The Cougar Point Tuff, Southwestern Idaho and Vicinity

by

Bill Bonnichsen and Gary P. Citron

ABSTRACT

The Cougar Point Tuff is a sequence of densely welded, rhyolitic ash-flow tuff cooling units that erupted from the Bruneau-Jarbidge eruptive center during late Miocene time. By the end of Cougar Point Tuff volcanism, the eruptive center had developed into a large structural and physiographic basin. The exposed part of the Cougar Point Tuff consists of outflow-facies rocks that extend beyond the margins of the eruptive center. Thicker intracaldera facies of the welded tuff units may be hidden beneath younger rhyolite and basalt lava flows and sediments which fill the basin.

The Cougar Point Tuff is best exposed in the canyons of the Bruneau River and the East and West Forks of the Jarbidge River near the Idaho-Nevada border. At Black Rock escarpment in Bruneau Canyon, eight units are exposed and have an aggregate thickness of 400-475 meters. At Cougar Point in the East Fork of Jarbidge Canyon, six of the units are exposed with a thickness of about 250 meters.

The various Cougar Point Tuff units are quite similar in composition and in the temperature and mode of eruption. Where relatively thick, all are simple cooling units, but some, traced into areas where they are thin, change into compound cooling units or even bifurcate into composite sheets. In a vertical section through a unit, the typical zones from base to top consist of (1) a basal layer of thinly bedded air-fall ash, (2) a vitrophyre layer at the base of the ash-flow cooling unit, (3) a massive, relatively thick, lithoidal central zone of the ash-flow sheet in which most structures have been obliterated by matrix crystallization, and (4) an upper zone of the ash-flow sheet with abundant primary flow marks and secondary folds.

Quartz, sanidine, plagioclase, augite, pigeonite, fayalite, magnetite, and ilmenite are the principal phenocryst minerals, and are accompanied by accessory zircon, monazite(?), and apatite. Hornblende and biotite are essentially absent, suggesting that the magmas were relatively hot and dry. The absence of hypersthene and the presence of pigeonite, the high-temperature Ca-poor pyroxene, in nearly every unit mean that the magmas were hotter than the pigeonite-hypersthene inversion boundary. Plagioclase-clinopyroxene-opaque oxide cumulophyric aggregates occur in most units; these are interpreted to be fragments of the rocks melted to form the magmas.

Chemically analyzed samples from locations many kilometers apart in each unit reveal that each has a relatively narrow compositional range. Overall, the Cougar Point Tuff becomes increasingly feric upwards, but local reversals in the trend exist. The tuff has been divided into three compositional cycles based on these local reversals. In each cycle the composition became increasingly feric upwards, as successive magma batches were erupted. The emplacement of each unit was a distinct volcanic event, separated by the deposition of sedimentary layers. In some cases sufficient time elapsed between eruptions for Earth's magnetic field to reverse its polarity.

A potassium-argon age of 11.3 million years is reported for one of the lower Cougar Point Tuff units. Initial strontium isotope ratios indicate a predominantly, if not exclusively, crustal origin for the Cougar Point Tuff, being similar in that respect to other rhyolitic rocks in the Snake River Plain-Yellowstone Plateau volcanic province. In all probability, the Cougar Point Tuff magmas originated in deep crustal rocks that were partially melted as successive large batches of basaltic magma were injected into the crust. The silicic magmas that gave rise to the ash-flow units are interpreted to have been relatively hot and dry as they rose through the crust, so that the disruptive vesiculation which propelled hot ash high into the atmosphere during their eruption occurred at comparatively shallow depths.

INTRODUCTION

The Cougar Point Tuff is a sequence of densely welded ash-flow tuff cooling units that were erupted...
from the Bruneau-Jarbidge eruptive center (Bonnichsen, 1982b this volume) during late Miocene time. The eruption of the Cougar Point Tuff was the first volcanic phase in the evolution of the Bruneau-Jarbidge eruptive center. By the end of Cougar Point Tuff volcanism, the eruptive center had developed as a large structural and physiographic basin. The subsequent extrusion of several large rhyolite lava flows nearly filled the basin, however. As now exposed, the Cougar Point Tuff consists only of outflow-facies rocks which escaped from the eruptive center. Presumably more voluminous portions of the individual units are buried within their source areas (calderas?) beneath the younger rhyolite lava flows, basalt flows, and sedimentary deposits.

Our main objective in this paper is to describe the internal features of the units that constitute the Cougar Point Tuff, and their stratigraphic, chemical, and general petrographic relations. This paper is a companion to others in this volume that describe the Bruneau-Jarbidge eruptive center and the rhyolite lava flows within it (Bonnichsen, 1982b, 1982c); thus, extensive reference has been made to figures and tables in these accompanying papers. The final section of this article discusses how the rhyolitic magmas behaved during their eruption and once they reached their final resting place. For a discussion of how the rhyolitic magmas may have been formed, the reader is referred to the final section of the following paper by Bonnichsen (1982c). Also of possible interest in that article is a comparative discussion of the chemical and physical features of the Cougar Point Tuff with the rhyolite lava flows in the Bruneau-Jarbidge eruptive center.

The general distribution of the Cougar Point Tuff in Idaho and northern Nevada is noted in Figure 3 of Bonnichsen (1982b this volume). The detailed distribution of the Cougar Point Tuff is known for some parts of northern Nevada (Rowland 15-minute quadrangle—Bushnell, 1967; Jarbidge 15-minute quadrangle—Coats, 1964; Elk Mountain 15-minute quadrangle—Mathias, 1959, Fifer, 1960, and Higgs, 1960), but for much of that region the unit has been lumped with Miocene welded-tuff units from other source areas (Hope and Coats, 1976; Stewart and Carlson, 1976, 1978).

Some of the Cougar Point Tuff units exposed in Jarbidge Canyon extend eastward into southwestern Twin Falls County. It has yet to be determined, however, if any of these correlate with the sequence of similar welded ash-flow tuff units east of Salmon Falls Creek Reservoir in southern Twin Falls County described by Alief (1962).

The Cougar Point Tuff occupies about the same stratigraphic position as the tuff of Little Jacks Creek (Ekren and others, 1981, 1982 this volume) which occurs west of 116° longitude, west and northwest of the area underlain by the Cougar Point Tuff. The stratigraphic and genetic relationship between the Cougar Point Tuff and the tuff of Little Jacks Creek has yet to be established. The extensive rhyolite unit which connects the two is referred to as the rhyolite of Grasmere escarpment (Bonnichsen, 1982b this volume), from its exposures along the east-facing escarpment west of Grasmere that forms the western margin of the Bruneau-Jarbidge eruptive center (Figures 2 and 3, Bonnichsen, 1982b this volume). As discussed elsewhere (Bonnichsen, 1982b this volume), the rhyolite of Grasmere escarpment is considered to be part of the Cougar Point Tuff even though its exact stratigraphic position relative to the units with Roman numeral designations has yet to be resolved.

The best places to examine the Cougar Point Tuff are in the canyons of the Bruneau River, Jarbidge River, and Sheep Creek. In the canyon of the East Fork of the Jarbidge River, the tuff is exposed southward from Murphy Hot Springs past Cougar Point to the Robinson Hole area where it unconformably overlies the Jarbidge Rhyolite (see Figures 2 and 3 in Bonnichsen, 1982b this volume). In the canyon of the West Fork of the Jarbidge River, it is exposed southward from about 0.6 kilometer north of the mouth of Buck Creek to about 2 kilometers south of the mouth of Jack Creek, where it overlies the Jarbidge Rhyolite. In Bruneau Canyon, the Cougar Point Tuff is exposed southward from the Bull Pens area to about 2 kilometers north of the mouth of McDonald Creek, where it unconformably laps onto the older Bieroth volcanics. In Sheep Creek canyon, units of the Cougar Point Tuff are exposed southwestward from 1.6 kilometers upstream from the mouth of Cat Creek to a few kilometers north of the Idaho-Nevada border, where they overlie the older volcanic units discussed by Bernt and Bonnichsen (1982 this volume). The extent and nature of the Cougar Point Tuff in the Sheep Creek drainage have recently been investigated by Bernt (1982).

UNITS WITHIN THE COUGAR POINT TUFT

The best exposed and most complete section of the Cougar Point Tuff is at Black Rock escarpment on the east side of Bruneau Canyon just north of the Idaho-Nevada border (see Figure 2 in Bonnichsen, 1982b this volume). The Black Rock escarpment (Figure 1) should be considered the principal reference locality for the Cougar Point Tuff. Eight cooling units are exposed there. The Cougar Point Tuff is named for its well-exposed occurrence in the canyon.
of the East Fork of the Jarbidge River near Cougar Point (Figure 2, Bonnichsen, 1982b this volume), and was called the Cougar Point welded tuff by Coats (1964). Six cooling units are exposed at Cougar Point (Figure 2); however, neither the lowest nor the highest part of the sequence is exposed there. At Black Rock escarpment the exposed portion of the Cougar Point Tuff ranges from 400 to 475 meters in thickness, whereas in Jarbidge Canyon the exposed portion is about 250 meters thick. It is not known what lies immediately below the Cougar Point Tuff in either canyon.

Based on the succession of units in the Bruneau and Jarbidge Canyons, geologic mapping, petrography, chemical composition, and magnetic polarity measurements, it is clear that the Cougar Point Tuff contains nine or more cooling units. Except in distal areas or where thin, each is a simple cooling unit (Smith, 1960) formed from one or a sequence of ash-flow emplacements closely spaced in time, probably during a virtually continuous eruption. A system of Roman numerals is used to designate the various units. Units that have been recognized on canyon walls are shown in Figures 1 and 2. The Roman numeral nomenclature system supercedes two previous designation systems, as discussed by Bonnichsen (1981). At the present time we know that the Cougar Point Tuff consists of the following cooling units: III, V, VII, IX, X, XI, XII, XIII, and XV. Units that would correspond to Roman numerals I, II, IV, VI, VIII, XIV, or XVI and higher are not known to exist, but further studies east and west of the region considered in this report might recognize additional units that could be designated by these numbers.

