Geology and Geochemistry of the Broken Ridge Area, Southern Wah Wah Mountains, Iron County, Utah

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By KAREN A. DUTTWEILER and WALLACE R. GRIFFITTS

Geologic, petrologic, and geochemical relationships of tin-bearing, rhyolitic lava flows of the 12-million-year-old Steamboat Mountain Formation in the area of Broken Ridge

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Geology and Geochemistry of the Broken Ridge Area, Southern Wah Wah Mountains, Iron County, Utah

By Karen A. Duttweiler *and* Wallace R. Griffitts

ABSTRACT

This study focuses on the geologic, petrologic, and geochemical relationships of the tin-bearing rhyolitic lava flows and domes of the 12-million-year-old Steamboat Mountain Formation in the area of Broken Ridge, southwest Utah. Early phases of volcanic activity produced a topaz-bearing rhyolite followed by eruption from many local centers of a crystal-poor rhyolite. The rhyolites contain high Si (>74 percent) and alkalies, and are enriched in tin, beryllium, fluorine, niobium, lithium, and rubidium. The calcium, magnesium, titanium, phosphorus, and barium contents are low. These characteristics suggest that the rhyolites formed as highly differentiated magmas.

Crystalline cassiterite and wood tin are abundant and widespread in heavy-mineral-concentrate samples. Some of the crystalline cassiterite occurs with specular hematite in veins within a brecciated rhyolite lava flow, which formed either as a result of degassing during cooling of the flow or from a later hydrothermal event.

Reactivation along a 23-million-year-old fault zone formed a series of high-angle normal faults that cut the 12-million-year-old rhyolite flows of the Steamboat Mountain Formation. Multiple hydrothermal events resulted in widespread alteration along the faults and concentration of beryllium, fluorine, tin, niobium, molybdenum, copper, zinc, tungsten, and barium.

INTRODUCTION

The geology and geochemistry of high-fluorine or topaz-bearing rhyolite lava flows in Nevada and Utah have been of considerable interest in recent years because of their structural and genetic implications and the moderate to high potential for beryllium, tin, molybdenum, uranium, and fluorine deposits associated with them. Deposits of beryllium and tin are commonly associated with high-fluorine rhyolites; rhyolitic flows and tuffs at Spor Mountain, Utah, are host to beryllium deposits (Burt and others, 1982) and uranium deposits (Lindsey, 1982), and tin occurs in rhyolite flows in the Sierra Madre Occidental in northern Mexico (Huspeni and others, 1984) and in the Black Range, N. Mex. (Lufkin, 1972; Eggleston and Norman, 1984). Two topaz-bearing rhyolitic lava flows occur in the southern Wah Wah Mountains, a north-south-trending mountain range in southwest Utah (fig. 1).

The presence of a 12-million-year-old topaz-bearing rhyolite flow and high beryllium, tin, and molybdenum contents in stream-sediment samples collected

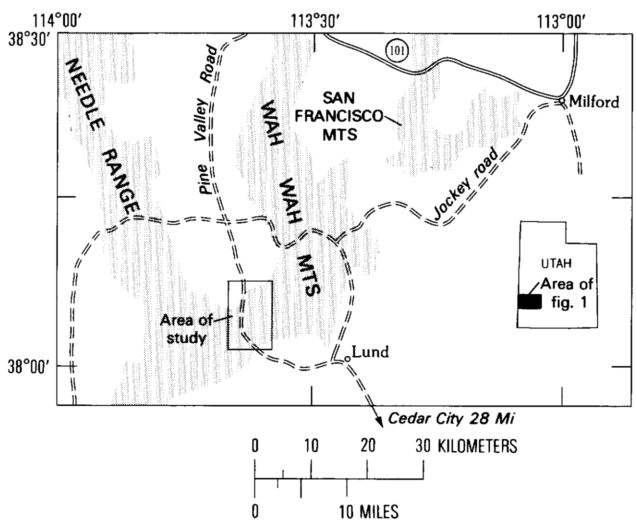

Figure 1. Location of study area, southwest Utah. Mountain ranges shaded.

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nearby during a reconnaissance geochemical survey by Miller and others (1985) spurred interest in the vicinity of Broken Ridge, in the Mountain Spring Peak 7½′ quadrangle, Iron County, Utah, located about 64 km northwest of Cedar City and 56 km southwest of Milford.

The purpose of this study was to determine the potential for deposits of beryllium, tin, molybdenum, or fluorite near Broken Ridge by documenting the geologic, petrologic, and geochemical relationships of the high-fluorine lava flows and domes, and the nature and extent of alteration along major faults.

Previous Work

A geologic map of the Mountain Spring Peak quadrangle was published at a scale of 1:24,000 by Best (1979); one of the Bible Spring quadrangle, to the west, was published by Best and Davis (1981); and the Teton quadrangle, to the north, was mapped by Best and Keith (1979). These maps at a scale of 1:24,000 and the accompanying descriptions of Oligocene and Miocene volcanic rocks in the area provided an excellent background for more detailed work.

A geochemical study of heavy-mineral concentrates in the Richfield 1°×2° sheet by Miller and others (1985) was the first geochemical study in the area. A rock geochemical study by Tucker and others (1981) is available for parts of the Mountain Spring Peak and Bible Spring 7½′ quadrangles. Steven and Morris (1984) compiled all available geologic and geochemical data on the Richfield 1°×2° sheet, at a scale of 1:250,000, to determine the mineral resource potential of the quadrangle.

Methods of Study

Fieldwork on which this paper is based was conducted by K.A. Duttweiler and W.R. Griffitts in the summer of 1983 and spring of 1984 with additional work in 1985. About 56 km^2 near Broken Ridge was mapped in detail at a scale of 1:24,000 (pl. 1). Detailed petrographic work was completed in 1985.

In addition to the mapping, 41 heavy-mineral-concentrate samples from stream sediment and 204 rock samples were collected for geochemical analysis in the area of Broken Ridge, Fourmile Wash, and west-southwestward along the Bible Spring fault zone. About 10 lbs of sediment from alluvium in dry washes was composited at each site and concentrated by panning. Most rock samples were chip samples composited from within a radius of about 2 m at each site. Samples of fresh rock were taken from outcrops ranging from ½ km to 2.5 km apart, depending on access and rock exposure. Samples of obviously altered or mineralized rock were collected every 8–10 m across an outcrop or zone of alteration. A representative specimen was retained for making thin sections, and very fine grained or altered rocks were split for X-ray diffraction studies to delineate alteration mineralogy.

Sample Preparation

The heavy-mineral concentrates were sieved through a 20-mesh screen, and the +20-mesh fraction was retained for mineralogical analysis. The light minerals, mainly quartz and feldspar, remaining in the –20-mesh fraction were removed with bromoform (sp. gr. 2.89). Magnetite was removed with a hand magnet. A Frantz Isodynamic Magnetic Separator with a 15° side slope and 25° forward slope was used to separate three fractions: magnetic at 0.5 ampere (M.5), magnetic at 1.0 ampere (M1), and nonmagnetic at 1.0 ampere (NM). The M.5 and M1 fractions were used only for mineralogical studies. The NM fraction contains the most common ore-forming sulfide and oxide minerals as well as such accessory minerals as zircon, sphene, topaz, and fluorite. The NM fraction was divided into two splits; one was saved for mineralogical analysis and one was hand-ground for spectrographic analysis.

All rock samples were crushed and pulverized to a fine powder. Major elements were obtained from analysis by X-ray fluorescence on splits of 19 selected samples. All rock samples were analyzed by spectrographic and other chemical methods.

Sample Analysis

Analyses of heavy-mineral concentrates and rock samples were by B.F. Arbogast and B.M. Adrian using a semiquantitative direct-current arc emission spectrographic method (Grimes and Marranzino, 1968). The elements and their limits of determination are listed in table 1. The semiquantitative spectrographic results were reported as one of six steps per order of magnitude (1, 0.7, 0.5, 0.3, 0.2, 0.15). The precision of the analytical method is approximately plus or minus 1 reporting interval at the 83 percent confidence level and plus or minus 2 reporting intervals at the 96 percent confidence level (Motooka and Grimes, 1976). Analyses for Li, Rb, and Cs in rock samples were by S.J. Sutley using a modification of the semiquantitative emission spectrographic method. Other analyses used on selected rocks are summarized in table 2.

