part of a nearly continuous curvilinear system of vents and intrusions extending for ~2 km, including the tephra cone to the south, and curvilinear vent zone to the north, and circumscribing a near circular 150° arc (Fig. 9). The arc has a radius of curvature of about 0.8 km, and may have originated by incipient formation of ring fractures above a shallow, compositionally zoned magma chamber.

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Layered ejecta deposited and deformed during a hydrovolcanic eruptive phase west of American Falls. The eruption produced a small tuff cone when basaltic magma encountered shallow groundwater near the Snake River. Exposures within the cone have been enhanced by recent excavations for road material. The cliff face is approximately 10 m high. Photo by Kari Lundeen.