UNIT III

Unit III is exposed in the bottom of Bruneau Canyon (Figure 1) between the fault-controlled gully in the southwestern part of sec. 9, T. 16 S., R. 7 E., and the Rowland, Nevada, area where it pinches out against the older Bieroth volcanics (Figure 3). It is the oldest unit assigned, so far, to the Cougar Point Tuff. It is in the correct stratigraphic position to be the same as unit I of Bernt (1982) in Cat Creek along the Idaho-Nevada border and in Cottonwood Creek southwest of the Bruneau-Jarbidge eruptive center, but this possible correlation is not firm. Erosion at Jarbidge Canyon is not deep enough to determine if unit III extends that far to the east. In Bruneau Canyon, the unit ranges from 50 meters to 90 meters in thickness.

Unit III is lighter in color than any of the overlying units. It contains numerous lithophysae generally concentrated in subhorizontal zones. At some localities the unit displays considerable internal contortions. The rocks of unit III appear somewhat altered and bleached, perhaps from vapor-phase crystallization.

Unit III contains phenocrysts of quartz, sanidine, and magnetite. Plagioclase has not been observed, but only two thin sections were studied. Small plagioclase crystal fragments do occur, but in the airfall ash at the base of the unit. Sanidine is more abundant than quartz. The sanidine crystals are as much as several millimeters across and are conspicuously larger than those in any of the overlying units. Quartz occurs as dipyramids 0.1-0.3 millimeter in diameter and as irregular to anhedral equant grains, commonly more than a millimeter across, suggesting that both phenocrysts and xenocrysts are present.

An analysis of the basal vitrophyre from unit III (Table 1) reveals that the unit is more silicic than any of the overlying units; this is confirmed by several additional analyses of the unit (Bonnichsen, 1982a and unpublished data). The magnetic polarity of unit III has not been determined.

UNIT V

Unit V forms a comparatively low cliff in Bruneau Canyon (Figure 1). The unit typically ranges from 10 meters to 40 meters in thickness, and generally thickens northward. At some localities where it is thin, the unit contains medial vitrophyre layers, clearly indicating that it is a compound cooling unit. Like the underlying unit III, unit V is observed to pinch out southwards against the older Bieroth volcanics in the Rowland, Nevada, area (Figure 3). Unit V is exposed in the Jarbidge River drainage only at the bottom of the West Fork canyon about 1.3 kilometers north of the mouth of Deer Creek (sec. 21, T. 47 N., R. 58 E.). At this locality the entire thickness of the unit is exposed and is seen to be only about 5 meters thick. Unit V is at the proper stratigraphic position to be equivalent to Bernt's (1982) unit 2, farther west, but this correlation is considered as only tentative. The unit has normal magnetic polarity (see Table 1, Bonnichsen, 1982b this volume).

Examination of two thin sections indicates that unit V contains phenocrystals of quartz, sanidine, plagioclase, augite, and magnetite. One grain of hematized biotite was found. Sanidine is more abundant than plagioclase which, in turn, is more abundant than quartz. Chemical analyses of unit V (Bonnichsen, 1982a and unpublished data) indicate a composition more femic than the underlying unit III, but less femic than VII, the overlying unit, and reveal that V is generally quite similar to units IX, XI, and XIII which occur stratigraphically higher.
UNIT VII

Unit VII forms a prominent cliff near the bottom of both Bruneau and Jarbidge Canyons (Figures 1 and 2). The unit is thicker in Bruneau Canyon, where it typically ranges from 40 meters to nearly 100 meters in thickness; it seems to thicken northward. In Jarbidge Canyon, it generally ranges from 20 to 40 meters in thickness and is the lowest unit there that can be continuously traced (Figure 2). Based on its similar chemical composition, reverse magnetic polarity, and stratigraphic position, unit 3 of Bernt (1982) to the west in the Cat Creek-Sheep Creek area is probably part of unit VII.

The multiple-step cliff formed by unit VII in Bruneau Canyon (see Figure 16 in Bonnichsen, 1981) suggests that the unit resulted from a sequence of ash-flow emplacements spaced closely enough in time to form a simple cooling unit. In both canyons, unit VII pinches out southward against older topography (Figure 3). Unit VII has reverse magnetic polarity (Table 1, Bonnichsen, 1982b this volume). In Bruneau Canyon, the upper part of VII is highly contorted, with curved sheeting joints that range from horizontal to vertical or overturned within a few meters.

The phenocryst minerals in unit VII are plagioclase, sanidine, quartz, pigeonite, augite, and magnetite. The average abundance of phenocrysts for seven modal analyses from the Jarbidge Canyon area is 10.7 percent. The approximate proportions of the various phenocryst minerals are shown in Figures 4, 5, and 6. Plagioclase is the most abundant; it com-
Bonnichsen and Citron—Cougar Point Tuff

Figure 2. View, looking north-northeast from Cougar Point, of the Cougar Point Tuff exposed in East Fork Jarbidge River canyon. The various units are indicated by Roman numerals.

monly accounts for nearly 40 percent of the total phenocrysts (Figure 6). Sanidine is second in abundance (Figure 4), and quartz occurs in most rocks but is scarce (Figures 4 and 5). Pigeonite commonly is more abundant than augite. Fayalite has not been detected in unit VII. Magnetite occurs in all thin sections examined, and possible ilmenite tablets occur in two of eleven sections. Magnetite and clinopyroxene occur in approximately equal amounts (Figure 5). Traces of biotite and hornblende occur in a few thin sections as overgrowths on pyroxenes, or as alteration products, but not as independent phenocrysts. Plagioclase-clinopyroxene-opaque oxide cumulophyric aggregates are common in unit VII.

An analysis of the basal vitrophyre of unit VII (Table 1) indicates a composition more femic than several of the other Cougar Point Tuff units. This is confirmed by eight additional analyses from the unit (Bonnichsen, 1982a and unpublished data).

A potassium-argon age determination* of 11.3±2.0 million years was obtained from a unit VII sample from near the bottom of Deer Creek grade in the West Fork of the Jarbidge River canyon.

*The material dated was a whole-rock sample (1-841) of the basal vitrophyre of unit VII from the SW¼NE¼, sec. 28, T. 47 N., R. 58 E., Elko County, Nevada. The analysis was performed by Professor Daniel Krummenacher, Department of Geological Sciences, San Diego State University, San Diego, California. Analytical data from the determination include: weight percent K=4.81%; moles per gram of 40Ar=9.48 x 10^-16; and 40Ar rad=90%. Constants used for age calculation are λ₀=4.96 x 10^-10 per year, λ₀=0.581 x 10^-10 per year, and percent 40K of total K=0.01167. This age determination should be considered a minimum age, in view of the ever-present possibility of argon leakage from somewhat hydrated volcanic glass, although less hydration for the dated sample than for most other Cougar Point Tuff vitrophyres is suggested by the relatively high sum of the major oxides (99.01%) (no. 2, Table 1) in comparison with other analyses in Table 1, and in Bonnichsen (1982a).
UNIT IX

Unit IX is exposed in both Bruneau and Jarbidge Canyons (Figures 1, 2, 3, and 7). In Jarbidge Canyon it forms a prominent horizontally layered cliff below 50 meters or more of nonresistant material (covered slope in Figure 2). In Bruneau Canyon unit IX forms a conspicuously layered cliff tightly sandwiched between the thicker and more massive units VII, below, and XI, above (Figures 1, 3, and 7). Its layered nature clearly shows that unit IX resulted from a sequence of emplacements. In some areas the unit appears to be a simple cooling unit, but at other places it might better be thought of as a compound cooling unit. Like the units beneath it, IX pinches out southward against older topography in the Rowland, Nevada, area (Figure 3). In Bruneau Canyon, unit IX typically is 40 to 50 meters thick, whereas in Jarbidge Canyon its resistant part generally is 30 to 40 meters thick. Unit IX has normal magnetic polarity (Table I, Bonnichsen, 1982b this volume).

In its Bruneau Canyon exposures, unit IX characteristically contains fairly abundant small, generally angular, devitrified and probably cognate volcanic rock clasts in its lower part. The welding does not extend completely to the base of the ash flow at some locations in Bruneau Canyon. The unit also contains veins and segregations of jasper in its upper portions in Bruneau Canyon, suggesting post-eruption interaction with water.

Unit IX contains phenocrysts of plagioclase, sanidine, quartz, augite, pigeonite, and magnetite. The average phenocryst abundance is 8.6 percent in eleven Jarbidge Canyon samples for which modal analyses are available. In most, sanidine is more abundant than plagioclase, which in turn is more abundant than quartz (Figure 4). Clinopyroxene, magnetite, and quartz occur in approximately equal proportions (Figure 5). Sanidine and quartz generally account for half or more of the phenocrysts; plagioclase accounts for 10 to 25 percent, and the mafic minerals for 20 to 40 percent (Figure 6). Locally, fragments of quartz-sanidine micrographic intergrowths occur, but they are much less abundant than in units XI and XIII. Plagioclase-clinopyroxene-opaque oxide cummophyric aggregates are common, and hornblende rims on augite grains were noted in a few samples from Jarbidge Canyon.

Chemical analyses (Bonnichsen, 1982a and unpublished data) reveal unit IX to be similar in composition to the thick overlying unit XI, but not as femic as the underlying unit VII.

UNIT X

Unit X is well exposed only in the canyon of the East Fork of the Jarbidge River. It is 20 to 25 meters thick in the Cougar Point area of that canyon (Figure 2). Scattered outcrops of what probably is the same unit also occur in the east wall of the West Fork of Jarbidge Canyon near the mouth of Deer Creek (sec. 77, T. 47 N., R. 58 E.); but there the unit is only a few meters thick and does not form a traceable ledge. Unit X has not been found in Bruneau Canyon. The limited distribution of this relatively thin unit suggests that it is not as voluminous as the other Cougar Point
Table 1. Chemical analyses and CIPW norms for representative samples of the Cougar Point Tuff.

