Geology and geochemistry of tertiary volcanic rocks in the northern Reveille and southern Pancake ranges, Nye County, Nevada

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Geology and Geochemistry of Tertiary Volcanic Rocks in the Northern Reveille and Southern Pancake Ranges, Nye County, Nevada

by

Kelly Brian Rash

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

Master of Science

in

Geology

Department of Geoscience
University of Nevada, Las Vegas
December 1995
Photograph of a caldera collapse megabreccia block of the tuff of Goblin Knobs within the caldera of northern Reveille Range.
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Abstract

The northern Reveille and southern Pancake Ranges, located in the south-central Great Basin, experienced a prolonged history of Tertiary volcanism. Volcanic activity in this area began with the eruption of large-volumes of ash-flow tuffs from calderas of the central Nevada caldera complex. The Reveille Range and the southernmost portion of the Pancake Range are the site of two calderas that are the sources for the tuff of Goblin Knobs and tuff of northern Reveille Range. The tuff of Goblin Knobs (70.4-75.3 wt.% SiO₂) erupted from the caldera of Goblin Knobs (25.6 Ma) and is the thickest (~1,700 m) ash-flow tuff in the Reveille and southern Pancake Range. Felsic volcanism ended with the eruption of the tuff of northern Reveille Range (71.4-78.5 wt.% SiO₂) from the caldera of northern Reveille Range (25.3 Ma). The caldera of northern Reveille Range is nested within the northern part of the caldera of Goblin Knobs.

Volcanic activity in the northern Reveille Range changed from felsic to mafic in composition between 18.5 and 14 Ma. Mafic volcanism began approximately 14 Ma with the eruption of lithospheric mantle derived basaltic andesites ($\varepsilon_{Nd} = -8.21$ to $-7.21$ and $^{87}\text{Sr} / ^{86}\text{Sr} = 0.7076-0.7081$). Between 14 and 6 Ma the mantle source changed from lithospheric to asthenospheric mantle. An asthenospheric mantle source dominated the final phases of volcanic activity between 6 and 3 Ma and resulted in the eruption of two isotopically distinct groups of basaltic lavas ($\varepsilon_{Nd} = 0.75$-4.47 and 3.52-5.35 and $^{87}\text{Sr} / ^{86}\text{Sr}$...
= 0.7043-0.7061 and 0.7034-0.7036, respectively). More evolved intermediate volcanism ($\varepsilon_{\text{Nd}} = 3.26-3.83$ and $^{87}\text{Sr}/^{86}\text{Sr} = 0.7037-0.7064$) occurred between the eruption of the two basaltic groups.
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Chapter 1

Introduction

The timing of magmatism and extensional tectonism provides clues for the evolution of the crust during upper crustal extension. The southern Great Basin and specifically the Reveille and Pancake Ranges are ideal for analyzing these processes because rocks are well exposed and Tertiary time-stratigraphic markers (ash-flow tuffs) are regionally widespread (Axen and others, 1993). The Reveille and Pancake Ranges are north trending ranges and are located in the south-central Great Basin, approximately 175 km southwest of Ely, 90 km east of Tonopah and 280 km north of Las Vegas (Fig. 1). They underwent a prolonged history of volcanism that ranged from basalt-to-rhyolite in composition. The initial phases of volcanism produced large volumes of ash-flow tuffs that erupted from calderas between 27 and 24 Ma. Volcanism in the Reveille Range changed at approximately 14 Ma from felsic to mafic with the eruption of basaltic andesites. The final phase of volcanism occurred between 6 and 3 Ma and produced three isotopically distinct groups of mafic lavas (Naumann and others, 1991). In addition, magmatism in the Reveille and Pancake Ranges occurred prior to, during, and after extension (intermittently between 32 to 3 Ma). Thus, changes in composition of magmatism through time can be determined.

Volcanism in the Reveille and Pancake Ranges also have important implications for
hazard assessment studies. To fully understand volcanism near the proposed high-level nuclear waste repository at Yucca Mountain, it is necessary to understand volcanism in surrounding areas. Because the Reveille and Pancake Ranges lie in the same volcanic belt as rocks in the Yucca Mountain area (Vaniman and Crowe, 1981), and Pliocene-to-Quaternary basaltic volcanism in the Reveille and Pancake Ranges is spatially and temporally related to basaltic volcanism at the proposed repository site (Martin, 1992), comparisons can be made between the two areas.

**Previous Work**

The Reveille Range was the site of periodic mining activity since the mid-1800's. Browne (1868), Stedfedt (in Raymond, 1869), Gilbert (1872) and Degroot (in Raymond, 1875) provided the first geologic descriptions of the range. It was not until the works of Spurr (1903) and Ball (1907) that sedimentary rocks were placed into proper stratigraphic sequence. Ekren and others (1973) mapped the Reveille 15' quadrangle (Fig. 2) at a scale of 1:48,000, using nomenclature of sedimentary and igneous rocks from central Nevada (Cook, 1965 and Ekren and others, 1971 for the volcanic stratigraphy; Spencer, 1917, Westgate, 1932, Nolan and others, 1956 and Merriam, 1963 for the sedimentary stratigraphy). Jones and Bullock (1985) mapped the Reveille mining district to evaluate its economic potential. Naumann and others (1991) first recognized that basalts in the Reveille Range consist of four isotopically distinct lavas: (1) basaltic andesites, (2) episode-1 basalts, (3) trachytic rocks and (4) episode-2 basalts. Yogodzinski and others (submitted) described in detail the source region for the episode-1 basalts, trachytic rocks and episode-2 basalts. Finally, Martin and Naumann (1995) mapped the Reveille 7½'
quadrangle at a scale of 1:24,000, using the stratigraphic framework developed by Ekren and others (1973), Jones and Bullock (1985) and Naumann and others (1991). Martin and Naumann (1995) first recognized caldera margins associated with the caldera of Goblin Knobs and caldera of northern Reveille Range.

The southern Pancake Range consists of well-bedded Oligocene-to-Miocene ash-flow tuffs that are not appreciably tilted. The northern Reveille Range, on the other hand, consists of two thick ash-flow tuff units and appears to have undergone extensive faulting. Based on these differences and the original assumption that two ash-flow tuffs, the Monotony Tuff (exposed in the Pancake Range) and the tuff of Goblin Knobs (exposed in the Reveille Range), are age equivalent, Ekren and others (1973) inferred that a left-lateral strike-slip fault separated the two ranges. Martin and Naumann (1995) and this study suggest a caldera margin is a more reasonable interpretation for the boundary between the two ranges (see Chapter 7).

**Regional Tectonics**

The Basin and Range province underwent large-scale approximately east-west extension (up to 100-300%) during the Cenozoic (Wernicke, 1981). Two Eocene-to-Oligocene, north-trending extensional belts (Fig. 3) are defined based on stratigraphic and structural relationships in the Great Basin (Axen and others, 1993). The eastern belt straddles the Nevada-Utah border and terminates near the Caliente caldera complex (Figs. 3 and 4). The northern boundary is poorly defined. The western belt extends from the Funeral Mountains, California, to the Ruby Mountains, Nevada, and north to the Albion Range, Idaho. The Reveille Range lies within the central part of this western belt.
Extension in the northern part of both belts occurred during or after volcanism, whereas, extension in the southern part of both belts occurred prior to volcanism (Axen and others, 1993).

Several east-west trending topographic and structural lineaments lie within or near these extensional belts (Fig. 4). These lineaments coincide with lithologic boundaries, range and valley termini, caldera boundaries, and strong magnetic anomalies (Ekren and others, 1976). The Blue Ribbon-Silver King Lineament (Rowley and others, 1978; Hurtubise, 1989; Hurtubise and du Bray, 1992) in southeastern Nevada and southwestern Utah consists of east-west striking normal faults (Hurtubise, 1989; Bartley, 1991; Hurtubise, 1994). Taylor and others (1989) found that east-west extension within this east-west zone occurred before and after volcanism in the Dry Lake Valley area (Fig. 1). Bartley and others (1992) indicated that north-south to northeast-southwest synvolcanic extension occurred just north of Dry Lake Valley within and near the western end of the Indian Peak caldera complex. They interpret this synvolcanic extension as part of a west trending synvolcanic rift linking the Indian Peak caldera complex with the caldera complex in the Quinn Canyon Range. The change in the direction of crustal extension may be due to weakening and active spreading along the Central Nevada-Pioche-Marysvale volcanic belt (Bartley and others, 1992).

Post-volcanic, Miocene-to-Pliocene, extension is common in the southern Great Basin. Normal faults in the surrounding ranges cut Miocene and younger volcanic rocks (Dixon and others, 1972; Eaton, 1984; Ekren and others, 1973, 1974 and 1977; Gardner and others, 1985; and Kleinhampl and Ziony, 1985). In addition, Pliocene-to-Quaternary
range-bounding normal faults are common throughout most of the ranges (Kleinhampil and Ziony, 1985; Dorenwend and others, 1992).

**Purpose**

The purpose of this thesis is to address several aspects of magmatism and extensional tectonism in the northern Reveille and southern Pancake Ranges. These aspects include: (1) determining the volcanic stratigraphy, (2) locating the source for the thick ash-flow tuffs, (3) determining the source of the mafic rocks, and (4) determining the type of boundary between the northern Reveille and southern Pancake Ranges (strike-slip fault, normal fault or caldera margin).

Detailed geologic mapping of the Twin Springs Slough 7½' quadrangle (Fig. 2) was the primary method used to address most of these issues. In addition to field studies, geochemical and petrographic analyses were used for stratigraphic correlation of the ash-flow tuffs and petrogenetic studies of the basalts. This work indicates that the northern Reveille Range underwent two caldera forming events, widespread extension and deep-seated lithospheric thinning that resulted in a change of mantle source for the mafic magmas.
Figure 1. Map of the southern Great Basin showing the location of the northern Reveille and southern Pancake Ranges (dark shaded rectangle). Selected ranges are lightly shaded.
Figure 2. Location map of recently mapped areas in the northern Reveille and southern Pancake Ranges. Ekren and others (1973) mapped the Reveille 15' quadrangle, and Martin and Naumann (1995) mapped the Reveille 7½' quadrangle. This study focuses on the Twin Springs Slough 7½' quadrangle. Ranges are shown as lightly shaded areas and basins in white.
Figure 3. Map showing the distribution of the Eocene-to-Oligocene extensional belts (lightly shaded area). Dotted lines are magmarchrons that indicate the onset of volcanism and that show the southern migration of caldera eruptions. Diagram is modified from Axen and others (1993).
Figure 4. Location of structural lineaments in Nevada and western Utah (modified from Hurtubise, 1994). The Pritchards Station, Pancake, Warm Springs and Timpahute Lineaments are from Ekren and others (1976b); the Blue Ribbon Lineament is from Rowley and others (1978); the Silver King Lineament is from Hurtubise (1989). The caldera margins that are shown are the Goblin Knobs (G), Northern Reveille Range (NR), Quinn Canyon Range (Q), Caliente caldera complex (CCC) and Indian Peak caldera complex (IP).
Chapter 2

General Stratigraphy of Tertiary Volcanic Rocks

Oligocene-to-Pliocene volcanic rocks comprise the northern Reveille and southern Pancake Ranges (Plate 1; Fig. 5). These volcanic rocks unconformably overlie Paleozoic miogeoclinal and eugeoclinal sedimentary rocks which are exposed south of the study area. Ekren and others (1973) and Martin and Naumann (1995) provide a complete description of the Paleozoic section and, therefore, it will not be described further.

Tertiary rocks in the northern Reveille and southern Pancake Ranges include: (1) extrusive rocks, including ash-flow and air-fall tuffs, rhyolite domes and mafic rocks, (2) intrusive rocks, including hypabyssal rhyolite dikes, and (3) nonmarine sedimentary rocks, including a lacustrine siltstone and megabreccia deposits (Plate 1; Fig. 5). The following discussion reviews the general stratigraphy of volcanic rocks in the northern Reveille and southern Pancake Ranges (compiled from Ekren and others (1971, 1973 and 1977); Phillips (1989); Best and others (1989 and 1993); Naumann and others (1991); Martin and Naumann (1995); Yogodzinski and others (submitted); and this study). The stratigraphy and petrography of these volcanic units are summarized in Figure 6 and described in detail in Appendices A and B.

Ash-flow Tuffs

Ash-flow tuffs are the most voluminous volcanic rocks in the study area and
erupted from calderas within the central Nevada caldera complex (Chapter 7). In addition, the Reveille Range is the site of calderas that are the source of the tuff of Goblin Knobs and tuff of northern Reveille Range (Martin and Naumann, 1995).

**Pancake Range**

**Monotony Tuff**

The lowermost tuff in the Pancake Range (Fig. 6), the Monotony Tuff (27.3 Ma; Taylor and others, 1989; 27.6 Ma, this study), is a crystal-rich, densely welded dacite ash-flow tuff (35-50% total phenocrysts) and contains phenocrysts of predominantly plagioclase and quartz and lesser amounts of sanidine, biotite and hornblende. Large books of biotite are abundant (up to 5 mm). The Monotony Tuff is one of the most voluminous ash-flow tuffs in central Nevada and has an estimated volume of 3000 km$^3$ (Ekren and others, 1971; Best and others, 1989). It covers an area of 31,000 km$^2$; however, Best and others (1989) corrected the area to 21,000 km$^2$ after compensating for east-west extension in the Basin and Range. The type locality for the Monotony Tuff is along the northeastern flank of Monotony Valley (Fig. 2; Ekren and others, 1971). The Monotony Tuff erupted from the Pancake Range caldera, which is nested within the southern part of the Williams Ridge caldera (Ekren and others, 1974).

**Tuff of Bald Mountain**

The tuff of Bald Mountain (26.5 Ma; this study) conformably overlies the Monotony Tuff (Fig. 6) and is a crystal-poor, densely welded rhyolite ash-flow tuff (2-10% total phenocrysts; rarely as high as 23%). It contains phenocrysts of predominantly plagioclase and lesser amounts of sanidine and biotite. Quartz is absent. The type
locality for the tuff of Bald Mountain is in the Bald Mountain caldera, Lincoln County, Nevada (Chapter 7). Outflow sheets of the tuff of Bald Mountain crop out only in the southern Pancake Range, on the south flank of the Quinn Canyon Range and in the Belted Range (Ekren and others, 1977). In the study area, the tuff of Bald Mountain crops out over an area of approximately 2.9 km².

*Shingle Pass Tuff*

The Shingle Pass Tuff (25.7-26.7 Ma; Ekren and others, 1973; Taylor and others, 1989; Best and others, 1993; this study) is a widely distributed ash-flow tuff, covering an area of approximately 4300 km² (Cook, 1965). In the southern Pancake Range, it consists of four cooling units of crystal-poor, moderately-to-densely welded rhyolite ash-flow tuff (Fig. 6) (5-35% total phenocrysts) and contains phenocrysts of predominantly sanidine and plagioclase and lesser amounts of biotite, quartz and hornblende. Total phenocryst content increases upward in the section. The type locality is at Shingle Springs near Shingle Pass in the Egan Range, Lincoln County, Nevada (Fig. 1). The Shingle Pass Tuff erupted from the Quinn Canyon Range caldera, central Quinn Canyon Range (Sargent and Houser, 1970; Best and others, 1989).

*Tuff of Arrowhead*

The tuff of Arrowhead consists of two cooling units (Ekren and others, 1973; Martin and Naumann, 1995); however, only the upper cooling unit (cooling unit B) was identified in the study area. The tuff of Arrowhead cooling unit B (26.6 Ma; this study) unconformably overlies Monotony Tuff and tuff of Bald Mountain and is conformably overlain by Shingle Pass Tuff cooling unit C (Fig. 6). The tuff of Arrowhead cooling unit
B is a crystal-poor, densely welded dacite ash-flow tuff (5-20% total phenocrysts) and contains phenocrysts of predominantly plagioclase and lesser amounts of sanidine and biotite. Quartz is absent. In the southern Pancake Range it crops out over an area of only 0.63 km$^2$.

**Reveille Range**

**Tuff of Goblin Knobs**

The lowermost tuff in the Reveille Range (Fig. 6), the tuff of Goblin Knobs (25.4 Ma; Best and others, 1993; 25.6 Ma; this study), is a crystal-rich, densely welded rhyolite ash-flow tuff (30-40% total phenocrysts) with a phenocryst assemblage similar to the Monotony Tuff; however, the tuff of Goblin Knobs contains less total phenocrysts, quartz are clearer and biotites are smaller than in the Monotony Tuff. The tuff of Goblin Knobs is the thickest (~ 1700 m) ash-flow tuff in the Reveille Range. In the study area, it covers an area of approximately 10 km$^2$. The tuff of Goblin Knobs erupted from the caldera of Goblin Knobs in the Reveille Range (Martin and Naumann, 1995).

**Tuff of northern Reveille Range**

The tuff of northern Reveille Range (25.3 Ma, this study) is a moderately crystal-rich, poorly-to-moderately welded rhyolite ash-flow tuff (10-20% total phenocrysts) and contains phenocrysts of predominantly sanidine, plagioclase and quartz and lesser amounts of biotite. In the study area the tuff of northern Reveille Range is 200+ m thick and covers an area of approximately 41 km$^2$. The tuff of northern Reveille Range erupted from the caldera of northern Reveille Range which is nested within the northern part of the caldera of Goblin Knobs (Martin and Naumann, 1995). The tuff of northern Reveille
Range makes up the matrix for the megabreccia of the caldera of northern Reveille Range, first described here (see Chapter 3, Chapter 7 and Appendix A for more detailed descriptions of this unit).

**Tuff of Streuben Knobs**

The tuff of Streuben Knobs (absolute age and source unknown) is a crystal-rich, poorly-to-moderately welded rhyolite ash-flow tuff (20-30% total phenocrysts) with a phenocryst assemblage similar to the tuff of northern Reveille Range; however, the tuff of Streuben Knobs lacks biotite. The tuff of Streuben Knobs has a small-volume (<0.50 km$^3$) and is exposed only in the western part of the Reveille Range.

**Mafic Volcanic Rocks**

Mafic rocks in the study area are restricted to the northern Reveille Range; however, mafic volcanism also occurred north of the study area in the Pancake Range. Geochemical data along with geologic mapping indicate that four distinct compositional types of mafic rocks are present: (1) basaltic andesites, (2) episode-1 basalts, (3) trachytic rocks and (4) episode-2 basalts (Naumann and others, 1991).

**Basaltic Andesites**

Basaltic andesite rocks (14? Ma) occur in the northwestern part of the range (Fig. 5). A similar basaltic andesite unit in the White Blotch Springs quadrangle near Rachel, Nevada yielded a K-Ar date of 14.1 ±0.14 Ma (Naumann and others, 1991). Because the two basaltic andesites are similar chemically and petrographically, they may have a similar age. The basaltic andesites exposed in the study area are aphyric. They have a
volume of 0.05 km$^3$ and range in thickness from 0-29 m.

*Episode-1 Basalts*

Episode-1 basalts (5.1-5.9 Ma; Naumann and others, 1991) are the most abundant basalts in the northern Reveille Range (Fig. 5). Episode-1 basalts are porphyritic olivine basalts and contain megacrysts (90%) of plagioclase. They erupted from 52 vents located throughout the range (Naumann and others, 1991) and have a volume of 8 km$^3$ (Yogodzinski and others, submitted).

*Trachytes*

The eruption of trachyte, tristanite and associated pyroclastic surge deposits (4.24-4.39 Ma; Naumann and others, 1991) conformably overlie episode-1 basalts along the northeast flank of the Reveille Range (not exposed in the study area). The eruption of these rocks resulted in the formation of two exogenous domes with finger-like flows extending to the east and northeast. These domes have a volume of 0.01 and 0.26 km$^3$, respectively. They generally contain less than 4-5% total phenocrysts of plagioclase, clinopyroxene, orthopyroxene and sanidine.

*Episode-2 Basalts*

The eruption of episode-2 basalts (3.00-4.64 Ma; Naumann and others (1991)) mark the end of volcanic activity in the northern Reveille Range. They erupted from 14 vents in the northeastern part of the range (Naumann and others, 1991) and have a minimum volume of 1 km$^3$ (Yogodzinski and others, submitted). Episode-2 basalts are porphyritic olivine basalts and contain phenocrysts of plagioclase, olivine and
clinopyroxene. At some locations, they contain xenocrysts of hornblende and xenoliths of gabbro.
Explanation of map symbols

- **Qal** alluvium
- **QTB** colluvium
- **Th** episode-2 basalts
- **Th** episode-1 basalts
- **Tmb** basaltic andesites
- **Tmb** unnamed Tertiary
- **Tmb** tuffaceous sandstone
- **Tmb** rhyolitic dikes of Twin Springs Ranch
- **Tmb** tuff of Streuben Knobs
- **Tmb** siltstone of Cane Springs
- **Tmb** megabreccia of northern Reveille Range
- **Tmb** tuff of northern Reveille Range surge deposit

- **Tnr** tuff of northern Reveille Range
- **Tmg** megabreccia of Goblin Knobs
- **Tmb** tuff of Goblin Knobs
- **Tmb** Shingle Pass Tuff cooling unit D
- **Tmb** Shingle Pass Tuff cooling unit C
- **Tmb** Shingle Pass Tuff cooling unit B
- **Tmb** Shingle Pass Tuff cooling unit A
- **Tmb** tuff of Arrowhead cooling unit B
- **Tmb** tuff of Bald Mountain
- **Tmb** Monotony Tuff

- " strike and dip of bed
- " strike and dip of compact foliation
- " strike and dip of vertical compact foliation
- " strike and dip of joint
- " strike and dip of vertical joint
- • basaltic vents
- • basaltic dikes
- • rhyolitic dikes of Twin Springs Ranch
- • vitrophyre

- ... contact. Dashed where approximately located and dotted where concealed.
- ... high-angle normal fault. Dashed where approximately located and dotted where concealed.
- ... strike-slip fault with component of late normal motion. Dashed where approximately located and dotted where concealed.
- ... reverse fault. Dashed where approximately located and dotted where concealed.
- ... caldera margin. Dashed where approximately located and dotted where concealed.

Figure 5. Simplified geologic map of the Twin Springs Slough 7.5' quadrangle.
Figure 5 (cont.). Simplified geologic map of the Twin Springs Slough 7.5' quadrangle.
siltstone of Cane Springs. Olive-gray siltstone containing finely laminated mudstone intercalated with silty sandstone. Unit consists of angular to subrounded feldspars and quartz, biotites aligned parallel with the lamination direction and cuspat glass shards. Total thickness is 20 m.

megabreccia of the caldera of northern Reveille Range. Large clasts (up to 300 m in diameter) of various ash-flow tuff compositions (see Appendix A). Minimum thickness is 61 m.

Shingle Pass Tuff cooling unit D. Grayish-orange pink to pale brown rhyolite ash-flow tuff. Vitrophyre is grayish-black. Unit contains 25-35% total phenocrysts with abundant hornblende. Total thickness is 65 m.

Shingle Pass Tuff cooling unit C. Light brown rhyolite ash-flow tuff. Unit contains 10-25% total phenocrysts with minor hornblende. Total thickness is 310 m. 25.7 Ma

tuff of Arrowhead cooling unit B. Dark yellowish-orange to dark brown dacite ash-flow tuff. Vitrophyre is grayish-black. Unit contains 5-20% total phenocrysts with minor quartz. Total thickness is 88 m. 26.6 Ma

Shingle Pass Tuff cooling unit B. Very light gray rhyolite ash-flow tuff. Unit contains 5-15% total phenocrysts with minor quartz. Total thickness is 50 m.

Shingle Pass Tuff cooling unit A. Grayish-orange to grayish-red rhyolite ash-flow tuff. Unit contains 5-10% total phenocrysts with minor quartz. Minimum thickness is 55 m.

tuff of Bald Mountain. Brick red rhyolite ash-flow tuff. Vitrophyre is grayish-black. Unit contains 2-10% total phenocrysts. Quartz is absent. Total thickness is 290 m. 26.5 Ma

Monotony Tuff. Light olive to dark yellowish-brown dacite ash-flow tuff. Unit contains 35-50% total phenocrysts with large books of biotite and large purple, smoky and clear quartz. Minimum thickness is 32 m. 27.6 Ma

Explanation of symbols for stratigraphic columns

Figure 6. Simplified composite stratigraphic column of rocks in (a) the southern Pancake Range and (b) the Reveille Range. The unnamed Tertiary tuffaceous sandstone, tuff of northern Reveille Range surge deposit, Window Butte Formation, siltstone of Cane Springs, megabreccia of the caldera of northern Reveille Range and Paleozoic sedimentary rocks are not discussed in this chapter. These units are described in detail in Appendices A and B. Unit thicknesses are reported as maximum values, unless otherwise noted. Ages of basalts are from Naumann and others, 1991, and ages of tuffs are from this study.
episode-2 basalts. Dark gray, porphyritic olivine basalt. Unit contains 20-30% total phenocrysts of plagioclase, olivine, clinopyroxene, orthopyroxene, Fe-Ti oxides and xenocrysts of hornblende. Thickness ranges from 0-100 m. 3.00-4.64 Ma.

episode-1 basalts. Medium gray, porphyritic olivine basalt. Unit contains 30-40% total phenocrysts of plagioclase, olivine, clinopyroxene and Fe-Ti oxides. Thickness ranges from 0-100 m. 5.13-5.94 Ma.

basaltic andesites. Medium dark gray, aphric basalt. Unit contains groundmass plagioclase, olivine, clinopyroxene, orthopyroxene, sanidine and Fe-Ti oxides. Thickness ranges from 0-20 m. 5.94 Ma.

unnamed Tertiary tuffaceous sandstone. Highly silicified, well sorted tuffaceous sandstone with well rounded quartz, plagioclase and sanidine grains. Thickness ranges from 0-70 m.

tuff of Streuben Knobs. Grayish-orange pink to pale red, moderately-to-densely welded, rhyolite ash-flow tuff. Unit contains 20-30% total phenocrysts.

tuff of northern Reveille Range surge deposit. Reddish-gray to buff tuff. Unit contains fine laminations and planar bedding and locally contains rounded accretionary lapilli, clasts of the tuff of northern Reveille Range, reworked surge deposits and fine-to-coarse-grained fluvial sedimentary deposits. Thickness ranges from 0-175 m.

tuff of northern Reveille Range. Pale orange-to-pinkish-gray and white, poorly welded, rhyolite ash-flow tuff. Unit contains 10-20% total phenocrysts. Unit makes up the matrix for the megabreccia of the caldera of northern Reveille Range. Thickness ranges from 0-160 m. 25.3 Ma.

tuff of Goblin Knobs. Pale yellowish-brown, densely welded, rhyolite ash-flow tuff. Unit contains 30-40% total phenocrysts with abundant large biotites and clear quartz. Unit makes up the matrix for the megabreccia of the caldera of Goblin Knobs. Thickness ranges from 0-1700 m. 25.6 Ma.

Windous Butte Formation. Unit is 150 m thick. See Ekren and others and Martin and Naumann for a more detailed description.

Paleozoic sedimentary rocks. The exposed section is 1850 m thick. See Ekren and others for a more detailed description.

Explanation of symbols for stratigraphic columns

- Ash-flow tuff
- Surge deposit
- Quartzite
- Basalt
- Tuffaceous sandstone
- Limestone
- Rhyolite dikes
- Siltstone
- Dolomite
- Caldera-collapse megabreccia
- Shale

Figure 6 (cont.). Simplified composite stratigraphic column of rocks in (a) the southern Pancake Range and (b) the Reveille Range. The unnamed Tertiary tuffaceous sandstone, tuff of northern Reveille Range surge deposit, Windous Butte Formation, siltstone of Cane Springs, megabreccia of the caldera of northern Reveille Range and Paleozoic sedimentary rocks are not discussed in this chapter. These units are described in detail in Appendices A and B. Unit thicknesses are reported as maximum values, unless otherwise noted. Ages of basalts are from Naumann and others, 1991, and ages of tuffs are from this study.
Chapter 3

Structural Geology

Faults

The study area contains four sets of faults (Plate 1; Fig. 5). These include: (1) northeast-striking normal faults, (2) northwest-striking normal and reverse faults, (3) a strike-slip fault, and (4) east-west-striking normal faults. Because talus or alluvial deposits obscure many fault traces, measurements of fault attitudes were difficult to obtain. In addition, faults exposed only in one lithologic unit (e.g., tuff of Goblin Knobs) were difficult to identify.

Northeast-Striking Normal Faults

A set of steeply dipping normal faults striking between N29°E and N62°E and dipping between 73° and 82° offset rocks in numerous locations in the southern Pancake Range (Plate 1; Fig. 5). Many of these faults cut rocks as young as the Shingle Pass tuffs; however, they do not cut the megabreccia of northern Reveille Range (Plate 1). Thus, these faults predate or are synchronous with the collapse of the caldera of northern Reveille Range (27-25 Ma). Throws on these faults range from less than 10 m to a maximum of about 45 m.
Northwest-Striking Normal and Reverse Faults

A set of steeply dipping normal faults and one high-angle reverse fault striking between N12°W and N42°W and dipping between 53° and 70° offset rocks in several areas of the southern Pancake Range. Similar to the northeast-striking faults, many of these faults predate the collapse of the caldera of northern Reveille Range, because they cut tuffs as young as the Shingle Pass tuffs but do not cut the megabreccia of northern Reveille Range (Plate 1). However, they cross cut many of the northeast-striking normal faults and, thus, postdate these faults. Throws on these faults range from less than 10 m to a maximum of about 85 m.

Strike-Slip Fault

Ekren and others (1973) originally mapped the megabreccia of the caldera of northern Reveille Range as a debris flow of chaotic blocks that underlies the tuff of Bald Mountain and Shingle Pass Tuff cooling unit C and that also overlies the tuff of Bald Mountain. They suggested that this deposit formed during a period of intense left-lateral strike-slip faulting between 26 and 18.5 Ma between the northern Reveille and southern Pancake Ranges (striking approximately N50°W). Based on the observation that the tuff of Bald Mountain and Shingle Pass Tuff cooling unit C do not overlie this deposit and the lack of field evidence for large-scale strike-slip motion, the megabreccia of the caldera of northern Reveille Range probably was not caused by faulting but, rather, by the collapse of the caldera of northern Reveille Range (Chapter 7).

East-West-Striking Normal Faults

Several east-west-striking faults are present in the northern Reveille and southern
Pancake Ranges (Plate I). In the Pancake Range, one east-west-striking fault is displaced by both a northeast- and a northwest-striking normal fault, indicating that it is older than these fault sets and, thus, was active prior to the formation of the caldera of northern Reveille Range. In the Reveille Range, however, two east-west-striking faults displace Oligocene-to-Miocene tuffs and episode-1 basalts. One of these faults, labeled fault A on Plate I and Figure 5, has an apparent right-lateral offset, displacing the caldera of northern Reveille Range margin approximately 3.9 km to the east. Fault A had a component of normal motion late in its history, vertically displacing episode-1 basalts approximately 15 m (Fig. 7).