Major elements for 19 pulverized rock samples were determined by A.E. Hubert using X-ray fluorescence spectrometry. Prior to analysis, 1 g of sample was

Table 1. Limits of determination for the spectrographic analysis of heavy-mineral concentrates and rocks

[Limits are based on a 10-mg sample for rocks, and a 5-mg sample for heavy-mineral concentrates; Fe, Mg, Ca, Ti in percent; other elements in parts per million; Li, Rb, Cs analyzed in rocks only]

Element	Lower determination limit		Upper determination limit	
	Concentrates	Rocks	Concentrates	Rocks
Iron (Fe)	0.1	0.05	50	20
Magnesium (Mg)	.05	.02	20	10
Calcium (Ca)	.1	.05	50	20
Titanium (Ti)	.005	.002	2	1
Manganese (Mn)	20	10	10,000	5,000
Silver (Ag)	1	0.5	10,000	5,000
Arsenic (As)	500	200	20,000	10,000
Gold (Au)	20	10	1,000	500
Boron (B)	20	10	5,000	2,000
Barium (Ba)	50	20	10,000	5,000
Beryllium (Be)	2	1	2,000	1,000
Bismuth (Bi)	20	10	2,000	500
Cadmium (Cd)	50	20	1,000	2,000
Cobalt (Co)	10	5	5,000	5,000
Chromium (Cr)	20	10	10,000	20,000
Copper (Cu)	10	5	50,000	1,000
Lanthanum (La)	50	20	2,000	2,000
Molybdenum (Mo)	10	5	5,000	2,000
Niobium (Nb)	50	20	5,000	5,000
Nickel (Ni)	10	5	10,000	20,000
Lead (Pb)	20	10	50,000	10,000
Antimony (Sb)	200	100	20,000	100
Scandium (Sc)	10	5	200	1,000
Tin (Sn)	20	10	2,000	5,000
Strontium (Sr)	200	100	10,000	10,000
Vanadium (V)	20	10	20,000	10,000
Tungsten (W)	100	50	20,000	2,000
Yttrium (Y)	20	10	5,000	10,000
Zinc (Zn)	500	200	20,000	1,000
Zirconium (Zr)	20	10	2,000	2,000
Thorium (Th)	200	100	5,000	5,000
Lithium (Li)		1		5,000
Rubidium (Rb)		10		5,000
Cesium (Cs)		20		50,000

dissolved in 7 g of lithium tetraborate flux by heating to 1100 °C in a Claisse fluxer for a minimum of 1 hour. The melt was poured into a mold to make a disk that was subsequently analyzed.

All analytical results for rock samples are given by Duttweiler (1985). Data for alluvial samples from Broken Ridge and for both rock and alluvial samples from the surrounding area appear in Detra and others (1986).

ACKNOWLEDGMENTS

Discussions with Dr. L.C. Hsu of the University of Nevada, M.G. Best of Brigham Young University, and T.A. Steven of the U.S. Geological Survey throughout this study were greatly appreciated. Discussions in the field with Robert L. Smith were especially enlightening. Numerous conversations with T. Botinelly improved the interpretation. Finally, we wish to thank the people of

Table 2. Chemical methods used for selected rock samples

Constituent determined	Analytical method	Determination limit[1] ppm	Analysts (USGS)	Reference
Gold (Au)	Atomic absorption.	0.05	T.A. Roemer and J.D. Sharkey.	Thompson and others, 1968.
Arsenic (As)	Atomic absorption.	10	T.A. Roemer and J.D. Sharkey.	Modification of Viets, 1978.
Fluorine (F)	Specific ion electrode.	100	D.L. Kelley and J.D. Sharkey.	Hopkins, 1977.
Uranium (U)	Fluorometry	.05	T.A. Roemer and J.D. Sharkey.	Modification of Cantanni and others, 1956.

[1]The determination limit is dependent on sample weight. Given limits imply use of sample weight required by method. Higher limits of determination result from using less than required sample weight.

Lund, Utah, and adjacent areas, especially Lehi Wood, for their hospitality and courtesy in giving valuable information concerning the history of mining in the area.

REGIONAL GEOLOGIC SETTING

Structural Setting

The southern Wah Wah Mountains lie near the eastern border of the Basin and Range physiographic province, 50–70 km west of the west edge of the Colorado Plateau. The area is within the Blue Ribbon lineament as described by Rowley and others (1978); this lineament is a prominent east-west structural zone within the Pioche mineral belt in southern Utah and Nevada that cuts across north-south-trending mountain ranges and valleys of the Basin and Range province (fig. 2). The lineament is about 25 km wide and several hundred kilometers in length, and it is marked by volcanic centers, mineral deposits, hydrothermally altered rocks, geophysical anomalies, and major faults (Rowley and others, 1978).

High-angle normal faults predominate in the southern Wah Wah Mountains. Most of the major faults characteristic of the Basin and Range province trend northeast, with the exception of the northwest-striking Blawn Wash fault zone northeast of The Tetons (fig. 2). Belts of silicic lava flows, magma centers, and dikes parallel the northeast-trending faults. Field evidence suggests the faults first formed in early to mid-Miocene time (Best and others, 1987), but movement has recurred along the faults since the mid-Miocene. For example, tilted and faulted Oligocene volcanic rocks are overlain by much less deformed late Miocene rocks of the Steamboat Mountain Formation. The Steamboat Mountain Formation is cut by small faults but not by any major throughgoing faults.

The general northeast trend of silicic magma centers, dikes, and faults in the southern Wah Wah Mountains suggests a northwest-southeast direction of extension in the early Miocene, contrary to a west-southwest–east-northeast direction of extension, described by Zoback and others (1981, p. 204) for the Western United States at 20–10 Ma (million years ago). Best and others (1987) suggested that a local perturbation in the regionally uniform early-mid Miocene stress field may have existed. They noted that the northeast trend of faults in the southern Wah Wah Mountains is nearly parallel to, and only a few tens of kilometers from, the long-standing hinge line between the thick craton to the east and the Paleozoic geosyncline to the west, the leading edge of the Sevier orogenic belt, and the transition zone between the Colorado Plateaus province and the Basin and Range province.

Thrust faults are prominent in sedimentary rocks of Paleozoic and Mesozoic age in adjacent areas but none are exposed in the Broken Ridge area.

General Stratigraphy

The southern Wah Wah Mountains consist primarily of Oligocene and Miocene volcanic and intrusive rocks that overlie and cut Paleozoic and Mesozoic sedimentary rocks.