<table>
<thead>
<tr>
<th>Unit</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>III</td>
<td>VII</td>
<td>XI</td>
<td>XII</td>
<td>XIII</td>
<td>XV</td>
<td>XV</td>
<td>XV</td>
</tr>
<tr>
<td>SiO₂</td>
<td>74.87</td>
<td>72.24</td>
<td>73.16</td>
<td>72.97</td>
<td>74.25</td>
<td>73.58</td>
<td>72.05</td>
<td>72.04</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>12.34</td>
<td>12.83</td>
<td>12.00</td>
<td>12.04</td>
<td>12.20</td>
<td>12.14</td>
<td>11.04</td>
<td>12.53</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.14</td>
<td>0.48</td>
<td>0.30</td>
<td>0.52</td>
<td>0.29</td>
<td>0.40</td>
<td>0.36</td>
<td>0.40</td>
</tr>
<tr>
<td>Fe as Fe₂O₃</td>
<td>1.40</td>
<td>3.27</td>
<td>2.32</td>
<td>3.36</td>
<td>2.26</td>
<td>3.47</td>
<td>4.54</td>
<td>2.84</td>
</tr>
<tr>
<td>MoO³</td>
<td>0.07</td>
<td>0.05</td>
<td>0.02</td>
<td>0.05</td>
<td>0.02</td>
<td>0.04</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>CaO</td>
<td>0.64</td>
<td>1.32</td>
<td>0.82</td>
<td>1.21</td>
<td>0.86</td>
<td>0.77</td>
<td>0.86</td>
<td>0.80</td>
</tr>
<tr>
<td>MgO</td>
<td>0.21</td>
<td>0.37</td>
<td>0.12</td>
<td>0.34</td>
<td>0.20</td>
<td>0.22</td>
<td>0.26</td>
<td>0.21</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.47</td>
<td>5.67</td>
<td>5.76</td>
<td>5.48</td>
<td>5.64</td>
<td>6.08</td>
<td>5.84</td>
<td>6.03</td>
</tr>
<tr>
<td>Na₂O</td>
<td>2.76</td>
<td>2.69</td>
<td>2.92</td>
<td>2.88</td>
<td>2.90</td>
<td>2.53</td>
<td>2.51</td>
<td>2.26</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.02</td>
<td>0.09</td>
<td>0.03</td>
<td>0.10</td>
<td>0.03</td>
<td>0.06</td>
<td>0.08</td>
<td>0.06</td>
</tr>
<tr>
<td>Total</td>
<td>97.87</td>
<td>99.01</td>
<td>97.45</td>
<td>99.55</td>
<td>98.71</td>
<td>99.09</td>
<td>100.27</td>
<td>97.21</td>
</tr>
</tbody>
</table>

Notes:
Except as noted below, the samples were analyzed for major oxides by a combination of X-ray fluorescence and atomic absorption at Washington State University (XRF) and at the Idaho Bureau of Mines and Geology (AA) and for minor elements by X-ray fluorescence at the Research and Development Department of Conoco, Inc.

For samples in which only the total iron was analyzed, the CIPW norms were calculated by assigning 40 atom percent of the Fe to Fe₂O₃ and 60 atom percent to FeO.

1. Sample L-569, basal vitrophyre of Cougar Point Tuff unit III; NW¼NE¼, sec. 28, T. 16 S., R. 7 E., Owyhee County, Idaho.
2. Sample I-841, basal vitrophyre of Cougar Point Tuff unit VII; SW¼NE¼, sec. 28, T. 47 N., R. 58 E., Elko County, Nevada.
3. Sample L-463, basal vitrophyre of Cougar Point Tuff unit XI; NW¼SW¼, sec. 9, T. 16 S., R. 7 E., Owyhee County, Idaho.
4. Sample L-799, basal vitrophyre of Cougar Point Tuff unit XII; SE¼NE¼, sec. 28, T. 16 S., R. 7 E., Owyhee County, Idaho.
5. Sample L-461, basal vitrophyre of Cougar Point Tuff unit XIII; SE¼SW¼, sec. 9, T. 16 S., R. 7 E., Owyhee County, Idaho.
6. Sample L-76, vitrophyre from Cougar Point Tuff unit XV; SE¼NW¼, sec. 24, T. 16 S., R. 9 E., Owyhee County, Idaho. In Bonnichsen (1982a), this sample was erroneously assigned to unit XIII. The revision to unit XV has also been made in Figure 21.
7. Sample L-76, same description and location as given in 6. Analyzed by K. Ramal at the University of Manitoba, 1972, by methods described in Wilson and others, 1969. The total includes 2.98 percent H₂O, 0.04 percent CO₂, 0.01 percent S, and Fe reported as 3.18 percent Fe₂O₃ and 1.22 percent FeO.
8. Sample S-193, vitrophyre from Cougar Point Tuff unit XV; SE¼NW¼, sec. 24, T. 16 S., R. 9 E., Owyhee County, Idaho.
Tuff units

The one thin section from unit X that has been examined contains phenocrysts of sanidine, plagioclase, and quartz with proportions similar to those in unit XI, and phenocrysts of magnetite and oxidized pyroxenes. A chemical analysis (Bonnichsen, 1982a) of X indicates a composition similar to the underlying unit, IX, and overlying unit, XI.

UNIT XI

Unit XI is one of the most voluminous and complex units in the Cougar Point Tuff. In Bruneau Canyon (Figures 1, 3, and 7), it forms a high cliff in about the middle of the section and ranges from 90 to probably more than 100 meters in thickness. In Jarbidge Canyon it ranges from 30 to more than 50 meters in thickness and is the thickest unit in that area (Figure 2). In both canyons the internal horizontal layering clearly shows that it resulted from a sequence of ash-flow emplacements. Where it is thick, unit XI forms a simple cooling unit. However, where XI has been mapped across northern Nevada between Bruneau and Jarbidge Canyons, it appears to bifurcate into thinner separate cooling units. This composite sheet behavior (Smith, 1960) probably is the result of overall southward thinning of the unit onto preexisting topographic irregularities distal from the unit's source.

Unit XI's distribution east of Jarbidge Canyon in northern Nevada has yet to be explored in detail, but it very likely extends as far east as Elk Mountain (see Figures 2 and 3, Bonnichsen, 1982b this volume). West of Bruneau Canyon, the unit which Bernt (1982) designated as unit 6 in the Sheep Creek area very likely is, at least in part, the same as unit XI.
In both Bruneau and Jarbidge Canyons, unit XI is characterized by many picturesque erosional pillars, as can be seen in Figures 7 and 8. In the West Fork of Jarbidge Canyon near Deer Creek grade, the upper part of the unit contains many flattened pumice inclusions, some as much as a meter long (Figure 9). Unit XI has reverse magnetic polarity (Table 1, Bonnichsen, 1982b this volume).

Unit XI contains sanidine, quartz, plagioclase, magnetite, ilmenite, augite, pigeonite, and fayalite phenocrysts. The average phenocryst abundance for twelve samples from the Jarbidge River drainage area is 5.5 percent. The overall proportion of quartz and sanidine generally ranges from 55 to 75 percent, that of plagioclase from 0 to 20 percent, and that of the mafic minerals from 20 to 35 percent (Figure 6). Sanidine is the most abundant; in most samples it exceeds quartz in abundance and is twice or more as plentiful as plagioclase (Figure 4). Generally, quartz is more abundant than plagioclase. In the Jarbidge Canyon area the proportion of quartz and plagioclase relative to sanidine increases upwards through the unit. Locally, quartz and plagioclase are absent or very sparse (Figure 4). Most of the quartz occurs as tiny dipyramids, although larger rounded to irregular quartz xenocrysts have been noted in a few rocks. In most unit XI samples a few sanidine grains have partial rims of quartz-sanidine micrographic intergrowths; fragments of these intergrowths also occur. Unit XI is similar only to unit XIII in its abundance of these intergrowths.

Magnetite is the most common mafic mineral (Figure 5), followed by augite. In the Jarbidge Canyon area, the augite is accompanied by minor fayalite, whereas in the Black Rock area of Bruneau Canyon and in northern Nevada between the Bruneau and Jarbidge Rivers, pigeonite occurs instead of fayalite. Fayalite and pigeonite have not been observed together in the same sample. A few plagioclase-olivine-pyroxene opaque oxide cumulophyric aggregates occur in most unit-XI thin sections. Many of these consist predominantly of granoblastic plagioclase containing inclusions of pyroxene and magnetite. The presence in most thin sections of a few small elongate laths of probable ilmenite distinguishes unit XI from all other units except XIII.

An analysis of typical basal vitrophyre material from unit XI (Table 1) indicates a composition quite similar to that of IX and XIII, and not as femic as units VII, XII, and XV. Additional analyses of XI (Bonnichsen, 1982a and unpublished data) generally confirm this.

UNIT XII

Unit XII is widely distributed but not as extensive as the units below (XI) and above (XIII). Its most prominent exposures are in the walls of the East and West Forks of Jarbidge Canyon (Figure 2) where it generally ranges from 30 to 40 meters in thickness. Unit XII has been traced east of Jarbidge Canyon, through the Jarbidge and Elk Mountain, Nevada, 15-minute quadrangles, to as far east as 115 degrees longitude (right side of Figures 2 and 3, Bonnichsen, 1982b this volume). The unit has been traced westward in northern Nevada to the Black Rock escarpment on the east side of Bruneau Canyon (Figures 1 and 7). It is thin and discontinuous there, indicating that the area is near its western margin. Unit XII was not reported farther west, in the area recently mapped by Bernt (1982). Unit XII has normal magnetic polarity (Table 1, Bonnichsen, 1982b this volume).

Unit XII contains phenocrysts of plagioclase,
Augite, pigeonite, and magnetite. Modal analyses of sixteen samples indicate an average phenocryst abundance of 10.9 percent. Plagioclase is the most abundant, followed by pyroxenes and magnetite (Figures 4, 5, and 6). Quartz and sanidine normally do not occur in the unit; in the few sections in which they have been noted, their habit suggests they are xenocrysts. Their absence distinguishes unit XII from all the other Cougar Point Tuff units. In most samples clinopyroxene is more abundant than magnetite (Figure 5), and generally pigeonite is more abundant than augite. Plagioclase-clinopyroxene-opaque oxide cumulophyric aggregates are common in unit XII, more so than in most other units.