**Joints**

Systematic jointing is common in tuffs in the study area. For example, joints within the tuff of Goblin Knobs are generally unidirectional, closely spaced and pervasive (Fig. 8). Joints strike between N25°W and N39°W and dip between 61° and 85° to the southwest. South of the study area, joints in the tuff of Goblin Knobs have similar orientations (Jones and Bullock, 1985; Martin and Naumann, 1995; T. Wickham, personal communication, 1995). Joints in tuffs of the southern Pancake Range, on the other hand, are not as systematic as those in the tuff of Goblin Knobs. These tuffs are cut by multiple joint sets.
Figure 7. (A) Photograph of fault A. This fault strikes east-west and has an apparent lateral offset of approximately 3.9 km. The fault offsets episode-1 basalts 15 m vertically. View is to the southwest. (B) Line drawing showing the location of fault A.
Figure 24. Map of the southern Basin and Range showing the distribution of asthenospheric mantle and lithospheric mantle source regions of mafic volcanic rocks discussed in the text. The northern Colorado River extensional corridor represents the area where the youngest mafic volcanic rocks were dominated by an asthenospheric mantle source. The southern portion of the amagmatic zone represents the area where all mafic volcanic rocks were dominated by a lithospheric mantle source. The enclosed solid line represents the boundary between lithospheric mantle and asthenospheric mantle derived basalts of Fitton and others (1991), and the dashed line represents the boundary between enriched mantle and OIB of Menzies (1989). The northern Colorado River extensional corridor was defined by Faulds and others (1990). The lightly shaded area represents the Death Valley- Pancake Range basalt zone of Vaniman and others (1982).
Figure 8. Photograph of the tuff of Goblin Knobs. Note the pervasive joints that strike approximately N30°W. View is to the northwest.
Chapter 4

Analytical Techniques

Thirty-five samples (twenty-nine samples of tuffs and six samples of basalts and basaltic andesites) were collected from most units in the stratigraphic section (Appendix A). Approximately 2 kg of fresh rock for each sample was collected in the field. Samples were first crushed in a Bico chipmunk rock crusher to less than 10 mm in size. Lithic fragments greater than 3 mm in size were hand picked from the sample to avoid contamination. Then the sample was pulverized to less than 325 mesh using a Bico shatter box. To avoid any further contamination of the sample, tungsten-carbide plates were used for the chipmunk rock crusher, and tungsten-carbide rings and a stainless steel bowl with a tungsten-carbide coated interior were used for the grinding assembly for the shatter box. Analyses described below were made on these whole rock samples with the exception of $^{40}$Ar/$^{39}$Ar dates which were completed on mineral separates.

Major and trace element analyses (XRF)

All thirty-five samples were analyzed for major and trace elements by X-ray fluorescence spectrometry (XRF). Ten gram fused glass disks were made for major element analyses using a flux/sample ratio of 9:1. This fusing was done by heating 9.00 g of lithium tetraborate ($\text{Li}_2\text{B}_4\text{O}_7$), 0.16 g of ammonium nitrate ($\text{NH}_4\text{NO}_3$) and 1.00 g of
sample at 1100°C in Au-Pt crucibles. The resultant melt was quenched in Au-Pt molds (Noorish and Hutton, 1969). Pressed pellets were made for trace element analyses by mixing 0.60 g of methyl cellulose and 3.00 g of sample (Hutchison, 1974). This mixture was backed with additional methyl cellulose and compressed to 3,000 psi in an Ashcroft hydraulic pellet press. All samples and chemicals were weighed to ± 0.0002 g. Fused glass disks and pressed pellets were stored in a desiccator prior to analysis.

All XRF analyses were done on a Rigaku 3030 spectrometer at the University of Nevada, Las Vegas. Table 1 lists the primary standards used for calibration of the X-ray spectrometer. Tables 2 and 3 show the accuracy and precision for major and trace elements.

Loss on Ignition (LOI) was determined for all samples, and this was done by heating approximately 3.00 g of sample in ceramic crucibles at 950°C for two hours. The samples were gradually cooled to 300°C in the oven over four to five hours and then finally cooled to room temperature in a desiccator (Hutchison, 1974). The samples were weighed immediately after they reached room temperature.

**Rare-earth and trace element analyses (INAA)**

Seventeen samples were analyzed for rare-earth elements and additional trace elements by instrumental neutron activation analysis (INAA) at the Phoenix Memorial Laboratory, Ann Arbor, Michigan. Tables 4 and 5 show the accuracy and precision for the rare-earth and trace element analyses.

Samples were prepared in the following manner. Eighteen eight-cm intervals of Suprasil silica tubing were cleaned by heating the tubes for one hour in a glass beaker
containing a 50% (by volume) solution of HNO₃ diluted with distilled water. One end of each tube was then sealed using a gas/oxygen mixture flame. Seventeen samples were weighed to 0.2000 ± 0.0025 g and were added to the respective tubes. The tubes were then sealed by heating the open end with the gas/oxygen flame. The eighteenth sample was prepared as a standard from sample #78-218, a basalt from the River Mountains, Clark County, Nevada, collected by Dr. Eugene I. Smith (Smith and others, 1990). The tubes were checked for leaks by placing them in a beaker, adding enough 50% HNO₃ to cover the tubes, and warming the samples on a hot plate.

**Isotope analyses (TIMS)**

Eleven samples were analyzed for Nd, Sr and Pb isotopic ratios and for Rb, Sr, Sm, Nd and Pb concentrations by thermal ionization mass spectrometry (TIMS). Isotopic compositions for Sr, Nd and Pb and elemental concentrations for Sr, Nd, Pb, Rb and Sm were done on a VG Sector 54 mass spectrometer at the University of Kansas. For a more thorough description of this procedure see Feuerbach and others (1993).

**Geochronology (⁴⁰Ar³⁹Ar incremental heating technique)**

Eleven mineral separates (five sanidine and six biotite separates) were analyzed by the ⁴⁰Ar/³⁹Ar incremental heating technique. Isotopic analyses were done on a Nuclide 6-60-SGA 1.25 mass spectrometer at the University of Maine, Orono. For a more thorough description of this procedure see Hubacher and Lux (1987). Because the dates were obtained after the thesis defense, a geochronology chapter was not incorporated into the text. The dates obtained, however, are incorporated within the appropriate sections of
the text and the data are presented in Appendix C: Part 4.

Samples were prepared in the following manner. Fresh rock from seven lithologic units were first crushed to less than 3 mm in size using the Bico chipmunk rock crusher, ground to less than \(900 \mu m\) using a Bico pulverizer disk mill and then sieved to size fractions greater than 600, 250 and 180 \(\mu m\) using a Rotap automated shaker. Sanidines and biotites from the size fraction between 250 \(\mu m\) and 180 \(\mu m\) initially were separated using the Frantz magnetic separator. Biotites were separated further using a heavy liquid combination of methylene iodide plus acetone, and sanidines were separated further using heavy liquid combinations of methylene iodide plus acetone and sodium polytungstate plus distilled water. Samples were cleaned by using an ultrasound and stirring the samples for 120 seconds in a 10\% HCl bath (Sarna-Wojcicki, personal communication, 1991). Finally, approximately 250 mg of clean sanidine and biotite were hand picked under a binocular microscope.
Table 1. Primary calibration standards for the Rigaku 3030 X-ray Fluorescence Spectrometer. Standards are United States Geological Survey standards except standard AL-1 which is a French standard (Govindaraju, 1994).

<table>
<thead>
<tr>
<th>Major Elements</th>
<th>Trace Elements</th>
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<tr>
<td>SCO-1</td>
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<tr>
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<td>GSP-1</td>
<td>BIR-1</td>
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Table 2. Accuracy for the Rigaku 3030 X-ray Fluorescence Spectrometer. U.S.G.S. standard BIR-1 and the French standard DR-N were used as references for major and trace elements, respectively. See Appendix E for the equation for the calculation of the % error.

<table>
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<tr>
<th>Element</th>
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Table 3. Precision for the Rigaku 3030 X-ray Fluorescence Spectrometry. The precision is determined by calculating 7 replicate analyses of U.S.G.S. standard BIR-1 for major elements and DR-N for trace elements. See Appendix E for the equations for the calculations of the standard deviation and the mean relative % error.

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<th>Element</th>
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<td>P₂O₅</td>
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<td>0.07</td>
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<td>404.58</td>
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<td>Zr</td>
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<td>Y</td>
<td>26</td>
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<td>367.86</td>
<td>9.97</td>
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Table 4. Accuracy for instrumental neutron activation analyses. U.S.G.S. standard BHVO-1 was used as a reference for the rare-earth elements.

<table>
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<th>Element</th>
<th>% error</th>
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<td>Ta</td>
<td>0.81</td>
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<tr>
<td>La</td>
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<td>Ce</td>
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<td>Sm</td>
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<td>Hf</td>
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<td>Eu</td>
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<td>Tb</td>
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<td>Yb</td>
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<td>Lu</td>
<td>30</td>
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<tr>
<td>Cr</td>
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<td>Sc</td>
<td>2.83</td>
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<tr>
<td>Co</td>
<td>4.00</td>
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Table 5. Precision for instrumental neutron activation analyses. The precision is determined by calculating 4 replicate analyses of U.S.G.S. standard BHVO-1 the rare-earth elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>Published concentration ppm</th>
<th>Mean of 4 replicate analyses</th>
<th>Standard deviation</th>
<th>Uncertainty</th>
</tr>
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<td>Ta</td>
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<td>1.24</td>
<td>0.09</td>
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<td>La</td>
<td>15.8</td>
<td>15.7</td>
<td>0.44</td>
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<td>Ce</td>
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<td>39.4</td>
<td>4.49</td>
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<td>Sm</td>
<td>6.20</td>
<td>6.47</td>
<td>0.15</td>
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</tr>
<tr>
<td>Hf</td>
<td>4.38</td>
<td>4.68</td>
<td>0.08</td>
<td>1.7</td>
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<tr>
<td>Eu</td>
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<td>Tb</td>
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<td>Yb</td>
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<tr>
<td>Lu</td>
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<tr>
<td>Cr</td>
<td>289</td>
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<tr>
<td>Sc</td>
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<td>30.9</td>
<td>0.37</td>
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<tr>
<td>Co</td>
<td>45.0</td>
<td>43.2</td>
<td>0.91</td>
<td>2.1</td>
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Chapter 5

Geochemistry

Geochemical descriptions of all volcanic rocks in the study area are presented in this chapter. These geochemical descriptions will be used in Chapters 6 and 7 for petrogenetic studies of the basalts and correlation between particular ash-flow tuffs, respectively. Major and trace element geochemical data, isotopic data and CIPW norms are presented in Appendix C, Parts 1, 2 and 3. Sample collection sites for these samples are in Appendix D and are shown on Figure 9. Major elements were normalized to 100% only for chemical plots. Volatile compounds were not taken into account in this normalization.

Felsic volcanic rocks

Major element data for the Monotony Tuff collected outside of the study area by Ekren and others (1971 and 1974) and Phillips (1989) were used in chemical plots in addition to the four samples collected for this study. For presentation clarity, all Monotony Tuff samples analyzed by these researchers and those collected outside of the study area are shown as a single symbol in chemical plots for this chapter. Similarly, all cooling units for the Shingle Pass Tuff were assigned a single symbol. In Chapter 7, Monotony Tuff samples analyzed by other researchers are assigned different symbols.
**Major elements**

Ash-flow tuffs of the northern Reveille and southern Pancake Ranges range from dacite-to-rhyolite (Table 6; Fig. 10). Each tuff has a restricted range of major elements (Appendix D; Fig. 11), with the exception of the tuff of northern Reveille Range (71.4-77.7 wt.% SiO₂; 3.0-6.6 wt.% K₂O). Major element abundances alone do not differentiate the tuffs; however, minor differences in major element chemistry exist among them (Table 6; Figures 10-11).

The tuff of Arrowhead and Monotony Tuff are dacites with silica values varying between 66.8-67.8 and 68.3-68.7 wt.% SiO₂, respectively. The Monotony Tuff has higher Al₂O₃ (14.9-15.7 wt.%), TiO₂ (0.48-0.53 wt. %), Fe₂O₃ (2.8-3.8 wt. %), CaO (3.0-3.5 wt.%), MgO (0.56-1.22 wt.%), P₂O₅ (0.09-0.16 wt.%), but lower K₂O (3.0-4.1) than other tuffs in the northern Reveille and southern Pancake Ranges. The tuff of Arrowhead has higher Al₂O₃ (14.05-15.71 wt.%) and P₂O₅ (0.06-0.19 wt.%) (Figs. 10-11) than the other tuffs.

The rhyolite ash-flow tuffs include the Shingle Pass tuffs and tuffs of Bald Mountain, Arrowhead, Goblin Knobs, northern Reveille Range and Streuben Knobs. The tuff of northern Reveille Range has the highest silica and the lowest Na₂O (0.2-1.1 wt.%) compared to the other rhyolite tuffs. Shingle Pass tuffs have lower TiO₂ (0.14-0.27 wt.%) and MgO (0.16-0.50 wt.%). The tuff of Streuben Knobs has lower Al₂O₃ (13.59-13.67 wt.%), TiO₂ (0.14 wt.%), Fe₂O₃ (1.08-1.30 wt.%), and CaO (0.80-0.86 wt.%). The tuff of Goblin Knobs has no distinguishing major element features (Figs. 10-11).

Minor metasomatism appears to have affected the tuff of northern Reveille Range
Metasomatism is a process in which K is enriched relative to Na or Na is enriched relative to K. In this case, the tuff of northern Reveille Range is enriched in K\textsubscript{2}O (3.0-6.6 wt.%) relative to Na\textsubscript{2}O (0.2-1.1 wt.%). In addition, Na\textsubscript{2}O decreases with increasing SiO\textsubscript{2} (Fig. 11e). Potassium also appears to decrease with increasing SiO\textsubscript{2}, but the data are scattered (Fig. 11f).

**Trace elements**

Similar to the major elements, trace elements do not solely differentiate the tuffs; however, minor differences in trace element chemistry exist among them (Table 7; Figs. 13-15). Trace element Harker variation diagrams (Fig. 13) show that trace elements behave compatibly in all tuffs, with the exception of Nb for the tuff of Goblin Knobs (Fig. 13c). Because of this characteristic, element/element and ratio/ratio chemical plots do not show differences among the tuffs. Therefore, with the exception of spider diagrams, detailed trace element chemical plots are not presented in this chapter. They will be reserved for the appropriate sections in Chapter 7.

Spider diagrams show notable similarities and differences among the tuffs (Figs. 14 and 15). For example, all ash-flow tuffs are more enriched in light rare-earth elements (LREE) relative to heavy rare-earth elements (HREE) and show slight to considerable Eu anomalies (Eu/Eu* = 0.25-0.82) when plotted on chondrite normalized spider diagrams.

The dacite ash-flow tuffs are similar in that they have small Eu anomalies (Eu/Eu* = 0.65-0.82). The Monotony Tuff, however, is enriched in Sr and depleted in Nb, Sm and Yb relative to the tuff of Arrowhead, whereas, the tuff of Arrowhead is enriched in Ba, Sr, Zr, Hf, and Eu and depleted in Th and Ta relative to the Monotony Tuff.
The rhyolite ash-flow tuffs have medium-to-large Eu anomalies (Eu/Eu* = 0.25-0.67) with the tuff of Streuben Knobs showing the largest anomaly (Eu/Eu* = 0.25). The tuff of northern Reveille Range is both enriched and depleted in Rb and depleted in Y, the large ion lithophile elements (LILE) Ba and Sr, the high field strength elements (HFSE) Ta, Nb, Hf and Zr, the LREE La, Ce, Nd and Sm and the HREE Tb, Yb and Lu relative to the other rhyolite tuffs. The tuff of Streuben Knobs also is enriched in Rb and depleted in Ba, Sr, La, Ce and Zr but also is enriched in Th, Nb, Ta, Y and Yb. The tuff of Goblin Knobs is enriched in Ta and depleted in Y, Nb, Tb, Yb and Lu. Finally, the Shingle Pass tuffs are enriched in Y, Nb, Hf and all rare-earth elements (REE) relative to the other rhyolite tuffs.

Isotopes

The ash-flow tuffs have similar initial $^{87}\text{Sr}/^{86}\text{Sr}$ but are slightly more variable in $\varepsilon_{\text{Nd}}$ (Appendix D; Fig. 16). No major differences in isotopes are present between the dacite and rhyolite ash-flow tuffs. For example, the dacite tuff of Arrowhead has the lowest initial $^{87}\text{Sr}/^{86}\text{Sr}$, and the rhyolite tuff of Streuben Knobs has the highest (0.70836 and 0.71361, respectively), but the dacite Monotony Tuff has intermediate values (0.70909-0.70910). Furthermore, the rhyolite tuff of Goblin Knobs has the lowest $\varepsilon_{\text{Nd}}$ and the rhyolite Shingle Pass Tuff cooling unit C has the highest (-8.453 and -6.219, respectively), but both dacites, Monotony Tuff and tuff of Arrowhead, have intermediate values (-7.494 to -6.845). $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios have a restricted range of values ($^{206}\text{Pb}/^{204}\text{Pb} = 19.25-19.30$ and $^{207}\text{Pb}/^{204}\text{Pb} = 15.63-15.69$). Shingle Pass Tuff cooling unit D has a slightly higher $^{208}\text{Pb}/^{204}\text{Pb}$ ratio than the other tuffs (41.55 and 38.92-
Mafic volcanic rocks

In addition to geochemical data collected for basalts from this study, geochemical data from Yogodzinski and others (submitted) were used in chemical plots.

Major elements

Mafic rocks in the Reveille Range range from tephrite basanite-to-trachyte (Fig. 17) and have fairly restricted ranges of major elements (Table 8; Figs. 17-19). Major element geochemical data can be used to differentiate the trachytes and basaltic andesites; however, episode-1 and episode-2 basalts show overlapping characteristics (Fig. 19). The following descriptions are based on comparisons among mafic rocks in the Reveille Range.

Episode-1 basalts range from basalt-to-trachybasalt (45.7-49.4 wt.% SiO₂) (Table 8; Fig. 17) and are alkalic (Fig. 18). They have high Fe₂O₃ (12.0-14.8 wt.%) and TiO₂ (2.5-3.5 wt. %) and moderate Al₂O₃ (15.2-17.1 wt.%), MgO (3.4-6.1 wt.%) and CaO (6.6-9.4 wt.%).

Episode-2 basalts range from tephrite-basanite-to-trachybasalt (Table 8; Fig. 17) and are alkalic (Fig. 18). These basalts are generally lower in SiO₂ (43.0-48.0 wt.%), Al₂O₃ (14.1-17.2 wt.%) and CaO (6.9-10.8 wt.%) and higher in TiO₂ (2.5-4.3 wt.%), Fe₂O₃ (11.2-15.4 wt.%), MgO (3.9-10.2 wt.%) and Na₂O (3.3-4.4 wt.%) than episode-1 basalts. Major elements between episode-1 and episode-2 basalts, however, are more similar than they are different (Fig. 19).

Stratigraphically separating episode-1 and episode-2 basalts are the trachytes (Table 8; Fig. 17), which are alkalic (Fig. 18). These rocks have higher SiO₂ (55.8-60.1
wt.%), Na₂O (5.5-6.6 wt.%) and K₂O (4.3-5.8 wt.%) and lower TiO₂ (0.5-1.1 wt.%), Fe₂O₃ (6.7-9.8 wt.%), MgO (0.3-1.2 wt.%) and CaO (2.0-3.8 wt.%) than the basalts. Al₂O₃ (16.1-17.4 wt.%) values are similar to the basalts (Fig. 19).

The oldest mafic rocks, the basaltic andesites (Appendix A; Table 8; Fig. 17), are subalkalic (Fig. 18) and are notably higher in SiO₂ (53.9-54.8 wt.%) and lower in Na₂O (2.6-3.1 wt.%), Fe₂O₃ (8.9-9.1 wt.%), and TiO₂ (1.1-1.5 wt.%) than episode-1 and episode-2 basalts (Fig. 17). They are similar in Al₂O₃ (15.9-17.1 wt.%), MgO (3.9-4.8 wt.%), CaO (7.5-8.3 wt.%) and K₂O (1.8-2.3 wt.%).

All mafic rocks show an increase in Al₂O₃, K₂O and Na₂O and a decrease in TiO₂ with increasing SiO₂ (Fig. 19). Calcium and MgO decrease in abundance in episode-1 basalts and the trachytes, whereas, these elements in episode-1 basalts and the basaltic andesites increase with increasing SiO₂. Episode-1 and episode-2 basalts show a decrease in Fe₂O₃ as SiO₂ increases, whereas, these elements increase in the basaltic andesites and trachytes. Basalts in general show very little variation in MnO with respect to SiO₂.

**Trace elements**

Compatible elements (Cr, Ni and Sr) show consistent overlapping characteristics for the mafic volcanic rocks; however, most of the incompatible trace elements can be used to differentiate the trachytes (Table 9; Figs. 20d). Incompatible trace elements, however, cannot be used to differentiate episode-1 basalts from episode-2 basalts.

Episode-1 basalts (5-146 ppm Cr and 1-68 ppm Ni) and the basaltic andesites (42-182 ppm Cr and 8-40 ppm Ni) are relatively evolved (Fig. 20a and 20b). The trachytes (0-19 ppm Cr and 0-1 ppm Ni) are highly evolved. Most episode-2 basalts are relatively
evolved, however, some are nearly primitive (14-348 ppm Cr and 9-193 ppm Ni).

All mafic rocks are more enriched in LREE than HREE (Figs. 21 and 22). The basaltic andesites and trachytes show slight negative Eu anomalies when plotted on chondrite normalized spider diagrams (Figs. 22c and 22d), whereas, Eu anomalies are absent in episode-1 and episode-2 basalts (Figs. 22a and 22b). Episode-1 and episode-2 basalts are very similar to ocean island basalts (OIB). This is shown in Figures 21a and 21b where the trace elements plot as a nearly horizontal line at 1 on an OIB normalized spider diagram. Episode-2 basalts are slightly enriched in Nb relative to OIB (Fig. 21b). The trachytes also appear similar to OIB but are enriched in Pb and depleted in Nb, P and Ti relative to OIB (Fig. 21c). The basaltic andesites, on the other hand, are different from OIB (Fig. 21d) in that they are enriched in Rb, Th, Nb, Nd, Zr Yb and Lu and depleted in Sr, P and Ti relative to OIB.

Isotopes

Isotope compositions widely vary among basalts. $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios can be used to differentiate episode-1 basalts from episode-2 basalts as well as the basaltic andesites (Fig. 23). Episode-1 basalts and the trachytes show a wide range of $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios (0.7043-0.7061 and 0.7037-0.7064, respectively). The basaltic andesites show a narrower range of $^{87}\text{Sr} / ^{86}\text{Sr}$ ratios (0.7076-0.7081). Episode-2 basalts vary slightly in $^{87}\text{Sr} / ^{86}\text{Sr}$ (0.7034-0.7036). $\varepsilon_{\text{Nd}}$ values, however, overlap between episode-1 and episode-2 basalts and the trachytes. The basaltic andesites show the lowest $\varepsilon_{\text{Nd}}$ (-8.21 to -7.21). Episode-1 basalts range from 0.75-4.47, episode-2 basalts range from 3.52-5.35 and the trachytes range from 3.26-3.83.
Figure 9. Location map of samples collected in the northern Reveille and southern Pancake Ranges. RR- and PR- designate Reveille and Pancake Ranges, respectively.
Table 6. Summary of major element similarities and differences among tuffs of the northern Reveille and southern Pancake Ranges.

<table>
<thead>
<tr>
<th>tuff</th>
<th>classification</th>
<th>range of SiO₂ (wt.%)</th>
<th>distinguishing characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monotony</td>
<td>dacite</td>
<td>68.3-68.9</td>
<td>low SiO₂ and K₂O (3.0-4.1 wt.%); high Al₂O₃ (14.9-15.7 wt.%), TiO₂ (0.48-0.53 wt.%), Fe₂O₃ (2.8-3.8 wt.%), CaO (3.0-3.5 wt.%), MgO (0.56-1.22 wt.%) and P₂O₅ (0.09-0.16 wt.%)</td>
</tr>
<tr>
<td>Bald Mountain</td>
<td>rhyolite</td>
<td>71.2-73.0</td>
<td>low P₂O₅ (0.03-0.05 wt.%)</td>
</tr>
<tr>
<td>Shingle Pass</td>
<td>rhyolite</td>
<td>72.9-75.7</td>
<td>low TiO₂ (0.14-0.27 wt.%) and MgO (0.16-0.50 wt.%); high Na₂O (2.34-2.97 wt.%)</td>
</tr>
<tr>
<td>Arrowhead</td>
<td>dacite</td>
<td>66.8-67.7</td>
<td>low SiO₂; high Al₂O₃ (14.05-15.71 wt.%) and P₂O₅ (0.06-0.19 wt.%)</td>
</tr>
<tr>
<td>Goblin Knobs</td>
<td>rhyolite</td>
<td>70.4-75.3</td>
<td>not distinguishable from the other tuffs</td>
</tr>
</tbody>
</table>
| N. Reveille Range   | rhyolite       | 71.4-78.5            | variable major element; high SiO₂ and K₂O (3.0-6.6 wt.%); low Na₂O (0.2-1.1 wt.%), Al₂O₃ (12.26-13.93 wt.%), Fe₂O₃ (1.00-1.58 wt.% and CaO (0.12-1.67 wt.%)
| Streuben Knobs      | rhyolite       | 73.1-76.6            | low Al₂O₃ (13.59-13.67 wt.%), TiO₂ (0.14 wt.%), Fe₂O₃ (1.08-1.30 wt.% and CaO (0.80-0.86 wt.%)

Table 7. Summary of trace element similarities and differences among tuffs of the northern Reveille and southern Pancake Ranges.

<table>
<thead>
<tr>
<th>tuff</th>
<th>trace elements characteristics</th>
<th>Eu/Eu*</th>
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<tbody>
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<td>Monotony</td>
<td>Sr</td>
<td>0.65-0.70</td>
</tr>
<tr>
<td>Bald Mountain</td>
<td>Ba, Nd, Hf, Y, Yb and Lu</td>
<td>not distinguishable from the other tuffs</td>
</tr>
<tr>
<td>Shingle Pass</td>
<td>Nb, La, Ce, Nd, Sm, Eu, Hf, Y, Yb and Lu</td>
<td>Sr</td>
</tr>
<tr>
<td>Arrowhead</td>
<td>Ba, Sr, Zr, Hf and Eu</td>
<td>Th and Ta</td>
</tr>
<tr>
<td>Goblin Knobs</td>
<td>Ta</td>
<td>Th, Nb, Y, Yb and Lu</td>
</tr>
<tr>
<td>N. Reveille Range</td>
<td>Rb</td>
<td>Ba, Rb, Th, Nb, Ta, La, Ce, Sr, Nd, Sm, Zr, Hf, Y, Yb and Lu</td>
</tr>
<tr>
<td>Streuben Knobs</td>
<td>Rb, Th, Nb, Ta, Y and Yb</td>
<td>Ba, La, Ce, Sr, Zr and Eu</td>
</tr>
</tbody>
</table>

* relative to other tuffs in this table
Figure 10. Classification of the ash-flow tuffs. Classification scheme is from Le Bas and others (1986).
Figure 11. Major element Harker variation diagrams for the ash-flow tuffs. Major elements were normalized to 100% on a volatile-free basis.
Figure 11 (cont.). Major element Harker variation diagrams for the ash-flow tuffs. Major elements were normalized to 100% on a volatile-free basis.
Figure 12. K₂O vs. Na₂O diagram showing the field of unaltered rocks (boxed area) from Carmichael and others (1974). Samples falling within the field are interpreted to be unaffected by K-metasomatism. Those falling outside of the field are interpreted to be either slightly or strongly affected by K-metasomatism. Major elements were normalized to 100% on a volatile-free basis.
Figure 13. Trace element Harker variation diagrams for the ash-flow tuffs. Major elements were normalized to 100% on a volatile-free basis.
Figure 14. Chondrite normalized spider diagrams for (a) Monotony Tuff, tuff of Goblin Knobs and tuff of Bald Mountain, (b) Shingle Pass Tuff and tuff of Arrowhead and (c) tuff of Northern Reveille Range and tuff of Streuben Knobs. Chondrite normalization values are from Thompson (1982).
Figure 14 (cont.). Chondrite normalized spider diagrams for (a) Monotony Tuff, tuff of Goblin Knobs and tuff of Bald Mountain, (b) Shingle Pass Tuff and tuff of Arrowhead and (c) tuff of Northern Reveille Range and tuff of Streuben Knobs. Chondrite normalization values are from Thompson (1982).

Figure 15. Chondrite normalized spider diagrams for (a) Monotony Tuff, tuff of Goblin Knobs and tuff of Bald Mountain, (b) Shingle Pass Tuff and tuff of Arrowhead and (c) tuff of Northern Reveille Range and tuff of Streuben Knobs. Chondrite normalization values are from Nakamura (1974).
Figure 15 (cont.). Chondrite normalized spider diagrams for (a) Monotony Tuff, tuff of Goblin Knobs and tuff of Bald Mountain, (b) Shingle Pass Tuff and tuff of Arrowhead and (c) tuff of Northern Reveille Range and tuff of Streuben Knobs. Chondrite normalization values are from Nakamura (1974).
Figure 16. Nd, Sr and Pb isotope ratio diagrams for the tuffs.

- ▲ Monotony Tuff
- ■ Shingle Pass Tuff
- ● tuff of Bald Mountain
- ○ tuff of Arrowhead
- △ tuff of Goblin Knobs
- ◇ tuff of Streuben Knobs
- ♦ tuff of Northern Reveille Range
Table 8. Summary of major element similarities and differences among basalts of the nonhem Reveille Range.

<table>
<thead>
<tr>
<th>basalt classification</th>
<th>range of SiO₂ (wt.%)</th>
<th>distinguishing characteristics</th>
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</thead>
<tbody>
<tr>
<td>basaltic andesites</td>
<td>53.9-54.8</td>
<td>low Na₂O (2.56-3.10 wt.%).</td>
</tr>
<tr>
<td>Episode-1 basalt, hawaiite</td>
<td>45.7-49.4</td>
<td>low K₂O (1.05-2.02 wt.%).</td>
</tr>
<tr>
<td>trachytic rocks</td>
<td>55.8-60.1</td>
<td>high SiO₂, Al₂O₃ (16.11-17.35 wt.%), K₂O (4.28-5.83 wt.%), Na₂O (5.53-6.58 wt.%); low TiO₂ (0.45-1.11 wt.%), MgO (0.28-1.2 wt.%), Fe₂O₃ (6.74-9.82 wt.%), CaO (1.97-3.8 wt.%), and P₂O₅ (0.11-0.3 wt.%).</td>
</tr>
<tr>
<td>Episode-2 basalt, hawaiite, basanite</td>
<td>43.0-48.0</td>
<td>low SiO₂ and Al₂O₃ (14.14-17.17 wt.%); high TiO₂ (2.50-4.29 wt.%), MnO (0.15-0.21 wt.%), Fe₂O₃ (11.17-15.42 wt.%), CaO (6.85-10.08 wt.%), and P₂O₅ (0.44-1.04 wt.%); MgO is highly variable (3.86-10.24 wt.%).</td>
</tr>
</tbody>
</table>

Table 9. Summary of trace element similarities and differences among basalts of the northern Reveille Range.