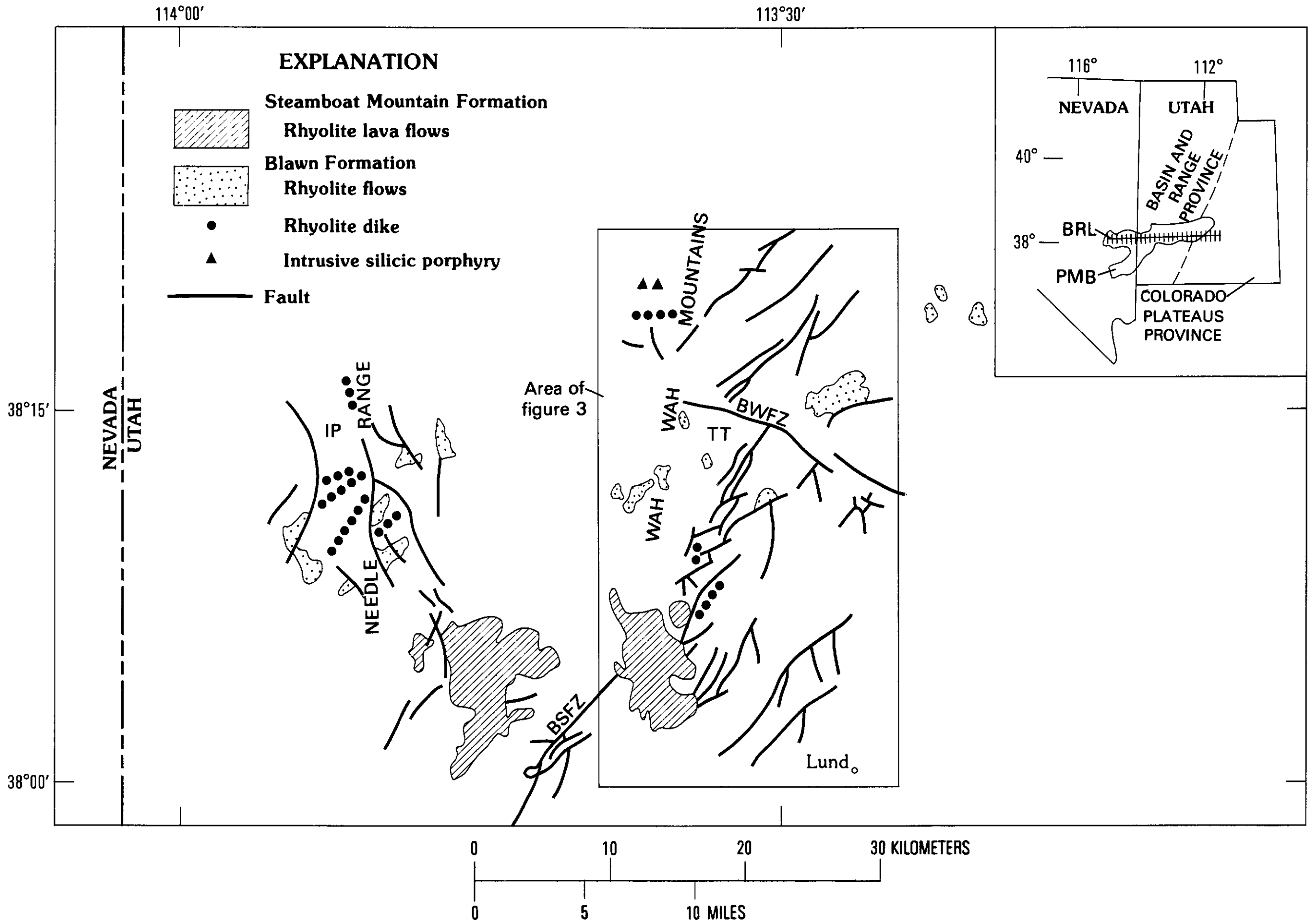

Figure 2. Southwest Utah and eastern Nevada, showing faults and extent of Miocene silicic volcanic rocks (after Best and others, 1987). BSFZ, Bible Spring fault zone; BWFZ, Blawn Wash fault zone; IP, Indian Peak; TT, The Tetons. Inset shows location of Pioche mineral belt (PMB) and Blue Ribbon lineament (BRL) (modified from Rowley and others, 1978).

From late Precambrian through the Paleozoic Era, deposition in southwest Utah took place in a miogeoclinal environment in which deposition of carbonate strata was dominant (Steven and Morris, 1984). During the Mesozoic Era the dominant mode of sedimentation was clastic sedimentation on a cratonic continental environment (Miller, 1966). The Laramide and Sevier orogenies in the late Mesozoic and early Tertiary terminated the extensive sedimentation and brought late Precambrian and Paleozoic carbonate rocks over clastic Mesozoic strata (Miller, 1966).

Oligocene Volcanic Rocks

Volcanic activity began about 33 Ma with deposition of the Sawtooth Peak Formation, a calc-alkalic ash-flow tuff of intermediate composition. This unit was covered, beginning at 30 Ma, by ash-flow tuff units in the Needles Range Group (Best and others, 1973; Best and Keith, 1979; Best and Grant, 1987) which comprise five formations: Escalante Desert Formation, Cottonwood Wash Tuff, Wah Wah Springs Formation, Ryan Spring Formation (not exposed near Broken Ridge), and Lund Formation. The Escalante Desert Formation consists of crystal-poor, rhyolitic ash-flow tuffs, rhyolite and pyroxene andesite lava flows, and local epiclastic deposits. The Cottonwood Wash Tuff is a crystal-rich dacite tuff which crops out primarily in the northern Needle Range (sometimes referred to as the Mountain Home Range) and in eastern Nevada. Following deposition of the Cottonwood Wash Tuff, eruption of the dacitic Wah Wah Springs Formation produced the Indian Peak caldera, which straddles the Utah–Nevada border. The Wah Wah Springs Formation is exposed in eastern Nevada and western Utah over an area of at least 22,000 km^2, and its eruption volume is estimated at nearly 1,500 km^3 (Best and Grant, 1987). Later episodes of volcanic activity produced the crystal-rich, dacitic Lund Formation, very widespread in the Needle Range and the southern Wah Wah Mountains, where it overlies either Paleozoic sedimentary rocks or the older volcanic rocks.

The Isom Formation overlies the Needles Range Group (Mackin, 1960) and consists of a trachytic ash-flow tuff. The Isom is generally only a few tens of meters thick and is widespread, reflecting the low relief in the area at the time of emplacement. This distinctive, crystal-poor densely welded tuff provides a prominent marker unit in the Oligocene sequence. It has been dated at 26–25 Ma (Armstrong, 1970; Fleck and others, 1975).

Ash-flow sheets of the Quichapa Group were erupted 25–22 Ma from the Caliente caldera complex south of Pioche, Nev. (Ekren and others, 1977). In the southern Wah Wah Mountains near Broken Ridge, the Condor Canyon Formation is the only unit of the Quichapa Group exposed. It has been dated at 22 Ma (Fleck and others, 1975).

Miocene Volcanic Rocks

Magmatism shifted from voluminous ash-flow tuff eruptions of intermediate composition to a bimodal mafic-rhyolite assemblage about 23 Ma, approximately at the onset of extensional tectonism in the eastern Basin and Range province (Best and others, 1987). The first pulse from 23–18 Ma was characterized by high-potassium mafic lava flows and rhyolitic tuffs and lava flows, accompanied by shallow intrusive porphyries. These are grouped together in the Blawn Formation (Best and others, 1987).

Another bimodal assemblage of less potassic mafic flows and rhyolitic ash-flow tuffs and lava flows belonging to the Steamboat Mountain Formation was erupted to the south of the Blawn Formation (fig. 2). Both formations occur in a general east-west trending belt and both periods of eruption were accompanied by alteration and mineralization.

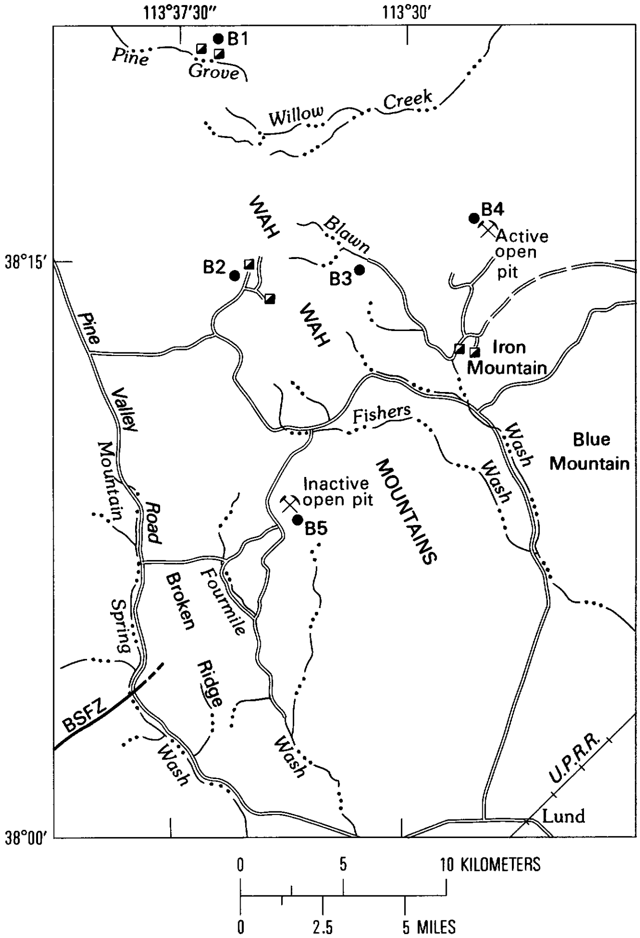

Figure 3. Locations of mines and prospect pits associated with the Blawn Formation. U.P.R.R., Union Pacific Railroad; BSFZ, Bible Spring fault zone; B1, Pine Grove deposit; B2, Staats mine; B3, Blawn Wash alunite; B4, gem quality red beryl; B5, Cima mine.

Blawn Formation and Associated Mineralization

Most of the exposed Blawn Formation consists of rhyolite lava flows that are rich in silica and fluorine. Intrusive masses of the same general age and composition are widely distributed but occupy a much smaller total area. Potassium-rich trachyandesite lava flows, approximately contemporaneous with the rhyolite tuffs and flows, are less abundant. Mineralization accompanied emplacement of some of the intrusive porphyries and high-silica lava flows of the Blawn Formation, as reflected in the locations of some mines and prospect pits on figure 3.