An analysis of a unit XII basal vitrophyre sample (Table 1) shows that XII is one of the most felsic units, along with VII and XV. Two additional analyses of XII (Bonnichsen, 1982a and unpublished data) are almost identical to the one reported.

UNIT XIII

Unit XIII is one of the most widespread of the Cougar Point Tuff units. It has been traced 65 kilometers along the southern margin of the Bruneau-Jarbidge eruptive center and its eastern limit has yet to be determined. It is the uppermost unit in most of the Jarbidge River drainage area, occurring at the canyon rim (Figure 2) where it ranges in thickness from 20 to 45 meters. In Bruneau Canyon (Figures 1 and 7) it ranges from less than 30 meters to 40 meters in thickness. It extends west of Bruneau Canyon into Sheep Creek canyon, where it pinches out westward (Bernt, 1982, unit 7) in the northwestern part of T. 15 S., R. 6 E. Unit XIII extends an undetermined distance east of 115 degrees longitude in Idaho and is widely distributed in the northern parts of the Contact, Elk Mountain, Jarbidge, and Rowland 15-minute quadrangles in northern Nevada.

Although it is a simple cooling unit, XIII has a horizontal layered appearance at some localities suggesting it may have resulted from a sequence of ash-flow emplacements. A characteristic feature of unit XIII throughout most of its distribution area is a thin (generally 1 to 2 meters) horizontal lithophysal zone (Figure 10) about two-thirds of the way up from its base. Unit XIII has normal magnetic polarity (Table 1, Bonnichsen, 1982b this volume).

Unit XIII contains plagioclase, sanidine, quartz, augite, fayalite, magnetite, and ilmenite phenocrysts. The average phenocryst abundance for twenty modal analyses of samples from the Jarbidge River drainage is 8.9 percent. Generally, sanidine is more abundant than either quartz or plagioclase (Figure 4), and the unit shows a greater variation in the ratio of feldspar to quartz than any of the other units for which modal data are available (Figures 4, 5, and 6). In general, sanidine decreases upwards in the unit relative to plagioclase and quartz. The proportions of quartz
Bonnichsen and Citron—Cougar Point Tuff

Figure 8. Erosional pillars in the massive central zone of Cougar Point Tuff unit XI in West Fork Jarbidge River canyon. The horizontal break about one-third of the way up from the cliff base is a boundary between successive ash emplacements. A lithophysal zone occurs just below this break. The basal vitrophyre is exposed in the alcove eroded at the base of the cliff.

and plagioclase vary widely in XIII (Figure 4), but no vertical trend has been noted. Quartz generally is more abundant than pyroxene or opaque minerals (Figure 5), and the ratio of magnetite to pyroxene varies more than for other units. Mafic minerals normally constitute 15 to 35 percent of the phenocrysts, plagioclase 5 to 40 percent, and quartz and sanidine together 50 to 75 percent (Figure 6).

Quartz occurs both as small dipyramidal grains, and as larger rounded and deeply embayed grains with undulatory extinction considered to be xenocrysts. Quartz-sanidine micrographic intergrowths occur as partial rims on some sanidine grains and as fragments in most thin sections. The only pyroxene identified is a clinopyroxene with an optic angle of about 60 degrees; it probably is subcalcic ferroaugite. No pigeonite grains have been found in XIII; evidently it is absent, and fayalite takes its place as
UNIT XV

The uppermost unit (XV) occurs most prominently along the rim of Bruneau Canyon (Figures 1 and 7) in the Black Rock escarpment area, where it ranges from 30 to nearly 100 meters in thickness. The dark appearance of the thick part of unit XV, especially as seen from the north and west in morning shadows or on cloudy days, is the reason the topographically high escarpment on the east side of Bruneau Canyon is called Black Rock.

In the Bruneau Canyon area unit XV thins southward into Nevada along the rim of Deep Creek, and pinches out a few kilometers south of the state line. However, it continues to the north and is downfaulted to a level below the Triguero Homestead rhyolite in the Bull Pens area (see Figure 6 in Bonnichsen, 1982b this volume). Unit XV occurs at the surface from Dorsey Creek and westward to about as far west as the Three Forks area of Sheep Creek in the southeastern part of T. 15 S., R. 5 E., where it pinches out (Bernt, 1982). In the canyon of Cat Creek between Bruneau Canyon and Sheep Creek, unit XV is 50 to 75 meters thick, and it thins and bifurcates into two separate cooling units both to the north and south to form a composite sheet (Bernt, 1982, unit 8). At all other localities the unit is observed to be a simple cooling unit.

East of Dorsey Creek, unit XV is discontinuously exposed as far east as the grade on the east side of Jarbidge Canyon at Murphy Hot Springs. Unit XV generally is less than 5 meters thick at all localities east of Dorsey Creek and consists mainly of vitrophyre.

In the thick part of the unit in the Black Rock area, the basal part of the unit contains abundant, generally small, greatly flattened pumice fragments. Unit XV has normal magnetic polarity (Table 1, Bonnichsen, 1982b this volume).

The phenocryst minerals in unit XV are plagioclase, sanidine, quartz, augite, pigeonite, fayalite, and magnetite. In general, plagioclase is considerably more abundant than either quartz or sanidine. Quartz is not present in all thin sections that have been examined, and sanidine occurs in only about half. Both augite and pigeonite occur in most of the thin sections examined. In sections from the Murphy Hot Springs area in the East Fork of Jarbidge Canyon, which probably is the location farthest removed from the source of the ash flow, fayalite takes the place of pigeonite. Cumulophyric aggregates of plagioclase, pyroxenes, and opaque oxides are common throughout the unit.

Analyses of two basal vitrophyre samples (Table 1) show unit XV to be one of the more femic Cougar Point Tuff units, along with VII and XII. This is confirmed by several additional analyses (Bonnichsen, 1982a and unpublished data; Bernt, 1982).
INTERNAL FEATURES
OF THE UNITS

Although each has its distinctive internal physical characteristics, the various Cougar Point Tuff units are quite similar in magma composition, temperature and mode of eruption, and nature of the landscape each was deposited upon. Where relatively thick, as in Bruneau and Jarbidge Canyons, they are simple cooling units in the sense of Smith (1960), and each unit can be divided into a vertical succession of distinct internal zones. Some units, when traced laterally into areas where they are thin, change into compound cooling units or even bifurcate into composite sheets. Units V, IX, XI, and XV exhibit this style of behavior, as noted in the preceding section. The internal zones are discussed below in relation to the simple cooling units, ignoring complications that arise where they are compound or split into composite sheets.

In this report rocks with a crystallized groundmass, regardless if due to devitrification alone or to vapor-phase crystallization as well (in the sense of Ross and Smith, 1961) are referred to as lithoidal. All relationships between glassy and lithoidal rocks in the Cougar Point Tuff can logically be interpreted as the result, or the lack, of crystallization and oxidation of the groundmass in the short time immediately after emplacement. None of the glassy-lithoidal relationships observed have resulted from subsequent reheating, structural processes, or groundwater-induced situations. Weathering has seldom caused devitrification of a thickness of more than a centimeter adjacent to exposed rock surfaces. More commonly, weathered zones (other than hydration of the glasses) are less than a millimeter thick. The introduction of meteoric water after the deposition of the ash flows may have hydrated some of the vitrophyres, however. Furthermore, the introduction of meteoric water probably caused the late-stage precipitation of local opal, chalcedony, and jasper near the tops of the cooling units, and may also have induced minor groundmass crystallization there.

Lithoidal rocks with crystallized groundmasses generally have red, orange, tan, or lavender colors, in marked contrast to the black or gray tones that characterize most glassy rocks. Some of the steeply dipping joint surfaces in lithoidal rhyolite in the upper zones of units, and some of the crumbly joint surfaces in lithoidal rhyolite in the massive central zones, have a distinctive red or reddish brown glazed appearance, generally brighter in appearance than fresh rock adjacent to the joints and fractures. This condition probably is the result of a greater amount of oxidation along fractures which formed during the cooling of the units. This characteristic tends to give the Cougar Point Tuff units an appearance that is more reddish from a distance than is the color of freshly broken rock surfaces.

Where it has occurred, groundmass crystallization has resulted in the partial to usually complete destruction of shards or other identifiable particles inherited from the ash-flow portion of a unit's history. However, larger, extremely flattened fragments of what probably was pumice, and rare small rock chips (Figures 9 and 11) are preserved in the lithoidal portions of some units. The flattened pumice fragments appear as small discoid inclusions with length-to-height ratios generally between 10 and 100.

In a typical vertical section through a simple cooling unit of the Cougar Point Tuff, basically four distinctive zones exist that differ in the manner of emplacement, cooling rate, amount of compaction, and thickness. Typical zones, from base to top, are (1) a basal layer of thinly bedded, principally air-fall ash, (2) a thoroughly welded vitrophyre layer which is the base of the ash-flow tuff, (3) a massive, relatively thick, lithoidal central zone in which most precrystallization structures have been obliterated, and (4) an upper zone where stretched vesicles, flow marks, and secondary folds are common and where vitrophyre may occur.

Figure 11. Flattened pumice fragments and small lithic inclusions within Cougar Point Tuff unit XI, from Deer Creek grade in West Fork Jarbidge River canyon. For scale, the jackknife is about 11 centimeters long.
BASAL BEDDED ASH ZONES

At the base of each cooling unit is a bedded air-fall volcanic ash layer that generally is between 1 and 3 meters thick (Figure 12). Typically, this material varies from white or tan to gray or nearly black. These ash deposits are characterized by numerous laminations and thin beds, arising from color and particle size variations. The layers typically vary from light colored and almost unconsolidated at the base to dark colored and hard at the top where fused by the overlying ash flow (Figure 12).

Nearly all of the material has a particle size of less than 2 millimeters. Only a minor proportion of lapilli-sized particles (2-64 millimeters) has been found, and nearly all fragments are less than a centimeter across. No volcanic blocks or bombs have been found. Ninety percent or more of the bedded ash is a mixture of shards, more or less equant to flattened glass particles, and glassy dust. Phenocrysts are generally present; typically they are the same minerals as in the overlying ash-flow portions of units. Feldspar phenocrysts are mainly crystal fragments, thus tending to be smaller than the intact phenocrysts in the ash-flow portion of a unit. Most commonly the volcanic rock inclusions are less than 2 millimeters across and range from angular to rounded, from glassy to lithoidal, and from pumiceous to devoid of vesicles. Rock fragments from nonvolcanic sources are exceedingly rare in these bedded ash deposits.