<table>
<thead>
<tr>
<th>basalt classification</th>
<th>higher concentration relative to OIB</th>
<th>lower concentration relative to OIB</th>
<th>Eu/Eu*</th>
<th>εNd</th>
</tr>
</thead>
<tbody>
<tr>
<td>basaltic andesites</td>
<td>Ba, Rb, Th and Sr</td>
<td>Nb, Ta and Eu</td>
<td>0.67-0.79</td>
<td>7.21-</td>
</tr>
<tr>
<td>Episode-1</td>
<td>Ba, Th, Nb, Ta, La, Ce, Nd, Sm, Zr, Tb, Y, Yb and Lu</td>
<td>1.00</td>
<td>0.75-4.47</td>
<td></td>
</tr>
<tr>
<td>trachytes</td>
<td>Rb, Th, Nb, Ta, La, Ce, Nd, Sm, Eu, Zr, Hf, Tb, Y, Yb and Lu</td>
<td>Sr</td>
<td>0.53-0.76</td>
<td>3.26-3.83</td>
</tr>
<tr>
<td>Episode-2</td>
<td>Nb</td>
<td>Rb, Th, Yb and Lu</td>
<td>1.00</td>
<td>3.52-5.35</td>
</tr>
</tbody>
</table>
Figure 17. Classification of the mafic rocks. Classification scheme is from Le Bas and others (1986).

Figure 18. Alkalies vs. SiO₂ diagram showing alkaline and subalkaline affinities of the mafic rocks. The alkaline/subalkaline field boundary is from Irvine and Baragar (1971).
Figure 19. Major element Harker variation diagrams for the mafic rocks. Major elements were normalized to 100% on a volatile-free basis.
Figure 19 (cont.). Major element Harker variation diagrams for the mafic rocks. Major elements were normalized to 100% on a volatile-free basis.
Figure 20. Trace element diagrams for the mafic rocks. Trace elements are in ppm; MgO and CaO are in wt. %.
Figure 21. Spider diagrams normalized to OIB for (a) episode-1 basalts, (b) episode-2 basalts, (c) trachytic rocks and (d) basaltic andesites. The shaded area represents the range of trace element values within the mafic rocks. Ocean island basalt normalization values are from Sun and McDonough (1989).
Figure 21 (cont.). Spider diagrams normalized to OIB for (a) episode-1 basalts, (b) episode-2 basalts, (c) trachytic rocks and (d) basaltic andesites. The shaded area represents the range of trace element values within the mafic rocks. Ocean island basalt normalization values are from Sun and McDonough (1989).
Figure 22. Spider diagrams normalized to chondrite for (a) episode-1 basalts, (b) episode-2 basalts, (c) trachytic rocks and (d) basaltic andesites. The shaded area represents the range of trace element values within the mafic rocks. Chondrite normalization values are from Nakamura (1974).
Figure 22 (cont.). Spider diagrams normalized to chondrite for (a) episode-1 basalts, (b) episode-2 basalts, (c) trachytic rocks and (d) basaltic andesites. The shaded area represents the range of trace element values within the mafic rocks. Chondrite normalization values are from Nakamura (1974).
Figure 23. Nd and Sr Isotope ratio diagram for the mafic rocks.
Chapter 6

Petrogenesis of the Basalts: Transition from a Lithospheric Mantle Source to Asthenospheric Mantle Source

Geochemical data for Late Cenozoic basalts in the western United States indicate that a transformation from a lithospheric mantle source to an asthenospheric mantle source occurred in selected locations throughout the area (Menzies and others, 1983; Fitton and others, 1988; Ormerod and others, 1988; Livaccari and Perry, 1993; Rogers and others, 1995). A shift from lithospheric to asthenospheric mantle sources occurred in the Reveille Range between 14 and 6 Ma. This shift is similar to that observed in other areas of the Great Basin. The Lake Mead area in southeastern Nevada and northwestern Arizona and the Lunar Crater volcanic field in central Nevada are two well-known areas where this transition occurred.

Mafic volcanic rocks in the Lake Mead area (Fig. 24) occur in the northern Colorado River extensional corridor (to the southeast of Las Vegas) and the amagmatic zone (to the north of Las Vegas) and consist of basaltic cinder cones and lava flows (Feuerbach and others, 1993). This area underwent significant crustal extension and magmatism during Miocene time (Anderson, 1971). In the northernmost part of the northern Colorado River extensional corridor mafic volcanism began at 14 Ma and was dominated by a lithospheric mantle source (εNd = -4 to -10; Feuerbach and others, 1993).
Lithospheric extension and subsequent upwelling of the asthenospheric mantle occurred between 11 and 6 Ma, at which time basaltic volcanism resumed with an asthenospheric mantle source in the northern Colorado River extensional corridor ($e_{Nd} = -1$ to $+6.7$; Bradshaw and others, 1992; Feuerbach and others, 1993). Mafic volcanism continued in the amagmatic zone and had a lithospheric mantle signature. Feuerbach and others (1993) postulated that a mantle boundary between an asthenospheric mantle source to the south and a lithospheric mantle source to the north formed during the Tertiary.

The Lunar Crater Volcanic Field is located in the northernmost end of a north-northeast-trending Pliocene-to-Recent mafic volcanic zone, extending from Death Valley to the Pancake Range (Fig. 24; Vaniman and others, 1982). The Lunar Crater Volcanic Field consists of basaltic cinder cones, maar volcanoes and lava flows (Scott and Trask, 1971). This area has undergone significant lithospheric extension since Early Cenozoic (Zoback, 1981; Eaton, 1984). Volcanism in the Lunar Crater Volcanic Field began approximately 9 million years ago and was dominated by a lithospheric mantle source ($e_{Nd} \sim -4$; Foland and others, 1987; Livaccari and Perry, 1993). Lithospheric extension and subsequent upwelling of the asthenospheric mantle (Lum and others, 1987) occurred between 9 and 4 Ma, at which time basaltic volcanism resumed with an asthenospheric mantle source ($e_{Nd} \sim +6$; Foland and others, 1987; Livaccari and Perry, 1993). Volcanism continued with an asthenospheric mantle source until 38 ka (Shepard and others, 1995). Unlike the Lake Mead area, the boundary between the asthenospheric and lithospheric mantle sources has not been located. The southernmost asthenospheric mantle derived basalts are in the Reveille Range (see discussion below). The northernmost lithospheric
mantle derived basalts (without an asthenospheric mantle component) are at Buckboard Mesa (Fig. 24; Farmer and others, 1989). The boundary is probably between the two areas.

**Reveille Range**

Geochemical data for the basalts in the Reveille Range indicate that the transformation from a lithospheric mantle source to an asthenospheric mantle source for the basalts occurred between 14 and 6 Ma.

**Lithospheric mantle derived basaltic andesites**

Mafic volcanism in the Reveille Range began in Middle-to-Late Miocene time, resulting in the formation of a basaltic andesite dome in the northwestern part of the Reveille Range. Trace element data indicate that the basaltic andesites are similar to basalts in Crater Flat and basaltic andesites of Calville Mesa in the Lake Mead area, both of which previously were interpreted to have a source in the lithospheric mantle (Feuerbach and others, 1993; Farmer and others, 1989). For example, the basaltic andesites plot close to the Crater Flat and Calville Mesa fields on selected incompatible ratio/ratio plots (Fig. 25). Furthermore, when plotted on spider diagrams the basaltic andesites have patterns very similar to Crater Flat and Calville Mesa samples (Figs. 26-28). Because of these similarities, the basaltic andesites are interpreted to have a lithospheric mantle source. Isotopic data confirm that the source of the basaltic andesites was the lithospheric mantle. The basaltic andesites have high $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7076-0.7081) and low $\varepsilon_{\text{Nd}}$ (-8.21 to -7.21) values which fall well into the lithospheric mantle field (Fig. 32).
Asthenospheric mantle derived episode-1, trachytic rocks and episode-2 basalts

After a hiatus of approximately 8 Ma, mafic volcanism resumed in the Reveille Range with the eruption of episode-1 basalts (5.1-5.9 Ma), trachytic rocks (4.2-4.4 Ma) and episode-2 basalts (3.0-4.6 Ma; Naumann and others, 1991). These basalts are discussed in detail in Yogodzinski and others (submitted) and, therefore, will only be described briefly here.

Trace element data indicate that these basalts are similar to OIB (Figs. 21a and 21b). Episode-1 basalts, trachytes and episode-2 basalts are interpreted as having originated from an asthenosphere mantle source, because OIB are widely interpreted as having an asthenospheric mantle source (Fitton, 1988). Isotopic data confirm that the source for these basalts was the asthenospheric mantle (Fig. 29). Episode-2 basalts and the trachytes have low initial $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7034-0.7036 and 0.7037-0.7064, respectively) and high $e_{\text{Nd}}$ (3.52-5.35 and 3.26-3.83, respectively). These values fall well into the OIB field. Most samples of episode-1 basalts also plot in the OIB field; however, other episode-1 basalts may have been contaminated in the crust by a carbonate-rich source (Yogodzinski and others, submitted).
Figure 25. Trace element ratio/ratio plots showing the similarities between the basaltic andesites and other lithospheric mantle-derived basalts. Episode-1 and episode-2 basalts also are shown for comparison.
Figure 26. Spider diagram normalized to chondrite showing the similarities between the basaltic andesites and other lithospheric mantle-derived basalts. Chondrite normalization values are from Thompson (1982).

Figure 27. Spider diagram normalized to ocean island basalt showing the similarities between the basaltic andesites and other lithospheric mantle-derived basalts. Ocean island basalt normalization values are from Sun and McDonough (1989).
Figure 28. Spider diagram normalized to chondrite showing the similarities between the basaltic andesites and other lithospheric mantle-derived basalts. Chondrite normalization values are from Nakamura (1974).

Figure 29. $e_{nu}$ vs. $^{87}Sr/^{86}Sr$ plot showing the similarities of episode-1 basalts, trachytes and episode-2 basalts to OIB and the basaltic andesites to other lithospheric mantle-derived basalts. The fields of OIB and lithospheric mantle derived basalts are from Feuerbach and others, 1993.
Chapter 7

Interpretations of Calderas in the Northern Reveille
and Southern Pancake Ranges

Calderas: A Brief Overview

Calderas are large volcanic collapse depressions that produce large volumes (up to $10^3$ km$^3$) of ash-flow tuff. Precaldera volcanism involves the eruption of large volumes of silicic pyroclastic material from vents along ring fractures (Fig. 30). As volcanism continues, the roof above an underlying shallow magma chamber collapses along ring faults to form a caldera. Breccias produced during and just after caldera collapse may slump into the depression, interfingering with other caldera fill deposits. Postcaldera activity may include continued volcanic activity within or near the caldera, deposition of sediments in the caldera, resurgence of the caldera floor and hydrothermal activity and mineralization (Lipman, 1984).

Recognition of a caldera and caldera walls

Recognition of calderas in the Basin and Range is difficult, because of the burial by younger volcanic and sedimentary rocks and the dissection of calderas into small segments by faulting (Best and others, 1989). Six criteria commonly are used to identify calderas and caldera walls. (1) The distribution of ash-flow tuff sequences. Ash-flow tuffs produced by caldera collapse form thick deposits within the caldera (intracaldera facies)
and well-bedded sequences of equivalent outflow tuffs (extracaldera facies) (Fig. 30).

Intracaldera tuffs commonly differ from outflow tuffs in thickness, joint density, abundance and size of pumice and lithic fragments, degree of welding and devitrification and chemical composition. Thick massive intracaldera tuffs sometimes rest against layered pyroclastic deposits at the caldera wall. Furthermore, intracaldera tuffs of one caldera may be in contact with the intracaldera tuff of the other caldera where one caldera is nested within another caldera. (2) The presence of wallrock megabreccias. Megabreccia deposits with large wallrock clasts may be found interbedded with the intracaldera facies in close proximity to caldera walls. These deposits form by the sliding of material along unstable (high angle) slopes after the collapse of the caldera. Therefore, megabreccia clasts correlate with the lithology of the caldera wall. Megabreccia deposits may abut against the erosional wall of a caldera. (3) The distribution of rhyolite domes. Rhyolite intrusions may be emplaced along structural boundaries near the caldera wall after collapse and during resurgence. (4) The resurgence of the caldera floor. A renewed rise of magma after caldera collapse may uplift the caldera floor. This resurgence may form a dome-like feature within the caldera. (5) The presence of sedimentary deposits within the caldera. Lacustrine deposits may form between the resurgent dome and the caldera wall. (6) The presence of secondary mineralization along structural boundaries. The ring fracture and the highly fractured caldera floor may form pathways for post-caldera mineralization. Mineralization commonly occurs near the caldera wall and may or may not be related to the magma chamber that is associated with the caldera (Lipman, 1984). All criteria except criteria four can be used to locate caldera walls. Criteria four, however, can be used to define the relative position of a caldera margin, because the caldera wall will lie between
the resurgent dome and the exposures of outflow tuff.

Due to the large volumes of Cenozoic pyroclastic deposits in the western United States, 250-500 calderas are thought to be present. Fewer than 100, however, have been identified (Lipman, 1984; Best and others, 1989; Best and others, 1993). Numerous researchers from the U.S. Geological Survey and various universities conducted extensive studies on ash-flow tuffs in the western United States during the 1960’s and 1970’s (United States Geological Survey, 1970). These studies led to the recognition of several caldera complexes. These complexes include the well known San Juan volcanic field in Colorado; the Mogollon-Datil volcanic field in eastern Arizona and western New Mexico; the McDermitt, central Nevada, southwestern Nevada and Caliente caldera complexes in Nevada; the Indian Peak caldera complex in eastern Nevada and western Utah; and the Long Valley caldera in California. Figure 31 shows the distribution of both known and suspected calderas in the central Nevada, southwestern Nevada, Caliente and Indian Peak caldera complexes. The Reveille Range is located within the central Nevada caldera complex (CNCC). The following section describes the CNCC in detail.

Central Nevada caldera complex

The central Nevada caldera complex (CNCC) consists of twelve calderas and two features that may be calderas (Fig. 31; Table 11). Most tuffs related to these calderas cover over 10,000 km\(^2\) (Best and others, 1993). The Windous Butte Formation is the most extensive tuff in the CNCC, covering a 40,000 km\(^2\) area; however, Best and others (1993) reduced this area by two-thirds after compensating for 50% Late Cenozoic east-west crustal extension.
Volcanism in the CNCC spanned a period of 17 Ma, beginning with the eruption of the Stone Cabin Formation from an unnamed caldera in the northeastern portion of the complex (35.3 Ma; Best and others, 1993), and ending with the eruption of the Fraction Tuff from the Cathedral Ridge caldera in the southern portion of the complex (18.3 Ma; Rogers and others, 1967; Ekren and others, 1971). Volcanic activity occurred fairly continuously during this 17 Ma interval and resulted in major caldera forming events, small-and-large-volume ash-flow eruptions and small-volume intermediate-to-felsic flows. The longest hiatus between major caldera forming events was 4.3 Ma, the time between the eruption of the tuffs of Pahranagat Lakes and White Blotch Spring from the Kawich caldera (22.6 Ma) and the eruption of the Fraction Tuff from the Cathedral Ridge caldera (18.3 Ma). The eruption of the Fraction Tuff marked the end of felsic volcanism in the CNCC.

The following sections of this chapter provide evidence for the location of caldera margins associated with the caldera of Goblin Knobs (G) and the caldera of northern Reveille Range (NR), both of which are located within the CNCC (Best and others, 1993; Martin and Naumann, 1995; this study).

**Caldera of Goblin Knobs**

Ekren and others (1973) first recognized that the tuff of Goblin Knobs in the Reveille Range is an intracaldera facies because of its great thickness. Martin and Naumann (1995) first identified margins associated with this caldera which they informally named the caldera of Goblin Knobs. Their interpretation is based on the following: (1) the great thickness (700+ m) and lack of internal cooling units within the tuff of Goblin Knobs;
(2) the large pumice and lithic fragments within the tuff of Goblin Knobs; (3) the juxtaposition the tuff of Goblin Knobs against Paleozoic sedimentary rocks; (4) the thin outflow of the tuff of Goblin Knobs west of the Paleozoic rocks; and (5) the lack of evidence for strike-slip faulting (originally mapped by Ekren and others, 1973) across the boundary between the tuff of Goblin Knobs and the Paleozoic rocks. In this study, a small segment of the northern boundary of this caldera was identified (Plate 1 and 3; Fig. 5). Three of the six criteria for identifying calderas described above were used to identify this caldera margin. These criteria include the distribution of ash-flow tuff sequences, the presence of wallrock megabreccia and the resurgence of the caldera floor.

The distribution of ash-flow tuff sequences

Intracaldera Tuff

The tuff of Goblin Knobs is interpreted as the intracaldera facies of the caldera of Goblin Knobs (Ekren and others, 1973; Martin and Naumann, 1995; this study). This interpretation is supported by the fact that the tuff of Goblin Knobs is approximately 1700 m thick and contains abundant large pumice and lithic fragments.

The stratigraphic relationship between the Monotony Tuff and the tuff of Goblin Knobs is critical information for documenting the location of the margin for the caldera of Goblin Knobs. Distinguishing Monotony Tuff from the tuff of Goblin Knobs in the field was difficult, because they have very similar phenocryst assemblages. In addition, the relative stratigraphy could not be determined, because they are not present in the same exposure (Plate 1; Fig. 5). Based on field relations and geochronology (described below), Ekren and others (1973) originally correlated the tuff of Goblin Knobs with Monotony
Tuff. The geochemical, petrographic, geochronologic and stratigraphic work in this thesis, along with the work of Martin and Naumann (1995) and Best and others (1993), contradicts this correlation and indicates that the tuff of Goblin Knobs and Monotony Tuff are different tuffs.

(1) Geochemistry

Most major elements show a distinction between the two tuffs (Table 7; Fig. 32). For example, Monotony Tuff is higher in Al₂O₃, TiO₂, FeO, MgO, CaO, Na₂O and P₂O₅ and lower in SiO₂ and K₂O than the tuff of Goblin Knobs. Two samples (PR-48 and PR-50) whose stratigraphic position was not clear from mapping also were plotted. These samples fall in the field of Monotony Tuff.

Trace elements, on the other hand, do not clearly distinguish between the two tuffs. Patterns on spider diagrams are nearly identical (Figs. 14a and 15a). The differences are within the limits of analytical uncertainty.

Isotopic ratios for the two tuffs are different in εNd but not in initial ⁸⁷Sr/⁸⁶Sr and Pb (Fig. 16). For example, the tuff of Goblin Knobs has a lower εNd (-8.453) than Monotony Tuff (εNd = -7.494 to -7.484). A larger number of samples, however, are required before correlations can be made based on isotopic analyses.

(2) Petrography

Petrographically the tuff of Goblin Knobs and Monotony Tuff (Appendix B) are very similar, and, thus, mineralogy may not distinguish the tuffs. Only minor differences in total phenocryst percentages and phenocrysts types exist between Monotony Tuff and the tuff of Goblin Knobs. These differences include: (1) Monotony Tuff contains
abundant large hexagonal, biotite (up to 5 mm). Biotite in the tuff of Goblin Knobs commonly are hexagonal but they are generally smaller (average ~ 2.0 mm) than Monotony Tuff. (2) Monotony Tuff contains abundant large clear, smoky and purple quartz. Quartz in the tuff of Goblin Knobs are as abundant and have similar sizes as Monotony Tuff but are always clear.

(3) Geochronology

Radiometric age dating is the most powerful tool to distinguish Monotony Tuff from the tuff of Goblin Knobs. Ekren and others (1973) obtained an age of 26.1 ± 0.7 (K-Ar, biotite from the Belted Range approximately 50 km south of the study area) for the Monotony Tuff and 25.3 ± 1.0 Ma (K-Ar, biotite) and 24.9 ± 0.6 Ma (K-Ar, sanidine) for the tuff of Goblin Knobs. If these dates are accurate, they statistically overlap and Monotony Tuff and the tuff of Goblin Knobs are coeval. Several samples for both tuffs recently have been dated by the $^{40}$Ar/$^{39}$Ar incremental heating technique (Taylor and others, 1989; Best and others, 1993; this study). An age of 27.6 ± 0.3 Ma (sanidine; this study) for Monotony Tuff and 25.6 ± 0.53 Ma and 25.6 ± 0.58 Ma (sanidine and biotite, respectively; this study) for the tuff of Goblin Knobs currently are the accepted ages for these tuffs. These $^{40}$Ar/$^{39}$Ar dates indicate that the tuff of Goblin Knobs and Monotony Tuff probably erupted at different times.

(4) Stratigraphy

The stratigraphic relationship between Monotony Tuff and the tuff of Goblin Knobs can be used to distinguish these tuffs. The contact between Monotony Tuff and the tuff of Goblin Knobs is obscured by alluvial deposits. Their relative stratigraphic position in the
stratigraphic columns, however, can be determined by their stratigraphic relationships with other units (Appendix A). The important observations include: (1) the tuff of Bald Mountain (26.5 Ma) conformably overlies Monotony Tuff (27.6 Ma), (2) Shingle Pass Tuff cooling unit C (25.7 Ma) conformably overlies the tuff of Arrowhead cooling unit B (26.6 Ma) and (3) south of the study area, the tuff of Goblin Knobs conformably overlies the tuff of Arrowhead cooling unit B. Therefore, Monotony Tuff and the tuff of Goblin Knobs apparently are separated by the tuff of Bald Mountain and tuff of Arrowhead cooling unit B.

(5) Summary statement

Based on the differences in age and stratigraphic position, and less importantly petrography and geochemistry, Monotony Tuff and the tuff of Goblin Knobs are different tuffs.

Outflow sheet

An outflow tuff related to the caldera of Goblin Knobs has not been identified. The tuff of Lunar Cuesta, in the northeastern portion of the Reveille 15' quadrangle, however, may be the outflow tuff related to the caldera of Goblin Knobs. This interpretation is based on similar phenocryst assemblages, proximity of the tuff of Lunar Cuesta to the tuff of Goblin Knobs and similar ages (25.4 Ma). This interpretation is uncertain and further work is required to determine if it is correct.

Wallrock megabreccias

The megabreccia of Goblin Knobs is exposed as small lenses within the tuff of
Goblin Knobs in the northernmost portion of the Reveille Range, approximately 1.2 km south of the southernmost exposures of Monotony Tuff (~2.7 km southwest of Twin Springs Ranch) (Plate 1 and Fig. 5). The megabreccia deposits probably formed by slumping from an oversteepened topographic wall, because clasts within the megabreccia unit have similar lithologies as rocks near the caldera wall. Furthermore, this slumping probably occurred synchronously with the collapse and eruption of the tuff of Goblin Knobs, because the megabreccias are interbedded within the tuff of Goblin Knobs.

The resurgence of the caldera floor

The uplift of the Reveille Range may be related to the resurgence of the caldera of Goblin Knobs. This interpretation is based on measurements of compaction foliation in the tuff of Goblin Knobs and the pervasive jointing within the tuff. Ekren and others (1973), Jones and Bullock (1985) and Martin and Naumann (1995) documented that, in the central portion of the Reveille Range, volcanic rocks on the east and west side of the range older than and including the tuff of Goblin Knobs gently dip to the east and west, respectively. Furthermore, in the northernmost portion of the range, the tuff of Goblin Knobs dips gently to the north (Ekren and others, 1973; this study). The southern portion of the Reveille Range has not been mapped, so compaction foliation measurements are unavailable here.

As mentioned in the introduction to this chapter, resurgence of the caldera floor produces a dome-like feature within the caldera. The compaction foliation measurements described above are consistent with a dome-like geometry, and, therefore, are interpreted to have formed as a result of resurgence of the caldera floor. In addition, the tuff of Goblin Knobs is pervasively jointed (Fig. 8). Joints strike approximately N30°W. In contrast to
columnar joints typically produced in outflow tuffs, closely spaced joints, like that exhibited by the tuff of Goblin Knobs, or rectilinear joints are common in intracaldera tuffs due to resurgence of the caldera floor (Lipman, 1975). Because pervasive jointing occurs within the tuff of Goblin Knobs throughout the entire range and similar jointing is absent in rocks of similar age or older in the southern Pancake Range, I suggest that the observed jointing was produced during the uplift of the caldera floor.

**Location of the caldera margin**

Based on the interpretation that the tuff of Goblin Knobs and Monotony Tuff are different tuffs and the observation that the megabreccia deposit only crops out within the tuff of Goblin Knobs, I interpret that the caldera margin of the caldera of Goblin knobs is approximately located between exposures of the tuff of Goblin Knobs and Monotony Tuff (buried beneath alluvium between the Reveille and Pancake Ranges). Furthermore, the interpretation that outcrops of the tuff of Goblin Knobs in the northern Reveille Range are related to resurgence of the caldera floor infers that the relative position of the caldera margin is north of the northern Reveille Range. Because the clasts of the megabreccia deposits are composed entirely of Shingle Pass Tuff cooling units B and C, I suggest that the caldera wall comprised these units. These units crop out in the southern Pancake Range.

**Caldera of northern Reveille Range**

Martin and Naumann (1995) first identified the caldera of northern Reveille Range in the Reveille 7½' quadrangle, and they defined a small segment of the eastern margin of this caldera. Their interpretation is based on the following: (1) the great thickness (300+...
m) and lack of internal cooling units within the tuff of northern Reveille Range; (2) the large pumice and lithic fragments within the tuff of northern Reveille Range; (3) the juxtaposition of the tuff of northern Reveille Range against the tuff of Goblin Knobs; (4) the intense silicification of the tuff of northern Reveille Range surge deposit near the contact of the tuff of Goblin Knobs; (5) the distribution of a possible outflow tuff (tuff of Streuben Knobs) relative to the tuff of northern Reveille Range; (6) the distribution of rhyolite intrusive rocks; and (7) the distribution of caldera collapse breccias. My mapping identified the northern (Plate 3) and part of the eastern segment of the caldera wall in the Twin Springs Slough 7½' quadrangle (Plate 1; Fig. 5). All six of the criteria for identifying calderas described above were used to identify these caldera margins.

The distribution of ash-flow tuff sequences

Intracaldera Tuff

The tuff of northern Reveille Range is interpreted as the intracaldera facies for the caldera of northern Reveille Range (Martin and Naumann, 1995; this study). This interpretation is supported by the fact that the tuff of northern Reveille Range is approximately 500 m thick and contains abundant large pumice and lithic fragments.

Outflow Tuff

The outflow tuff related to the caldera of northern Reveille Range has not been identified. Martin and Naumann (1995) suggested that the tuff of Streuben Knobs is the outflow tuff of the caldera of northern Reveille Range. Geochemical, petrographic and stratigraphic studies indicate that these tuffs probably are not related.
(1) Chemistry

Metasomatism affected the major elements in the tuff of northern Reveille Range; however, the trace elements were not modified during this event (Fig. 13). Therefore, only trace elements were used to compare the tuff of northern Reveille Range and the tuff of Streuben Knobs.

Spider diagrams (based on only one analysis for the tuff of Streuben Knobs and two for the tuff of northern Reveille Range) show small differences between the tuff of Streuben Knobs and the tuff of northern Reveille Range. For example, the tuff of Streuben Knobs is lower in P and Ti, higher in Ta, Tb, Y, and Lu, and shows a larger negative Eu anomaly than the tuff of northern Reveille Range (Figs. 14c and 15c). These differences are within analytical uncertainty and probably are not significant. Based on this fact and that only three samples were analyzed, more analyses are required to accurately compare these tuffs using trace elements.

Isotope analyses also show some differences between the two tuffs. The tuff of Streuben Knobs has a lower $\varepsilon_{\text{Nd}}$ than the tuff of northern Reveille Range (-8.03 and -7.476, respectively). Furthermore, $^{87}\text{Sr}/^{86}\text{Sr}$ shows significant differences. The tuff of Streuben Knobs has higher $^{87}\text{Sr}/^{86}\text{Sr}$ (0.71361) than the tuff of northern Reveille Range (0.70900). Lead isotopes for the tuff of Streuben Knobs and the tuff of northern Reveille Range are similar (Fig. 16). The tuff of northern Reveille Range and the tuff of Streuben Knobs contain lithic fragments. Isotopic ratios, especially Pb, could be affected significantly if lithic fragments are incorporated into the analyzed samples. Because Pb values for the tuffs are similar, the differences in Sr and Nd isotopes are probably not due to differential contamination. Therefore, the differences in Sr and Nd probably are
significant.

(2) Petrography

Phenocryst mineralogies for the tuff of northern Reveille Range and the tuff of Streuben Knobs (Appendix B) are very similar. The major difference, however, is that the tuff of northern Reveille Range generally contains more biotite and less sanidine than the tuff of Streuben Knobs. These differences alone are not significant enough to conclude that the tuff of northern Reveille Range and the tuff of Streuben Knobs are different.

(3) Stratigraphy

South of the study area, in the Reveille 7½' quadrangle, field relations indicate that the tuff of Streuben Knobs may be the outflow tuff of the caldera of northern Reveille Range (see mapping by Martin and Naumann, 1995). Their field observations include: (1) similar phenocryst assemblages, (2) similar clast assemblages consisting of andesite and dacite, (3) similar glassy pumice and lithic clasts in the basal vitrophyre of the tuff of Streuben Knobs and vertical vitrophyre that they interpreted as part of the vent for the tuff of northern Reveille Range, (4) relative differences in thickness between the tuffs and (5) similar stratigraphic position of the tuffs. However, in the study area, the tuff of Streuben Knobs crops out within the caldera of northern Reveille Range. This relationship is possible but unlikely if the tuff of Streuben Knobs is the outflow tuff of the tuff of northern Reveille Range. Exposures of the tuff of Streuben Knobs within the caldera may be landslide blocks; however, no evidence was found to support this interpretation.
(4) Summary statement

Based on the stratigraphic relationships between the tuff of Streuben Knobs and the tuff of northern Reveille Range alone, I suggest that the tuff of Streuben Knobs is not the equivalent outflow tuff for the tuff of northern Reveille Range. Chemical data and petrography show minor differences between the two tuffs, but they are not significant enough to support or refute the correlation of the tuffs.

Wallrock megabreccias

The megabreccia of Northern Reveille Range is exposed in two locations in the study area (Plate 1; Fig. 5). The largest of the two exposures is in the southern Pancake Range and is buttressed against the tuff of Bald Mountain. Megabreccia also overlies the tuff of Bald Mountain. I suggest that slumping of an oversteepened caldera wall was synchronous with the caldera collapse and eruption of the tuff of northern Reveille Range, because clasts within the megabreccia unit have similar lithologies as rocks near the caldera wall and some clasts were interbedded within the tuff of northern Reveille Range (Fig. 33). The other exposure of megabreccia is located in the south-central portion of the study area, along the eastern margin of the boundary of the caldera of northern Reveille Range (Fig. 34). In this exposure, a megabreccia clast of the tuff of Goblin Knobs (~250 m in diameter) is interbedded with the tuff of northern Reveille Range. This relationship implies that the block slumped into the caldera of northern Reveille Range during caldera formation.