The Pine Grove porphyry molybdenum deposit in the west-central Wah Wah Mountains (fig. 3, loc. B1) is associated with altered quartz latite and quartz monzonite intrusions of Blawn age (Abbott and others, 1983). The igneous rocks are moderately to strongly argillized, silicified, sericitized, and pyritized, and locally contain disseminated ore and gangue minerals (Steven and Morris, 1984). The stockwork Mo-W porphyry deposit lies at a depth of 900 m to greater than 2,000 m (Abbott and others, 1983). Keith (1980) and Keith and others (1986) described a comagmatic ash-flow tuff that completely surrounds the Pine Grove pluton. Correlation of the intrusions with an ash-flow tuff is made possible by the presence of an yttrium-rich, almandine-spessartine accessory garnet of identical composition in both the ash-flow and intrusive units (Keith and others, 1986).

Porphyritic, flow-layered rhyolite emplaced 20.2 Ma (Rowley and others, 1978) forms a small intrusion at the Staats mine (fig. 3, loc. B2), an intermittent producer of fluorspar and uranium for many years. The ore minerals occur in brecciated and extremely altered rocks along contacts with Paleozoic carbonate rocks. Lindsey and Osmonson (1978) reported high concentrations of beryllium, gallium, lithium, molybdenum, niobium, and tin in unmineralized rhyolitic rocks from the Staats mine area.

An area about 6 km wide on the lower eastern slopes of Blawn Mountain (loc. B3, east of the Staats mine) consists of large bodies of the Blawn Formation altered to alunite, kaolinite, iron oxides, and silicified breccia (Lindsey and Osmonson, 1978). The source of the sulfur to form the alunite appears to be magmatic (R.O. Rye, written commun., 1982; from Steven and Morris, 1984). Samples of alunite from one of the deposits have been dated by K-Ar methods as 22.5–20 Ma (H.H. Mehnert, unpub. data, 1982–1983; from Steven and Morris, 1984), indicating that alteration took place during the Blawn period of igneous activity. The alteration at Blawn Mountain and the mineralization at the Staats mine could have resulted from the same hydrothermal event or from two separate events.

Rhyolite lava flows east of Blawn Wash and Willow Creek (fig. 3, loc. B4) have a K-Ar age of 22±0.8 Ma (Best and others, 1987), and locally contain gem quality red beryl in altered rock and along small fractures or veins. Topaz and bixbyite are also present, and the latter forms inclusions in some red beryl crystals.

The Cima (Katie) mine is located 5 km south-southwest of Jockey Spring (loc. B5). Ash-flow tuffs of the Blawn Formation are argillized and silicified along a fault contact with Paleozoic sedimentary rocks. Native sulfur with small stringers of cinnabar occurs within the altered rhyolitic tuffs. The Cima mine is located along the projection of the Bible Springs fault zone, suggesting that this deposit may have formed from hydrothermal fluids circulating along the Bible Spring fault zone soon after deposition of the Blawn Formation. Alternatively, it is possible that the mineralization and alteration resulted from hydrothermal activity at a later time that was associated with the Steamboat Mountain Formation (Steven and Morris, 1984).

Steamboat Mountain Formation

The Steamboat Mountain Formation consists of mafic lava flows, topaz-bearing rhyolitic lava flows and domes, ash-flow tuff, airfall deposits and reworked water-laid volcaniclastic rocks. The mafic lava flows are minor in extent in the southern Wah Wah Mountains (Best and others, 1987), whereas the rhyolite lava flows are extensive in both the Wah Wah Mountains and the southern Indian Peak range (fig. 2): they reach the greatest thickness of 500 m at Steamboat Mountain (Best and Davis, 1981; Best and others, 1987).

Hydrothermally altered rocks of the Steamboat Mountain Formation are particularly prominent along faults such as the Bible Spring fault zone and around the dome north of Mountain Spring. Altered and mineralized rocks associated with the Steamboat Mountain Formation in the vicinity of Broken Ridge and southwestward along the Bible Spring fault zone are the primary subject of later sections of this report.

GEOLOGY OF THE BROKEN RIDGE AREA

On the geologic map of the Broken Ridge area (pl. 1), the area west of about long 113°37′30″ W. is from Best (1979) and Best and Davis (1981), and the area east of this longitude was mapped as part of the present study. Best (1979) and Best and Davis (1981) gave detailed descriptions of units west of 113°7′30″ W.

Rhyolite lava flows and domes and pyroclastic rocks of the Steamboat Mountain Formation on Broken Ridge and Fourmile Wash unconformably overlie Oligocene volcanic rocks or Paleozoic rocks. The unconformity at the base of the Steamboat Mountain Formation must have a topographic relief of as much as 100 meters because the entire sequence of rocks belonging to the Blawn Formation is missing from Broken Ridge. All rocks are cut by numerous north- to northeast-trending normal faults and a few east-west- or northwest-trending faults.

Stratigraphy

Rocks Older Than the Steamboat Mountain Formation

Paleozoic sedimentary rocks.—This unit consists of undivided Paleozoic sedimentary rocks including limestone, dolomite, and some clastic sedimentary rocks.

Needles Range Group (Oligocene).—The upper part, undivided, of the Needles Range Group is represented by a small area east of Fourmile Wash in the east-central portion of the map area (pl. 1) that is underlain by the Needles Range Group, described by Best (1979). The Wah Wah Springs Formation is a crystal-rich dacitic ash-flow tuff containing abundant plagioclase, hornblende, and biotite phenocrysts with less than 25 percent quartz phenocrysts. It has been dated as 29.5 m.y. (Best, 1979). The Lund Formation is a 27.9-m.y. dacitic ash-flow tuff characterized by 25 percent quartz and biotite phenocrysts, with lesser amounts of hornblende. Locally, it contains a black basal vitrophyre (Best, 1979).

Isom Formation (Oligocene).—The Isom Formation, dated at 26 m.y., consists of a densely welded, red-brown to lavender ash-flow tuff with less than 20 percent phenocrysts of plagioclase and minor pyroxene.

It is widespread in the southern part of the map area, where it overlies the Lund Formation. It is generally only a few tens of meters thick. The unit weathers to distinctive brown plates or grus. Best (1979) and Best and Davis (1981) provided a detailed description.

Hornblende andesite (Miocene).—The hornblende andesite is a platy, gray rock with abundant black hornblende and lesser green augite phenocrysts in a very fine grained trachytic matrix rich in plagioclase. Locally, it is phenocryst poor or even aphyric. The thickness ranges from 50 to 100 m (Best, 1979).

Bauers Tuff Member of the Condor Canyon Formation (Miocene).—The Bauers Tuff Member is a gray, buff, and lavender, firmly welded ash-flow tuff containing 10 percent phenocrysts of plagioclase, sanidine, and biotite that crops out only in the northern portion of the map area. Age is 22 m.y. (Fleck and others, 1975).

Andesite (Miocene).—The andesite unit contains large plagioclase and smaller pyroxene phenocrysts set in a red-brown felsitic matrix (Best, 1979), and crops out only in the far northern portion of the map area.

Steamboat Mountain Formation (Miocene)

The Steamboat Mountain Formation was first mapped by Best (1979) as the formation of Blawn Wash and later reclassified as the Steamboat Mountain Formation on the basis of three samples of rhyolite yielding K-Ar dates of 13–12 Ma (Best and others, 1987). The original description of the rhyolite member of Broken Ridge included sequences of gray, red-brown, and lavender felsitic lava flows, and vertically flow-layered green glass (Best, 1979).

The Steamboat Mountain Formation on Broken Ridge includes extensive clastic tuffaceous beds, pumice-rich vent tuff, and rhyolite lava flows and domes. If the clastic rocks are used as markers of the base of rhyolite flows, the ridge contains several individual flows ranging in thickness from 40 to 200 feet. In most places, individual flows cannot be separated.

Where possible, we mapped two petrographically distinct phases of the rhyolite flow rocks as separate cartographic units: the crystal-rich gray rhyolite, which locally includes a basal vitrophyre, and red crystal-poor flow-layered rhyolite called the rhyolite member of Pine. Where the phases were not separated, undivided rhyolite is shown on the geologic map (pl. 1).

Broken Ridge is a mass of rhyolite of late Miocene age that is about 330 m thick (1,000 ft). This great thickness is due to repeated volcanic eruptions; each eruption resulted in part or all of a cycle of rock deposition, starting with deposition of the basal silicic clastic rocks, followed by eruption of compact, strongly layered rhyolite of Pine, and then by rather soft porous gray rhyolite flows that constitute most of the Steamboat Mountain Formation. Either or both of the two lower units, the silicic clastic rocks or the compact rhyolite of Pine, may be missing from a single cycle of rock deposition. For instance, on the east side of Broken Ridge, flow rocks of the gray rhyolite directly overlie Oligocene volcanic rocks, and in many places, the gray rhyolite overlies silicic clastic rocks. The rhyolite of Pine is missing from the depositional cycle in these two places.