Much of the bedding in the basal bedded ash zones is the result of particle size variation. Graded beds with upwards-decreasing average particle size are common, and other, more complex particle size variations have also been noted. Massive ash zones up to 20-30 centimeters thick, which occur locally in the bedded ash layers, may be small ash flows. Locally, thin intervals within the basal ash zones are cross-bedded, generally with dips of less than 10 degrees and with cross-bedded sections commonly only a few centimeters thick. Whether these cross-beds resulted from base-surge deposition, water or aeolian deposition, or from some other origin is unknown.

The bedded ash zones are poorly exposed, because they are not resistant and because they become covered with rocks falling from the overlying cliffs. Local exposures do reveal that the ash was deposited on tan-colored, generally structureless, silt-sized material which probably represents old soil layers. In other places, however, the material under the bedded ash has been found to be white clay-sized laminated sedimentary material, probably of lacustrine origin, or coarse-grained sandstone composed principally of materials derived from underlying volcanic units and probably deposited in a fluvial or deltaic environment. Such features, along with local lithophysal zones near the bases of the overlying welded ash flows, suggest that in some places ash fell and ash flows erupted into shallow water.

The upper parts of basal ash zones commonly have been fused or welded to such an extent as to resemble

Figure 12. The basal bedded ash zone, overlain by the basal vitrophyre, of Cougar Point Tuff unit XV at Black Rock escarpment. Note that the upper part of the bedded ash zone is darker in color and more resistant where it has been thoroughly fused. The large spherulite in the basal vitrophyre in just below the bottom of the devitrified massive central zone. For scale, note the hammer immediately below the top of the basal bedded ash zone.
the dark-colored overlying basal vitrophyre zone (Figure 12). The basal ash, however, retains its bedded character, whereas the overlying basal vitrophyre is massive. Wherever observed, the contacts between the two zones are sharp and subhorizontal. The boundaries between the fused and nonfused portions of the basal bedded ash zones always are gradational, generally through an interval from 0.5 meter to 1.5 meters thick. Locally, beneath particularly thick units, the fusing has extended completely through the basal bedded ash zone and into the underlying sedimentary material.

BASAL VITROPHYRE ZONES

A vitrophyre layer occurs at the base of the ash-flow portion of each Cougar Point Tuff unit. These layers are black to dark gray and generally 1 to 3 meters thick (Figure 12). Thicker vitrophyre zones occur where the units are thin in their distal portions. Only locally did welding not extend to the base of the ash-flow portion of a unit to entirely fuse the particles into continuous glass, as at the base of IX at Black Rock.

The boundaries between basal vitrophyre layers and central lithoidal zones are sharp, slightly undulating, subhorizontal planes separating the reddish lithoidal rhyolite from the underlying dark-colored vitrophyre (Figure 13). The undulations result from convex-downward lithoidal growth surfaces that merged together at the frozen front of downward-progressing groundmass crystallization.

Red-colored spherulites are common in the basal vitrophyre zones (Figures 14 and 15). Their spacing varies from several meters apart to crowded so closely together that only patches of vitrophyre remain. Spherulites tend to be most abundant in the upper parts of the basal vitrophyre zones (Figure 12). Most spherulites are less than 15 centimeters across, although individuals may exceed one-half meter (Figure 15). Typically, all but the smallest have interior shrinkage cavities. Some cavities contain deposits of jasper, opal, chalcedony, carbonate minerals, zeolites, and possibly other minerals, but the quantity of material is generally minor. The shrinkage cavities typically are angular (Figures 12 and 15); star-shaped cross sections of 3 to 6 points are common. Ghosts of spherulites locally can be seen at the bottoms of the central lithoidal zones (Figure 13), as indicated by the angular shrinkage cavities.

MASSIVE CENTRAL ZONES

The massive central zone constitutes most of a typical cooling unit of the Cougar Point Tuff. These zones are completely welded lithoidal rhyolite, compacted to such an extent that virtually no pore space exists. It is primarily these zones which form the

Figure 13. The contact between the basal vitrophyre zone (below) and devitrified rhyolite (above) at the bottom of the central massive zone in Cougar Point Tuff unit XV at Black Rock escarpment. Note the flattened pumice fragments within the basal vitrophyre and the ghosts of spherulites within the devitrified rhyolite.
prominent cliff exposures of the units (Figure 16), and which may weather to hoodoo-like vertical pinnacles (Figure 8). Only where a unit is thin does the massive central zone become subordinate in thickness to the basal vitrophyre and the upper zone. Where cooling units are less than about 10 meters thick, the massive zone may be absent, leading to poor exposures.

Most rhyolite in the massive central zones has only weakly developed, closely spaced, subhorizontal jointing (sheeting), but is characterized by fairly well-developed, widely spaced, vertical joints. Vertical joints are most conspicuously developed where the massive zones are thickest (Figures 1, 7, 8, and 16). The massive central zones characteristically are cut by numerous closely spaced irregular fractures that vary in orientation. This causes rock surfaces to be crumbly and leads to the rounding of pinnacles and other angular protuberances on cliffs (Figure 16). At the upper and lower margins of massive central zones, closely spaced, subhorizontal sheeting joints may be prominent (Figures 16 and 17). Such sheeting also tends to be more abundant where massive central zones are thin. The relatively abrupt upward increase in abundance of such sheeting marks the gradational transition between the central and upper zones in a unit.

Figure 14. Small spherulites enclosed within vitrophyre in Cougar Point Tuff unit XV where the unit is only a few meters thick near Murphy Hot Springs, East Fork Jarbidge River canyon.

Figure 15. Large spherulites in the basal vitrophyre zone of Cougar Point Tuff unit XV at Black Rock escarpment. Note the shrinkage cracks and minor encrustations of secondary minerals in the spherulites, and the flattened pumice fragments within the vitrophyre.
Figure 11. Well-developed subhorizontal sheeting joints near the base of the massive central zone of Cougar Point Tuff unit XII along Deer Creek grade, West Fork Jarbidge River canyon.

...tutes from less than one fourth to more than one half of a unit, depending on its thickness. Thinner units have a greater proportion of upper-zone material.

The rhyolite in the upper zones commonly contains vesicles. Most commonly these are elongate parallel to one another, and were partially to completely flattened to flow marks (Figure 19) after they were formed. Lithophysal horizons and zones of spherulites also occur locally in the upper zones.

A zone of vitrophyre has been observed at the very top of some units. At most locations, however, the tops of units are poorly exposed, or not exposed at all.

UPPER ZONES

The upper zones consist mainly of lithoidal rhyolite which characteristically is quite variable in structure and appearance. Most upper-zone rhyolite is cut by well-developed, closely spaced, subparallel sheeting joints which commonly are contorted into foldlike forms (Figure 18). The upper zones contain local ramp structures and chaotically jointed areas where the sheeting varies from subhorizontal to steeply dipping within a few meters or less. Downward toward the massive central zones the sheeting becomes less pronounced and is confined to more nearly horizontal attitudes. The upper zone generally consti...
all, because they are porous and easily eroded or have become covered by scree that has fallen down canyon walls from the overlying units; thus, not much is known of detailed relations at unit tops. The best exposure of an original cooling-unit top that has been found is in unit XV along the lower part of the grade leading out of Jarbidge Canyon on the road from Murphy Hot Springs to Rogerson in sec. 24, T. 16 S., R. 9 E. The ash flow is only a few meters thick here, and consists mainly of vitrophyre containing centimeter-sized spherulites but very few vesicles in its central part (Figure 14). In the upper meter of the unit the vitrophyre changes upwards from a dense black glass to a friable gray vitric ash, which, at the very top of the unit, is so weak that it can be hand-crushed. The upper contact is sharp and overlain by brown silty sediment, probably loess, containing fragments of the underlying gray ash.

LITHOPHYSAL ZONES

Lithophysal zones containing numerous angular to spherical gas cavities occur in most of the Cougar Point Tuff units. These zones vary from rather local features with limited lateral continuity to subhorizontal layers that have been traced for tens of kilometers, but they are not considered to be major subdivisions of the ash-flow units in the same fashion as the basal, central, and upper zones. Lithophysal zones most commonly are within a few meters of the upper or lower boundaries of the massive central zones of the units in which they occur. They range from about a meter to several meters thick. The spacing of individual cavities in these zones varies from widely separated to closely packed (Figure 10). Individual lithophysae may be nearly solid, resembling spherulites, but more commonly they are hollow vugs. Individual lithophysae in such zones generally are a few centimeters across and are essentially undeformed, commonly having irregular outlines but being equant overall. In other instances they may be flattened or somewhat elongate, indicating they formed before compaction and local lateral motion of the rhyolite had ended (Figure 10).

Some lithophysal zones were probably formed when successive ash emplacements were deposited closely enough in time to trap the last of the volatiles being expelled from the one below. This may be the origin of the thin, areally extensive zones such as the one in unit XIII. Other lithophysal zones, especially those locally near the base of a unit, very likely have resulted from the ash flow having come to rest above a moisture-laden zone. The lithophysae in some zones are associated with inclusions of what probably were pumice fragments, suggesting the gas cavities resulted from water initially trapped in the inclusions. In fact, some lithophysae contain marginal crusts of what may have been pumice.

In one place (upper zone of unit XI on Deer Creek grade, West Fork of Jarbidge Canyon), a horizontal lithophysal zone of undeformed gas cavities has been observed to cut across a zone of steeply inclined flattened pumice fragments and sheeting. This relationship establishes that those particular lithophysal cavities formed later than the sheeting and folding, and very likely shows lithophysal zones to be relatively late structures. The most common cause for lithophysal zones to form in the Cougar Point Tuff units is probably the entrapment of the last gases that were expelled, as in this example.