The distribution of rhyolite domes

The rhyolitic dikes and plugs of Twin Springs Ranch may be genetically related to
the caldera of northern Reveille Range (Martin and Naumann, 1995; this study). This interpretation is based on the similarities in phenocryst assemblages among the dikes, domes and the tuff of northern Reveille Range, proximity to the proposed caldera margins, and the observation that the rhyolitic dikes do not intrude rocks younger than the tuff of northern Reveille Range.

The resurgence of the caldera floor

The resurgence of the caldera of northern Reveille Range occurred after collapse of the caldera; however, the extent of the resurgent dome is difficult to determine because of extensive faulting in the northern Reveille Range. Fault A displaces the tuff of northern Reveille Range, including what appears to be a portion of the resurgent dome (Fig. 35), approximately 4 km to the east. Because of extensive faulting, compaction foliation measurements could not be used as reliable indicators of doming. The tuff of northern Reveille Range, however, is topographically higher than the surrounding rocks that make up the caldera wall.

The presence of sedimentary and volcanic deposits within the caldera

The siltstone of Cane Springs is interpreted to be deposited in a basin that resulted from the collapse of the caldera of northern Reveille Range. This interpretation is based on the observation that the siltstone lies with buttress unconformity against the tuff of Bald Mountain. Furthermore, this deposit probably formed in a lacustrine environment close to the source (probably a moat that formed between the tuff of Bald Mountain and the resurgent dome) rather than from a pyroclastic surge deposit. This interpretation is based on the following: (1) the deposit is finely laminated, (2) biotites are aligned parallel to the
laminations and (3) the siltstone of Cane Springs contains angular-to-subrounded quartz and feldspar and cusparate glass shards.

**The presence of secondary mineralization along structural boundaries**

Silicification along the proposed caldera margin is intense. Along the northern margin, chalcedony veins are pervasive within the tuff of Bald Mountain. Silicification also is prevalent in some of the megabreccia clasts along the northernmost portion of the outcrop of megabreccia. Furthermore, along the eastern margin of the caldera wall in the southernmost portion of the study area, the tuff of northern Reveille Range and surge deposits are locally silicified along the contact with the caldera of Goblin Knobs. Hydrothermal deposits and alteration commonly are found localized along caldera margins resulting in the silicification of surrounding rocks. (Lipman, 1984). I suggest that the observed silicification is the result of hydrothermal fluids migrating along fractures near the contact between the tuff of northern Reveille Range and the tuff of Goblin Knobs.

**Location of caldera margin**

Based on the above observation and interpretations, I suggest that the northern margin of the caldera wall is located at the contact between the tuff of Bald Mountain and the megabreccia deposit. Because clasts of the megabreccia deposits comprise Monotony Tuff, tuff of Bald Mountain and Shingle Pass Tuff cooling units A, B and C, all of which are located within close proximity to the caldera wall, I suggest that the caldera wall comprised these units at the time of caldera collapse. Furthermore, I suggest that a portion of the eastern margin of the caldera is located at the contact between the tuff of northern...
Reveille Range and the tuff of Goblin Knobs.

**Extent of Caldera Margins**

*Caldera of Goblin Knobs*

The extent of the caldera of Goblin Knobs is unknown because of extensive alluvial cover in the adjoining valleys (Railroad, Hot Creek, Reveille and Kawich Valleys) and lack of detailed mapping in the surrounding mountain ranges. The northernmost boundary is fairly well constrained to the southernmost Pancake Range. This boundary may extend as far east as the Grant and Quinn Canyon Ranges and as far west as the Hot Creek and Kawich Range. The southern boundary also is poorly defined and, it may extend into the Belted Range. Because the entire northern part of the Reveille Range may be a resurgent dome, caldera margins may not exist within the range. The margins are probably buried beneath the alluvial deposits in the valleys that surround the range (Fig. 31).

*Caldera of northern Reveille Range*

The western margin of the caldera of northern Reveille Range has not been discovered because of alluvial cover in the Reveille and Hot Creek Valleys, however, it may be present in the Kawich Range. The tuff of northern Reveille Range does not crop out south of approximately $38^\circ05'00''$ N latitude. This boundary may be close to the southern margin of the caldera of northern Reveille Range. The northern part of the caldera wall probably bends to the west and extends into the Hot Creek Range (Plate 1; Figs. 5 and 31).
**History of Volcanism in the Northern Reveille Range**

The following section summarizes the eruptive history of volcanic rocks in the northern Reveille and southern Pancake Ranges (Fig. 36).

1. Prior to the collapse of the caldera of Goblin Knobs (25.6 Ma), the northern Reveille and southern Pancake Ranges comprised horizontal-to-subhorizontal pre-tuff of Goblin Knobs ash-flow tuffs (Fig. 36a).

2. The collapse of the caldera of Goblin Knobs (25.6 Ma) resulted in the eruption of the tuff of Goblin Knobs and synchronous deposition of the megabreccia of Goblin Knobs. Resurgence of the caldera floor soon followed, uplifting the entire northern Reveille Range (Fig. 36b).

3. The collapse of the caldera of northern Reveille Range (25.3 Ma) resulted in the eruption of the tuff of northern Reveille Range and synchronous deposition of the megabreccia of northern Reveille Range. Rhyolitic dikes and plugs of Twin Springs Ranch (24.7 Ma) erupted along the structural boundary of the caldera margin. Resurgent uplift of the caldera floor soon followed, forming a moat between the caldera wall and the resurgent dome. This moat was the site for the deposition of the siltstone of Cane Springs (Fig. 36c).

4. Episode-1 basalts migrated through structural weaknesses caused by the collapse of the caldera of northern Reveille Range and ponded within the caldera (Fig. 36e). The tuff of Goblin Knobs and the tuff of northern Reveille Range were topographic barriers during the eruption of these phases of episode-1 basalts (Figs. 37 and 38).
Figure 30. A generalized ash-flow caldera eruption. (A) Precaldera collapse. Uplift due to the emplacement of plutons causes ring fractures, dotted lines. Arrows indicate movement direction of magma. (B) Geometry just after caldera collapse and ash-flow eruption. Intracaldera tuff forms a massive poorly sorted sequence and is an order of magnitude thicker than the related outflow sheet. The collapse forms oversteepened walls along which slumping occurs producing megabreccia deposits. (C) Resurgence and postcaldera deposition. The magma body rises into the volcanic sequence and uplifts the welded ash-flow tuff (modified from Lipman, 1984).
Figure 31. Caldera margins of the central Nevada caldera complex (CNCC), southeastern Great Basin. Caldera margins (heaviest lines) are dashed where approximately located, and dotted lines indicate indefinite source areas. Calderas and sources in the CNCC include the Broken Back 2 (BB), source of the Stone Cabin Formation (S), Williams Ridge (W), Hot Creek (H), Pancake Range (P), Kiln Canyon (KC), Big Ten Peak (BT), unnamed caldera for the tuff of Lunar Cuesta (L), Kawich (K), Goblin Knobs (G), Northern Reveille Range (NR), Quinn Canyon Range (Q), Bald Mountain (BM) and Cathedral Ridge (CR). Other calderas include the Caliente caldera complex (CCC), Kane Springs (KS), the Indian Peak caldera complex (IP) and the southwestern Nevada caldera complex. The Indian Peak caldera complex includes the White Rock (WR) and Mount Wilson (MW) calderas. The southwestern Nevada caldera complex includes the Timber Mountain (TM), Silent Canyon (SC), Black Mountain (BK), Sleeping Butte (SB) and the Oasis Valley (OV) calderas. The lightly shaded area outlines the extent of the outflow sheets related to the CNCC. The boundary for the Bald Mountain caldera is from Ekren and others (1977), and the boundary for the southwestern Nevada caldera complex is from Farmer and others (1991). All other caldera boundaries and the outline for the extent of the outflow sheets for the CNCC are from Best and others (1993) with the exception of the northern boundary of the Northern Reveille Range caldera, which is from this study.
Table 10. Summary description of tuffs related to the central Nevada caldera complex shown in Figure 31.

<table>
<thead>
<tr>
<th>caldera</th>
<th>intracaldera tuff</th>
<th>outflow sheet</th>
<th>age (Ma)</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>unnamed (S)</td>
<td>Stone Cabin</td>
<td>Stone Cabin</td>
<td>35.4</td>
<td>Best and others (1993)</td>
</tr>
<tr>
<td>Broken Back 2 (BB)</td>
<td>Sod House Tuff</td>
<td>Pancake Summit</td>
<td>34.8</td>
<td>Sargent and Roggensack (1984); Best and others (1993); Smith and Ketner (1978)</td>
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<tr>
<td>Williams Ridge (W)</td>
<td>Morey Peak</td>
<td>Windous Butte</td>
<td>32.2</td>
<td>Dixon and others (1972); Ekren and others (1973, 1974 and 1976); Quinlivan and others (1974); John (1987)</td>
</tr>
<tr>
<td>Hot Creek Valley (HC)</td>
<td>Hot Creek Canyon</td>
<td>Hot Creek Canyon</td>
<td>29.7</td>
<td>Ekren and others (1973); Ekren and others (1976)</td>
</tr>
<tr>
<td>Pancake Range (P)</td>
<td>unnamed</td>
<td>Monotony</td>
<td>27.3</td>
<td>Ekren and others (1972, 1974 and 1976)</td>
</tr>
<tr>
<td>Kiln Canyon (KC)</td>
<td>Kiln Canyon</td>
<td>Orange Lichen Creek</td>
<td>26.8</td>
<td>Ekren and others (1974); Quinlivan and Rogers (1974); Best and others (1993)</td>
</tr>
<tr>
<td>Bald Mountain (BM)</td>
<td>Bald Mountain</td>
<td>Bald Mountain</td>
<td>26</td>
<td>Ekren and others (1977)</td>
</tr>
<tr>
<td>Quinn Canyon Range (Q)</td>
<td>Shingle Pass</td>
<td>Shingle Pass</td>
<td>26.0-26.7</td>
<td>Ekren and others (1977)</td>
</tr>
<tr>
<td>Big Ten Peak (BT)</td>
<td>Big Ten Peak</td>
<td>Rye Patch</td>
<td>26</td>
<td>Bonham and Garside (1979); Kleinhampl and Ziony (1985)</td>
</tr>
<tr>
<td>unnamed (L)</td>
<td>Lunar Cuesta</td>
<td>Lunar Cuesta</td>
<td>25.4</td>
<td>Best and others (1993)</td>
</tr>
<tr>
<td>Goblin Knobs (G)</td>
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<td>unknown</td>
<td>25.4</td>
<td>Martin and others (1992); Best and others (1993); this study</td>
</tr>
<tr>
<td>Northern Reveille Range (NR)</td>
<td>N. Reveille Range</td>
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<td>24.6</td>
<td>Martin and others (1992); this study</td>
</tr>
<tr>
<td>Kawich (K)</td>
<td>Kawich Peak</td>
<td>Pahranagat Lakes; White Blotch Spring</td>
<td>22.6</td>
<td>Ekren and others (1976); Gardner and others (1980); Best and others (1989)</td>
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<tr>
<td>Cathedral Ridge (CR)</td>
<td>Fraction</td>
<td>unknown</td>
<td>18.3</td>
<td>Rogers and others (1967); Ekren and others (1971)</td>
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</table>

see Phillips (1989) for a more detailed and concise description of ash-flow tuffs erupted in the CNCC.
Figure 32. Major element Harker variation diagram showing the distribution of tuff of Goblin Knobs samples relative to the Monotony Tuff. The lightly shaded area represents the range of chemical data from all other tuff samples in the northern Reveille and southern Pancake Ranges.
Monotony Tuff from other studies (see text)
Monotony Tuff collected in the study area
Monotony Tuff collected north of the study area
Tuff of Goblin Knobs collected south of the study area
Tuff of Goblin Knobs collected in the study area

Figure 32 (cont.). Major element Harker variation diagram showing the distribution of tuff of Goblin Knobs samples relative to the Monotony Tuff. The lightly shaded area represents the range of chemical data from all other tuff samples in the northern Reveille and southern Pancake Ranges.
Figure 33. (A) Photograph showing the tuff of northern Reveille Range interbedded within megabreccia clasts of the megabreccia of northern Reveille Range. The clast is approximately 6 m in diameter. View is to the northwest. (B) Line drawing of the photograph showing the contact between the tuff and clast.
Figure 34. (A) Photograph of a caldera collapse megabreccia block of tuff of Goblin Knobs within the caldera of northern Reveille Range. Block is approximately 250 m in diameter. The block appears to be interbedded within the tuff of northern Reveille Range. View is to the northwest. (B) Line drawing showing the contact between the tuff of Goblin Knobs and tuff of northern Reveille Range.
Figure 35. Photograph of the tuff of northern Reveille Range (light-colored tuff). The tuff of Goblin Knobs is in the foreground and is separated from the tuff of northern Reveille Range by fault A. View is to the northwest.
Figure 36. Simplified block diagrams showing the general eruptive history of volcanic rocks in the northern Reveille and southern Pancake Ranges. (A) Initial collapse of the caldera of Goblin Knobs, showing the formation of the tuff of Goblin Knobs. The surrounding walls comprise tuffs older than the tuff of Goblin Knobs. (B) Resurgence of the caldera floor of the caldera of Goblin Knobs. (C) Formation of the caldera of northern Reveille Range. This caldera is partially nested within the caldera of Goblin Knobs. (D) Major east-west faulting showing dextral offset. (E) Eruption of mafic rocks. The eruption of episode-1 basalts occurred during the late stages of the activity of fault A. (F) Erosion to present day topography.
Figure 36 (cont). Simplified block diagrams showing the general eruptive history of volcanic rocks in the northern Reveille and southern Pancake Ranges. (A) Initial collapse of the caldera of Goblin Knobs, showing the formation of the tuff of Goblin Knobs. The surrounding walls comprise tuffs older than the tuff of Goblin Knobs. (B) Resurgence of the caldera floor of the caldera of Goblin Knobs. (C) Formation of the caldera of northern Reveille Range. This caldera is partially nested within the caldera of Goblin Knobs. (D) Major east-west faulting showing dextral offset. (E) Eruption of mafic rocks. The eruption of episode-1 basalts occurred during the late stages of the activity of fault A. (F) Erosion to present day topography.
Figure 36 (cont.). Simplified block diagrams showing the general eruptive history of volcanic rocks in the northern Reveille and southern Pancake Ranges. (A) Initial collapse of the caldera of Goblin Knobs, showing the formation of the tuff of Goblin Knobs. The surrounding walls comprise tuffs older than the tuff of Goblin Knobs. (B) Resurgence of the caldera floor of the caldera of Goblin Knobs. (C) Formation of the caldera of northern Reveille Range. This caldera is partially nested within the caldera of Goblin Knobs. (D) Major east-west faulting showing dextral offset. (E) Eruption of mafic rocks. The eruption of episode-1 basalts occurred during the late stages of the activity of fault A. (F) Erosion to present day topography.
Figure 37. Photograph of episode-1 basalt (Tb1) overlying the tuff of northern Reveille Range (Tnr). This flow terminates at the contact between the tuff of northern Reveille Range and tuff of Goblin Knobs (Tg). This relationship indicates that the tuff of Goblin Knobs was topographically higher than the tuff of northern Reveille Range prior to the eruption of the basalt. This topographic high caused a barrier to the basalt flow. The contact between the tuff of Goblin Knobs and tuff of northern Reveille Range is the eastern boundary of the caldera margin for the caldera of northern Reveille Range. View is to the northwest.
Figure 38. (A) Photograph of episode-1 basalts overlying the tuff of northern Reveille Range. Ekren and others (1973) originally mapped this contact as a fault. It appears, however, that this contact is depositional. The tuff of northern Reveille Range was a topographic barrier to the flow of the lower basalts. The basalt capping the tuff of northern Reveille Range does not appear to be offset to the west of the contact. View is to the south. (B) Line drawing showing the contact between the tuff of northern Reveille Range and episode-1 basalts.
Chapter 8

Summary and Conclusions

Volcanism in the northern Reveille Range began approximately 26 Ma and resulted in the formation of two calderas (caldera of Goblin Knobs and caldera of northern Reveille Range). The northern margins of both of these calderas are located between the northern Reveille and southern Pancake Ranges. Ekren and others (1973) suggested that the differences in geology between the two ranges were the result of intense strike-slip faulting between 26 and 18.5 Ma. They also suggested that the Tertiary debris located in the southern Pancake Range was deposited during this period of faulting. Because of the lack of evidence for a strike-slip fault and the new interpretation that the Tertiary debris formed during the collapse of the caldera of northern Reveille Range, a caldera margin is the preferred interpretation for the geological boundary between the two ranges.

The collapse of the caldera of Goblin Knobs resulted in the eruption of the tuff of Goblin Knobs (25.6 Ma). This tuff ponded within the caldera. The northern Reveille Range was uplifted by resurgence of the caldera of Goblin Knobs.

The caldera of northern Reveille Range is nested within the northern portion of the caldera of Goblin Knobs. The collapse of the caldera of northern Reveille Range resulted in the eruption of the tuff of northern Reveille Range (25.3 Ma) and the
deposition of the megabreccia of northern Reveille Range. Rhyolitic dikes and plugs that are cogenetic with the tuff of northern Reveille Range intruded along the structural boundaries of the caldera. Major east-west-striking faults displaced the northern caldera margin approximately 4 km to the east. The tuff of Streuben Knobs was interpreted as the outflow tuff sheet of the caldera of northern Reveille Range; however, field relationships and geochemical data apparently contradict this interpretation.

Volcanic activity was quiescent in the Reveille Range between the formation of the caldera of northern Reveille Range and the onset of mafic volcanism 14 Ma. Basaltic andesites originated by melting of a lithospheric mantle source. Between 14 and 6 Ma the source for mafic volcanism shifted from the lithospheric mantle to the asthenosphere. Three chemically distinct mafic units erupted between 6 and 3 Ma and include episode-1 basalts, trachytic rocks and episode-2 basalts.
Chapter 9

Future Work

Problems and questions arose while I worked on this thesis that, due to lack of funds and time, could not be addressed. Future work on some of these problems and questions may help provide a more detailed understanding of the complex geology of the area. These questions and problems are summarized below.

1. The outflow tuff sheet of the caldera of Goblin Knobs has not been identified. The identification of this tuff is important for a more complete understanding of the geologic history of the caldera of Goblin Knobs. The tuff of Lunar Questa, located northeast of the study area, may be the outflow tuff sheet based on its age, similar phenocryst assemblages and stratigraphic position. Further geochemical and field studies must be done to determine if this interpretation is correct.

2. The outflow tuff sheet of the caldera of northern Reveille Range also has not been identified. The tuff of Streuben Knobs previously was interpreted as the outflow tuff sheet based on similar phenocryst assemblages and stratigraphic position. However, I suggested that a correlation cannot be made, because the stratigraphy in the study area along with geochemical data contradict this interpretation. Additional geochemistry must be done to correlate the tuffs.

3. Hurtubise (1989) terminated the west edge of the Silver King Lineament in
the Quinn Canyon Range, approximately 25 km east of the Reveille Range. In addition, Ekren and others (1977) terminate the eastern end of the Warm Springs Lineament at Warm Springs. Major east-west striking faults associated with north-south extension were identified within these lineaments. Because several east-west-striking faults were mapped in the study area, I suggest that the two lineaments may connect in the Reveille Range. However, further structural research must be completed to make an absolute determination.

(4) The Reveille Range is the southernmost occurrence of asthenospheric mantle derived basalts. Buckboard Mesa is the northernmost occurrence of lithospheric derived basalts. Further research on basalts between these areas needs to be done to locate the lithospheric/asthenospheric mantle boundary.
References Cited


Vaniman, D., Crowe, B. and Gladney, E.S., 1981, Petrology and geochemistry of hawaiite lavas from Crater Flat, Nevada: Contributions to Mineralogy and Petrology, v. 80, p. 341-357.


Appendix A: Stratigraphy
Appendix A: Stratigraphy

Nomenclature for stratigraphic units used in this thesis are from Ekren and others (1973), Naumann and others (1991) and Martin and Naumann (1995) with the exception of four newly identified units. Naumann and others (1991), Martin and Naumann (1995) and this study present a different stratigraphic succession than that of Ekren and others (1973) (Fig. 6). Ekren and others (1973) mapped most contacts between Tertiary volcanic units in the northern Reveille and southern Pancake Ranges as faults. Detailed mapping by Martin and Naumann (1995) and this study indicate that most of these contacts are depositional rather than faults. Furthermore, Ekren and others (1973) did not differentiate between basalt types. However, based on field relations, petrography, geochemistry and geochronology, Naumann and others (1991) recognized four types of basalt.

The following stratigraphic descriptions are to accompany Plate 1 and Figure 5. Ages of tuffs are averages (calculated as a weighted mean) from multiple dates that were obtained from other sources. Ages of basalts are from Naumann and others (1991). Phenocryst percentages and phenocryst sizes are from hand samples and thin section analyses (Tables A1 and A2). Thicknesses were calculated from the geologic map (Appendix E).

Paleozoic Marine Sedimentary Rocks (Reveille Range)

Paleozoic miogeoclinal and eugeoclinal rocks form the basement of the Reveille Range and are exposed south of the study area. Units include the Antelope Valley Limestone (middle and lower Ordovician), Eureka Quartzite (middle Ordovician), Ely Springs Dolomite (upper middle Ordovician), Roberts Mountain ? Formation (Silurian), Lone Mountain ? Dolomite (Devonian and Silurian), Nevada Formation (Devonian), Pilot Shale (lower Mississippian and upper Devonian), Joana Limestone (lower Mississippian), and Diamond Peak ? Formation (upper Mississippian). The thickness of the entire exposed Paleozoic section ranges from 0-1853 m. See Ekren and others (1973) for a more detailed description of these units.

Windous Butte Formation (Tw) (Reveille Range)

The Windous Butte Formation (31.2 ± 0.6 Ma, sanidine; Taylor and others, 1989) is the oldest known tuff in the northern Reveille Range and crops out south of the study area. This unit is the outflow equivalent of the Morey Peak intracaldera tuff of the Williams Ridge caldera in the Pancake Range (Fig. 31; Best and others, 1989). The thickness ranges from 0-150 m. Martin and Naumann (1995) and Ekren and others (1973) present a more detailed description of this unit.

Monotony Tuff (Tm) (Pancake Range)

The Monotony Tuff (27.64 ± 0.34 Ma, sanidine; this study) is a compound cooling unit of olive-to-dark yellowish-brown, densely welded dacite ash-flow tuff, containing 35-50% phenocrysts of smoky quartz (15-20%) up to 4.2 mm, sanidine (10-15%) up to 3.0 mm, plagioclase (45-55%) up to 4.2 mm, biotite (5-10%) up to 4.5 mm, hornblende (1-3%) up to 1.3 mm, Fe-Ti oxides (1-2%) up to 0.6 mm, sphene (trace) up to 0.15 mm, apatite (trace) up to 0.14 mm, and zircon (trace) up to 0.14 mm. Pumice
Appendix A: Stratigraphy (cont.)

generally is absent. The Monotony Tuff crops out in the east-central part of the study
area and has an exposed thickness of 0-32 m. The base of the tuff is not exposed.

**Tuff of Bald Mountain (Tbm) (Pancake Range)**

The tuff of Bald Mountain (26.46 ± 0.42 Ma, sanidine; this study) is a compound
cooling unit of densely welded rhyolite ash-flow tuff, containing 2-23% phenocrysts of
sanidine (5-30%) up to 2.0 mm, plagioclase (65-90%) up to 2.6 mm, biotite (5-15%) up
to 1.7 mm, hornblende (1-3%) up to 0.3 mm, clinopyroxene (trace) up to 0.6 mm, Fe-Ti
oxides (0-2%) up to 0.5 mm, spherule (trace) up to 0.8 mm, and zircon (trace) up to 0.06
mm. The tuff of Bald Mountain is divided into four texturally different zones that include
(from base to top): (1) a white, moderately welded portion that contains numerous lithic
fragments (10-15%) up to 60 mm in size, (2) a densely welded grayish-black vitrophyre
approximately 11 m thick, (3) a much more densely welded zone that weathers brick red,
and (4) another grayish-black vitrophyre approximately 8 m thick. The three upper zones
contain lesser amounts of pumice (1-5%) and lithic fragments (1-10%). Pumice
are flattened and range in length from 2 to 20 mm. Lithic fragments are typically blocky and
appear to be rhyolitic in composition. The tuff of Bald Mountain unconformably overlies
Monotony Tuff. The thickness ranges from 0-290 m.

**Shingle Pass Tuff Cooling Unit A (Tspa) (Pancake Range)**

The Shingle Pass Tuff (26.7-26.0 Ma; Ekren and others, 1973; Taylor and others,
1989; Best and others, 1993) is divided into four cooling units. Shingle Pass Tuff Unit A
is a simple cooling unit of grayish-orange-to-grayish-red, moderately-to-densely welded
rhyolite ash-flow tuff that weathers brick red. It contains 5-10% phenocrysts of quartz (2-
4%) up to 1.2 mm, sanidine (25-35%) up to 3.5 mm, plagioclase (45-60%) up to 2.9 mm,
biotite (5-10%) up to 2.2 mm, Fe-Ti oxides (0-2%) up to 0.8 mm, apatite (trace) up to
0.09 mm, and zircon (trace) up to 0.13 mm. It also contains pumice (5-10%) and lithic
fragments (1-2%). Pumice fragments are typically flattened and range in length from 5 to
40 mm. Lithic fragments are typically blocky, range in size from 2 to 8 mm and appear to
be mostly dacite-to-rhyolite in composition. The basal contact of this unit is not exposed
in the study area. The exposed thickness is 0-55 m. The base of the tuff is not exposed.

**Shingle Pass Tuff Cooling Unit B (Tspb) (Pancake Range)**

Shingle Pass Tuff Unit B is a simple cooling unit of very light gray, moderately-
to-densely welded rhyolite ash-flow tuff that weathers brick red. It contains 5-15%
phenocrysts of quartz (0-5%) up to 1.3 mm, sanidine (30-70%) up to 2.1 mm, plagioclase
(25-55%) up to 3.2 mm, biotite (5-15%) up to 1.5 mm, Fe-Ti oxides (trace-1%), apatite
(trace) up to 0.21 mm, and zircon (trace) up to 0.02 mm. Pumice (20-30%) and lithic
(15-20%) fragments are abundant at the base of the tuff and decrease in abundance
toward the top. Pumice are typically flattened and range in length from 5 to 44 mm.
Lithic fragments are typically blocky, range in size from 0.2 to 40 cm and appear to be
rhyolite in composition, possibly tuff and vitrophyre of tuff of Bald Mountain and
Monotony Tuff. Shingle Pass Tuff cooling unit B conformably overlies Shingle Pass
Tuff cooling unit A. The unit has a maximum thickness of 50 m.
Appendix A: Stratigraphy (cont.)

Tuff of Arrowhead Cooling Unit B (Tab) (Pancake Range)

The tuff of Arrowhead cooling unit B (26.56 ± 0.59 Ma, biotite; this study) is a compound cooling unit of poorly-to-densely welded dacite ash-flow tuff, containing 5-20% phenocrysts of quartz (0-5%), sanidine (5-25%), plagioclase (55-80%), biotite (2-20%), hornblende (1-10%) and Fe-Ti oxides (0-3%). White pumice (15-20%) and lithic fragments (5-10%) are abundant at the base of the tuff and decrease in abundance toward the top. Pumice are typically flattened and range in length from 1 to 54 mm. Lithic fragments are typically blocky, range in size from 0.1 to 45 cm and appear to consist predominantly of the tuff of Bald Mountain. A 15 to 20-foot-thick grayish-black vitrophyre separates the yellowish-gray basal portion from the more densely welded, dark yellowish-orange-to-dark brown upper zone. The tuff of Arrowhead cooling unit B conformably overlies the tuff of Bald Mountain and unconformably overlies Monotony Tuff. The unit has a maximum thickness of 88 m.

Shingle Pass Tuff Cooling Unit C (Tspc) (Pancake Range)

The Shingle Pass Tuff cooling unit C (25.78 ± 0.39 Ma, sanidine; this study) is a compound cooling unit of light brown, moderately-to-densely welded rhyolite ash-flow tuff, containing 10-25% phenocrysts of quartz (5-15%) up to 2.4 mm, sanidine (20-60%) up to 3.3 mm, plagioclase (10-30%) up to 2.1 mm, biotite (2-10%) up to 2.5 mm, hornblende (1-3%) up to 0.7 mm, Fe-Ti oxides (trace) up to 0.5 mm, apatite (trace) up to 0.04 mm, and zircon (trace) up to 0.06 mm. White pumice (10-20%) and lithic fragments (5-10%) are abundant at the base of the tuff. Pumice are typically flattened and range in length from 2-35 mm. Lithic fragments are typically blocky, range in size from 2-50 mm, and are dacitic-to-rhyolitic in composition. Shingle Pass Tuff cooling unit C conformably overlies Shingle Pass Tuff cooling unit B and tuff of Arrowhead cooling unit B. The unit has a maximum thickness of 310 m.

Shingle Pass Tuff Cooling Unit D (Tspd) (Pancake Range)

Shingle Pass Tuff cooling unit D (absolute age unknown) was identified in the southern Pancake Range during this study. I designated this tuff as Shingle Pass Tuff cooling unit D because it conformably overlies Shingle Pass Tuff cooling unit C, the phenocryst assemblage is different from other tuffs and it has chemical similarities to other Shingle Pass tuffs (Figs. A1-A3). Shingle Pass Tuff cooling unit D is a simple cooling unit of densely welded rhyolite ash-flow tuff with a light gray basal vitrophyre grading into a grayish-orange pink-to-pale brown portion. It contains 25-35% phenocrysts of quartz (10-20%) up to 1.2 mm, sanidine (15-55%) up to 2.3 mm, plagioclase (20-40%) up to 2.1 mm, biotite (3-15%) up to 1.4 mm, hornblende (10-20%) up to 1.2 mm, Fe-Ti oxides (trace-2%), apatite (trace) up to 0.13 mm, and zircon (trace) up to 0.05 mm. It also contains abundant pumice (0-25%) with lesser amounts of lithic fragments (0-5%). Pumice are typically flattened and range in length from 2-54 mm. Lithic fragments are typically blocky and range in size from 1-24 mm. Fragments appear to be predominantly fragments of Shingle Pass Tuff cooling unit C. The minimum thickness of the unit is 65 m. The top of the unit is not exposed.
Appendix A: Stratigraphy (cont.)

**Tuff of Goblin Knobs (Tg) (Reveille Range)**

The tuff of Goblin Knobs (25.64 ± 0.53 Ma, sanidine; this study) consists of a thick sequence of pale yellowish-brown, densely welded rhyolite ash-flow tuff and crops out over most of the southern portion of the study area. In the study area, this tuff is a compound cooling unit, containing 30-40% phenocrystals of quartz (25-30%) up to 5.6 mm, sanidine (15-35%) up to 3.3 mm, plagioclase (40-50%) up to 3.1 mm, biotite (1-15%) up to 3.1 mm, hornblende (trace) up to 3.2 mm, Fe-Ti oxides (trace-2%) up to 0.06 mm,apatite (trace) up to 0.02 mm, and zircon (trace) up to 0.08 mm. It also contains pumice (2-5%) and lithic fragments (5-7%). Pumice is typically white-to-gray (sometimes orangish-pink), flattened and ranges in length from 5 to 65 mm. Lithic fragments are typically blocky and range in size from 2 to 40 mm. Fragments consist predominantly of porphyritic volcanic fragments (predominantly dacite-to-rhyolite) with minor amounts of carbonate and quartzite. The thickness ranges from 0-1700 m.