The unit mapped as green glass formed as the enclosing rhyolite flow came to rest. The glass occurs as dikelike wedges in ramps at the top of the flow and small bodies elsewhere. Therefore, the green glass formed contemporaneously with the crystallized flow rocks.

Another local variant, the vent tuff, is approximately equivalent to the silicic clastic rocks, overlying the gray rhyolite of the preceding eruption and underlying the compact rhyolite of Pine which marks the new eruption. It is mainly pumice that was emplaced in and near the vent through which it was erupted.

Silicic Clastic Rocks

The silicic clastic rocks of Best (1979) are pyroclastic and epiclastic rocks associated with the Steamboat Mountain Formation that cover a large part of the southern Wah Wah Mountains (Best and Davis, 1981). The following description is restricted to the area mapped in this study.

In the Broken Ridge area, the clastic rocks for the most part underlie individual lava flows of the Steamboat Mountain Formation and unconformably overlie Oligocene volcanic rocks of the Needles Range Group and the Isom Formation, and Miocene andesitic rocks. Because they are less resistant than most of the surrounding rocks, the clastic rocks usually occur in small valleys between the topographically higher ridges of rhyolite. The thickness of the unit is from a few meters to 30 m. Most commonly, the unit dips gently from 5° to 15°; near faults dips may reach 35°.

The unit consists of a heterogeneous sequence of buff to pink weakly welded ash-flow tuff and minor air-fall tuff both of which interfinger with slope wash deposits and reworked water-deposited epiclastic rocks. The light- to dark-pink, weakly welded ash-flow tuff contains abundant lithic and pumice fragments 0.5–5 mm in diameter, and 1–5 percent quartz, feldspar, and biotite phenocrysts. As a whole, it is loosely cemented, though in some places it is silicified or calcified. The unit is conspicuous in aerial photographs because of its light color.

In the northern part of the map area the silicic clastic unit consists of a pumice-lapilli tuff which alternates with moderately sorted, mostly sand sized, water-laid deposits and poorly sorted slope wash deposits. The pumice-lapilli tuff contains sparse phenocrysts of quartz, feldspar, and biotite. Green pumice clasts from 0.5 to 4 cm in diameter constitute 30 percent or more of some beds. Other lithic fragments include green and black glass, and clasts of the Lund Formation and Wah Wah Springs Formation. East of Fourmile Wash, the pumice-lapilli tuff alternates with crudely bedded buff sandstone. Local lenses of angular fragments of Lund Formation up to 20 cm in diameter probably are slope wash deposits. Thus, both explosively erupted volcanic debris and water-transported volcanic particles were deposited prior to extrusion of overlying rhyolite lava flows.

The silicic clastic rocks in the southern portion of the map area were highly faulted and extensively argillized and silicified by hydrothermal solutions.

Vent Tuff

The vent tuff forms two small apronlike areas in the SE¼ sec. 23, T. 31 S., R. 16 W., where it underlies the rhyolite member of Pine. The unit resembles a breccia made up almost entirely of angular fragments of green glass and pumice averaging 1.3 cm in diameter with sparse lithic fragments of gray rhyolite. Most of the vent tuff is poorly sorted and gives no indication of bedding or layering and no apparent orientation of clasts. The unit is generally heterolithologic and varies greatly in composition in single outcrops.

The vent tuff is a product of very nearby explosive eruption and deposition. The older gray rhyolite from a previous eruptive cycle and the overlying flow of rhyolite member of Pine may have come from the same vent (pl. 1, cross sections *B–B′* and *C–C′*).

Rhyolite Member of Pine

The rhyolite member of Pine is most abundant near Pine triangulation station (NE¼ sec. 35, T. 31 S., R. 16 W.), but is common to the east and south as well. The unit consists of a red-brown, strongly flow layered, locally autobrecciated rhyolite and averages 30 m thick. The autobreccia, usually at the base, contains angular clasts of rhyolite in a felsitic matrix. Clasts range from a few centimeters across to large blocks a few meters in diameter. Some clasts are still largely glass whereas others are partially crystalline. The unit as a whole weathers to give honeycomb or mottled outcrops. Massive and resistant to erosion, it caps ridges made up primarily of the gray rhyolite, with which it may interfinger.

The rhyolite caps the ridges near Pine triangulation station, in a circular pattern that is conspicuous on aerial photographs. This circular structure is defined by the east-trending ridge north of Pine, where the rhyolite is near vertical, and the south-trending ridges east and southwest of Pine. This circular structure may reflect a subjacent intrusive dome.

Phenocrysts, generally less than 1 mm in diameter, average 3–5 percent of the rhyolite (table 3). Carlsbad-twinned sanidine comprises 2–3 percent of the rock; 1–2 percent subhedral embayed quartz is also present. Plagioclase is sparse. The crystalline and flow-layered groundmass consists of interlocking quartz and feldspar grains and contains up to 2 percent disseminated green-brown biotite. Flow layers are alternating dark red-brown and lavender, contorted and folded bands less than 1 mm across. Few textural or mineralogical differences between layers are visible, though some layers are replaced by secondary silica wherein quartz crystals fill small vugs and lithophysae. The spotty distribution and the autobrecciated and strongly flow layered nature of the rock suggest a very viscous lava, erupted from local centers. The initial flow material very likely extruded in many eruptions, preceded in places by tuff or pumice-rich ejecta.

Basal Vitrophyre

This unit consists of a crystal-rich vitrophyre with an underlying basal breccia that crops out north of Broken Ridge in the northernmost part of the map area. The thickness of this unit is about 30 m. The vitrophyre is light gray to black with locally abundant chalcedony in small veinlets and cavities; the chalcedony was probably deposited from fluids circulating during cooling of the gray rhyolite. Phenocrysts (in order of decreasing abundance) of moonstone sanidine, plagioclase, quartz, biotite, and opaques, accompanied by sparse crystals of zircon and apatite, are mostly between 0.5 and 1.5 mm in diameter and make up 15–25 percent of the rock (table 3).

Moonstone sanidine, comprising 7–12 percent of the rock, ranges in size from 0.8 to 2.5 mm. Twinned plagioclase makes up 6 percent of the rock. Smoky quartz, comprising 5 percent of the rock, occurs as euhedral to subhedral grains, ranging from 0.5 to 1 mm in diameter. Many grains are embayed. Red to dark-brown biotite, partially oxidized, constitutes 1 percent of the rock. Opaques constitute up to 1 percent of the rock.

The matrix is mainly glassy, with some shard structures. Large circular cracks are present as a result of cooling or of hydration of the glass. Small spherulites are present in the glass as a result of devitrification. Light-brown rims of devitrification minerals surround most of the quartz and sanidine phenocrysts.

This vitrophyre is the glassy margin or base of the gray rhyolite flow to the north of Broken Ridge.

Table 3. Modal analysis of rocks of the Steamboat Mountain Formation in the Broken Ridge area

[Tr., trace; leaders (--), not observed]

Latitude 38° min. s. N.	Longitude 113° min. s. W.	Sample No.[1]	Rock type	Matrix	Quartz	Sanidine	Plag-ioclase	Bio-tite	Opaques	Zircon	Apatite	Other
06 34	35 54	83K135 Tsv	vitrophyre	77.9	5.9	7.6	6.0	1.0	1.0	Tr.	Tr.	
06 34	36 00	83K239 Tsv	vitrophyre	74.9	6.8	10.2	7.6	Tr.	--	--	--	
03 23	34 08	83K199 Tsp	rhyolite	93.0	2.0	3.4	1.0	--	--	--	--	1-2 percent biotite in groundmass.
05 25	36 15	83K105 Tsp	rhyolite	97.0	1.0	2.0	Tr.	--	--	--	--	1-2 percent biotite in groundmass.
05 27	35 44	83K102 Tsgr	fl-lyd-rh[2]	88.4	3.7	7.0	0.5	--	0.2	--	--	
05 48	36 34	83K236 Tsgr	pheno-rich[3]	70.3	8.2	13.9	5.9	0.3	0.9	--	--	
04 49	34 52	83K191 Tsgr	fl-lyd-rh[2]	90.8	0.9	4.5	1.7	--	1.1	--	Tr.	
03 35	34 55	83K265 Tsgr	green glass	96.6	1.1	1.0	1.2	--	--	--	--	

[1]Tsv, basal vitrophyre; Tsp, rhyolite member of Pine; Tsgr, gray rhyolite.