ELONGATE VESICLES AND FLOW MARKS

The rhyolite in the upper zones of the units is variably vesicular, with scattered small vesicles to abundant vesicles more than a centimeter across. The amount of vesicularity generally increases upwards and towards the distal ends of the flows, but varies markedly on a local scale. Most vesicles are greatly stretched parallel to one another. Elongations with lengths of 10 to 100 times the diameters are normal. Most vesicles are subhorizontal, but some plunge at various angles, having been deflected by the same forces that formed and deformed the sheeting joints.

Parallel streaks or flow marks are locally numerous in lithoidal rhyolite of most of the Cougar Point Tuff units. These marks vary considerably in appearance.
and size. Some are merely color variations on joint surfaces. Others, probably most, are shallow parallel grooves on subhorizontal sheeting-joint planes (Figure 19), and others are elongate vesicles which have not been completely flattened. Flow marks range from a millimeter to several centimeters wide and from about a centimeter to many meters long. It is common for streaks of various widths and lengths to occur in proximity to one another. The flow marks are considered to have been gas cavities that became extremely stretched in the direction the ash was flowing at the time of its final emplacement, and that then were flattened. Both the flow marks and stretched gas cavities are considered to be primary flow lineations in the sense of Chapin and Lowell (1979).

Linear streaks and elongate vesicles are most abundant in the upper zones of units, but have also been found near the bases of some massive central zones. Most flow marks occur in lithoidal rhyolite. Where elongate features occur in vitrophyre, they generally are seen to be open vesicles rather than completely flattened streaks.

The elongation directions of many flow marks and linear vesicles have been measured. At a given locality (perhaps tens of meters across) all generally are within 10 or 20 degrees of one another. Throughout much larger areas (a kilometer or more across) the streaks and vesicles tend to be subparallel, generally with azimuths approximately perpendicular to the margin of the Bruneau-Jarbidge eruptive center. All available flow marks and elongate vesicle orientations for units XV and XIII are plotted in Figure 20, where the azimuths can be seen to generally converge toward the interior of the eruptive center. Figure 20 also shows some areas where preexisting topographic obstructions may have caused local deviations in the flow-mark azimuths.

Flow-mark and elongate-vesicle azimuths have been measured in all the other Cougar Point Tuff units except X and III. The pattern for units XII and XI is essentially the same as shown for units XV and XIII in Figure 20. In general, the flow azimuths for the units below XI suggest that their source may have been somewhat west of the source region indicated for the upper units, but not enough measurements are available to be sure. If the marks do reveal a more westerly source, it would be consistent with the lower units being thicker in Bruneau Canyon to the west, than in Jarbidge Canyon.

PETROGRAPHY

PHENOCRYST MINERALOGY

Quartz, sanidine, plagioclase, augite, pigeonite, fayalitic olivine, magnetite, and ilmenite are the principal phenocryst minerals in the Cougar Point Tuff. Accessory minerals are zircon, monazite(?), and apatite. Notably absent are phenocrysts of hornblende, biotite, and hypersthene. The phenocryst

![Figure 20. Regional distribution of flow azimuths, as measured from flow marks and elongate vesicles in Cougar Point Tuff units XV (solid symbols) and XIII (open symbols). The measurements are by Citron (1976), Bernt (1982), and Bonnichsen (unpublished data). The tails on the symbols indicate the inferred directions of flow away from the Bruneau-Jarbidge eruptive center.](image-url)
assemblage suggests that the Cougar Point Tuff magmas were comparatively hot as they rose through the crust and that they apparently had relatively low water contents. Also notable is the occurrence of plagioclase-pyroxene-opaque oxide cumulophyric aggregates, commonly with metamorphic textures, within most of the Cougar Point Tuff units. These are most abundant in the more felsic (VII, XII, and XV) and upper units, and are interpreted as fragments of protolithic material carried up from the magma source area.

The various Cougar Point Tuff units are mineralogically fairly homogeneous. Vertical zonation involving the loss or addition of a phenocryst phase has not been documented at any particular site. Slight vertical variations in the ratios of phenocryst minerals, however, do exist in some units. The principal lateral variation noted is the substitution of fayalite for pigeonite in thinner, probably more distal portions of some units. The total abundance of phenocrysts is greater in the more felsic units (VII, XII, and XV) than in the other units. The abundance of phenocrysts decreases generally but sporadically away from the Bruneau-Jarbidge eruptive center in many of the cooling units.

Quartz occurs mainly as small, dipyramidal grains, nearly always between 0.05 and 0.3 millimeter across. These vary from euhedral to rounded and may be embayed; they probably crystallized from the magma, and then locally were partially resorbed by it. In some units, larger rounded to irregular quartz grains occur in addition; these probably are xenocrysts.

Sanidine occurs as euhedral to subhedral grains with only modest local zoning at crystal margins, and more commonly as crystal fragments. Unbroken grains range from 0.5 millimeter to 3 millimeters in length. Some sanidines are partially resorbed, with rim embayments and interior zones of isolated glass inclusions. The sanidine crystals tend to be more abundant and larger in the more silicic units. In some of these units sanidine has also locally overgrown and has partially replaced plagioclase or has formed micrographic intergrowths with quartz. The micrographic intergrowths occur as partial rims attached to sanidine crystals, and as broken fragments.

Plagioclase is abundant, and various textural types commonly are seen together in individual thin sections. Plagioclase compositions are mainly in the An_{10} to An_{35} range, with the higher anorthite contents occurring in the more felsic units. Single plagioclase crystals, generally subhedral tablets or laths, and fragments broken from such grains, are common; these mainly are 0.5 and 2.0 millimeters long, but locally are as much as 4 or 5 millimeters long.

In many rocks some of the plagioclases have ordinary combined albite-Carlsbad twinning and weakly to strongly developed, normal or oscillatory concentric zoning. Such individuals are interpreted as phenocrysts which crystallized from the magma during ascent. Others have characteristics suggesting they are refractory protolithic material which was not entirely melted when the magma was generated. These include anhedral grains, grain fragments, and clots with annealed textures, patchy, irregular, or negligible zoning, and anhedral equant inclusions of pyroxene and opaque oxide minerals.

Cumulophyric aggregates of plagioclase, augite, pigeonite, magnetite, and perhaps ilmenite in variable proportions are common. These aggregates have internal textures ranging from plutonic igneous with subhedral crystal forms to metamorphic with anhedral grains arranged as in a granulite or as in refractory rocks from which substantial quantities of interstitial melt have been extracted. Individual aggregates are similar in size to the larger feldspar grains, ranging from a millimeter to about 4 millimeters across.

The plagioclases in the cumulophyric aggregates show little or no zoning or have patchy, irregular, or local domain zoning. Part of the plagioclase grains in many rocks show minor to extensive embayment and contain small brown glass inclusions commonly arranged in internal zones, whereas adjacent grains may be unsieved. Although it may not be entirely evident in an individual thin section, it is hard to escape the conclusion that in most Cougar Point Tuff units the plagioclase phenocrysts are a mixture of crystals which grew from the magma and of grains inherited from the protolith.

The pyroxenes are a mixture of augite and pigeonite. No hypersthene has been observed. Augite occurs in all units and pigeonite in most, but pigeonite is absent in rocks containing fayalite. Pigeonite and augite are texturally identical, but their ratio varies with more pigeonite than augite in some rocks and the reverse in others. The pyroxenes occur as rounded equant to subhedral prismatic single crystals and as equant to irregular anhedral crystals in the cumulophyric aggregates. Some pyroxene grains are wholly enclosed within plagioclase, and pyroxene grains locally enclose rounded magnetite grains in some aggregates. Pyroxene crystals typically are 0.1 to 0.75 millimeter long, and few exceed this size. Rare poikilitic pyroxenes have been found, with groundmass material filling the holes rather than any mineral, suggesting a former included mineral was melted from the pyroxene during magma formation or ascent. Pyroxenes in glassy rocks commonly are fresh, but pyroxenes in lithoidal rhyolite are partially to completely oxidized.
Fayalitic olivine occurs in parts of units XI and XV and is ubiquitous in XIII. The olivine is texturally very similar to the pyroxenes but it generally occurs as isolated crystals; however, in a few rocks the olivine grains are attached to augite or magnetite. It is likely that most, if not all, of the olivine crystallized from the enclosing magma rather than representing part of the protolith. Olivine grains commonly are partially oxidized, primarily to opaque material (probably magnetite). They are preserved best in vitrophyre samples.

Opaque oxides occur in all of the Cougar Point Tuff units. Both magnetite and ilmenite probably are present, but systematic polished-section confirmations have yet to be made. Most of this material occurs as small (generally less than 0.25 millimeter) anhedral to euhedral equant, probably octahedral, grains, believed to be magnetite. Locally, irregular grains and groups of equant to irregular grains occur. Small plates of what is believed to be ilmenite occur in some units. These plates are most abundant in two of the least femic units (XI and XIII). Opaque oxide grains in the cumulophyric aggregates range in shape from anhedral equant to irregular. Some of the opaque grains in these aggregates may be ilmenite rather than magnetite, as is the case in some of the rhyolite lava flows in the Bruneau-Jarbidge eruptive center (Bonichsen, 1982 this volume).

Accessory minerals identified in the Cougar Point Tuff are apatite, monazite(?), and zircon. Zircon probably is the most abundant. These minerals are most commonly associated with pyroxene and opaque oxide grains, especially those within the cumulophyric aggregates. Single crystals of zircon and monazite(?) have been noted, however, and apatite occurs as elongate grains enclosed within plagioclase in some rocks.

The Cougar Point Tuff is virtually free of hydrous phenocryst phases. The principal occurrences are in some of the lower units, where brown hornblende and biotite sporadically occur as partial rims on pyroxene. One partially hematized biotite grain was found as a free-floating phenocryst in unit V. No independent hornblende grains have been observed in numerous thin sections from the region around Bruneau and Jarbidge Canyons, but Bernt (1982) reported a single grain from unit XV in the Cat Creek-Sheep Creek area.