Although no cooling breaks were observed, the following evidence suggests two cooling units. First, chemical data from samples collected in the study area were compared to data from samples south of the area. Differences in chemistry may indicate the existence of two cooling units. Second, Martin and Naumann (1995) mapped thin beds of white air-fall tuff within the southern portion of the Reveille 7½' quadrangle. Finally, Ekren and others (1973) reported reversed and normal magnetic polarity within the tuff of Goblin Knobs.

**Megabreccia of Goblin Knobs (Tmg) (Reveille Range)**

The megabreccia of Goblin Knobs is first described here and is named for its association with the caldera of Goblin Knobs. The megabreccia of Goblin Knobs is exposed as small lenses within the tuff of Goblin Knobs in the northernmost part of the Reveille Range, approximately 1.2 km south of the northern caldera margin. Clasts are composed entirely of Shingle Pass Tuff cooling units B and C and range in size from less than one meter up to 15 meters.

**Tuff of Northern Reveille Range (Tnr) (Reveille Range)**

The tuff of northern Reveille Range (25.27 ± 0.86 Ma, biotite; this study) crops out over much of the southwestern portion of the study area and comprises two rhyolite cooling units. Ekren and others (1973) described three cooling units, however, only two were observed in the study area. The lower cooling unit is white and poorly welded, containing 15-20% phenocrysts of quartz (15-35%), sanidine (10-20%), plagioclase (25-50%), biotite (2-4%), Fe-Ti oxides (trace),apatite (trace) up to 0.03 mm and zircon (trace) up to 0.09 mm. It also contains white pumice (5-20%) and lithic fragments (1-5%). Pumice are commonly zeolitized, flattened and range in length from 5 to 26 mm. Lithic fragments are typically blocky and range in size from 2 to 24 mm. Martin and Naumann (1995) reported numerous 1-m blocks of tuff of Goblin Knobs within the tuff of northern Reveille Range. In addition, Ekren and others (1973) reported fragments of dacitic lava, dirty sandstone and Shingle Pass and Monotony Tuffs. Lithic fragments in tuffs exposed in the study area appear to be dacite-to-rhyolite in composition, but it was not determined from which tuffs they were derived.
Appendix A: Stratigraphy (cont.)

The upper unit is pale orange-to-pinkish-gray and poorly-to-moderately welded, containing 10-15% phenocrysts of quartz (25-45%), sanidine (30-40%), plagioclase (5-30%), biotite (0-2%), Fe-Ti oxides (trace-3%), apatite (trace) up to 0.04 mm and zircon (trace) up to 0.2 mm. It also contains pumice (5-10%) and lithic fragments (1-2%). Pumice are flattened and range in size from 5 to 26 mm. Lithic fragments are typically blocky and range in size from 2-7 mm. The thickness ranges from 0-160 m.

The tuff of northern Reveille Range has an unconformable contact with the tuff of Goblin Knobs in all locations. The tuff of northern Reveille Range is highly silicified at the contact with the tuff of Goblin Knobs.

**Tuff of Northern Reveille Range Surge Deposit (Tsd) (Reveille Range)**

The tuff of northern Reveille Range surge deposit crops out in the southwestern portion of the study area. The surge deposit conformably overlies tuff of northern Reveille Range and is juxtaposed against the tuff of Goblin Knobs. It is intensely silicified near the contact with tuff of Goblin Knobs. The surge deposit is reddish-gray-to-buff, finely laminated (up to 5 mm) and has planar bedding. Martin and Naumann (1995) reported wavy-to-low amplitude crossbedding. Cross-beds were not observed in the surge deposits in the study area. The unit locally contains rounded accretionary lapilli, up to 2 cm, clasts of the tuff of northern Reveille Range, reworked surge deposits and fine-to-coarse-grained fluvial sedimentary deposits (Martin and Naumann, 1995; this study). The unit has a maximum thickness of 175 m.

**Megabreccia of Northern Reveille Range (Tmn) (Reveille and Pancake Ranges)**

The megabreccia of northern Reveille Range is first described here and is named for its association with the caldera of northern Reveille Range. It crops out at two locations in the study area, the southern portion of the Pancake Range and the northwestern portion of the northern Reveille Range. In the Pancake Range, the megabreccia of northern Reveille Range is divided into two members. The upper member consists of polylithologic mesobreccia embedded in a thick massive non-welded portion of the tuff of northern Reveille Range. The member contains blocks of Shingle Pass Tuff cooling units A, B, and C, and tuff of Bald Mountain. The clasts range from 2-3 cm to 1 m. The majority of the clasts range from 30-60 cm. The lower member consists of polylithologic megabreccia with clasts up to approximately 300 m in size, locally interbedded within the tuff of northern Reveille Range. Clasts include blocks of Shingle Pass Tuff cooling units A, B, and C, highly silicified tuff of northern Reveille Range (?), tuff of Bald Mountain, and Monotony Tuff. Clasts types tend to be geographically restricted within the outcrop area. Shingle Pass Tuffs occurs in the easternmost part of the outcrop area. The tuff of northern Reveille Range (?) blocks are abundant in the westernmost part of the outcrop area. The tuff of Bald Mountain clasts are the least abundant and are scattered throughout the unit. Two blocks of Shingle Pass Tuff cooling unit A (120 m and 90 m) crop out just to the north of Twin Springs Ranch and are interpreted to be part of this unit. Similarly, two blocks of Monotony Tuff (300 m and 20 m) crop out just to the south of highway 375 and southwest of the Pancake Range and also are included in this unit. In the northern Reveille Range, a 250-m block of the tuff of Goblin Knobs is interbedded within the tuff of northern Reveille Range. This
Appendix A: Stratigraphy (cont.)

block is the only known occurrence of the megabreccia of northern Reveille Range in this part of the study area.

Siltstone of Cane Springs (Tc) (Pancake Range)

This unit is first described here and is herein named the siltstone of Cane Springs, after Cane Springs near Twin Springs Ranch. The olive-gray unit contains finely laminated mudstone intercalated with silty sandstone. It appears that some megabreccia of northern Reveille Range is interbedded within the siltstone of Cane Springs. However, due to extensive cover this observation is difficult to confirm. Laminations range from less than 1 mm up to 1 cm in thickness. The unit consists of predominantly angular to subrounded feldspar and quartz grains, biotites aligned with the lamination direction, and less abundant cuspate glass shards. The thickness ranges from 0-20 m.

Tuff of Streuben Knobs (Tst) (Reveille Range)

The tuff of Streuben Knobs (absolute age unknown) crops out in the southwestern portion of the study area. It is a grayish-orange pink-to-pale red, moderately-to-densely welded, rhyolite ash-flow tuff, containing 18-35% phenocrysts of quartz (25-45%) up to 4.2 mm, sanidine (8-50%) up to 3.2 mm, plagioclase (20-45%) up to 3.0 mm, biotite (1-5%) up to 1.6 mm, Fe-Ti oxides (trace), sphene (trace) up to 0.13 mm, apatite (trace) up to 0.05 mm, and zircon (trace) up to 0.07 mm. It also contains pumice (5-10%) and lithic fragments (2-3%). Pumice fragments range in size from 2 to 53 mm and form elongate fiamme that define a eutaxitic texture. Lithic fragments are typically blocky and range in size from 1 to 7 mm. Clasts are mostly granitic with minor amounts of felsic lava. The thickness ranges from 0-90 m (Ekren and others, 1973; Martin and Naumann, 1995; this study).

Unnamed Tertiary Tuffaceous Sandstone (Tt) (Reveille Range)

The unnamed Tertiary tuffaceous sandstone is highly silicified and crops out in the northwestern portion of the Reveille Range. It is well sorted, well rounded and contains 2-3 mm-size quartz, plagioclase and sanidine. Although not observed, Ekren and others (1973) reported biotite in the unnamed Tertiary tuffaceous sandstone. The thickness ranges from 0-70 m.

Rhyolitic Dikes and Plugs of Twin Springs Ranch (Trt) (Reveille and Pancake Ranges)

The rhyolitic dikes and plugs of Twin Springs Ranch (24.74 ± 0.50 Ma, sanidine, and 24.70 ± 0.28 Ma, sanidine; this study) are light gray and pale red flow-banded rhyolite, containing 3-15% phenocrysts of quartz (10-25%), sanidine (trace-10%), plagioclase (30-70%), biotite (5-15%) and Fe-Ti oxides (trace-2%) (Ekren and others, 1973; this study). Two rhyolitic plugs crop out in the southern Pancake Range. One of the plugs intrudes Shingle Pass Tuff cooling unit C. Because the other plug is surrounded by alluvium, its intrusive relationship is unclear. The dikes intrude the Monotony Tuff, tuff of Goblin Knobs and tuff of northern Reveille Range.
Appendix A: Stratigraphy (cont.)

Basaltic Andesites (Tba) (Reveille Range)

The basaltic andesites (~14 Ma; Naumann and others, 1991) are the oldest basalts in the study area and unconformably overlying the unnamed Tertiary tuffaceous sandstone in the northwestern part of the Reveille Range. The basaltic andesites have a volume of 0.05 km$^3$ and range in thickness from 0-29 m. They are medium dark gray and aphyric, containing groundmass plagioclase, iddingsitized olivine, clinopyroxene, orthopyroxene, sanidine and Fe-Ti oxides.

Episode-1 Basalts (Tb1) (Reveille Range)

Episode-1 basalts (5.13 ± 0.15 to 5.94 ±0.14 Ma; Naumann and others, 1991)) are medium gray, porphyritic olivine basalts, containing 30-40% phenocrysts of plagioclase (75-95%; commonly occurs as glomerocrystic megacrysts) up to 19 mm, iddingsitized olivine (3-21%) up to 1.5 mm, clinopyroxene (trace-2%) up to 2.4 mm and Fe-Ti oxides (trace-2%) up to 0.5 mm (Naumann and others, 1991; Martin and Naumann, 1995, Yogodzinski and others, submitted; this study). Although not observed in the study area, Yogodzinski and others (submitted) reported that biotite and primary calcite were locally present. Episode-1 basalts are the most abundant basalts in the northern Reveille Range, erupted from 52 vents throughout the range (Naumann and others, 1991) and have a volume of 8 km$^3$ (Yogodzinski and others, submitted). They unconformably overlie the tuff of northern Reveille Range, tuff of northern Reveille Range surge deposit, tuff of Streuben Knobs, and tuff of Goblin Knobs. In many locations episode-1 basalts occupies depressions and channels in the underlying tuffs. Individual flow thicknesses range from 0-10 m, and the total thickness ranges from 0-100 m (Martin and Naumann, 1995).

Episode-2 Basalts (Tb2) (Reveille Range)

Episode-2 basalts (3.00 ± 0.08 to 4.64 ±0.14 Ma; Naumann and others, 1991) are dark gray, porphyritic olivine basalts, containing 20-30% phenocrysts of plagioclase (10-20%) up to 12 mm, iddingsitized olivine (10%) up to 2.0 mm, clinopyroxene (0-40%) up to 3.2 mm, orthopyroxene (0-5%) up to 2.8 mm, xenocrysts of hornblende (0-50%) up to 8 mm, and Fe-Ti oxides (trace-6%) (Naumann and others, 1991; Yogodzinski and other, submitted; Martin and Naumann, 1995; this study). Although not observed in the study area, episode-2 basalts also contain xenoliths of coarse-grained gabbro and dunite (Naumann and others, 1991; Yogodzinski and others, submitted). Episode-2 basalts are the youngest volcanic rocks in the northern Reveille Range. They erupted from 14 vents in the northeastern part of the Range (Naumann and others, 1991) and have a minimum volume of 1 km$^3$ (Yogodzinski and others, submitted). One flow and several dikes of episode-2 basalts crop out in the southeastern part of the study area. Individual lava flows of range in thickness from 0-10 m. The total thickness of episode-2 basalts ranges from 0-100 m (Martin and Naumann, 1995).

Tertiary/Quaternary Colluvium Reveille and Pancake Ranges)

The Tertiary and Quaternary colluvium consist of unconsolidated broken boulders of tuff and basalt.
Appendix A: Stratigraphy (cont.)

*Tertiary/Quaternary Alluvium (Reveille and Pancake Ranges)*

The Tertiary and Quaternary alluvium consist of unconsolidated and poorly consolidated sand and gravel. This includes alluvium in washes, talus, alluvial fans and slope wash. The thickness ranges from 0-600 m.
Table A1. Modal percentages (based on hand sample analyses) of ash-flow tuffs in the northern Reveille and southern Pancake Ranges.

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<th>sanidine</th>
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<th>hornblende</th>
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*mostly smoky quartz

Table A2. Modal percentages (based on hand sample analyses) of mafic rocks in the northern Reveille Range.

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\*fiddlingsitized
\*commonly occurs as megacrysts
Figure A1. Major element Harker variation diagrams showing the distribution of Shingle Pass Tuff Unit D relative to other Shingle Pass tuffs. The lightly shaded area represents the chemical range of all other tuffs in the northern Reveille and southern Pancake Ranges.
Figure A1 (cont.). Major element Harker variation diagrams showing the distribution of Shingle Pass Tuff Unit D relative to other Shingle Pass tuffs. The lightly shaded area represents the chemical range of all other tuffs in the northern Reveille and southern Pancake Ranges.
Figure A2. Trace element ratio/ratio diagrams showing the distribution of Shingle Pass Tuff Unit D relative to other Shingle Pass tuffs. The lightly shaded area represents the chemical range of all other tuffs in the northern Reveille and southern Pancake Ranges.
Figure A3. Spider diagrams normalized to chondrite for Shingle Pass cooling units A, B, C and D. Chondrite normalization values are from Thompson (1982).
Appendix B: Petrography

Part 1. Petrographic Descriptions
Part 2. Point Count Analyses
Appendix B: Part 1. Petrographic Descriptions

Percentages of phenocrysts, matrix, pumice and lithic fragments are based on a point counting analysis of a thin section. Five hundred points were counted on each slide. Colors are from the Geological Society of America rock-color chart (1984). Samples with the prefix R8-1- and R9-1- were collected by Terry Naumann and others (1991).

**Reveille Range**

**tuff of Goblin Knobs**

Sample number: RR-31  
Location: 38°07'59"N Latitude; 116°07'45"W Longitude  
Description: Pyroclastic, porphyritic, hypocrystalline, welded tuff containing phenocrysts (33.2%) of subhedral sanidine (13.9%) up to 2.6 mm, subhedral-to-euhedral zoned plagioclase (50.0%) up to 3.1 mm, anhedral oscillatory quartz (25.9%) up to 4.9 mm, subhedral-to-euhedral biotite (8.4%) up to 2.1 mm, anhedral opaque minerals (1.8%) up to 0.6 mm, subhedral apatite (trace) up to 0.02 mm, and euhedral zircon (trace) up to 0.08 mm. Some plagioclase form as glomerocrysts, many biotites are bent, and most quartz are resorbed. The pale yellowish-brown matrix (64.6%) is slightly-to-moderately devitrified glass and is composed of pumice fragments that show eutaxitic texture. Larger pumice fragments (1.6%) are flattened, slightly-to-moderately devitrified, and up to 28 mm in length. Some show vapor phase crystallization of sanidine and quartz. Lithic fragments (0.6%) are up to 9.5 mm in length and contain holocrystalline porphyritic fragments with phenocrysts of up to 0.45 mm plagioclase, 0.3 mm sanidine and 0.5 mm quartz. Some microcrystalline fragments are present.  
Rock name: rhyolite ash-flow tuff

**tuff of Northern Reveille Range**

Sample number: RR-1  
Location: 38°11'51"N Latitude; 116°11'11"W Longitude  
Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (13.0%) of anhedral-to-subhedral sanidine (35.4%) up to 3.2 mm, subhedral-to-euhedral plagioclase (4.6%) up to 1.2 mm, anhedral oscillatory quartz (41.5%) up to 2.2 mm, subhedral-to-euhedral biotite (18.5%) up to 1.9 mm, subhedral-to-euhedral zircon (trace) up to 0.09 mm, subhedral-to-euhedral apatite (trace) up to 0.03 mm, and anhedral opaque minerals (trace) up to 0.3 mm. Some quartz are resorbed and some biotites are bent. The white matrix (87.0%) is slightly-to-moderately devitrified fine-grained glass and is composed of bubble wall shards.  
Rock name: rhyolite ash-flow tuff
Appendix B: Part 1. Petrographic Descriptions (cont.)

Sample number: RR-2
Location: 38°11'37"N Latitude; 116°11'14"W Longitude

Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (17.4%) of anhedral-to-subhedral sanidine (31.0%) up to 1.7 mm, subhedral-to-euhedral zoned plagioclase (27.6%) up to 2.0 mm, anhedral-to-subhedral oscillatory quartz (36.8%) up to 3.2 mm, subhedral-to-euhedral biotite (4.6%) up to 1.0 mm, subhedral-to-euhedral apatite (trace) up to 0.03 mm, subhedral zircon (trace) up to 0.02 mm, and anhedral opaque minerals (trace) up to 0.5 mm. Some quartz are resorbed and some biotite are bent. The white matrix (82.8%) is slightly-to-moderately devitrified fine-grained glass and is composed of bubble wall shards. Lithic fragments (0.4%) are up to 2.0 mm in length and are hypocrystalline pyroclastic fragments with up to 0.6 mm plagioclase in a fine-grained glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: PR-25
Location: 38°12'02"N Latitude; 116°09'20"W Longitude

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (18.0%) of subhedral sanidine (67.8%) up to 2.4 mm, subhedral-to-euhedral zoned plagioclase (16.7%) up to 2.1 mm, anhedral oscillatory quartz (11.1%) up to 2.0 mm, subhedral-to-euhedral biotite (3.3%) up to 1.5 mm, subhedral-to-euhedral zircon (trace) up to 0.2 mm, subhedral-to-euhedral apatite (trace) up to 0.02 mm, and anhedral-to-subhedral opaque minerals (0.1%) up to 0.5 mm. The pale olive matrix (69.2%) is moderately-to-highly devitrified glass and is composed of mostly bubble wall shards with minor amounts of blocky shards and pumice fragments. Larger pumice fragments (1.4%) are flattened, slightly-to-moderately devitrified, and up to 12 mm in length. Lithic fragments (11.4%) are up to 5.3 mm in length and are porphyritic and hypocrystalline with phenocrysts of plagioclase up to 1.0 mm, biotite up to 0.3 mm and zircon up to 0.09 mm in a slightly devitrified glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: PR-27
Location: 38°11'59"N Latitude; 116°09'15"W Longitude

Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (34.8%) of subhedral sanidine (17.8%) up to 2.5 mm, subhedral-to-euhedral zoned plagioclase (28.7%) up to 1.6 mm, anhedral oscillatory quartz (40.8%) up to 2.3 mm, subhedral-to-euhedral biotite (12.1%) up to 1.8 mm, subhedral zircon (trace) up to 0.03 mm, subhedral-to-euhedral apatite (trace) up to 0.02 mm, and anhedral-to-subhedral opaque minerals (0.6%) up to 1.6 mm. Some quartz are resorbed. The very pale orange matrix (60.6%) is moderately-to-highly devitrified glass and is composed of mostly bubble wall shards with minor amounts of blocky shards and pumice fragments. Lithic fragments (4.6%) are up to 4.1 mm
Appendix B: Part 1. Petrographic Descriptions (cont.)

in length and are porphyritic and hypocrystalline with phenocrysts of plagioclase up to 0.6 mm and sanidine up to 0.3 mm in a glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: RR-44
Location: 38°07'31"N Latitude; 116°10'41"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (20.9%) of anhedral-to-euhedral zoned plagioclase (61.1%) up to 2.1 mm, anhedral oscillatory quartz (36.1%) up to 1.5 mm, subhedral-to-euhedral biotite (trace) up to 0.5 mm, subhedral-to-euhedral apatite (trace) up to 0.04 mm, subhedral-to-euhedral zircon (trace) up to 0.07 mm, and anhedral opaque minerals (2.8%) up to 0.5 mm. The pinkish-gray matrix (71.5%) is highly devitrified glass. Pumice fragments (4.3%) are flattened, highly devitrified and up to 17 mm in length. Some fragments show vapor phase crystallization of quartz. Lithic fragments (3.3%) are up to 24 mm in length and are holocrystalline and microcrystalline. Some are hypocrystalline with up to 0.3 mm quartz in a highly devitrified glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: RR-45
Location: 38°07'11"N Latitude; 116°10'29"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (22.0%) of anhedral-to-subhedral zoned plagioclase (57.3%) up to 1.1 mm, anhedral-to-subhedral oscillatory quartz (42.1%) up to 1.4 mm, subhedral-to-euhedral biotite (trace) up to 0.4 mm, subhedral-to-euhedral zircon (trace) up to 0.06 mm, subhedral-to-euhedral apatite (trace) up to 0.03 mm, and anhedral opaque minerals (trace) up to 0.3 mm. Some quartz are resorbed and some plagioclase are highly altered to sericite. The light brown matrix (76.2%) is highly devitrified glass. Lithic fragments (1.8%) are up to 6 mm and are holocrystalline porphyritic with up to 1.1 mm plagioclase, 0.6 mm sanidine, and 0.6 mm quartz in a very fine grained matrix.

Rock name: rhyolite ash-flow tuff

Tuff of Streuben Knobs

Sample number: RR-12
Location: 38°10'32"N Latitude; 116°12'08"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (35.2%) of anhedral-to-subhedral sanidine (15.9%) up to 2.4 mm, subhedral-to-euhedral zoned plagioclase (38.6%) up to 3.0 mm, anhedral oscillatory quartz (42.6%) up to 4.2 mm, subhedral-to-euhedral biotite (2.8%) up to 0.8 mm, subhedral sphene (trace) up to 0.09 mm, subhedral-to-euhedral zircon (trace) up to 0.07 mm, subhedral-to-euhedral apatite (trace) up to 0.02 mm, and anhedral opaque
Appendix B: Part 1. Petrographic Descriptions (cont.)

minerals (trace) up to 0.5 mm. Some biotites are bent and nearly all quartz are resorbed. The grayish-orange pink glassy matrix (59.0%) is highly devitrified to chalcedony and is composed of pumice fragments that show eutaxitic texture. Larger pumice fragments (5.8%) are flattened, highly devitrified to chalcedony, and up to 53 mm in length. Some show vapor phase crystallization of quartz and sanidine. Lithic fragments (trace) are up to 7 mm in length and are hypocrystalline and microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: RR-43
Location: 38°08’15"N Latitude; 116°10’56"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (18.0%) of anhedral-to-subhedral sanidine (7.8%) up to 3.2 mm, subhedral-to-euhedral zoned plagioclase (43.3%) up to 0.3 mm, anhedral-to-subhedral oscillatory quartz (44.4%) up to 2.3 mm, subhedral-to-euhedral biotite (4.4%) up to 1.6 mm, subhedral-to-euhedral sphene (trace) up to 0.13 mm, subhedral-to-euhedral zircon (trace) up to 0.06 mm, subhedral-to-euhedral apatite (trace) up to 0.05 mm, and anhedral opaque minerals (trace) up to 0.4 mm. Some quartz are resorbed and some biotites are bent. The pale red matrix (73.8%) is highly devitrified glass, shows eutaxitic texture and is composed of mostly pumice fragments with minor amounts of bubble wall shards. Larger pumice fragments (7.8%) are flattened, highly devitrified to chalcedony, and up to 26 mm in length. Some show vapor phase crystallization of quartz and sanidine. Lithic fragments (0.4%) are up to 3 mm in length and are hypocrystalline and microcrystalline.

Rock name: rhyolite ash-flow tuff

__unnamed Tertiary tuffaceous sandstone__

Sample number: RR-6
Location: 38°11’46"N Latitude; 116°11’44"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (28.2%) of anhedral-to-subhedral sanidine (58.2%) up to 1.1 mm, subhedral-to-euhedral zoned plagioclase (7.8%) up to 1.9 mm, anhedral-to-subhedral oscillatory quartz (30.0%) up to 3.8 mm, subhedral-to-euhedral biotite (4.3%) up to 2.9 mm, subhedral-to-euhedral zircon (trace) up to 0.05 mm, subhedral-to-euhedral apatite (trace) up to 0.06 mm, and subhedral-to-euhedral opaque minerals (trace) up to 0.7 mm. Some quartz are resorbed and some biotites are bent. The grayish-orange pink matrix (49.4%) is slightly-to-moderately devitrified glass shows eutaxitic texture and is composed of mostly pumice fragments with very minor amounts of bubble wall shards. Larger pumice fragments (22.2%) are flattened, highly devitrified to chalcedony, and up to 31 mm in length. They show vapor phase crystallization of quartz and sanidine. Lithic fragments (0.2%) are up to 9 mm in length and are hypocrystalline and
Appendix B: Part 1. Petrographic Descriptions (cont.)

microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: RR-8
Location: 38°11'47"N Latitude; 116°11'25"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (24.0%) of anhedral-to-subhedral sanidine (30.0%) up to 0.8 mm, subhedral-to-euhedral zoned plagioclase (40.0%) up to 0.7 mm, anhedral oscillatory quartz (19.2%) up to 0.6 mm, subhedral-to-euhedral biotite (9.2%) up to 1.0 mm, subhedral hornblende (1.7%) up to 0.42 mm, subhedral-to-euhedral zircon (trace) up to 0.05 mm, euhedral apatite (trace) up to 0.03 mm and anhedral opaque minerals (trace) up to 0.5 mm. Some biotites are bent. The light olive gray matrix (73.6%) is highly devitrified glass, shows eutaxitic texture and is composed of mostly pumice fragments with very minor amounts of bubble wall shards. Larger pumice fragments (1.2%) are flattened, moderately-to-highly devitrified to chalcedony and up to 2.2 mm in length. Lithic fragments (1.2%) are up to 8 mm in length and are microcrystalline and hypocrystalline. Some are porphyritic and hypocrystalline with up to 0.4 mm plagioclase (highly altered to sericite) in a highly devitrified glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: RR-1
Location: 38°11'32"N Latitude; 116°11'39"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (14.8%) of anhedral-to-subhedral sanidine (52.7%) up to 1.6 mm, subhedral-to-euhedral zoned plagioclase (25.7%) up to 2.6 mm, anhedral oscillatory quartz (16.2%) up to 4.5 mm, subhedral-to-euhedral biotite (5.4%) up to 0.8 mm, subhedral-to-euhedral zircon (trace) up to 0.09 mm, subhedral-to-euhedral apatite (trace) up to 0.03 mm, and anhedral opaque minerals (trace) up to 0.3 mm. Most plagioclase are highly altered to sericite, most quartz are resorbed and some biotite are bent. The grayish-orange pink glassy matrix (79.2%) is highly devitrified to chalcedony and is composed of mostly bubble wall shards with minor amounts of blocky shards and pumice fragments. Larger pumice fragments (4.2%) are flattened, highly devitrified to chalcedony, and up to 26 mm in length. Some show vapor phase crystallization of quartz and sanidine. Lithic fragments (1.8%) are up to 6 mm in length and are microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: RR-33
Location: 38°08'48"N Latitude; 116°08'16"W Longitude

clasts within megabreccia of caldera of Goblin Knobs

Sample number: RR-33
Location: 38°08'48"N Latitude; 116°08'16"W Longitude
Appendix B: Part 1. Petrographic Descriptions (cont.)

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (3.0%) of anhedral-to-subhedral sanidine (33.3%) up to 1.1 mm, subhedral-to-euhedral zoned plagioclase (40.0%) up to 0.6 mm, anhedral-to-subhedral oscillatory quartz (6.7%) up to 0.8 mm, subhedral-to-euhedral biotite (13.3%) up to 1.9 mm, subhedral-to-euhedral zircon (trace) up to 0.4 mm, and anhedral-to-euhedral opaque minerals (trace) up to 0.3 mm. The grayish-red glassy matrix (97.0%) is highly devitrified to chalcedony and is composed of pumice fragments. Larger pumice fragments (trace) are flattened, highly devitrified to chalcedony, and up to 3.2 mm in length. Lithic fragments (6.7%) are up to 2.3 mm in length and are hypocrystalline and microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: RR-37
Location: 38°08'04"N Latitude; 116°08'15"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (13.8%) of subhedral sanidine (49.3%) up to 2.3 mm, anhedral-to-euhedral zoned plagioclase (43.5%) up to 3.4 mm, anhedral oscillatory quartz (4.3%) up to 1.5 mm, subhedral-to-euhedral biotite (2.9%) up to 1.0 mm, subhedral-to-euhedral zircon (trace) up to 0.16 mm, subhedral-to-euhedral apatite (trace) up to 0.03 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.6 mm. Most quartz are resorbed. The pale red glassy matrix (85.8%) is highly devitrified to chalcedony, shows eutaxitic texture and is composed of bubble wall shards with minor amounts of blocky shards and pumice fragments. Larger pumice fragments (0.4%) are flattened, highly devitrified to chalcedony, and up to 9.0 mm in length. Some show vapor phase crystallization of sanidine and plagioclase.

Rock name: rhyolite ash-flow tuff

Sample number: RR-38
Location: 38°08'03"N Latitude; 116°08'13"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (15.8%) of subhedral sanidine (22.8%) up to 2.5 mm, subhedral-to-euhedral zoned plagioclase (65.8%) up to 2.0 mm, anhedral-to-subhedral oscillatory quartz (2.5%) up to 1.1 mm, subhedral-to-euhedral biotite (8.9%) up to 1.0 mm, subhedral-to-euhedral zircon (trace) up to 0.03 mm, and anhedral opaque minerals (trace) up to 0.4 mm. The moderate red glassy matrix (84.2%) is highly devitrified to chalcedony, shows eutaxitic texture and is composed of mostly pumice fragments with minor amounts of bubble wall and blocky shards.

Rock name: rhyolite ash-flow tuff

*rhyolitic dikes of Twin Springs Ranch*

Sample number: RR-18
Location: 38°10'48"N Latitude; 116°11'03"W Longitude
Appendix B: Part 1. Petrographic Descriptions (cont.)

Description: Porphyritic, hypocrystalline rhyolite containing phenocrysts (1.8%) of anhedral-to-subhedral zoned plagioclase (100%) up to 1.5 mm, and anhedral opaque minerals (trace) up to 0.05 mm. The white glassy matrix (95.4%) is slightly-to-moderately devitrified to chalcedony. Lithic fragments (2.8%) are up to 5.6 mm in length and are porphyritic and hypocrystalline with plagioclase phenocrysts up to 0.9 mm in a moderately devitrified glassy matrix.

Rock name: rhyolite

Sample number: RR-26
Location: 38°11’45”N Latitude; 116°11’00”W Longitude

Description: Porphyritic, hypocrystalline, rhyolite containing phenocrysts (6.8%) of anhedral-to-subhedral sanidine (55.9%) up to 2.4 mm, subhedral-to-euhedral plagioclase (26.5%) up to 1.3 mm, anhedral oscillatory quartz (8.8%) up to 0.6 mm, subhedral-to-euhedral biotite (8.8%) up to 1.2 mm, subhedral-to-euhedral zircon (trace) up to 0.04 mm, and anhedral opaque minerals (trace) up to 0.25 mm. The light gray pumice matrix (93.2%) is highly devitrified to chalcedony. Lithic fragments (trace) are microcrystalline and holocrystalline and up to 2.0 mm in length.