[2]Flow-layered rhyolite.

[3]Phenocryst-rich rhyolite.

Figure 4. The gray rhyolite (unit Tsgr) showing steep flow banding (NW¼ sec. 24, T. 31 S., R. 16 W.). View looking north. Flow banding has an overall westerly dip.

Gray Rhyolite

Gray and lavender felsitic lava flows and domes of the gray rhyolite occur throughout the map area and generally overlie silicic clastic rocks and interlayer with flows of the rhyolite member of Pine. Thickness of individual flows varies greatly. The flow rocks are massive to strongly flow-layered, sometimes giving a pancakelike appearance in outcrop. Flow-layers vary from laminae thinner than 1 mm to layers many meters thick, and are often contorted and isoclinally folded. Small pressure ridges and cracks or "stretch" features were seen at many outcrops. The "stretch" features formed during cooling, and the direction of elongation is considered to be perpendicular to the direction of flow. Measurements taken perpendicular to the elongation of these features were noted with an arrow on the strike and dip symbol (pl. 1). Ramps, larger pressure ridges, are prominent in secs. 24 (fig. 4) and 35 (T. 31 S., R. 16 W.). Some contain vitrophyre. For the most part, the gray rhyolite is crystalline and porphyritic but locally includes a basal vitrophyre and vertically flow layered green glass.

Gray rhyolite flows.—Petrographically, the crystalline flow rocks of the gray rhyolite vary greatly. Three basic types can be distinguished: a phenocryst-rich rhyolite, a light-gray aphyric rhyolite, and a light-purple or lavender flow-layered rhyolite. All three types locally contain abundant lithophysae and vugs.

The rhyolite at the north end of Broken Ridge contains 30 percent phenocrysts of smoky quartz, sanidine, and plagioclase that are up to 3 mm in diameter (table 3). Dark-brown biotite is present in small amounts. The groundmass is a fine-grained intergrowth of quartz and feldspar containing minor disseminated biotite and opaques. Locally, the unit contains numerous lithophysae and vugs 3–5 mm in diameter that are completely filled with secondary quartz and topaz. Topaz crystals in the vugs are generally clear with few inclusions. Overlying the basal vitrophyre north of Broken Ridge, abundant lithophysae and vugs in the rhyolite are filled with chalcedony. A vug in the phenocryst-rich rhyolite (NE¼ sec. 14, T. 31 S., R. 16 W.) contains needle-like prisms of mordenite, a zeolite with a high Si:Al ratio. Chalcedony and zeolites as secondary minerals in vugs and lithophysae result from fluids circulating during cooling of the rhyolite and from later circulation of ground water.

Light-gray, aphyric rhyolite, abundant in and south of the area of Broken Ridge, consists of equigranular, interlocking quartz and feldspar grains with minor biotite and up to 5 percent disseminated needle-like opaque minerals. Locally, it is altered to clays, primarily kaolinite. Massive in outcrop, it is locally flow layered. Topaz crystals set in groundmass range from 1 cm to 3.5 cm in length (fig. 5) and contain numerous inclusions of rhyolitic material and opaque black minerals, largely hematite. The topaz is concentrated in places, perhaps where fluorine-rich fluids were trapped near the top of a cooling lava flow beneath an overlying flow. On either

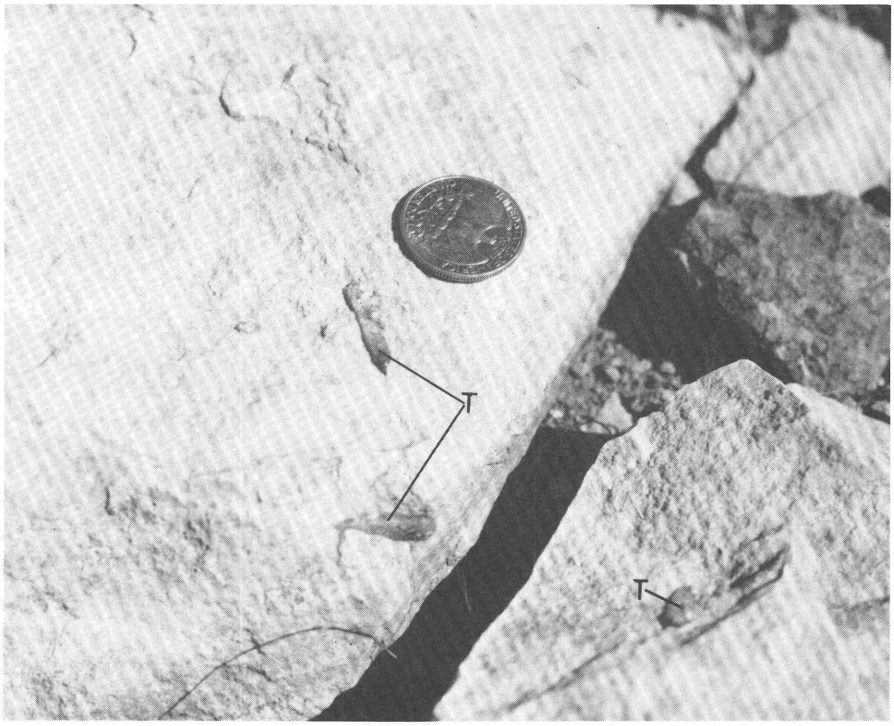

Figure 5. The gray rhyolite (unit Tsgr) with topaz (T).

side of Fourmile Wash in section 30 are outcrops with 5–7 topaz crystals per square foot. A thick sequence of gray rhyolite in the southern part of the map area (NE¼ sec. 12, T. 32 S., R. 15 W.) also has abundant topaz in groundmass. Vugs lined with quartz and clear topaz are prevalent locally and are the products of vapor phase deposition. Small hematite plates are abundant in cavities wherever topaz is abundant.

Light-purple flow-layered porphyritic rhyolite occurs with the aphyric rhyolite. Phenocrysts of quartz, sanidine, plagioclase, minor opaques and sparse apatite 0.5–1 mm in diameter constitute 10 percent of the rock (table 3). The groundmass consists of dark-purple compact layers of fine-grained quartz and feldspar alternating with light-gray, more porous layers of coarse-grained quartz. Average thickness of layers is 0.5–1.5 mm. Phenocrysts are restricted to the fine-grained layers of quartz and feldspar. Vugs, where present, are at the boundaries between layers and contain secondary quartz and topaz.

Gray rhyolite domes.—Two domes composed of the gray rhyolite are well exposed in the area mapped. The one in the northeast corner of the geologic map area (pl. 1) is clearly evident on the topographic map as a nearly circular hill. It is referred to in this report as the dome of Fourmile Wash (fig. 6). A smaller dome, referred to as the dome of Mountain Spring, near the south end of the geologic map area, is more deeply eroded and not conspicuous topographically. A third dome may exist in the NW¼ sec. 24, where the rhyolite has rather steep flaring dips. Both the dome of Fourmile Wash and the possible dome in the NW¼ sec. 24 lie along the projection of the Bible Spring fault zone.

Dips of flow banding on the west side of the dome of Fourmile Wash are generally eastward at 15°–55°. Those on the east dip westward. Towards the center and top of the structure, dips of flow bands vary greatly. The structure suggests an upward movement of magma in the center of the dome with flaring and lessening of dips along the margins.

The dome of Fourmile Wash is bounded on the west, north, and south by thin beds of pumice-lapilli tuffs, but these beds have been faulted off on the eastern boundary (pl. 1). The rocks in the dome are phenocryst rich and similar to those north of Broken Ridge directly overlying the basal vitrophyre. Phenocrysts of smoky quartz, sanidine, and plagioclase make up 25–40 percent of the rock. Rhyolite in a zone trending north to northeast on the east side of the dome contains abundant lithophysae that contain quartz and topaz, and minor fluorite as vapor-deposited crystals.

The dome of Mountain Spring, about 1–1½ km northeast of Mountain Spring Peak, can be recognized by the consistently steep dips of the rhyolite over a 1 km^2 area. Its north end was truncated by an east-trending fault, and north- to northwest-trending faults cut the eastern part of the dome. Due to extensive faulting and erosion in this area, present surface exposures are within the feeder of the dome (cross section *B–B'*; pl. 1).