**THE GROUNDMASS**

The groundmass varies from wholly glassy to devitrified. Where glassy, it commonly is gray glass containing abundant microlites or brown glass with few, if any, microcrystals. The glass occurring in embayments and as inclusions in plagioclase, sanidine, and other minerals tends to be brown and free of crystals. At the bases of the thicker units, the gray glass may contain wispy darker layers that probably represent squashed pumice fragments, but it generally shows little evidence of shard preservation. At the tops of the units and in the basal vitrophyres of thin units, however, shards are well preserved and vary in shape depending on their amount of compaction. The glass in shards commonly is brown and free of crystals. Where shards are preserved it is also common to find small, variably compacted, angular to rounded, lumps of pumice and of less-vesicular layered glass of variable gray to brown color. Such fragments commonly are less than 2 millimeters across.

Where devitrified, the groundmass commonly is too fine-grained for its mineralogy to be readily distinguished. In the interior of the thick units, however, cooling evidently was prolonged enough so that groundmass quartz grew epitaxially from the surfaces of quartz phenocrysts to yield, in crossed polarizers, snowflake-like micrographic intergrowths with other groundmass constituents.

Where the rhyolite has been devitrified, it is common for the mafic minerals to have been partially to completely oxidized. In fact, the devitrification process generally involved strong oxidation, so as to impart a definite red color to most devitrified rocks, and to generate abundant very fine-grained hematite, and perhaps rutile, in the groundmass. In some rocks with partially crystallized groundmasses in which only a little compaction has occurred, some individual glass particles contained delicate dendritic growths of red opaque material, probably hematite.

This oxidation, although not understood in detail, seems to have strongly affected all of the Cougar Point Tuff units, but only some of the associated younger rhyolite lava flows to the same extent (Bonichsen, 1982c this volume). The fact that the oxidation is generally restricted to the lithoidal portions of the rhyolite units but is rare in the glassy parts argues that the oxidation occurred during cooling of the flows, and is not an unrelated later feature.

Vesicles are common in the upper part of the Cougar Point Tuff units. All filling material has been identified as tridymite. Most vesicles are only partially filled, and some have no filling at all. No other vapor-phase mineral has been noted, although local quartz and calcite of probable secondary origin have been observed in a few vesicles.
CHEMICAL COMPOSITION OF
THE COUGAR POINT TUFF

The major oxide analyses, norms, and abundances of some minor elements for a few Cougar Point Tuff samples are presented in Table 1. The major oxide abundances of these samples have been determined two or more times. The Table 1 values combine the available X-ray fluorescence and atomic absorption data and are thought to be more accurate, especially for Na₂O and MgO, than previously reported values for the same rocks (Bonnichsen, 1982a). The analyses in Table 1 were prepared in the same manner as those of the associated rhyolite lava flows (Table 1, Bonnichsen, 1982c this volume) and older volcanics from the region (Table 1, Bernt and Bonnichsen, 1982 this volume); thus, the three data sets can readily be compared.

For the Cougar Point Tuff units, samples that were analyzed from localities many kilometers apart reveal that each unit has a compositional range considerably narrower than the group as a whole (Figures 21 and 22; for details regarding individual samples see Bonnichsen, 1982a). Nearly all of the analyses used for Figures 21 and 22 are of basal vitrophyres. Some units have a composition easily distinguishable from that of adjacent units (for example, compare XI with XII), but other pairs (for example, compare VII with XII or XI with XIII) cannot easily be distinguished.

Some units are distinctly more femic than others. Inspection of the variation from unit to unit in Figures 21 and 22 reveals that a femic group of constituents (Fe₂O₃, MgO, CaO, TiO₂, MnO, P₂O₅, Sr, and Zr) varies in a coherent fashion with stratigraphic position, whereas a salic group (SiO₂, K₂O, Rb, Th, and Pb) shows opposing trends. Triangular variation diagrams showing the femic or salic behavior of some of the elements are also presented in Bonnichsen (1982a and 1982c this volume, Figure 34). The variation exhibited by Al₂O₃, Na₂O, Zn, and Mo is not distinctive enough to conclusively assign them to either group.

The Cougar Point Tuff generally becomes increasingly femic upwards (Figures 21 and 22); however, there are local reversals. Units VII, XII, and XV are the three most femic. The two reversals in this overall trend (between units VII and IX and between units XII and XIII) suggest that the Cougar Point Tuff consists of three cycles (separated by the horizontal dashed lines in Figures 21 and 22) and that in each cycle the magma became increasingly femic as successive batches were erupted. The lower cycle consists of units III, V, and VII; the middle cycle of units IX, X, XI, and XII; and the upper cycle of units XIII and XV. The two lava flows, the Triguero Homestead rhyolite (TH) and the Indian Batt rhyolite (IB) that directly overlie unit XV in Bruneau Canyon (Bonnichsen, 1982b and 1982c this volume), appear to continue the upward increase in femic constituents of this upper cycle.

The subdivision of the Cougar Point Tuff into these compositional cycles should be considered as descriptive and not meant to imply any particular genetic relationship among successive magma batches. The eruption of each unit was a distinct volcanic event, separated from the eruption of the other units by sufficient time for complete cooling and the deposition of sediment layers between units. In many cases sufficient time elapsed for Earth’s magnetic field to reverse its polarity (Bonnichsen, 1981 and Table 1, 1982b this volume). The overall chemical similarity of the Cougar Point Tuff units suggests a similar source and mode of formation for all.
INITIAL STRONTIUM ISOTOPE RATIOS

The initial \(^{87}\text{Sr}/^{86}\text{Sr}\) ratios for four Cougar Point Tuff units and one rhyolite lava flow, reported in Table 2, are calculated using alternate assumptions of a 12 million-year-old and a 9 million-year-old age. Although few radiometric dates are available for the Cougar Point Tuff and lava flows in the Bruneau-Jarbidge eruptive center (see Table 3, Bonnichsen, 1982b this volume), these assumed ages probably are sufficient to bracket the true Cougar Point Tuff age range, since unit VII was noted earlier to have an age of about 11.3 million years.

The strontium isotope ratios in Table 2 strongly suggest that the ash flows and lava flows in the Bruneau-Jarbidge eruptive center had a predominantly, if not exclusively, crustal origin, and are similar to other rhyolites in the Snake River Plain-Yellowstone Plateau volcanic province in their strontium isotope ratios, such as those reported by Leeman (1982 this volume), Leeman and Manton (1971), and Doe and others (1982).

DISCUSSION

The conditions and processes that led to the formation of many of the physical features that characterize the Cougar Point Tuff ash-flow units are discussed below. These features generally are discussed in the sequence in which they are believed to have formed, as the rhyolitic magmas erupted, flowed across the surface, came to rest, and were cooled and compacted.

Each Cougar Point Tuff unit formed from one or a succession of pyroclastic eruptions that blew hot vesiculated magma particles high into the atmosphere. The 1 to 3 meters of bedded ash at the base of each unit suggests that the pyroclastic eruptions began with large volumes of vesiculated magma being propelled to great enough heights so that the ash could be buoyed by air currents and transported through the atmosphere for long distances. Gravitational collapse of these eruption columns imparted high velocities to the hot ash and permitted it to flow long distances along the surface. The great lateral extent and uniformity of the units and the planar nature of their bases and internal layering suggests the hot ash flowed away from the venting areas over a terrain of low relief (Figures 1 and 2).

The large volumes of the units and their rapid eruption implies that subsidence probably occurred over the magma chambers (see Bonnichsen, 1982b this volume). Extensive younger rocks and the shallow erosion level do not permit knowing for sure whether such subsidence formed calderas. Taken collectively, however, the series of subsidences accompanying the ash-flow eruptions formed the Bruneau-Jarbidge eruptive center. The exposed portions of all of the Cougar Point Tuff units have been interpreted as outflow-facies rocks, rather than intracaldera-facies rocks; thicker deposits of the latter may be buried within the eruptive center.

The pyroclastic eruptions require that the magmas contained sufficient water for disruptive vesiculation to occur when the confining lithostatic pressure became sufficiently low, during their ascent through the upper crust. Much of the vesiculation may have occurred at relatively shallow depths, in comparison with the situation for ash flows in many other regions. Suggesting shallow vesiculation is the near absence of accidental xenoliths in the units. Evidently the magmas had little opportunity to incorporate wall-rock material as they rose, either below or above the level of vesiculation. Aside from the plagioclase-clinopyroxene-opaque oxide cumulophyric aggregates, which we have interpreted as protolithic fragments of the zone of melting rather than xenoliths from the zone of high-level intrusion, the only other common lithic inclusions are small angular to subrounded fragments of Cougar Point Tuff-type volcanic rocks. These very likely were obtained from earlier units at shallow depths, perhaps of a kilometer or less, or from the surface during flow of the ash away from the venting areas. The subsequent extrusion of the rhyolitic lava flows that are petrologically similar to the Cougar Point Tuff (Bonnichsen, 1982c this volume), but with so little water that disruptive vesiculation did not occur, additionally suggests that the water contents of the Cougar Point Tuff magmas were...
relatively low, restricting vesiculation to shallow depths.

The abundant vesicles, flow marks, and fold structures preserved in most of the units, the very dense nature of the massive central zones, and the fusing of the underlying bedded ash zones suggest that emplacement temperatures for the ash flows were high. This is confirmed by temperatures ranging from about 900° to more than 1000° C, as determined by electron microprobe analysis of iron-titanium oxides (Hildreth, 1981, Figure 3). Such high temperatures are in accord with the anhydrous nature of the phenocryst assemblage and the occurrence of pigeonite rather than hypersthen.

The internal features of the cooling units suggest that, once erupted, each had a similar evolution. After gravitational collapse of the eruption columns, we believe the eruptive material consisted primarily of particles (mainly shards, some pumice, and a few lithic fragments) traveling at high speed away from the site of eruption as a dense cloud buoyed up by hot gases, possibly some of which were still being exsolved from the hot glass particles. This conventional glowing avalanche, or fluidized bed, flowage style seems plausible as the way the flows were transported the large distances from their sources, especially since shards and flattened pumice fragments are preserved in many units.

As the hot ash flowed away from its source it slowed down and eventually came to rest, after losing most of the gases which suspended the hot particles during flowage and making local structural adjustments while the hot masses compacted and cooled. Using the terminology of Chapin and Lowell (1979), the flowage away from the source, and the structures preserved from that part of a unit's history, are termed primary. Later motion and structures which formed after primary motion had ceased are termed secondary.