Rock name: rhyolite

Episode-I basalts

Sample number: RR-3
Location: 38°11’26”N Latitude; 116°11’18”W Longitude

Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing phenocrysts (36.8%) of subhedral-to-euhedral zoned labradorite (75.5%) up to 4.9 mm, anhedral iddingsitized olivine (20.7%) up to 0.9 mm, subhedral clinopyroxene (1.6%) up to 2.4 mm, and anhedral-to-euhedral opaque minerals (2.2%) up to 0.3 mm. The medium dark gray matrix (63.2%) contains microlites of euhedral plagioclase, anhedral-to-subhedral iddingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-euhedral opaque minerals. Vesicles (trace) are either coated or filled with calcite.

Rock name: olivine basalt

Sample number: RR-11
Location: 38°10’26”N Latitude; 116°12’09”W Longitude

Description: Porphyritic, holocrystalline and slightly vesicular basalt containing phenocrysts (37.8%) of anhedral-to-euhedral zoned labradorite (84.7%) up to 13 mm, anhedral iddingsitized olivine (15.3%) up to 1.3 mm, and anhedral-to-euhedral opaque minerals (trace) up to 0.3 mm. The dark gray matrix (62.2%) contains microlites of euhedral plagioclase, anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals. Vesicles (trace) are filled with calcite.

Rock name: olivine basalt
Appendix B: Part 1. Petrographic Descriptions (cont.)

Sample number: RR-13
Location: 38°10'18"N Latitude; 116°12'10"W Longitude
Description: Porphyritic, holocrystalline and slightly vesicular basalt containing
phenocrysts (34.6%) of subhedral-to-euhedral zoned labradorite (80.3%) up to 7.8
mm, anhedral iddingsitized olivine (18.5%) up to 1.3 mm, subhedral clinopyroxene
(1.2%) up to 0.6 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.5
mm. Many clinopyroxenes show subophitic texture. The medium dark gray matrix
(65.4%) contains microlites of euhedral plagioclase, anhedral-to-subhedral
идdingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-
euhedral opaque minerals. Vesicles (trace) are either coated or filled with calcite.

Rock name: olivine basalt

Sample number: RR-30
Location: 38°08'42"N Latitude; 116°07'34"W Longitude
Description: Porphyritic, holocrystalline and slightly vesicular basalt containing
phenocrysts (16.8%) of subhedral-to-euhedral zoned labradorite (88.1%) up to 18
mm, anhedral iddingsitized olivine (11.9%) up to 1.6 mm, subhedral clinopyroxene
(trace) up to 0.6 mm and anhedral-to-subhedral opaque minerals (trace) up to 0.2
mm. The medium gray matrix (83.2%) contains microlites of euhedral plagioclase,
anhedral iddingsitized olivine and anhedral-to-subhedral opaque minerals. Vesicles
(trace) are either coated or filled with calcite.

Rock name: olivine basalt

Sample number: RR-41
Location: 38°08'03"N Latitude; 116°10'49"W Longitude
Description: Porphyritic, holocrystalline and slightly vesicular basalt containing
phenocrysts (34.8%) of subhedral-to-euhedral zoned labradorite (82.8%) up to 14
mm, anhedral iddingsitized olivine (11.8%) up to 1.1 mm, anhedral clinopyroxene
(5.7%) up to 2.0 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.2
mm. The medium gray matrix (65.2%) contains microlites of euhedral plagioclase,
anhedral iddingsitized olivine and subhedral-to-subhedral opaque minerals.
Vesicles (trace) are coated with calcite.

Rock name: olivine basalt

Sample number: RR-42
Location: 38°08'15"N Latitude; 116°10'56"W Longitude
Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing
phenocrysts (21.8%) of subhedral-to-euhedral zoned labradorite (78.9%) up to 19
mm, anhedral iddingsitized olivine (14.7%) up to 0.7 mm, anhedral clinopyroxene
(6.4%) up to 0.8 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.3
mm. The dark gray matrix (78.2%) contains microlites of euhedral plagioclase,
anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals. Vesicles
(trace) are filled with calcite.

Rock name: olivine basalt
Appendix B: Part 1. Petrographic Descriptions (cont.)

Sample number: RR-46
Location: 38°08'21"N Latitude; 116°10'54"W Longitude
Description: Porphyritic, holocrystalline and vesicular basalt containing phenocrysts (33.0%) of subhedral-to-euhedral zoned labradorite (92.7%) up to 8 mm, anhedral iddingsitized olivine (6.7%) up to 1.1 mm, anhedral clinopyroxene (0.6%) up to 1.0 mm, and anhedral-to-euhedral opaque minerals (trace) up to 0.1 mm. The medium gray matrix (67.0%) contains microlites of euhedral plagioclase, anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals. Vesicles (trace) are either coated or filled with calcite.

Rock name: olivine basalt

Sample number: R8-1-24-LN
Location: 38°03'18"N Latitude; 116°08'52"W Longitude
Description: Porphyritic, holocrystalline and vesicular basalt containing phenocrysts (50.4%) of subhedral-to-euhedral zoned labradorite (96.4%) up to 12.5 mm, anhedral iddingsitized olivine (3.2%) up to 1.5 mm, anhedral-to-subhedral clinopyroxene (0.4%) up to 1.1 mm, and anhedral-to-euhedral opaque minerals (trace) up to 0.3 mm. The medium dark gray matrix (49.6%) contains microlites of euhedral plagioclase, anhedral iddingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-euhedral opaque minerals.

Rock name: olivine basalt

Episode-2 basalts

Sample number: RR-28
Location: 38°08'10"N Latitude; 116°07'41"W Longitude
Description: Porphyritic and holocrystalline basalt containing phenocrysts (18.4%) of subhedral-to-euhedral zoned trachytic labradorite (92.4%) up to 12 mm, anhedral iddingsitized olivine (5.4%) up to 1.3 mm, subhedral xenocrysts of hornblende (trace) up to 18 mm, and subhedral-to-euhedral opaque minerals (2.2%) up to 0.3 mm. The dark gray matrix (81.6%) contains microlites of euhedral plagioclase, anhedral olivine and anhedral-to-euhedral opaque minerals.

Rock name: olivine basalt

Sample number: R8-1-2-LN
Location: 38°03'30"N Latitude; 116°08'20"W Longitude
Description: Porphyritic, holocrystalline and slightly vesicular basalt containing phenocrysts (20.2%) of subhedral-to-euhedral zoned labradorite (81.2%) up to 3.2 mm, anhedral olivine (12.9%) up to 2.0 mm, anhedral-to-subhedral clinopyroxene (0.1%) up to 1.2 mm, and anhedral-to-euhedral opaque minerals (5.9%) up to 2.5 mm. Most plagioclase are resorbed, and most olivine are iddingsitized. The medium dark gray matrix (%) contains microlites of euhedral plagioclase, anhedral
Appendix B: Part 1. Petrographic Descriptions (cont.)

iddingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-euhedral opaque minerals.

Rock name: olivine basalt

Sample number: RS-1-13-LN
Location: 38°04'23''N Latitude; 116°07'18''W Longitude
Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing phenocrysts (15.0%) of anhedral-to-euhedral zoned labradorite (76.0%) up to 3.7 mm, anhedral olivine (10.7%) up to 1.7 mm, anhedral-to-subhedral clinopyroxene (5.3%) up to 3.2 mm, anhedral-to-subhedral orthopyroxene (5.3%) up to 2.3 mm, subhedral-to-euhedral hornblende (trace) up to 0.9 mm, and anhedral-to-euhedral opaque minerals (2.1%) up to 2.4 mm. Most plagioclase are resorbed and most olivine are iddingsitized. The sample contains xenoliths of gabbro up to 4.2 mm with subhedral-to-euhedral plagioclase and subhedral-to-euhedral clinopyroxene. Variolitic texture within the plagioclase is common within these autoliths. The medium dark gray matrix (85.0%) contains microlites of subhedral-to-euhedral plagioclase, anhedral iddingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-euhedral opaque minerals.

Rock name: olivine basalt

Sample number: RS-1-18-LN
Location: 38°04'20''N Latitude; 116°07'24''W Longitude
Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing phenocrysts (20.4%) of anhedral-to-euhedral labradorite (40.2%) up to 4.7 mm, anhedral olivine (5.9%) up to 1.5 mm, subhedral clinopyroxene (52.0%) up to 2.4 mm, anhedral-to-euhedral orthopyroxene (2.0%) up to 2.8 mm, anhedral-to-euhedral opaque minerals (trace) up to 1.1 mm, and primary anhedral calcite (trace) up to 0.26 mm. Most olivine are resorbed, most orthopyroxene show vermicular texture and some clinopyroxene occur as glomerocrysts. The sample contains xenoliths of gabbro up to 4.2 mm with subhedral-to-euhedral plagioclase and subhedral-to-euhedral clinopyroxene. The medium dark gray matrix (85.0%) contains microlites of subhedral-to-euhedral plagioclase, anhedral iddingsitized olivine, anhedral-to-subhedral clinopyroxene and anhedral-to-euhedral opaque minerals.

Rock name: olivine basalt

Trachytic rocks

Sample number: R8-1-16-LN
Location: 38°03'18''N Latitude; 116°08'52''W Longitude
Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing phenocrysts (14.0%) of subhedral-to-euhedral zoned trachytic labradorite (92.9%) up to 5.1 mm, anhedral olivine (2.9%) up to 0.5 mm, subhedral clinopyroxene
Appendix B: Part 1. Petrographic Descriptions (cont.)

(trace) up to 1.7 mm, and anhedral-to-euhedral opaque minerals (4.3) up to 1.4 mm. Most olivine have reaction rims of orthopyroxene. The medium dark gray matrix (86.0%) contains microlites of subhedral-to-euhedral plagioclase, subhedral clinopyroxene and anhedral-to-euhedral opaque minerals.

Rock name: trachyte

Sample number: R8-1-43-LN
Location: 38°07'45"N Latitude; 116°05'20"W Longitude
Description: Porphyritic, holocrystalline and very slightly vesicular basalt containing phenocrysts (7.6%) of subhedral-to-euhedral zoned labradorite (100%) up to 1.0 mm, anhedral iddingsitized olivine (trace) up to 0.18 mm, anhedral-to-subhedral clinopyroxene (trace) up to 1.0 mm, anhedral-to-subhedral orthopyroxene (trace) up to 0.15 mm and anhedral-to-euhedral opaque minerals (trace) up to 0.5. The medium dark gray matrix (92.4%) contains microlites of subhedral-to-euhedral plagioclase, anhedral-to-euhedral opaque minerals and primary anhedral calcite. The calcite has an interlocking texture with other minerals.

Rock name: trachyte

Basaltic andesites

Sample number: RR-4
Location: 38°11'43"N Latitude; 116°12'31"W Longitude
Description: Porphyritic and holocrystalline basalt containing phenocrysts (19.0%) of subhedral-to-euhedral zoned labradorite (76.8%) up to 1.2 mm, anhedral iddingsitized olivine (1.1%) up to 0.4 mm, anhedral-to-subhedral hedenbergite (16.8%) up to 0.74 mm, anhedral ferrosilite (4.2%) up to 0.26 mm, anhedral sanidine (trace) up to 0.6 mm, and anhedral-to-subhedral opaque minerals (1.1%) up to 0.2 mm. The medium dark gray matrix (81.0%) contains microlites of euhedral plagioclase, anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals. Naumann and others (1991) identified hedenbergite and ferrosilite by x-ray diffraction (XRD) analyses. These names are used here for the clinopyroxenes and orthopyroxenes in the basaltic andesites.

Rock name: basaltic andesite

Sample number: R9-1-63-LN
Location: 38°11'36"N Latitude; 116°12'5"W Longitude
Description: Porphyritic and holocrystalline basalt containing phenocrysts (10.6%) of subhedral-to-euhedral zoned labradorite (79.2%) up to 1.5 mm, anhedral iddingsitized olivine (3.8%) up to 0.3 mm, anhedral-to-subhedral hedenbergite (13.2%) up to 2.05 mm, anhedral ferrosilite (3.8%) up to 0.4 mm, anhedral sanidine (trace) up to 0.28 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.13 mm. The medium dark gray matrix (89.4%) contains microlites of euhedral
Appendix B: Part 1. Petrographic Descriptions (cont.)

plagioclase, anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals.

Rock name: basaltic andesite

Sample number: R9-1-65-LN
Location: 38°10'56"N Latitude; 116°11'45"W Longitude
Description: Porphyritic and holocrystalline basalt containing phenocrysts (15.4%) of subhedral-to-euhedral zoned labradorite (84.5%) up to 1.1 mm, anhedral iddingsitized olivine (3.9%) up to 0.25 mm, anhedral-to-subhedral hedenbergite (10.4%) up to 0.6 mm, anhedral ferrosilite (6.5%) up to 0.9 mm, anhedral sanidine (1.3) up to 1.0 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.1 mm. Plagioclase commonly occur as glomerocrysts. The medium dark gray matrix (84.6%) contains microlites of euhedral plagioclase, anhedral iddingsitized olivine and anhedral-to-euhedral opaque minerals.

Rock name: basaltic andesite

Pancake Range

Monotony Tuff

Sample number: PR-7
Location: 38°12'41"N Latitude; 116°09'41"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (39.2%) of subhedral sanidine (12.8%) up to 1.1 mm, anhedral-to-euhedral zoned plagioclase (45.4%) up to 2.5 mm, anhedral-to-subhedral oscillatory quartz (31.1%) up to 2.6 mm, subhedral-to-euhedral biotite (8.7%) up to 2.0 mm, anhedral opaque minerals (2.0%) up to 0.5 mm, euhedral apatite (trace) up to 0.14 mm, and subhedral zircon (trace) up to 0.07 mm. Most quartz are resorbed and most plagioclase are highly altered to sericite. The light olive glassy matrix (60.2%) is highly devitrified to chalcedony and shows eutaxitic texture. Pumice fragments (0.6%) are flattened, highly devitrified, and up to 3.3 mm in length. Most show vapor phase crystallization of quartz and sanidine.

Rock name: rhyolite ash-flow tuff

Sample number: RR-14
Location: 38°11'38"N Latitude; 116°10'25"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (44.8%) of anhedral-to-subhedral sanidine (16.1%) up to 3.0 mm, anhedral-to-euhedral zoned plagioclase (50.9%) up to 1.5 mm, anhedral oscillatory quartz (23.2%) up to 3.0 mm, subhedral-to-euhedral biotite (6.3%) up to 1.3 mm, anhedral-to-subhedral opaque minerals (1.6%) up to 0.6 mm, euhedral sphene (trace) up to 0.15 mm, euhedral apatite (trace) up to 0.02 mm, and subhedral zircon
Appendix B: Part 1. Petrographic Descriptions (cont.)

(trace) up to 0.14 mm. Some quartz and sanidines are resorbed and some biotites are bent. The dark yellowish-brown matrix (57.2%) is highly devitrified glass and shows eutaxitic texture.

Rock name: dacite ash-flow tuff

Sample number: RR-15
Location: 38°11′18″N Latitude; 116°09′53″W Longitude

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (43.8%) of anhedral-to-subhedral sanidine (20.1%) up to 1.1 mm, subhedral-to-euhedral zoned plagioclase (50.2%) up to 4.2 mm, anhedral oscillatory quartz (20.1%) up to 4.2 mm, subhedral-to-euhedral biotite (7.3%) up to 1.7 mm, anhedral-to-subhedral opaque minerals (1.4%) up to 0.5 mm, euhedral apatite (trace) up to 0.03 mm, and euhedral zircon (trace) up to 0.1 mm. Some quartz are resorbed and some biotites are bent. The grayish-orange pink matrix (56.2%) is highly devitrified glass.

Rock name: dacite ash-flow tuff

Sample number: PR-37
Location: 38°10′47″N Latitude; 116°08′09″W Longitude

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (49.6%) of anhedral-to-subhedral sanidine (30.6%) up to 1.2 mm, subhedral-to-euhedral zoned plagioclase (46.4%) up to 2.3 mm, anhedral oscillatory quartz (10.1%) up to 3.7 mm, subhedral-to-euhedral biotite (11.7%) up to 2.7 mm, subhedral hornblende (trace) up to 1.3 mm, subhedral-to-euhedral zircon (trace) up to 0.07 mm, subhedral-to-euhedral apatite (trace) up to 0.04 mm, and anhedral-to-euhedral opaque minerals (1.2%) up to 0.6 mm. Some quartz are resorbed and some biotite are bent. The dark yellowish-brown matrix (49.8%) is highly devitrified glass, shows eutaxitic texture and is composed of pumice fragments. Larger pumice fragments (0.6) are flattened, highly devitrified to chalcedony, and up to 5.1 mm in length.

Rock name: dacite ash-flow tuff

tuff of Bald Mountain

Sample number: PR-1
Location: 38°12′07″N Latitude; 116°08′28″W Longitude

Description: Pyroclastic, vitrophyric, densely welded tuff containing phenocrysts (21.8%) of anhedral-to-subhedral sanidine (26.6%) up to 1.5 mm, subhedral-to-euhedral zoned plagioclase (65.1%) up to 1.6 mm, subhedral-to-euhedral biotite (4.6%) up to 1.1 mm, subhedral hornblende (1.8%) up to 0.3 mm, subhedral clinopyroxene (trace) up to 0.5 mm, subhedral-to-euhedral zircon (trace) up to 0.06 mm, subhedral-to-euhedral sphene (trace) up to 0.20 mm, and anhedral-to-subhedral opaque minerals (1.8%) up to 0.5 mm. The grayish-black matrix (75.4%) is very slightly devitrified glass, shows eutaxitic texture and is composed mostly of
Appendix B: Part 1. Petrographic Descriptions (cont.)

gas bubble wall shards with lesser amounts of blocky shards. Pumice fragments (1.4%) are flattened, very slightly devitrified and are up to 14 mm in length. Some fragments show vapor phase crystallization of sanidine. Lithic fragments (1.4%) are up to 3.2 mm in diameter and contain up to 0.7 mm plagioclase and sanidine laths in a glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: PR-2
Location: 38°12′12″N Latitude; 116°08′27″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (9.2%) of anhedral-to-subhedral sanidine (6.5%) up to 1.2 mm, subhedral-to-euhedral zoned plagioclase (76.1%) up to 1.5 mm, subhedral-to-euhedral biotite (13.0%) up to 1.2 mm, anhedral-to-euhedral opaque minerals (1.3%) up to 0.5 mm, subhedral clinopyroxene (trace) up to 0.6 mm, subhedral sphene (trace) up to 0.06 mm, and subhedral zircon (trace) up to 0.04 mm. The light gray matrix (82.8%) is slightly-to-moderately devitrified glass and is composed mostly of gas bubble wall shards with lesser amounts of blocky shards. Pumice fragments (0.4%) are blocky, moderately devitrified and are up to 12 mm in length. Lithic fragments (10.6%) are up to 15 mm in length and contain up to 0.7 mm sanidine, 1.2 mm plagioclase and 0.9 mm biotite crystals in a highly devitrified glassy matrix.

Rock name: rhyolite ash-flow tuff

Sample number: PR-3
Location: 38°12′04″N Latitude; 116°08′39″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (9.8%) of anhedral-to-subhedral sanidine (15.6%) up to 1.5 mm, subhedral-to-euhedral zoned plagioclase (70.3%) up to 2.6 mm, subhedral-to-euhedral biotite (16.3%) up to 1.3 mm, subhedral hornblende (4.4%) up to 0.3 mm, anhedral-to-euhedral opaque minerals (trace) up to 0.5 mm, subhedral zircon (trace) up to 0.05 mm, and euhedral sphene (trace) up to 0.8 mm. The medium gray matrix (85.0%) is slightly-to-moderately devitrified glass and is composed mostly of gas bubble wall shards with lesser amounts of blocky shards. Pumice fragments (2.2%) are flattened, moderately devitrified, and up to 12 mm in length. Lithic fragments (3.0%) are holocrystalline containing up to 0.2 mm sanidine, 0.5 mm plagioclase and 0.35 mm biotite crystals.

Rock name: rhyolite ash-flow tuff

Sample number: PR-5
Location: 38°12′38″N Latitude; 116°09′33″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (6.2%) of anhedral-to-subhedral sanidine (61.3%) up to 2.0 mm, anhedral-to-euhedral zoned plagioclase (29.0%) up to 1.8 mm, subhedral-to-euhedral biotite (9.7%) up to 1.7 mm, subhedral-to-euhedral zircon (trace) up to
Appendix B: Part 1. Petrographic Descriptions (cont.)

0.06 mm, subhedral sphene (trace) up to 0.8 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.5 mm. Some sanidines are resorbed. The pinkish-gray matrix (83.4%) is slightly-to-moderately devitrified glass, shows eutaxitic texture and is composed mostly of gas bubble wall shards with lesser amounts of blocky shards. Pumice fragments (0.8%) are blocky, moderately devitrified, and up to 18 mm in length. Lithic fragments (9.6%) are up to 6 mm in length and contain up to 0.5 mm of sanidine and plagioclase and up to 0.7 mm biotite in a devitrified glassy matrix. Some holocrystalline lithic fragments up to 0.7 mm in length and containing what appear to be fine-grained sanidine and quartz crystals are present.

Rock name: rhyolite ash-flow tuff

Shingle Pass Tuff Unit A

Sample number: PR-17a
Location: 38°13'24''N Latitude; 116°07'41''W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (7.2%) of anhedral-to-subhedral sanidine (33.3%) up to 1.0 mm, subhedral-to-euhedral zoned plagioclase (50.0%) up to 2.9 mm, anhedral oscillatory quartz (2.8%) up to 0.9 mm, subhedral-to-euhedral biotite (11.1%) up to 1.0 mm, anhedral-to-subhedral opaque minerals (2.8%) up to 0.8 mm, subhedral-to-euhedral zircon (trace) up to 0.13 mm, and euhedral apatite (trace) up to 0.08 mm. The grayish-orange pink matrix (81.7%) is slightly-to-moderately devitrified glass and is composed of mostly bubble wall shards with minor amounts of blocky shards. Pumice fragments (9.7%) are flattened, slightly devitrified, and up to 37 mm in length. Lithic fragments (1.4%) are up to 8.0 mm in length and are mostly porphyritic and hypocrystalline with phenocrysts of plagioclase up to 0.9 mm in a glassy matrix. Some fragments are holocrystalline and microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: PR-17b
Location: 38°13'24''N Latitude; 116°07'41''W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (9.0%) of anhedral-to-subhedral sanidine (31.1%) up to 0.9 mm, subhedral-to-euhedral zoned plagioclase (47.7%) up to 2.6 mm, anhedral oscillatory quartz (4.4%) up to 0.8 mm, subhedral-to-euhedral biotite (17.8%) up to 2.1 mm, anhedral-to-subhedral opaque minerals (trace) up to 0.6 mm, a subhedral-to-euhedral zircon (trace) up to 0.04 mm, and euhedral apatite (trace) up to 0.06 mm. Some biotite are bent. The grayish-orange pink matrix (82.3%) is slightly-to-moderately devitrified glass and is composed of mostly bubble wall shards with minor amounts of blocky shards. Pumice fragments (6.6%) are flattened, slightly-to-moderately devitrified, and up to 37 mm in length. Lithic fragments (2.1%) are up to 5.0 mm in length and are mostly porphyritic and hypocrystalline with
Appendix B: Part 1. Petrographic Descriptions (cont.)

phenocrysts of plagioclase up to 0.6 mm in a glassy matrix. Some fragments are holocrystalline and others are microcrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: PR-39
Location: 38°13'22"N Latitude; 116°07'43"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (7.4%) of subhedral-to-euhedral sanidine (32.4%) up to 3.5 mm, subhedral-to-euhedral zoned plagioclase (45.9%) up to 2.7 mm, anhedral quartz (2.7%) up to 0.5 mm, subhedral-to-euhedral biotite (13.5%) up to 2.2 mm, subhedral-to-euhedral zircon (trace) up to 0.05 mm, subhedral-to-euhedral apatite (trace) up to 0.09 mm, and anhedral-to-euhedral opaque minerals (1.4%) up to 0.4 mm. The very light gray glassy matrix (83.8%) is highly devitrified glass and shows eutaxitic texture. Pumice fragments (12.8%) are flattened, highly devitrified to chalcedony and up to 30 mm in length. Some show vapor phase crystallization of quartz and sanidine.

Rock name: rhyolite ash-flow tuff

Shingle Pass Tuff Unit B

Sample number: PR-40
Location: 38°13'25"N Latitude; 116°07'48"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately-to-densely welded tuff containing phenocrysts (12.2%) of anhedral-to-subhedral sanidine (72.1%) up to 1.5 mm, subhedral zoned plagioclase (21.3%) up to 3.2 mm, subhedral-to-euhedral biotite (6.6%) up to 0.8 mm, subhedral-to-euhedral zircon (trace) up to 0.02 mm, subhedral-to-euhedral apatite (trace) up to 0.21 mm, and subhedral-to-euhedral opaque minerals (trace) up to 0.6 mm. The very light gray glassy matrix (59.8%) is moderately-to-highly devitrified to chalcedony and is composed of mostly bubble wall shards with minor amounts of blocky shards and pumice fragments. Larger pumice fragments (24.8%) are flattened, highly devitrified to chalcedony, and up to 16 mm in length. Some show vapor phase crystallization of sanidine and plagioclase. Lithic fragments (3.2%) are up to 6.0 mm and are porphyritic and hypocrystalline containing phenocrysts of plagioclase up to 0.08 mm and quartz up to 0.8 mm in a glassy matrix.

Rock name: rhyolite ash-flow tuff

Shingle Pass Tuff Unit C

Sample number: PR-46
Location: 38°13'06"N Latitude; 116°07'38"W Longitude
Appendix B: Part 1. Petrographic Descriptions (cont.)

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (10.0%) of anhedral-to-subhedral sanidine (58.0%) up to 2.0 mm, zoned anhedral-to-subhedral plagioclase (14.0%) up to 1.6 mm, anhedral quartz (8.0%) up to 1.0 mm, subhedral-to-euhedral biotite (14.0%) up to 2.3 mm, subhedral-to-euhedral hornblende (2.0%) up to 0.7 mm, subhedral-to-euhedral zircon (trace) up to 0.06 mm, subhedral-to-euhedral apatite (trace) up to 0.04 mm, and subhedral-to-euhedral opaque minerals (1.8%) up to 0.5 mm. Some sanidines are embayed. The light brown glassy matrix (76.4%) is highly devitrified to chalcedony, shows eutaxitic texture and is composed of mostly bubble wall shards with minor amounts of blocky shards. Pumice fragments (15.8%) are flattened, highly devitrified and up to 15 mm in length.

Rock name: rhyolite ash-flow tuff

Shingle Pass Tuff Unit D

Sample number: PR-18
Location: 38°13'08"N Latitude; 116°10'38"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (28.2%) of anhedral-to-euhedral sanidine (15.6%) up to 1.8 mm, subhedral-to-euhedral zoned plagioclase (37.6%) up to 2.0 mm, anhedral oscillatory resorbed quartz (17.7%) up to 1.2 mm, subhedral-to-euhedral biotite (15.6%) up to 1.4 mm, subhedral-to-euhedral hornblende (12.1%) up to 0.7 mm, anhedral-to-euhedral opaque minerals (1.4%) up to 0.5 mm, subhedral-to-euhedral zircon (trace) up to 0.05 mm, and euhedral apatite (trace) up to 0.13 mm. The grayish-orange pink matrix (45.8%) is highly devitrified glass and shows eutaxitic texture. Pumice fragments (25.4%) are flattened, highly devitrified to chalcedony, and are up to 25 mm in length. Lithic fragments (0.6%) are composed of fine holocrystalline material and are up to 2.5 mm in diameter. Some have a minor amount of euhedral plagioclase crystal up to 1 mm in length.

Rock name: rhyolite ash-flow tuff

Sample number: PR-19
Location: 38°13'11"N Latitude; 116°09'56"W Longitude
Description: Pyroclastic, vitrophyric, densely welded tuff containing phenocrysts (36.2%) of anhedral-to-euhedral sanidine (44.2%) up to 2.2 mm, subhedral-to-euhedral zoned plagioclase (23.8%) up to 2.1 mm, anhedral oscillatory quartz (9.4%) up to 0.8 mm, subhedral-to-euhedral biotite (2.8%) up to 0.8 mm, subhedral-to-euhedral hornblende (18.2%) up to 1.2 mm, subhedral-to-euhedral zircon (trace) up to 0.02 mm, euhedral apatite (trace) up to 0.07 mm, and anhedral-to-subhedral opaque minerals (1.7%) up to 0.3 mm. The light gray matrix (39.2%) is moderately devitrified glass and shows eutaxitic texture. Pumice fragments (24.6%) are flattened, moderately-to-highly devitrified to chalcedony, and are up to
Appendix B: Part 1. Petrographic Descriptions (cont.)

45 mm in length. This sample lacks lithic fragments.

Rock name: rhyolite ash-flow tuff

Sample number: PR-28
Location: 38°13'10"N Latitude; 116°09'50"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (26.2%) of anhedral-to-euhedral sanidine (51.9%) up to 2.3 mm, subhedral-to-euhedral zoned plagioclase (19.1%) up to 1.7 mm, subhedral resorbed quartz (12.2%) up to 1.0 mm, subhedral-to-euhedral biotite (4.6%) up to 0.8 mm, anhedral-to-euhedral hornblende (10.7%) up to 0.7 mm, euhedral apatite (trace) up to 0.09 mm, subhedral-to-euhedral zircon (trace) up to 0.03 mm, and anhedral opaque minerals (1.5%) up to 0.5 mm. The pale brown matrix (44.0%) is highly devitrified glass and shows eutaxitic texture. Pumice fragments (25.8%) are flattened, highly devitrified to chalcedony, and are up to 15 mm in length. Lithic fragments (4.0%) are up to 4.7 mm in diameter and appear to be basaltic in composition with plagioclase laths up to 1.5 mm in length.

Rock name: rhyolite ash-flow tuff

tuff of Arrowhead

Sample number: PR-8
Location: 38°12'16"N Latitude; 116°08'05"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (23.8%) of anhedral sanidine (9.2%) up to 0.5 mm, anhedral-to-euhedral zoned plagioclase (63.9%) up to 2.2 mm, subhedral-to-euhedral biotite (17.6%) up to 1.7 mm, anhedral-to-subhedral hornblende (5.9%) up to 1.0 mm, anhedral-to-subhedral opaque minerals (1.8%) up to 0.5 mm, and subhedral zircon (trace) up to 0.02 mm. The dark yellowish-orange matrix (37.4%) is highly devitrified glass. Pumice fragments (31.7%) are flattened, highly devitrified, and up to 11 mm in length.