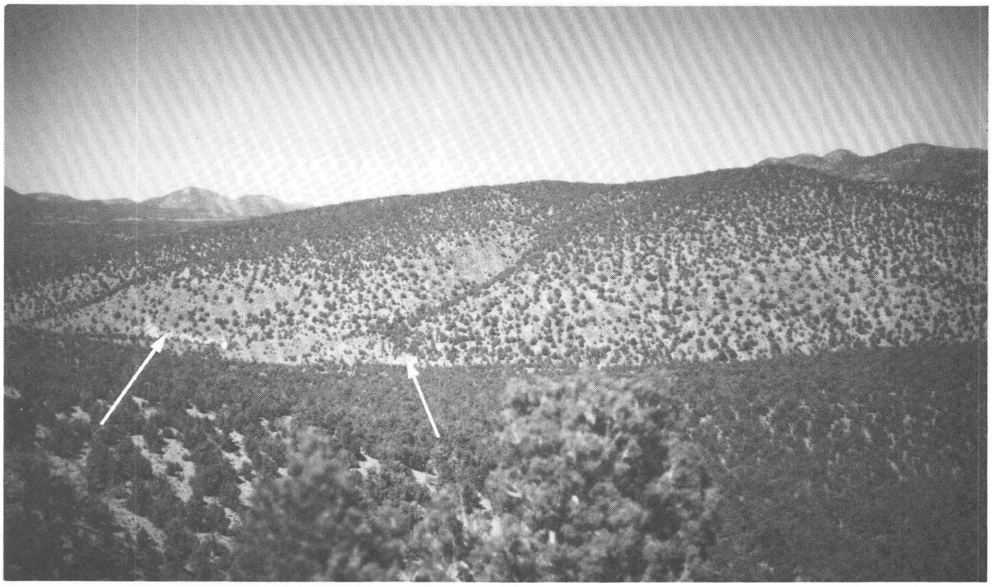

Figure 6. Dome of Fourmile Wash. View looking east, of west side of dome. Light-weathering unit where slope levels out is clastic rocks of unit Tsc (arrows).

The rhyolite in the dome is similar petrographically to that outside the dome, but no topaz-rich layers were recognized in the dome. The south end is obscured by thorough argillization near Mountain Spring.

Along the edge of the Mountain Spring dome, the rhyolite has been extensively silicified and commonly is stained red. Argillization and silicification were also localized along the northwest-trending faults on the east side of the dome. Caliche is unusually abundant along the western margin of the dome, possibly as a result of calcium carbonate brought up along the structure from subjacent Paleozoic carbonate rocks by solutions moving along the edge of the dome.

Green Glass

The green glass is 5–20 m of partly hydrated, devitrified, locally brecciated glass which crops out in the south-central part of the map area. A roughly east-west-trending zone of small patches of the glass is about 0.5 km north of Pine triangulation station (NE¼ sec. 35, T. 31 S., R. 16 W.), and moderate amounts crop out about 1½ km west of Fourmile Spring (NE¼ sec. 6, T. 32 S., R. 15 W.). A very small outcrop is in the western half of sec. 24 (T. 31 S., R. 16 W.). In every place, it is adjacent to clastic rocks of the silicic clastic unit.

The glass has nearly vertical flow-layering. Alternating thick glassy layers and spherulitic layers are about 2 mm across. Phenocrysts of plagioclase, quartz, and minor sanidine, generally less than 0.5 mm in diameter, constitute only 1–3 percent of the rock (table 3). The matrix is mostly glass, with some small spherulites. Large circular cracks due to hydration are in some places filled with clays. Locally, the glass is almost entirely altered to clinoptilolite. Abundant chalcedony and opaline silica occur as veins or cavity fillings. The bodies of glass grade into lithophysae-rich crystalline rhyolite such as the large body in the eastern part of section 1 (T. 32 S., R. 16 W.). Dikelike elongate bodies are wedges associated with ramp structures, which genetically are parts of the neighboring flows. In that setting, the glass is accompanied by and may enclose clasts of gray rhyolite and may be overlain by younger tuffaceous rocks.

Alluvium and Colluvium (Quaternary)

Unconsolidated, poorly sorted stream and slope wash deposits of silt, sand and gravel are included in this unit. Locally, it includes talus and colluvial debris.

Structure

Post-rhyolite faults are widespread in the Broken Ridge area. The northeast-trending Bible Spring fault zone is older than the 12 Ma rhyolitic rocks and projects beneath them. Numerous small faults on young flow rocks show minor later movement along the trend of the older fault.

Most of the faults in the Broken Ridge area are high-angle normal faults trending north to northeast. A few minor northwest-trending faults cut the northerly trending faults. In the southern part of the map area, most of the faults trend nearly east-west. Movement on the faults produced a series of horsts and grabens. (See cross sections *A–A′*, *B–B′*, and *C–C′*, pl. 1.) These faults were active during and following emplacement of the gray rhyolite and silicic clastic rocks.

Slickensides on rock surfaces in the southwest and southern parts of the map area are subhorizontal rather than downdip as would be expected for normal faults. According to M.G. Best (oral commun., 1984), the anomalous gently plunging slickensides on faults with predominantly vertical offset are widespread in the southern Wah Wah Mountains. For instance, along the Bible Spring fault zone in the NW¼ sec. 8, T. 32 S., R. 16 W. and NW¼ sec. 4, T. 32 S., R. 16 W., slickensides on altered volcanic rocks plunge southwest at approximately 10° (Best and Davis, 1981), indicating slight strike-slip movement along the fault. Likewise, in the southern part of the map area, slickensides along a north-trending fault (E¼ sec. 12, T. 32 S., R. 16 W.) plunge only 20° N. However, no evidence for large-scale lateral displacement is indicated by offset of map units. Rather, vertical displacements must be great (500 to at least 1,000 m) to juxtapose Miocene rocks with Oligocene and Paleozoic rocks. Possibly the subhorizontal slickensides reflect only the latest movement along the faults (M.G. Best, oral commun., 1983).

The Steamboat Mountain Formation is less broken by faults than the older rocks exposed in adjacent areas. Older faults in the northeast-trending Bible Spring fault zone to the southwest are covered by unbroken Steamboat Mountain rocks, but reemerge from beneath the Steamboat Mountain Formation northeast of the map area, and extend several more kilometers along the same trend (fig. 2). The north-trending normal fault in sec. 24 (pl. 1) is nearly perpendicular to the Bible Spring fault zone, and may mark a fissure vent along which a flow of gray rhyolite was erupted. A possible intrusion, emplaced just west of the north-trending fault, may have initiated movement along an already weakened zone; such an intrusion may be responsible for the vent tuff, the abundance of the rhyolite member of Pine, and tin-bearing veins (cross sections *B–B′*, *C–C′*, pl. 1).

The gravity map of the Richfield 1° × 2° quadrangle (Cook and others, 1981) shows a prominent low under the valley west of Broken Ridge, which must reflect the low-density filling of the Indian Peak caldron and the trough of Pine Valley. An appendage of that low extends northeastward along the northwest side of the Bible Springs fault zone at least as far as the dome of Fourmile Wash. The low-density material causing this appendage might be alluvium or tuffaceous material deposited against a fault-line scarp, or it might be similar light material faulted down against denser rocks. Alternatively, the material with low density might have resulted from strong alteration similar to that of the strongly altered rocks exposed along the Pine Valley road along and just north of the fault zone.

Rock Alteration

Four types of alteration that affected the rocks in the Broken Ridge area are shown on figure 7: silicification, argillic alteration, quartz-fluorite alteration, and quartz-alunite alteration. The most intensely altered rocks are along and between faults. In a general way, alunitically altered rocks in the southwest give way to argillically altered rocks to the northeast. The alteration removed alkalis and calcium from the rocks, and introduced silica, sulfur, and water.

Silicification

Rhyolitic rocks along faults in the Broken Ridge area were commonly replaced by quartz, chalcedony, and opaline silica. Rhyolitic rocks of the Steamboat Mountain Formation near the northeast end of the Bible Spring fault zone were silicified to jasperoid (fig. 7, loc. A1). About 1 km to the north, where volcanic rocks overlie Paleozoic limestones and dolomites, a small prospect pit exposes Paleozoic rocks that have been converted to jasperoid. Volcanic rocks overlying the jasperoid were intensely silicified and argillized; the volcanic rocks were replaced by chalcedony and opaline silica with local iron and manganese oxide coatings and veins, grading upward within the volcanics into extensively argillized rocks.