By this classification, the elongate vesicles and flow marks (Figures 19 and 20) in the units are primary structures, whereas the sheeting joints and folds defined by them, and the variety of compaction features, are secondary. This sequential age relation between the flow marks and sheeting is indicated by the observation that the elongate vesicles and flow marks have commonly been rotated to steeply dipping attitudes where they follow around the folds in the sheeting.

The existence of the flow marks and elongate vesicles shows that the ash flows had partly, if not largely, coalesced to viscous liquid similar to that in a rhyolitic lava flow before the cessation of primary motion. Such coalescence to a silicate melt before flowage was complete is termed primary welding by Chapin and Lowell (1979). Only in this way could the elongate vesicles and flow marks be formed and preserved, since a liquid medium was necessary to contain the gas bubbles.

The later secondary flowage is manifested mainly by structures preserved in the upper zones of the

<table>
<thead>
<tr>
<th>Sample Number</th>
<th>Geologic Unit</th>
<th>Sample Location</th>
<th>Rb(ppm)</th>
<th>Sr(ppm)</th>
<th>Present Day *Sr/*Sr</th>
<th>Initial *Sr/*Sr calculated for:</th>
<th>9 m.y. age</th>
<th>12 m.y. age</th>
</tr>
</thead>
<tbody>
<tr>
<td>I-529 Dorsey Creek rhyolite NE1SW1/2 sec. 3, T. 16 S., R. 9 E. Owyhee County, Idaho</td>
<td>117 ± 4</td>
<td>108 ± 1.3</td>
<td>0.71283</td>
<td>± 0.00003</td>
<td>± 0.00004</td>
<td>± 0.00004</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-459 Cougar Point Tuff - XV SE1SW1/2 sec. 9, T. 16 S., R. 7 E. Owyhee County, Idaho</td>
<td>190 ± 3</td>
<td>79 ± 1.7</td>
<td>0.71047</td>
<td>± 0.00001</td>
<td>± 0.00003</td>
<td>± 0.00005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>X-37 Cougar Point Tuff - XIII NW1/4 sec. 20, T. 47 N., R. 59 E. Elko County, Nevada</td>
<td>211 ± 4</td>
<td>29 ± 1.4</td>
<td>0.71234</td>
<td>± 0.00004</td>
<td>± 0.00016</td>
<td>± 0.00020</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-841 Cougar Point Tuff - VII SW1/4NE1/2 sec. 28, T. 47 N., R. 58 E. Elko County, Nevada</td>
<td>218 ± 3</td>
<td>92 ± 2.2</td>
<td>0.71165</td>
<td>± 0.00003</td>
<td>± 0.00005</td>
<td>± 0.00005</td>
<td></td>
<td></td>
</tr>
<tr>
<td>I-569 Cougar Point Tuff - III NW1/4NE1/2 sec. 28, T. 16 S., R. 7 E. Owyhee County, Idaho</td>
<td>306 ± 5</td>
<td>147 ± 0.1</td>
<td>0.71922</td>
<td>± 0.00003</td>
<td>± 0.00016</td>
<td>± 0.00019</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Analyzed at Geochronology Laboratory, Conoco, Inc. Research and Development Department, Ponca City, Oklahoma. All rubidium and strontium analyses and calculations are by Lois Jones using TEFA (tube excited X-ray fluorescence), except that strontium for sample I-569 was analyzed by James Rathman by isotope dilution. Each analysis is an average of six determinations and ± values are for a standard deviation of 2 n. The interlaboratory strontium carbonate standard is NBS-987, with *Sr/*Sr of 0.71036 ± 0.00002. All *Sr/*Sr values are normalized to *Sr/*Sr of 0.11940. Initial ratios were calculated using the *Rb decay constant of 1.42 x 10⁻¹¹ yr⁻¹. All samples are vitrophyres from the bases of their units.
units. Secondary and probably primary structures as well, which may have formed in the central massive areas, very likely were destroyed by the essentially complete compaction which occurred later as the final step of secondary flowage and by the complete crystallization of those zones. Formation and folding of the sheeting joints, the compaction which occurred throughout the units as most of the remaining gases were expelled, and the freezing of devitrification fronts around spherulites and at the bases of the units are the most conspicuous of the secondary structures.

The near lack of secondary flowage structures that penetrate down through the units probably is the result of the flat topography on which they were deposited, rather than the lack of any capacity of the coalesced silicate liquids to undergo mass flowage like that in a rhyolite lava flow. Mass flowage could more easily occur if the material moved down a slope, such as would occur in an area of uneven topography.

The scarcity of flow banding in the vitrophyric portions of the units probably also suggests that the silicate liquids had nowhere to flow once they had been emplaced and coalesced to a viscous mass, rather than indicating any incapacity to flow had a slope been available. Flow banding is common in the vitrophyric parts of the rhyolite lava flows in the eruptive center and is thought (Bonnichsen, 1982c this volume) to have been caused mainly by mass flowage within a unit, rather than by simple compaction. After coalescence, the ash-flow sheets would have been nearly enough like the rhyolite lava flows, so that if mass flowage had occurred, one would expect flow-banding to commonly be preserved; it is rare, however.

Sheeting joints evidently formed and were deformed during secondary flowage, probably concurrent with, or shortly following, the onset of devitrification. Sheetings joints are restricted to lithoidal rhyolite in the Cougar Point Tuff units and in the rhyolite lava flows in the Bruneau-Jarbidge eruptive center; they do not occur in the glassy rocks (Figures 12-15, and see the discussion of sheeting joints and related structures in Bonnichsen, 1982c this volume). Parallel sheeting joints, the type most common in the upper zones of the cooling units, may have followed flow bands that were established in the coalesced flows immediately after the end of primary flowage, while gases were still being expelled from the silicate liquid. Such gas would have been in bubbles which might have become concentrated into parallel planes, along which most of the shear during flowage of the coalesced silicate liquid was occurring. Such bubble layers would have become planes of weakness along which the sheeting joints would ultimately form, once devitrification and the concomitant shrinkage were to occur.

The end-stage of sheeting-joint formation may very well have coincided with the final compaction within the units, as the pattern typical of some, as depicted in Figure 17, is to outline elongate lensoidal fragments which may have undergone slight lateral slip relative to one another.

The "pencil" type of jointing locally found in lithoidal parts of most rhyolite lava flows in the Bruneau-Jarbidge eruptive center (Bonnichsen, 1982c this volume), where the intersection of two or more closely spaced sheeting-joint sets has formed elongate fragments, are virtually nonexistent in the Cougar Point Tuff units. This, again, may be due to the general lack of mass flowage of great enough thicknesses to develop sufficient internal stresses for this type of joint pattern to form.

Sheeting joints are not known to occur in any of the vitrophyres in the Cougar Point Tuff units and are rare and imperfectly developed in vitrophyres of the rhyolite lava flows in the eruptive center. In fact, it has been shown that sheeting joints in lithoidal rhyolite die out as they abut against adjacent vitrophyres in the lava flows (Bonnichsen, 1982c this volume, Figure 27). Both the ash-flow and lava-flow vitrophyres are characterized by jointing which is entirely different from the type in lithoidal rhyolite (compare Figures 12, 13, 14, and 15 with Figures 9, 16, 17, and 18). These observations strongly suggest that the crystallization and oxidation, or devitrification, of the ash flows commenced before the sheeting joints were formed. Very likely the shrinkage which accompanied devitrification was influential in promoting the formation of the sheeting. Devitrification may have commenced at temperatures as high as 950-1000°C (see Tuttle and Bowen, 1958, Figures 26-28, which show the increasing crystallization temperature and lowered content of water that can be dissolved in synthetic granite as the total pressure is decreased).

The basal vitrophyre zones were prevented from crystallizing because of the much more rapid cooling of the magma at the flow bases than within the flow interiors. The sharp, cuspatate nature of the contacts between the basal vitrophyre zones and devitrified rock above them (Figure 13), imply that the crystallization fronts were moving downward until low temperatures froze them in place. The spherulitic ghosts within the devitrified rocks and the overall planar nature of these vitrophyre-lithoidal rock contacts attest to the lack of mass flowage or other lateral motion in the flow bases at any time since their formation.

As the ash-flow sheets devitrified and cooled further, they underwent a small percentage of shrinkage. Evidence that such shrinkage accompanied the devitrification process is indicated by the irregular open
cavities within many spherulites, especially large ones (Figure 15) that are enclosed within glassy rhyolite. The gases, which kept the shrinkage cavities in the spherulites inflated, very likely were the last bits of water dissolved in the silicate melts. They were released as the groundmass crystallized to an essentially anhydrous mixture of largely quartz and feldspars.

The last gases exsolved in the interior parts of the units are also believed to have been responsible for the generation of some of the lithophysal zones. Some lithophysal zones may have resulted from relatively complex cooling situations such as would arise along the boundary of successive ash flows in the same cooling unit. The little-deformed or nondeformed shapes of the gas cavities in these zones imply they formed late, and it is not unlikely that some may have formed during devitrification.

The bulk shrinkage that resulted from degasing, devitrification, and cooling would first have been accommodated by compaction. Later, during post-devitrification cooling, after compaction of the flows was complete, the prominent vertical joints that characterize the massive central zones formed. This essentially ended the development of the welded ash-flow sheets.

ACKNOWLEDGMENTS

The writers take pleasure in thanking John Bernt, Dale Conover, Falma Moye, and Maura Weathers Bird for their assistance during the field work; Nancy Wotruba, Steve Devine, Ivan Herrick, and Peter Hooper for their assistance with the X-ray fluorescence analyses; and Fred Hutchinson for performing the atomic absorption analyses. We also are pleased to thank Bill Rehrig and Bob Wilson for making the arrangements with Conoco, Inc., to provide the minor element analyses, the strontium isotope analyses, and the potassium-argon age date. Finally, we would like to thank Bob Christiansen, Dave McIntyre, and Margi Jenks for their very helpful reviews of our manuscript.

REFERENCES


Bonnichsen and Citron—Cougar Point Tuff