Rock name: dacite ash-flow tuff

Sample number: PR-9
Location: 38°12'17"N Latitude; 116°08'05"W Longitude
Description: Pyroclastic, vitrophyric, moderately-to-densely welded tuff containing phenocrysts (19.4%) of anhedral sanidine (4.1%) up to 0.6 mm, subhedral-to-euhedral zoned plagioclase (77.3%) up to 2.1 mm, subhedral-to-euhedral biotite (9.3%) up to 1.7 mm, anhedral-to-subhedral hornblende (5.2%) up to 0.8 mm, subhedral-to-euhedral zircon (trace) up to 0.26 mm, subhedral-to-euhedral apatite (trace) up to 0.17 mm, and anhedral-to-euhedral opaque minerals (2.1%) up to 0.5 mm. The dark gray matrix (82.6%) is slightly-to-moderately devitrified glass and is composed mostly of gas bubble wall shards with lesser amounts of blocky shards. Lithic fragments (trace) are up to 1.6 mm in length and are hypocrystalline,
Appendix B: Part 1. Petrographic Descriptions (cont.)

containing very fine-grained crystals in glassy matrix. Spherulites of chalcedony are up to 0.5 mm in diameter.

Rock name: dacite ash-flow tuff

Sample number: PR-10
Location: 38°12'21"N Latitude; 116°08'05"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (9.4%) of anhedral-to-subhedral sanidine (4.3%) up to 1.3 mm, anhedral-to-euhedral zoned plagioclase (61.7%) up to 1.3 mm, subhedral-to-euhedral biotite (27.7%) up to 1.3 mm, anhedral-to-subhedral hornblende (4.3%) up to 0.25 mm, subhedral-to-euhedral zircon (trace) up to 0.06 mm, subhedral-to-euhedral apatite (trace) up to 0.05 mm, and anhedral-to-subhedral opaque minerals (2.1%) up to 0.6 mm. The moderate brown matrix (90.0%) is highly devitrified glass and is composed mostly of fine-to-medium-grained pumice fragments with lesser amounts of gas bubble wall and blocky shards. Larger pumice fragments (0.6%) are flattened, moderately devitrified, and up to 10 mm in length.

Rock name: dacite ash-flow tuff

Sample number: PR-38
Location: 38°12'28"N Latitude; 116°08'24"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, moderately welded tuff containing phenocrysts (16.8%) of anhedral-to-subhedral sanidine (27.4%) up to 2.4 mm, subhedral-to-euhedral zoned plagioclase (69.0%) up to 2.6 mm, subhedral-to-euhedral biotite (3.6%) up to 0.9 mm, subhedral-to-euhedral zircon (trace) up to 0.08 mm, subhedral-to-euhedral apatite (trace) up to 0.06 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.5 mm. Most biotites are bent. The yellowish-gray matrix (82.6%) is slightly-to-moderately devitrified glass and is composed of mostly bubble wall shards with minor amounts of blocky shards and pumice fragments. Lithic fragments (0.6%) are up to 1.5 mm in length and are porphyritic and hypocrystalline containing phenocrysts of plagioclase up to 0.2 mm in a highly devitrified glassy matrix.

Rock name: dacite ash-flow tuff

Sample number: PR-43
Location: 38°12'22"N Latitude; 116°08'19"W Longitude
Description: Pyroclastic, vitrophyric, moderately-to-densely welded tuff containing phenocrysts (15.6%) of anhedral sanidine (5.1%) up to 1.0 mm, anhedral-to-euhedral zoned plagioclase (70.5%) up to 2.6 mm, subhedral-to-euhedral biotite (14.1%) up to 1.6 mm, anhedral-to-euhedral hornblende (10.3%) up to 1.8 mm, subhedral-to-euhedral zircon (trace) up to 0.04 mm, subhedral-to-euhedral apatite (trace) up to 0.16 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.5 mm. The dark gray matrix (84.4%) is moderately-to-highly devitrified glass and is composed mostly of fine-to-medium-grained pumice fragments up to 0.5 mm with lesser amounts of gas bubble wall and blocky shards.
Appendix B: Part 1. Petrographic Descriptions (cont.)

Rock name: dacite ash-flow tuff

clasts within megabreccia of caldera of northern Reveille Range

Sample number: PR-15
Location: 38°11'44"N Latitude; 116°08'39"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (9.0%) of anhedral-to-subhedral sanidine (22.2%) up to 1.2 mm, anhedral-to-euhedral zoned plagioclase (60.0%) up to 2.2 mm, anhedral oscillatory quartz (11.1%) up to 2.0, mm, subhedral-to-euhedral biotite (2.2%) up to 1.2 mm, euhedral hornblende (trace) up to 1.8 mm, anhedral-to-subhedral opaque minerals (2.4%) up to 1.0 mm, subhedral zircon (trace) up to 0.03 mm, and subhedral sphene (trace) up to 0.08 mm. Some quartz are resorbed, and some biotites are bent. The yellowish-gray matrix (75.6%) is slightly-to-moderately devitrified glass, shows eutaxitic texture and is composed of mostly bubble wall shards with minor amounts of blocky shards and fine-to-medium-grained pumice fragments. Larger pumice fragments (15.0%) are flattened, moderately devitrified, and up to 4.0 mm in length. Lithic fragments (1.6%) are up to 8.0 mm in length and contain up to 0.35 mm sanidine and up to 3.0 mm plagioclase in a slightly devitrified glassy matrix. Some lithic fragments are holocrystalline consisting of sanidine and plagioclase crystals.

Rock name: rhyolite ash-flow tuff

Sample number: PR-22
Location: 38°12'27"N Latitude; 116°09'53"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, poorly-to-moderately welded tuff containing phenocrysts (23.2%) of anhedral-to-subhedral sanidine (43.1%) up to 3.1 mm, anhedral-to-euhedral zoned plagioclase (50.9%) up to 3.3 mm, anhedral oscillatory quartz (1.7%) up to 2.7 mm, subhedral-to-euhedral biotite (4.3%) up to 2.1 mm, anhedral-to-subhedral opaque minerals (trace) up to 0.7 mm, subhedral zircon (trace) up to 0.1 mm, and subhedral sphene (trace) up to 0.17 mm. Some quartz are resorbed, some biotites are bent and many plagioclase crystals are slightly altered to sericite. The very pale orange matrix (75.6%) is highly devitrified glass, shows eutaxitic texture and is composed of mostly bubble wall shards with minor amounts of pumice fragments. Larger pumice fragments (0.8%) are flattened, highly devitrified mostly to clay minerals, and up to 35 mm in length. Some fragments show vapor phase crystallization of sanidine and quartz. Lithic fragments (0.4%) are very fine-grained, holocrystalline and up to 20 mm in length.

Rock name: rhyolite ash-flow tuff

Sample number: PR-24
Location: 38°12'11"N Latitude; 116°09'30"W Longitude
Appendix B: Part 1. Petrographic Descriptions (cont.)

Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (17.8%) of subhedral sanidine (31.5%) up to 3.8 mm, subhedral-to- euhedral zoned plagioclase (62.9%) up to 1.2 mm, anhedral-to-subhedral oscillatory quartz (2.3%) up to 1.5 mm, subhedral-to-euhedral biotite (2.3%) up to 1.2 mm, anhedral opaque minerals (1.1%) up to 0.7 mm, euhedral apatite (trace) up to 0.15 mm, and anhedral sphene (trace) up to 0.1 mm. The pale red matrix (81.2%) is highly devitrified glass, shows eutaxitic texture and is composed of mostly pumice fragments with minor amounts of bubble wall and blocky shards. Larger pumice fragments (0.4%) are flattened, highly devitrified to chalcedony and up to 15 mm in length. Some fragments show vapor phase crystallization of quartz and sanidine.

Lithic fragments (0.6%) are very fine-grained, holocrystalline and up to 9.0 mm in length and consist of very fine holocrystalline material.

Rock name: rhyolite ash-flow tuff

Sample number: PR-30
Location: 38°11'42"N Latitude; 116°08'41"W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (7.2%) of anhedral-to-subhedral sanidine (19.4%) up to 1.7 mm, subhedral-to-euhedral zoned plagioclase (55.6%) up to 4.8 mm, anhedral oscillatory quartz (5.6%) up to 0.8 mm, subhedral-to-euhedral biotite (11.1%) up to 1.4 mm, anhedral opaque minerals (2.3%) up to 1.0 mm, subhedral-to-euhedral apatite (trace) up to 0.11 mm, and anhedral zircon (trace) up to 0.04 mm. The pale reddish-brown glassy matrix (30.8%) is highly devitrified to chalcedony. Pumice fragments (65.6%) are flattened, highly devitrified to chalcedony, and up to 45 mm in length. Many fragments show vapor phase crystallization of quartz and sanidine. Lithic fragments (2.4%) are very fine-grained, holocrystalline and up to 7 mm in length.

Rock name: rhyolite ash-flow tuff

Sample number: PR-31
Location: 38°11'43"N Latitude; 116°08'39"W Longitude. This sample is a 45 cm long lithic fragment with the ash-flow tuff unit described in sample PR-15.
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (25.6%) of anhedral-to-subhedral sanidine (40.8%) up to 4.0 mm, subhedral-to-euhedral zoned plagioclase (51.5%) up to 4.2 mm, anhedral oscillatory quartz (3.1%) up to 2.3 mm, subhedral-to-euhedral biotite (2.3%) up to 1.2 mm, anhedral opaque minerals (2.3%) up to 0.5 mm, subhedral zircon (trace) up to 0.11 mm, and euhedral apatite (trace) up to 0.10 mm. The pale brown glassy matrix (53.6%) is highly devitrified to chalcedony, shows eutaxitic texture and is composed of mostly pumice fragments with minor amounts of bubble wall and blocky shards. Larger pumice fragments (20.2%) are flattened, highly devitrified to chalcedony, and up to 30 mm in length. Some fragments show vapor phase crystallization of quartz and sanidine. Lithic fragments (0.2%) are up to 3.0 mm
Appendix B: Part 1. Petrographic Descriptions (cont.)

and are mostly hypocrystalline, containing very fine-grained crystals in a glassy matrix, and minor amounts of very fine-grained holocrystalline fragments.

Rock name: rhyolite ash-flow tuff

Sample number: PR-32b
Location: 38°11′47″N Latitude; 116°08′43″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (15.8%) of anhedral-to-subhedral sanidine (38.0%) up to 2.1 mm, anhedral-to-subhedral zoned plagioclase (51.9%) up to 2.4 mm, anhedral oscillatory quartz (5.1%) up to 1.5 mm, subhedral-to-euhedral biotite (2.5%) up to 1.1 mm, anhedral opaque minerals (2.5%) up to 0.7 mm, euhedral sphene (trace) up to 0.12 mm, and euhedral apatite (trace) up to 0.15 mm. The pale yellowish-brown glassy matrix (79.8%) is highly devitrified to chalcedony, shows eutaxitic texture and is composed of mostly pumice fragments with minor amounts of bubble wall shards. Larger pumice fragments (3.2%) are flattened, highly devitrified to chalcedony, and up to 25 mm in length. Some fragments show vapor phase crystallization of sanidine and quartz. Lithic fragments (1.2%) are up to 6.5 mm in length and are holocrystalline porphyritic fragments with phenocrysts of plagioclase up to 1.3 mm.

Rock name: rhyolite ash-flow tuff

Sample number: PR-32c
Location: 38°11′47″N Latitude; 116°08′43″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (16.8%) of anhedral-to-subhedral sanidine (40.5%) up to 3.6 mm, anhedral-to-euhedral zoned plagioclase (51.2%) up to 4.0 mm, anhedral quartz (3.6%) up to 1.7 mm, subhedral-to-euhedral biotite (3.6%) up to 1.2 mm, anhedral-to-subhedral opaque minerals (1.2%) up to 1.2 mm, anhedral-to-subhedral zircon (trace) up to 0.04 mm, and anhedral sphene (trace) up to 0.04 mm. The grayish-red matrix (74.6%) is highly devitrified glass, shows eutaxitic texture and is composed of mostly pumice fragments with very minor amounts of bubble wall shards. Larger pumice fragments (6.8%) are flattened, highly devitrified, and up to 32 mm in length. Some fragments show vapor phase crystallization of quartz and sanidine. Lithic fragments (1.8%) are up to 6 mm in length and are fine-grained and holocrystalline.

Rock name: rhyolite ash-flow tuff

Sample number: PR-45
Location: 38°12′14″N Latitude; 116°08′27″W Longitude
Description: Pyroclastic, porphyritic, hypocrystalline, densely welded tuff containing phenocrysts (23.4%) of anhedral-to-subhedral sanidine (47.9%) up to 3.5 mm, subhedral-to-euhedral zoned plagioclase (30.8%) up to 2.7 mm, anhedral oscillatory quartz (16.2%) up to 1.5 mm, subhedral-to-euhedral biotite (5.1%) up to 0.8 mm, anhedral opaque minerals (0.9%) up to 1.0 mm, anhedral zircon (trace) up to 0.02 mm, and euhedral apatite (trace) up to 0.10 mm. Most quartz are resorbed. The
Appendix B: Part 1. Petrographic Descriptions (cont.)
pale brown glassy matrix (63.6%) is highly devitrified to chalcedony and is composed of mostly bubble wall shards with minor amounts of pumice fragments. Larger pumice fragments (12.6%) are flattened, highly devitrified to chalcedony, and up to 46 mm in length. Lithic fragments (0.4%) are up to 3.0 mm in length and are microcrystalline and holocrystalline.

Rock name: rhyolite ash-flow tuff

rhyolitic dikes of Twin Springs Ranch

Sample number: PR-11
Location: 38°13′06″N Latitude; 116°08′41″W Longitude
Description: Porphyritic, vitrophyric, flow banded rhyolite containing phenocrysts (3.0%) of anhedral sanidine (trace) up to 2.5 mm, euhedral zoned plagioclase (60.0%) up to 1.5 mm, anhedral oscillatory quartz (13.3%) up to 0.7 mm, euhedral biotite (26.7%) up to 1.4 mm, subhedral opaque minerals (trace) up to 0.3 mm, subhedral-to-euhedral zircon (trace) up to 0.04 mm, subhedral-to-euhedral apatite (trace) up to 0.13 mm, and subhedral sphene (trace) up to 0.08 mm. The medium bluish-gray matrix (97.0%) is slightly devitrified flow banded glass.

Rock name: flow-banded rhyolite

Sample number: PR-12
Location: 38°13′08″N Latitude; 116°08′43″W Longitude
Description: Porphyritic, hypocrystalline, flow banded rhyolite containing phenocrysts (12.4%) of anhedral sanidine (11.8%) up to 1.2 mm, subhedral-to-euhedral zoned plagioclase (70.6%) up to 1.8 mm, anhedral-to-subhedral oscillatory quartz (11.8%) up to 2.0 mm, subhedral-to-euhedral biotite (5.9%) up to 1.9 mm, subhedral-to-euhedral apatite (trace) up to 0.08 mm, subhedral-to-euhedral zircon (trace) up to 0.02 mm, and anhedral-to-subhedral opaque minerals (trace) up to 0.4 mm. The pale red matrix (96.6%) is composed of microcrystalline material and moderately-to-highly devitrified glass containing up to 0.1 mm abundant amygdules.

Rock name: flow-banded rhyolite

Sample number: PR-34
Location: 38°11′00″N Latitude; 116°07′28″W Longitude
Description: Porphyritic, hypocrystalline, flow banded rhyolite containing phenocrysts (10.8%) of subhedral sanidine (3.7%) up to 1.3 mm, subhedral-to-euhedral zoned plagioclase (27.8%) up to 2.9 mm, anhedral oscillatory quartz (24.1%) up to 5.1 mm, subhedral-to-euhedral biotite (42.6%) up to 2.5 mm, subhedral-to-euhedral opaque minerals (1.9%) up to 0.2 mm, subhedral-to-euhedral zircon (trace) up to 0.1 mm, subhedral-to-euhedral apatite (trace) up to 0.04 mm, and euhedral sphene (trace) up to 0.66 mm. Some biotite are bent. The grayish-orange pink glassy matrix (89.2%) is highly devitrified to chalcedony.

Rock name: flow-banded rhyolite
Appendix B: Part 1. Petrographic Descriptions (cont.)

Cane Springs Unit

Sample number: PR-26
Location: 38°12′00″N Latitude; 116°09′18″W Longitude
Description: Finely laminated mudstone intercalated with silty sandstone. Laminations range from less than 0.25 mm up to 0.8 mm in thickness. The rock consists of angular to subrounded feldspar and quartz grains, biotites with cleavage aligned parallel with the lamination direction, and less abundant cuspate glass shards in a microcrystalline and highly devitrified glassy matrix. Based on these observations it appears that these sediments were deposited in a lacustrine environment close to the source as opposed to a fluvial environment or as a pyroclastic surge.

Rock name: mudstone
### Appendix B: Part 2. Point Count Analyses of the Ash-flow Tuffs

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<th>Sanidine</th>
<th>Plagioclase</th>
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*modal percentages of minerals total 100% of total phenocrysts. Point counts consist of 500 points per slide.*
### Appendix B: Part 2. Point Count Analyses of the Ash-flow Tuffs (cont.)

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<th>Sample</th>
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Appendix C: Geochemical Data

Part 1. Major and Trace Element Abundances
Part 2. Sr, Nd and Pb Isotope Ratios and Elemental Abundances
Part 3. CIPW Cation Norms
Part 4. New $^{40}$Ar/$^{39}$Ar Dates
## Appendix C: Part 1. Major and Trace Element Abundances

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| Eu/Eu* | 0.67 | 0.65 | 0.70 |

Samples were analyzed by x-ray fluorescence analyses (XRF) and/or instrumental neutron activation analyses (INAA). Cr and Ni values obtained from XRF were used in chemical plots only when INAA values were not available. See Naumann and others (1991) and Yogodzinski and others (1995) for complete chemical data for all basalt types in the Reveille Range. Samples RR-52 and RR-53 were collected by Mark Martin.
### Appendix C: Part 1. Major and Trace Element Abundances (cont.)

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<th>Major elements</th>
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<td><strong>SiO(_2)</strong></td>
<td>73.20</td>
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<td>0.27</td>
<td>0.16</td>
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<tr>
<td><strong>Fe(_2)O(_3)</strong></td>
<td>2.35</td>
<td>1.56</td>
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<td><strong>MgO</strong></td>
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<td>0.33</td>
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<tr>
<td><strong>CaO</strong></td>
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<td>1.38</td>
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<td><strong>K(_2)O</strong></td>
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<td><strong>MnO</strong></td>
<td>0.05</td>
<td>0.02</td>
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<tr>
<td><strong>P(_2)O(_5)</strong></td>
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| Mg# | 0.30 | 0.32 | 0.27 | 0.38 | 0.40 | 0.20 | 0.22 | 0.46 | 0.17 |

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<tr>
<td><strong>K(_2)O</strong></td>
</tr>
<tr>
<td><strong>Nb (XRF)</strong></td>
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<td><strong>Ta (INAA)</strong></td>
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<tr>
<td><strong>La (INAA)</strong></td>
</tr>
<tr>
<td><strong>Ce (INAA)</strong></td>
</tr>
<tr>
<td><strong>Sr (XRF)</strong></td>
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<tr>
<td><strong>Nd (INAA)</strong></td>
</tr>
<tr>
<td><strong>Sm (INAA)</strong></td>
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<td><strong>Zr (XRF)</strong></td>
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<td><strong>Hf (INAA)</strong></td>
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</tr>
<tr>
<td><strong>Lu (INAA)</strong></td>
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<td><strong>Cr (INAA)</strong></td>
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<td><strong>Cr (XRF)</strong></td>
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<td><strong>Ni (INAA)</strong></td>
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<td><strong>Eu/Eu</strong>*</td>
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\(^a\)Shingle Pass Tuff cooling unit A
\(^b\)Shingle Pass Tuff cooling unit B
\(^c\)Shingle Pass Tuff cooling unit C
\(^d\)Shingle Pass Tuff cooling unit D
## Appendix C: Part 1. Major and Trace Element Abundances (cont.)

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<td>TiO$_2$</td>
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<td>MgO</td>
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<td>CaO</td>
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<td>Mg#</td>
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<td>U (INAA)</td>
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<td>Sr (XRF)</td>
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<td>Hf (INAA)</td>
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Appendix C: Part 1. Major and Trace Element Abundances (cont.)

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<tr>
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<tr>
<td>TiO₂</td>
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<tr>
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<tr>
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<td>0.45 0.49 0.47 0.49</td>
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| Eu/Eu* | 0.82 | 1.00 1.00 | |
## Appendix C: Part 1. Major and Trace Element Abundances (cont.)

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<td>8.34</td>
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<td>4.68</td>
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<td>8.18</td>
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### Trace elements in ppm

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<td>Y (XRF)</td>
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<td>Yb (INAA)</td>
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<td>2.96</td>
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<td>Lu (INAA)</td>
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<td>0.46</td>
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<td>Cr (INAA)</td>
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<tr>
<td>Cr (XRF)</td>
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<td>142</td>
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<tr>
<td>Sc (INAA)</td>
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<td>18.3</td>
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<td>Co (INAA)</td>
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<td>19.7</td>
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<tr>
<td>Ni (INAA)</td>
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<td>25</td>
</tr>
<tr>
<td>Ni (XRF)</td>
<td>&lt;36</td>
<td>&lt;36</td>
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</table>

| Eu/Eu*         | 1.00      | 0.67                |

Samples were collected by Terry Naumann and analyzed by Gene Yododzinski.
### Appendix C: Part 2. Sr, Nd and Pb Isotope Ratios and Elemental Abundances

<table>
<thead>
<tr>
<th>Sample</th>
<th>Rb</th>
<th>Sr</th>
<th>(^{87}\text{Sr}/^{86}\text{Sr})</th>
<th>Sm</th>
<th>Nd</th>
<th>(^{147}\text{Sm}/^{144}\text{Nd})</th>
<th>(^{143}\text{Nd}/^{144}\text{Nd})</th>
<th>(\varepsilon_{\text{Nd}})</th>
<th>Pb</th>
<th>(^{206}\text{Pb}/^{204}\text{Pb})</th>
<th>(^{207}\text{Pb}/^{204}\text{Pb})</th>
<th>(^{208}\text{Pb}/^{204}\text{Pb})</th>
</tr>
</thead>
<tbody>
<tr>
<td>tuff of Goblin Knobs</td>
<td>RR-31</td>
<td>138</td>
<td>449</td>
<td>0.70917</td>
<td>4.24</td>
<td>28.47</td>
<td>0.0901</td>
<td>0.512172</td>
<td>-8.453</td>
<td>20.41</td>
<td>19.307</td>
<td>15.689</td>
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<tr>
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<td>PR-47a</td>
<td>147</td>
<td>429</td>
<td>0.70903</td>
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<td>0.1023</td>
<td>0.512219</td>
<td>-7.494</td>
<td>19.99</td>
<td>19.289</td>
<td>15.666</td>
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<tr>
<td></td>
<td>PR-48</td>
<td>149</td>
<td>412</td>
<td>0.70910</td>
<td>4.65</td>
<td>28.31</td>
<td>0.0993</td>
<td>0.512219</td>
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<td>20.84</td>
<td>19.296</td>
<td>15.651</td>
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<td>Shingle Pass Tuff</td>
<td>PR-28</td>
<td>151</td>
<td>237</td>
<td>0.70888</td>
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<td>37.43</td>
<td>0.1399</td>
<td>0.512231</td>
<td>-7.280</td>
<td>25.15</td>
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<td>15.655</td>
</tr>
<tr>
<td></td>
<td>PR-46</td>
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<td>115</td>
<td>0.70975</td>
<td>6.09</td>
<td>55.74</td>
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<td>29.30</td>
<td>19.234</td>
<td>15.628</td>
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<td>259</td>
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<td>21.40</td>
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<td>15.653</td>
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<td>230</td>
<td>187</td>
<td>0.70900</td>
<td>5.02</td>
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<td>0.0963</td>
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<td>16.99</td>
<td>19.278</td>
<td>15.669</td>
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<tr>
<td>tuff of Bald Mountain</td>
<td>PR-1</td>
<td>181</td>
<td>243</td>
<td>0.70915</td>
<td>6.85</td>
<td>41.70</td>
<td>0.0994</td>
<td>0.512205</td>
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<td>24.99</td>
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<td>15.640</td>
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<tr>
<td>tuff of Arrowhead</td>
<td>PR-43</td>
<td>138</td>
<td>569</td>
<td>0.70836</td>
<td>5.72</td>
<td>34.48</td>
<td>0.1003</td>
<td>0.512256</td>
<td>-6.845</td>
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<td>15.650</td>
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<tr>
<td>Episode-1 basalt</td>
<td>RR-46</td>
<td>28.3</td>
<td>703</td>
<td>0.70550</td>
<td>6.87</td>
<td>32.20</td>
<td>0.1290</td>
<td>0.512669</td>
<td>0.751</td>
<td>3.06</td>
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<td>15.615</td>
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<td>RR-28</td>
<td>44.3</td>
<td>1087</td>
<td>0.70360</td>
<td>7.96</td>
<td>43.15</td>
<td>0.1115</td>
<td>0.512885</td>
<td>4.920</td>
<td>3.14</td>
<td>19.280</td>
<td>15.565</td>
</tr>
</tbody>
</table>

Samples were obtained from thermal ionization mass spectrometry (TIMS). Elemental concentrations are in ppm. Rb and Sr values here are from XRF analyses. Sr isotopes are based on \(^{87}\text{Sr}/^{86}\text{Sr}=0.1194. Replicate analyses for Sr of NBS987 standard equal 0.71025 ± 2 (2σ analytical precision based on 15-20 analyses). Nd isotopes are based on \(^{146}\text{Nd}/^{144}\text{Nd}=0.7219. Replicate analyses of Nd for LaJolla standard equal 0.511860 ± 25. Assuming \(\varepsilon_{\text{Nd}}\) for LaJolla= -15.15 (Lugmair and Carlson, 1978; Wasserburg and others, 1981), \(\varepsilon_{\text{Nd}}\) are deviations in \(10^4\) from present-day chondritic \(^{143}\text{Nd}/^{144}\text{Nd}\). Pb isotope analyses are referenced to NBS-981 standard \(^{206}\text{Pb}/^{204}\text{Pb}=16.937, ^{207}\text{Pb}/^{204}\text{Pb}=15.493, ^{208}\text{Pb}/^{204}\text{Pb}=36.705\).
### Appendix C: Part 3. CIPW Cation Norms

<table>
<thead>
<tr>
<th>Mineral</th>
<th>tuff of Goblin Knobs</th>
<th>Monotony Tuff</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>RR-23</td>
<td>RR-24</td>
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<td>% anorthite</td>
<td>38.61</td>
<td>38.79</td>
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<td>30.47</td>
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<td>orthoclase</td>
<td>27.16</td>
<td>27.58</td>
</tr>
<tr>
<td>albite</td>
<td>22.17</td>
<td>21.14</td>
</tr>
<tr>
<td>nepheline</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>corundum</td>
<td>0.63</td>
<td>1.01</td>
</tr>
<tr>
<td>diopside</td>
<td>0.00</td>
<td>0.00</td>
</tr>
<tr>
<td>hypersthene</td>
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<tr>
<td>olivine</td>
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<td>0.47</td>
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<td>apatite</td>
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<tr>
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<table>
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<th>Shingle Pass Tuff</th>
<th>tuff of Streuben Knobs</th>
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<tbody>
<tr>
<td></td>
<td>RR-28&lt;sup&gt;d&lt;/sup&gt;</td>
<td>RR-29&lt;sup&gt;e&lt;/sup&gt;</td>
<td>RR-39&lt;sup&gt;f&lt;/sup&gt;</td>
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<tr>
<td>% anorthite</td>
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<td>20.56</td>
<td>19.20</td>
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<tr>
<td>quartz</td>
<td>31.17</td>
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<td>orthoclase</td>
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<td>24.01</td>
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<td>0.00</td>
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<td>0.23</td>
<td>0.33</td>
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<td>apatite</td>
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<td>100.01</td>
<td>100.00</td>
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<sup>d</sup>Shingle Pass Tuff cooling unit A  
<sup>e</sup>Shingle Pass Tuff cooling unit B  
<sup>f</sup>Shingle Pass Tuff cooling unit C  
<sup>g</sup>Shingle Pass Tuff cooling unit D
### Appendix C: Part 3. CIPW Cation Norms (cont.)

<table>
<thead>
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<th>tuff of Bald Mountain</th>
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<td>9.34</td>
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<td>4.37</td>
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<td>0.00</td>
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<tr>
<td>ilmenite</td>
<td>0.31</td>
<td>0.34</td>
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<td>0.09</td>
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<td>Total</td>
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<table>
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### Appendix C: Part 3. CIPW Cation Norms (cont.)

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<th>Basaltic andesites</th>
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<td>3.00</td>
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Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates

Eleven mineral separates from seven stratigraphic units were analyzed by the $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating technique. Because these samples were received from the laboratory after the thesis defense, a geochronology chapter was not incorporated into the thesis. The dates given below, however, are incorporated into the appropriate sections of the text.

With the exception of the ages for the tuff of northern Reveille Range (biotite), the plateau age for each analysis falls within analytical uncertainty with the respective total gas age. Therefore, the plateau age for each analysis are the accepted values for this thesis. A plateau age of $25.27 \pm 0.86$ Ma and a total gas age of $24.07 \pm 0.90$ Ma were obtained from a biotite separate for the tuff of northern Reveille Range. An isochron age of $25.53$ Ma was calculated from an isotope correlation diagram. Because the plateau age is consistent with the isochron age and the stratigraphic relationships with other lithologic units, the plateau age is the accepted value for the tuff of northern Reveille Range.

Ages of tuffs exposed in the Reveille and Pancake Ranges obtained from this study and from other researchers from various locations in central Nevada are listed in Table C1. The following dates are the accepted ages for the tuffs analyzed in this thesis:

<table>
<thead>
<tr>
<th>Tuff Type</th>
<th>Age (Ma ± Error)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tuff of Goblin Knobs</td>
<td>$25.64 \pm 0.53$ (sanidine)</td>
</tr>
<tr>
<td>tuff of northern Reveille Range</td>
<td>$25.27 \pm 0.86$ (biotite)</td>
</tr>
<tr>
<td>Monotony Tuff</td>
<td>$27.64 \pm 0.34$ (sanidine)</td>
</tr>
<tr>
<td>tuff of Bald Mountain</td>
<td>$26.46 \pm 0.42$ (sanidine)</td>
</tr>
<tr>
<td>Shingle Pass Tuff cooling unit C</td>
<td>$25.78 \pm 0.39$ (sanidine)</td>
</tr>
<tr>
<td>tuff of Arrowhead cooling unit B</td>
<td>$26.56 \pm 0.59$ (biotite)</td>
</tr>
<tr>
<td>rhyolitic dikes and domes of Twin Springs Ranch</td>
<td>$24.70 \pm 0.28$ (sanidine)</td>
</tr>
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</table>
Table C1. Known ages of tuffs in the Reveille and Pancake Ranges. Errors are given where known.

<table>
<thead>
<tr>
<th>Tuff</th>
<th>Source (caldera)</th>
<th>Age (Ma)</th>
<th>mineral</th>
<th>method</th>
<th>reference</th>
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</thead>
<tbody>
<tr>
<td>Windous Butte</td>
<td>Williams Ridge</td>
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<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Taylor and others, 1989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.6 ± 0.8</td>
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<td>K-Ar</td>
<td>Grommé and others, 1972</td>
</tr>
<tr>
<td></td>
<td></td>
<td>29.3 ± 0.6</td>
<td>sanidine</td>
<td>K-Ar</td>
<td>Armstrong, 1970</td>
</tr>
<tr>
<td></td>
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<td>31.3 ± 0.1</td>
<td>sanidine</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Best and other, 1989</td>
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<tr>
<td>Monotony</td>
<td>Pancake Range</td>
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<td>K-Ar</td>
<td>Ekren and others, 1973</td>
</tr>
<tr>
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<td>27.3</td>
<td>sanidine</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Best and other, 1989</td>
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<tr>
<td></td>
<td></td>
<td>27.1 ± 0.6</td>
<td>biotite</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Taylor and others, 1989</td>
</tr>
<tr>
<td></td>
<td></td>
<td>26.7 ± 0.3</td>
<td>hornblende</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Taylor and others, 1989</td>
</tr>
<tr>
<td></td>
<td></td>
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<td>sanidine</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>this study</td>
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<tr>
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<td>Bald Mountain</td>
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<td>this study</td>
</tr>
<tr>
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<td></td>
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<td>this study</td>
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<tr>
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<td>Quinn Canyon</td>
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<td>sanidine</td>
<td>$^{40}$Ar/$^{39}$Ar</td>
<td>Best and other, 1989</td>
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<td>Range</td>
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<td>$^{40}$Ar/$^{39}$Ar</td>
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<td>Range</td>
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<td>Ekren and others, 1973</td>
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<tr>
<td></td>
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<td>N. Reveille</td>
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*Sufficient data was not available to recalculate with decay constants of Steiger and Jäger (1977).
### New $^{40}$Ar/$^{39}$Ar date for the tuff of Goblin Knobs

#### (sample RR-31-sandine)

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<th>$^{40}$Ar/$^{39}$Ar</th>
<th>$^{37}$Ar/$^{39}$Ar</th>
<th>$^{36}$Ar/$^{39}$Ar</th>
<th>moles $^{39}$Ar</th>
<th>cumulative $^{39}$Ar</th>
<th>% radiogenic $^{40}$Ar</th>
<th>K/Ca</th>
<th>age (Ma)</th>
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<td>26.03 ± 1.08</td>
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Plateau age = 25.64 ± 0.53
Total gas age = 25.65 ± 0.60

### New $^{40}$Ar/$^{39}$Ar date for the tuff of Goblin Knobs

#### (sample RR-31-biotite)

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<th>$^{36}$Ar/$^{39}$Ar</th>
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<th>age (Ma)</th>
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Plateau age = 25.69 ± 0.58
Total gas age = 25.87 ± 0.58
Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates (cont.)

Spectrum of apparent age vs. cumulative $%^{39}\text{Ar}$ released for the tuff of Goblin Knobs

Isotope correlation diagram of $^{40}\text{Ar}/^{36}\text{Ar}$ vs. $^{39}\text{Ar}/^{34}\text{Ar}$ for the tuff of Goblin Knobs
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative $^{39}$Ar released for the tuff of Goblin Knobs

Isotope correlation diagram of $^{40}$Ar/$^{36}$Ar vs. $^{39}$Ar/$^{38}$Ar for the tuff of Goblin Knobs
**New \(^{40}\text{Ar}/^{39}\text{Ar}\) dates for Monotony Tuff**

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>(^{40}\text{Ar})</th>
<th>(^{39}\text{Ar}/^{39}\text{Ar})</th>
<th>(^{36}\text{Ar}/^{39}\text{Ar})</th>
<th>moles (^{39}\text{Ar})</th>
<th>cumulative % (^{39}\text{Ar})</th>
<th>% radiogenic (^{40}\text{Ar})</th>
<th>K/Ca</th>
<th>age (Ma)</th>
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Plateau age = 27.64 ± 0.34
Total gas age = 27.65 ± 0.42

**New \(^{40}\text{Ar}/^{39}\text{Ar}\) date for the tuff of northern Reveille Range**

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<th>(^{36}\text{Ar}/^{39}\text{Ar})</th>
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<th>cumulative % (^{39}\text{Ar})</th>
<th>% radiogenic (^{40}\text{Ar})</th>
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Plateau age = 25.27 ± 0.86
Total gas age = 24.07 ± 0.90
Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates (cont.)

Spectrum of apparent age vs. cumulative $%^{39}\text{Ar}$ released for the Monotony Tuff

![Graph showing the spectrum of apparent age vs. cumulative $%^{39}\text{Ar}$ released for the Monotony Tuff. The graph includes a line indicating the isotope correlation diagram.]

Isotope correlation diagram of $^{40}\text{Ar}/^{39}\text{Ar}$ vs. $^{39}\text{Ar}/^{36}\text{Ar}$ for the Monotony Tuff

![Graph showing the isotope correlation diagram of $^{40}\text{Ar}/^{39}\text{Ar}$ vs. $^{39}\text{Ar}/^{36}\text{Ar}$ for the Monotony Tuff. The graph includes a line indicating the correlation and a linear equation $y = 1.7698x + 296.6$.]

$T_r = 27.65 \pm 0.42 \text{ Ma}$

$T_r = 27.64 \pm 0.34 \text{ Ma}$
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative % $^{39}$Ar released for the tuff of northern Reveille Range

sample RR-47; biotite

$T_e = 24.07 \pm 0.90 \text{ Ma}$

$T_r = 25.27 \pm 0.86 \text{ Ma}$

Isotope correlation diagram of $^{40}$Ar/$^{36}$Ar vs. $^{39}$Ar/$^{36}$Ar for the tuff of northern Reveille Range

sample RR-47; biotite

$y = 1.6432x + 279.3$

$T_e = 24.07 \pm 0.90 \text{ Ma}$

$T_r = 25.27 \pm 0.86 \text{ Ma}$
New $^{40}$Ar/$^{39}$Ar date for the tuff of Bald Mountain

(sample PR-1; sanidine)

<table>
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<th>Temp °C</th>
<th>$^{40}$Ar/$^{39}$Ar</th>
<th>$^{39}$Ar/$^{38}$Ar</th>
<th>$^{38}$Ar/$^{39}$Ar</th>
<th>moles $^{39}$Ar</th>
<th>cumulative $^{39}$Ar</th>
<th>% radiogenic $^{39}$Ar</th>
<th>K/Ca</th>
<th>age (Ma)</th>
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<td>0.128</td>
<td>0.0115</td>
<td>560.0</td>
<td>2.5</td>
<td>32.8</td>
<td>3.83</td>
<td>26.53 ± 3.11</td>
</tr>
</tbody>
</table>

Plateau age = 26.46 ± 0.42
Total gas age = 26.56 ± 1.44

---

New $^{40}$Ar/$^{39}$Ar date for the tuff of Bald Mountain

(sample PR-1; biotite)

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>$^{40}$Ar/$^{39}$Ar</th>
<th>$^{39}$Ar/$^{38}$Ar</th>
<th>$^{38}$Ar/$^{39}$Ar</th>
<th>moles $^{39}$Ar</th>
<th>cumulative $^{39}$Ar</th>
<th>% radiogenic $^{39}$Ar</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>470</td>
<td>19.75</td>
<td>0.055</td>
<td>0.0611</td>
<td>23.6</td>
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<td>8.5</td>
<td>8.85</td>
<td>26.07 ± 29.97</td>
</tr>
<tr>
<td>880</td>
<td>5.266</td>
<td>0.024</td>
<td>0.0117</td>
<td>85.5</td>
<td>2.3</td>
<td>34.1</td>
<td>20.69</td>
<td>27.98 ± 2.26</td>
</tr>
<tr>
<td>980</td>
<td>2.598</td>
<td>0.008</td>
<td>0.0030</td>
<td>232.2</td>
<td>6.2</td>
<td>65.7</td>
<td>58.22</td>
<td>26.63 ± 0.52</td>
</tr>
<tr>
<td>1060</td>
<td>2.093</td>
<td>0.005</td>
<td>0.0012</td>
<td>396.3</td>
<td>10.5</td>
<td>81.5</td>
<td>100.35</td>
<td>26.63 ± 0.92</td>
</tr>
<tr>
<td>1155</td>
<td>1.924</td>
<td>0.005</td>
<td>0.0007</td>
<td>660.7</td>
<td>17.6</td>
<td>87.8</td>
<td>94.87</td>
<td>26.37 ± 0.44</td>
</tr>
<tr>
<td>1225</td>
<td>1.886</td>
<td>0.005</td>
<td>0.0006</td>
<td>916.0</td>
<td>24.4</td>
<td>89.6</td>
<td>98.29</td>
<td>26.39 ± 0.31</td>
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<tr>
<td>1330</td>
<td>1.911</td>
<td>0.005</td>
<td>0.0006</td>
<td>1013.8</td>
<td>27.0</td>
<td>89.0</td>
<td>101.21</td>
<td>26.54 ± 0.30</td>
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<td>2.195</td>
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<td>0.0016</td>
<td>429.6</td>
<td>11.4</td>
<td>77.3</td>
<td>71.18</td>
<td>26.49 ± 0.60</td>
</tr>
</tbody>
</table>

Plateau age = 26.51 ± 0.36
Total gas age = 26.51 ± 0.67
Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates (cont.)

Spectrum of apparent age vs. cumulative $^{39}\text{Ar}$ released for the tuff of Bald Mountain

Isotope correlation diagram of $^{40}\text{Ar}/^{16}\text{Ar}$ vs. $^{39}\text{Ar}/^{16}\text{Ar}$ for the tuff of Bald Mountain
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative $^{39}$Ar released for the tuff of Bald Mountain

![Graph]

Isotope correlation diagram of $^{40}$Ar/$^{36}$Ar vs. $^{39}$Ar/$^{36}$Ar for the tuff of Bald Mountain

![Graph]
### New 40Ar/39Ar date for Shingle Pass Tuff cooling unit C

#### (sample PR-46; sanidine)

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>40Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>38Ar/39Ar</th>
<th>moles 39Ar</th>
<th>cumulative % 39Ar</th>
<th>% radiogenic 39Ar</th>
<th>J = 0.008882</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>870</td>
<td>5.190</td>
<td>0.150</td>
<td>0.0107</td>
<td>43.7</td>
<td>1.6</td>
<td>39.0</td>
<td>3.27</td>
<td>32.13 ± 6.29</td>
<td></td>
</tr>
<tr>
<td>980</td>
<td>2.328</td>
<td>0.116</td>
<td>0.0024</td>
<td>112.7</td>
<td>4.1</td>
<td>69.0</td>
<td>4.23</td>
<td>25.55 ± 2.51</td>
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</tr>
<tr>
<td>1110</td>
<td>1.860</td>
<td>0.091</td>
<td>0.0008</td>
<td>266.1</td>
<td>9.6</td>
<td>86.8</td>
<td>5.37</td>
<td>25.70 ± 0.70</td>
<td></td>
</tr>
<tr>
<td>1205</td>
<td>1.740</td>
<td>0.067</td>
<td>0.0003</td>
<td>382.3</td>
<td>13.7</td>
<td>93.5</td>
<td>7.36</td>
<td>25.87 ± 0.68</td>
<td></td>
</tr>
<tr>
<td>1270</td>
<td>1.730</td>
<td>0.048</td>
<td>0.0003</td>
<td>497.4</td>
<td>17.9</td>
<td>94.1</td>
<td>10.15</td>
<td>25.91 ± 0.42</td>
<td></td>
</tr>
<tr>
<td>1320</td>
<td>1.730</td>
<td>0.032</td>
<td>0.0003</td>
<td>604.8</td>
<td>21.7</td>
<td>93.4</td>
<td>15.26</td>
<td>25.72 ± 0.63</td>
<td></td>
</tr>
<tr>
<td>1375</td>
<td>1.765</td>
<td>0.026</td>
<td>0.0004</td>
<td>521.4</td>
<td>18.7</td>
<td>92.2</td>
<td>18.81</td>
<td>25.88 ± 0.43</td>
<td></td>
</tr>
<tr>
<td>Fuse</td>
<td>1.895</td>
<td>0.027</td>
<td>0.0009</td>
<td>353.1</td>
<td>12.7</td>
<td>85.7</td>
<td>17.85</td>
<td>25.82 ± 0.63</td>
<td></td>
</tr>
</tbody>
</table>

Plateau age = 25.78 ± 0.39

Total gas age = 25.91 ± 0.73

### New 40Ar/39Ar date for Shingle Pass Tuff cooling unit C

#### (sample PR-46; biotite)

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>40Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>38Ar/39Ar</th>
<th>moles 39Ar</th>
<th>cumulative % 39Ar</th>
<th>% radiogenic 39Ar</th>
<th>J = 0.008803</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>740</td>
<td>11.96</td>
<td>0.130</td>
<td>0.0344</td>
<td>177.5</td>
<td>2.0</td>
<td>14.9</td>
<td>3.76</td>
<td>28.14 ± 6.62</td>
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</tr>
<tr>
<td>880</td>
<td>4.224</td>
<td>0.078</td>
<td>0.0088</td>
<td>466.6</td>
<td>5.2</td>
<td>38.2</td>
<td>6.27</td>
<td>25.43 ± 0.66</td>
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</tr>
<tr>
<td>980</td>
<td>2.755</td>
<td>0.980</td>
<td>0.0040</td>
<td>1276.1</td>
<td>14.3</td>
<td>59.2</td>
<td>0.50</td>
<td>25.72 ± 0.75</td>
<td></td>
</tr>
<tr>
<td>1060</td>
<td>2.050</td>
<td>2.219</td>
<td>0.0020</td>
<td>1368.2</td>
<td>15.3</td>
<td>77.7</td>
<td>0.22</td>
<td>25.14 ± 1.22</td>
<td></td>
</tr>
<tr>
<td>1160</td>
<td>1.925</td>
<td>1.496</td>
<td>0.0014</td>
<td>2404.0</td>
<td>27.0</td>
<td>85.5</td>
<td>0.33</td>
<td>25.37 ± 0.58</td>
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</tr>
<tr>
<td>1250</td>
<td>2.001</td>
<td>1.343</td>
<td>0.0016</td>
<td>1832.4</td>
<td>20.5</td>
<td>80.7</td>
<td>0.36</td>
<td>25.49 ± 0.48</td>
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</tr>
<tr>
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<td>2.672</td>
<td>1.321</td>
<td>0.0040</td>
<td>924.2</td>
<td>10.4</td>
<td>59.2</td>
<td>0.37</td>
<td>24.95 ± 2.04</td>
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<tr>
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<td>4.118</td>
<td>1.301</td>
<td>0.0085</td>
<td>469.1</td>
<td>5.3</td>
<td>40.7</td>
<td>0.38</td>
<td>26.46 ± 1.85</td>
<td></td>
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</tbody>
</table>

Plateau age = 25.35 ± 0.66

Total gas age = 25.48 ± 1.02
Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates (cont.)

Spectrum of apparent age vs. cumulative % $^{39}\text{Ar}$ released for Shingle Pass Tuff cooling unit C

Isotope correlation diagram of $^{40}\text{Ar}/^{39}\text{Ar}$ vs. $^{38}\text{Ar}/^{36}\text{Ar}$ for Shingle Pass Tuff cooling unit C
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative % $^{39}$Ar released for Shingle Pass Tuff cooling unit C

- Sample PR-46; biotite

- $T_1 = 25.48 \pm 1.02$ Ma
- $T_2 = 25.35 \pm 0.66$ Ma

Isotope correlation diagram of $^{40}$Ar/$^{39}$Ar vs. $^{39}$Ar/$^{40}$Ar for Shingle Pass Tuff cooling unit C

- Sample PR-46; biotite

- $y = 1.6007x = 305.6$

- $T_1 = 25.48 \pm 1.02$ Ma
- $T_2 = 25.35 \pm 0.66$ Ma
### New 40Ar/39Ar date for the rhyolitic dikes and plugs of Twin Springs Ranch

#### (sample PR-20; sanidine)

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>40Ar/39Ar</th>
<th>39Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>moles 39Ar</th>
<th>cumulative % 39Ar</th>
<th>% radiogenic</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>870</td>
<td>2.185</td>
<td>0.194</td>
<td>0.0021</td>
<td>2845.6</td>
<td>7.4</td>
<td>70.8</td>
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<td>24.27 ± 0.65</td>
</tr>
<tr>
<td>1020</td>
<td>1.806</td>
<td>0.183</td>
<td>0.0008</td>
<td>5829.2</td>
<td>15.1</td>
<td>86.1</td>
<td>2.67</td>
<td>24.40 ± 0.32</td>
</tr>
<tr>
<td>1170</td>
<td>1.669</td>
<td>0.132</td>
<td>0.0003</td>
<td>9405.0</td>
<td>24.3</td>
<td>94.0</td>
<td>3.71</td>
<td>24.61 ± 0.26</td>
</tr>
<tr>
<td>1245</td>
<td>1.653</td>
<td>0.102</td>
<td>0.0002</td>
<td>9595.9</td>
<td>24.8</td>
<td>95.2</td>
<td>4.80</td>
<td>24.69 ± 0.26</td>
</tr>
<tr>
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<td>1.687</td>
<td>0.093</td>
<td>0.0003</td>
<td>7982.8</td>
<td>20.5</td>
<td>93.7</td>
<td>5.26</td>
<td>24.77 ± 0.36</td>
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<td>83.5</td>
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<td>24.65 ± 0.47</td>
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<td>57.5</td>
<td>3.62</td>
<td>24.79 ± 1.49</td>
</tr>
</tbody>
</table>

Plateau age = 24.70 ± 0.28  
Total gas age = 24.61 ± 0.36

#### New 40Ar/39Ar date for the rhyolitic dikes and plugs of Twin Springs Ranch

#### (sample PR-20; biotite)

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>40Ar/39Ar</th>
<th>39Ar/39Ar</th>
<th>36Ar/39Ar</th>
<th>moles 39Ar</th>
<th>cumulative % 39Ar</th>
<th>% radiogenic</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>740</td>
<td>15.14</td>
<td>0.042</td>
<td>0.0458</td>
<td>150.1</td>
<td>0.4</td>
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<td>11.75</td>
<td>25.05 ± 12.33</td>
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<tr>
<td>880</td>
<td>4.005</td>
<td>0.014</td>
<td>0.0082</td>
<td>694.8</td>
<td>2.0</td>
<td>39.0</td>
<td>35.49</td>
<td>24.83 ± 2.38</td>
</tr>
<tr>
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<td>1.735</td>
<td>0.002</td>
<td>0.0005</td>
<td>2002.0</td>
<td>5.8</td>
<td>89.7</td>
<td>210.01</td>
<td>24.73 ± 1.03</td>
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<tr>
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<td>0.0006</td>
<td>1427.4</td>
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<td>203.13</td>
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</tr>
<tr>
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<td>0.0006</td>
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<td>14.9</td>
<td>88.1</td>
<td>207.99</td>
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</tr>
<tr>
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<td>0.0006</td>
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</tr>
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<td>0.0007</td>
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<td>97.58</td>
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<td>97.31</td>
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<td>0.0083</td>
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<td>3.1</td>
<td>37.8</td>
<td>71.92</td>
<td>23.85 ± 1.12</td>
</tr>
</tbody>
</table>

Plateau age = 24.77 ± 0.38  
Total gas age = 24.77 ± 0.56
Appendix C: Part 4. New $^{40}\text{Ar}/^{39}\text{Ar}$ Dates (cont.)

Spectrum of apparent age vs. cumulative $^{39}\text{Ar}$ released for the rhyolitic dikes and domes of Twin Springs Ranch

Sample PR-20; sanidine

$T_s = 24.61 \pm 0.36$ Ma

$T_p = 24.70 \pm 0.28$ Ma

Isotope correlation diagram of $^{40}\text{Ar}/^{38}\text{Ar}$ vs. $^{39}\text{Ar}/^{40}\text{Ar}$ for the rhyolitic dikes and domes of Twin Springs Ranch

Sample PR-20; sanidine

$y = 1.5947x + 282.3$

$T_s = 24.61 \pm 0.36$ Ma

$T_p = 24.70 \pm 0.28$ Ma
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative $^{39}$Ar released for the rhyolitic dikes and domes of Twin Springs Ranch

Isotope correlation diagram of $^{40}$Ar/$^{36}$Ar vs. $^{39}$Ar/$^{36}$Ar for the rhyolitic dikes and domes of Twin Springs Ranch
New $^{39}$Ar/$^{40}$Ar date for the tuff of Arrowhead cooling unit B

<table>
<thead>
<tr>
<th>Temp °C</th>
<th>$^{40}$Ar/$^{39}$Ar</th>
<th>$^{37}$Ar/$^{39}$Ar</th>
<th>$^{38}$Ar/$^{39}$Ar</th>
<th>moles $^{39}$Ar</th>
<th>cumulative $^{39}$Ar</th>
<th>% radiogenic Ar</th>
<th>K/Ca</th>
<th>age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>740</td>
<td>11.57</td>
<td>0.138</td>
<td>0.0336</td>
<td>192.8</td>
<td>1.9</td>
<td>14.1</td>
<td>3.55</td>
<td>26.02 ± 9.06</td>
</tr>
<tr>
<td>880</td>
<td>4.983</td>
<td>0.094</td>
<td>0.0109</td>
<td>502.0</td>
<td>5.0</td>
<td>35.2</td>
<td>5.22</td>
<td>27.90 ± 2.17</td>
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<tr>
<td>980</td>
<td>2.895</td>
<td>0.077</td>
<td>0.0041</td>
<td>876.6</td>
<td>8.8</td>
<td>57.3</td>
<td>6.34</td>
<td>26.41 ± 0.72</td>
</tr>
<tr>
<td>1060</td>
<td>2.364</td>
<td>0.170</td>
<td>0.0023</td>
<td>1115.1</td>
<td>11.2</td>
<td>70.4</td>
<td>2.88</td>
<td>26.49 ± 0.72</td>
</tr>
<tr>
<td>1155</td>
<td>2.197</td>
<td>1.934</td>
<td>0.0023</td>
<td>1869.0</td>
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<td>0.25</td>
<td>26.34 ± 0.71</td>
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<td>0.0014</td>
<td>3096.4</td>
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<td>26.88 ± 0.40</td>
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<td>1350</td>
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<td>0.0024</td>
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<td>71.8</td>
<td>0.49</td>
<td>26.45 ± 0.84</td>
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<td>0.0056</td>
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<td>8.0</td>
<td>51.4</td>
<td>0.50</td>
<td>26.82 ± 1.47</td>
</tr>
</tbody>
</table>

Plateau age = 26.56 ± 0.59
Total gas age = 26.66 ± 0.93
Appendix C: Part 4. New $^{40}$Ar/$^{39}$Ar Dates (cont.)

Spectrum of apparent age vs. cumulative % $^{39}$Ar released for the tuff of Arrowhead cooling unit B

Isotope correlation diagram of $^{40}$Ar/$^{39}$Ar vs. $^{39}$Ar/$^{40}$Ar for the tuff of Arrowhead cooling unit B
Appendix D: Sample Locations for Chemical Data
## Appendix D: Sample Locations for Chemical Data

<table>
<thead>
<tr>
<th>Reveille Range</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Pancake Range</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>RR-1</td>
<td>38°11'51&quot;N</td>
<td>116°11'11&quot;W</td>
<td>PR-1</td>
<td>38°12'07&quot;N</td>
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<td>116°11'18&quot;W</td>
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<td>PR-29</td>
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*Samples were collected in the northern Reveille Range but south of the study area.

*Samples were collected north of the study area near Sandy Summit, Pancake Range.

Refer to Figure 8 for the location map of these samples.
Appendix E: Statistical and Geochemical Equations
Appendix E: Statistical and Geochemical Equations

% error:

\[
\% error = \left( \frac{[X]_{\text{measured}} - [X]_{\text{known}}}{[X]_{\text{known}}} \right) \times 100\%
\]

where,

\([X] = \text{concentration of oxide or element}\)

Standard deviation (s):

\[
s = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n - 1}}
\]

where,

\(x_i = \text{individual analysis}\)

\(\bar{x} = \text{mean of replicate analyses}\)

\(n = \text{number of samples}\)

Mean relative % error:

\[
\% error = \frac{s}{\bar{x}} \times 100\%
\]

where,

\(s = \text{standard deviation}\)

\(\bar{x} = \text{mean of replicate analyses}\)

Loss on ignition:

\[
LOI = \left( \frac{\text{weight}_i - \text{weight}_f}{\text{weight}_i} \right) \times 100\%
\]

where,

\(\text{weight}_i - \text{weight}_f = \text{weight of water in the sample}\)

\(\text{weight}_i = \text{weight of the sample}\)
Appendix E: Statistical and Geochemical Equations (cont.)

Epsilon Nd:

$$\varepsilon_{Nd} = \left[ \left( \frac{^{143}Nd}{^{144}Nd} \right)' \right] - 1 \times 10^4$$

where,

$$\frac{^{143}Nd}{^{144}Nd} = \text{initial} \frac{^{143}Nd}{^{144}Nd}$$

$$\left( \frac{^{143}Nd}{^{144}Nd} \right)'_{\text{CHUR}} = \text{initial CHUR}$$

Initial CHUR (Nd):

$$\left( \frac{^{143}Nd}{^{144}Nd} \right)'_{\text{CHUR}} = \left( \frac{^{143}Nd}{^{144}Nd} \right)_{\text{CHUR}}^0 - \left( \frac{^{147}Sm}{^{144}Nd} \right)_{\text{CHUR}}^0 \left( e^{\lambda t} - 1 \right)$$

where,

$$\frac{^{143}Nd}{^{144}Nd} _{\text{CHUR}}^0 = 0.512638 \text{ ratio of modern CHUR}$$

modern CHUR is based on LaJolla, in which $\varepsilon_{Nd} = -15.15$

$$\left( \frac{^{147}Sm}{^{144}Nd} \right)_{\text{CHUR}}^0 = 0.1967 = \text{present day value of CHUR}$$

$$\lambda = 6.54 \times 10^{-12} \text{ y}^{-1}$$

$t = \text{age of sample}$

Initial $^{143}Nd/^{144}Nd$:

$$\frac{^{143}Nd}{^{144}Nd} = \left( \frac{^{143}Nd}{^{144}Nd} \right)_0^0 - \left( \frac{^{147}Sm}{^{144}Nd} \right)_{^{143}Nd/^{144}Nd}^0 \left( e^{\lambda t} - 1 \right)$$
Appendix E: Statistical and Geochemical Equations (cont.)

\[
\frac{^{143}\text{Nd}}{^{144}\text{Nd}} = \text{ratio of the sample at the present time}
\]

\[
\frac{^{147}\text{Sm}}{^{144}\text{Nd}} = \text{present day ratio of the sample}
\]

\[\lambda = 6.54 \times 10^{-12} \text{ y}^{-1}\]

\[t = \text{age of the sample}\]

Initial \(^{87}\text{Sr}/^{86}\text{Sr}\):

\[\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right) = \left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)^0 - \left(\frac{^{87}\text{Rb}}{^{86}\text{Sr}}\right)^0 \left(e^{\lambda t} - 1\right)\]

where,

\[\left(\frac{^{87}\text{Sr}}{^{86}\text{Sr}}\right)^0 = \text{ratio of the sample at the present time}\]

\[\left(\frac{^{87}\text{Rb}}{^{86}\text{Sr}}\right)^0 = \text{present day ratio of the sample}\]

\[\lambda = 1.42 \times 10^{-11} \text{ y}^{-1}\]

\[t = \text{age of the sample}\]

Mg#:

\[
\text{Mg\#} = \frac{\text{Mg}}{\text{Mg} + \text{Fe}}
\]

where,

\[\text{Mg} = \frac{\text{MgO}}{40.305}\]

\[\text{Fe} = \frac{2(\text{FeO}) \times 0.9}{159.676}\]

Eu Anomaly:

\[
\frac{\text{Eu}}{\text{Eu}^*} = \frac{\text{Eu(measured)}}{\text{Eu(chondrite)}} / \frac{\text{Eu(projected)}}{\text{Eu(chondrite)}}
\]
Appendix E: Statistical and Geochemical Equations (cont.)

where,

\( \text{Eu (measured)} / \text{Eu (chondrite)} = \) actual value of Eu on spider diagram
(Figure 13.)

\( \text{Eu (projected)} / \text{Eu (chondrite)} = \) value of Eu (Figure 13) if no Eu/Ca
substitution in plagioclase occurred

Total Gas Age \((t_g)\):

\[
t = \frac{1}{\lambda} \ln \left( \frac{40\text{Ar}^*}{40\text{K}} \times \frac{\lambda_{\text{total}}}{\lambda_{\text{EC}}} + 1 \right)
\]

where,

\( \lambda_{\text{total}} = 5.543 \times 10^{-10} \text{y}^{-1} \)

\( \lambda_{\text{EC}} = 0.581 \times 10^{-10} \text{y}^{-1} \)

\( 40\text{Ar}^* = \) radiogenic Argon

\( 40\text{K} = \) naturally occurring radioactive isotope of K (0.01167%)

Isochron Age \((t_i)\):

\[
t = \frac{1}{\lambda} \ln \left( \frac{40\text{Ar}^*}{39\text{Ar}} \times J + 1 \right)
\]

where,

\( \frac{40\text{Ar}^*}{39\text{Ar}} = \) slope \((m)\) of the isochron

\( J = J\)-value

\( \lambda = 5.543 \times 10^{-10} \text{y}^{-1} \)

Plateau Age \((t_p)\) using a weighted mean:

\[
t \pm \sigma = \frac{\sum_{i=1}^{n} t_i w_i}{\sum_{i=1}^{n} w_i} \pm \sqrt{\frac{1}{\sum_{i=1}^{n} w_i}}
\]

where,

\( t_i = \) age of each increment

\( w_i = \frac{1}{\sigma_i^2} \) of each increment

where,

\( \sigma = t_i \sigma_t \)
Appendix E: Statistical and Geochemical Equations (cont.)

\[ \sigma_i = \sqrt{\frac{J^2 F^2 (\sigma_F^2 + \sigma_J^2)}{t^2 \lambda^2 (1 + FJ)^2}} \]

where,
- \( J \) = \( J \)-value
- \( F = \frac{\text{Ar}^{40}}{\text{Ar}^{39}} \)
- \( \sigma_J^2 \) = variance in \( J \)-value
- \( \sigma_F \) = variance in \( F \)
- \( \lambda = 5.543 \times 10^{-10} \, \text{y}^{-1} \)
- \( t = \text{age of increment (y)} \)

Unit Thickness:

a). slope and dip opposed; slope angle + dip angle < 90°.

\[ \text{BC} = \text{AB} \sin (x + y) \]

b). slope and dip opposed; slope angle + dip angle > 90°.

\[ \text{BC} = \text{AB} \cos (x + y - 90°) \]

c). slope and dip in same direction; dip angle > slope angle.

\[ \text{BC} = \text{AB} \sin (x - y) \]
Appendix E: Statistical and Geochemical Equations (cont.)

d). slope and dip in same direction; dip angle < slope angle.

\[ BC = AB \sin (y - x) \]

where,
BC = thickness of the unit
AB = slope distance
slope distance = change in elevation + \sin slope angle
slope angle = \tan^{-1}(change in elevation + map distance)
x = dip angle
y = slope angle