Quartz veins are widespread in the Oligocene volcanic rocks in the southwestern part of the map area (fig. 7, loc. A2). Subhorizontal slickensides on surfaces of the silicified volcanic rocks provide direct evidence of the faulting in this area.

Argillic Alteration

The most widespread altered rocks in the area have been argillized and converted to quartz, kaolinite, montmorillonite, and minor sericite; local introduction of oxidized iron also occurred. Rocks of the Steamboat Mountain Formation and the silicic clastic rocks were thoroughly bleached or are bright red orange where oxidized iron is abundant. In most places, the argillized rock is spatially related to silicified fault zones. Intensely argillized rocks along the Bible Spring fault zone (fig. 7, loc. A1) were explored for uranium by means of pits and adits. The pits are in red oxidized rocks that grade westward to extensive white bleached rock. Northeast along the fault, argillized rock gives way to silicified rhyolite.

Other areas of argillized rock occur along small faults east of Broken Ridge. Near Mountain Spring (fig. 7, loc. A3), silicic clastic rocks and gray rhyolite are

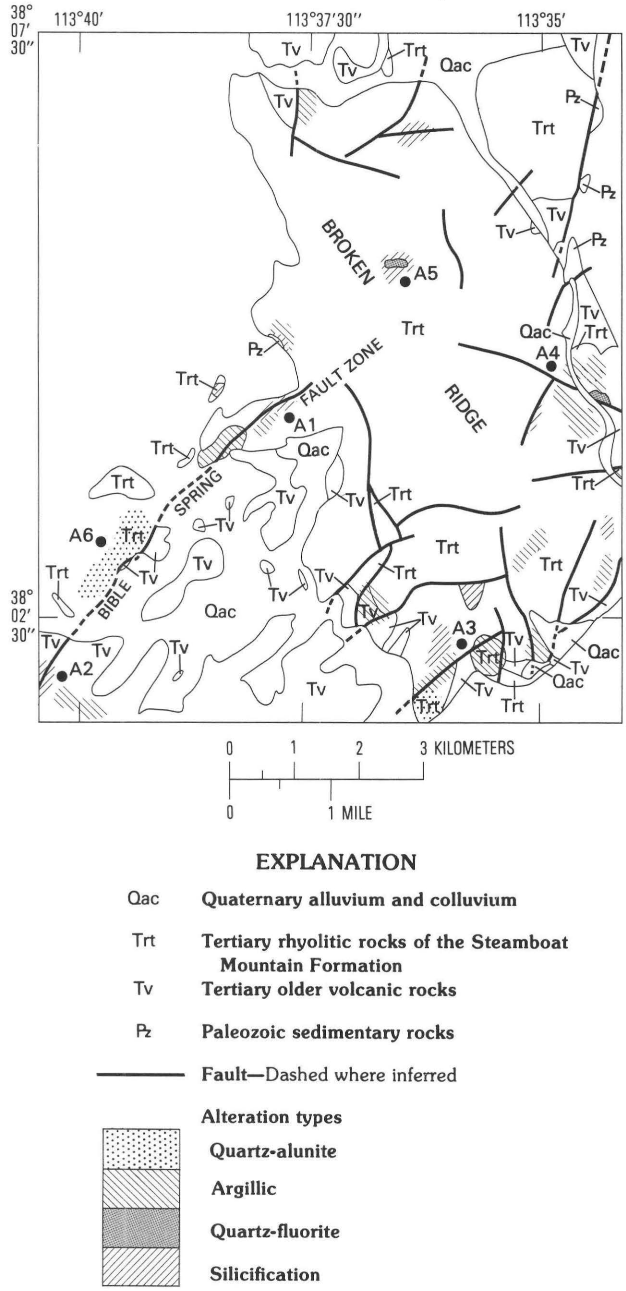

Figure 7. Simplified geologic map showing areas of alteration. Labeled dots are areas of alteration referred to in the text.
A1 Rhyolite argillized and silicified.
A2 Quartz veins.
A3 Clastic rocks and rhyolite argillized and alunitized .
A4 Rhyolite argillized and silicified.
A5 Silicified and fluoritized rhyolite breccia.
A6 Clastic rocks silicified, alunitized, and argillized.

extensively altered to clays. At Mountain Spring Peak, clastic rocks were argillized, and overlying rhyolite was silicified and alunitized. A thick pile of gray rhyolite along both sides of a northwest-trending fault in Fourmile Wash east of Broken Ridge (fig.7, loc. A4), is argillized and contains quartz, kaolinite, and oxidized iron.

Quartz-Fluorite Alteration

This type of altered rock is similar to the silicified rock already described except that fluorite crystals are found in the silicified rhyolite and on joint surfaces. In the northern Broken Ridge area (fig. 7, loc. A5), gray rhyolite is separated from the rhyolite member of Pine by pumice-rich vent tuff (SE¼ sec. 23, T. 31 S., R. 16 W., pl. 1). Several small prospect pits expose highly silicified and fluoritized rocks within the flow-layered gray rhyolite. Small dark-purple fluorite crystals line cavities and vugs in the silicified rhyolite, and small cassiterite crystals occur in veins within a small breccia body with specular hematite and quartz.

A northwest-striking normal fault about 3 km east of Broken Ridge on the east side of Fourmile Wash (fig. 7, loc. A4) separates Oligocene volcanic rocks and Miocene rhyolite lava flows of the Steamboat Mountain Formation (fig. 7). At the fault contact, green glass is locally altered to clay, and joint surfaces near the fault are coated with fine-grained quartz and fluorite. A partially hydrated and devitrified sample of the green glass nearby but away from the fault yielded 900 ppm F and low Li, U, Na, Al, and Mg. Perhaps some of these elements were released from the glass during hydration and devitrification, and removed by throughgoing hydrothermal fluids.

Quartz-Alunite Alteration

A thick pile of clastic rocks on the far southwestern part of the Bible Spring fault zone is pervasively altered to quartz, alunite, kaolinite, and minor montmorillonite (fig. 7, loc. A6). The rocks are weakly welded ash-flow tuffs with as much as 35 percent of the rock consisting of somewhat flattened and elongated cavities believed to be relict pumice fragments. The cavities are filled with clear euhedral tabular crystals of alunite (as much as 2 mm in diameter), feldspar, quartz, iron oxides, kaolinite, and minor montmorillonite. In the groundmass, fine-grained alunite and quartz are locally abundant. Textural relationships suggest that the tuff was first replaced by quartz and feldspar, and later, sulfate-rich solutions partially replaced feldspar with alunite.

At Mountain Spring Peak (fig. 7, loc. A3), alunitized rocks grade northward to very extensive areas of argillized rocks.

GEOCHEMISTRY

Petrology of the Steamboat Mountain Formation

The petrology of the Steamboat Mountain Formation is best documented by utilizing geochemical data of

Table 4. Chemical composition of selected volcanic rocks from the southern Wah Wah Mountains

[Tsp, rhyolite member of Pine; Tsgr, gray rhyolite; Tsv, basal vitrophyre; Tsg, green glass. N, not detected; L, less than the detection limit; million; F by specific ion electrode; U by fluorometry; all others by emission spectroscopy. Starred samples from Best and others (1987)]

Unit--	Tsp		Tsgr							Tsv	(Tsv)	Tsg	
Sample	83K199	83K105	83K233	83K236	83K133	83K275	83K281	83K132	83K031	83K135	1*	83K265	2*
SiO_2	73.9	72.2	75.1	75.7	76.0	74.8	74.1	74.95	75.8	77.6	76.4	74.4	52.6
TiO_2	0.12	0.08	0.03	0.06	0.06	0.03	0.05	0.07	0.10	0.06	0.08	0.04	1.89
Al_2O_3	12.1	16.0	12.4	12.5	12.9	11.8	13.0	12.4	12.4	11.2	12.2	11.0	16.4
Fe_2O_3	1.1	1.4	1.07	0.91	1.16	1.03	1.01	1.51	1.3	0.94	1.2	1.13	9.72
MgO	0.1	0.1	0.07	0.1	0.03	0.1	0.1	0.1	0.2	0.1	0.03	0.02	4.6
CaO	1.0	0.4	1.78	0.94	0.43	0.90	0.55	0.22	0.2	0.37	0.48	0.62	6.92
Na_2O	3.7	3.6	3.3	3.54	3.06	4.55	3.0	3.09	3.4	3.93	3.2	2.88	3.9
K_2O	4.6	4.1	4.85	4.7	5.13	4.49	4.98	5.60	4.6	4.92	4.88	5.08	2.79
P_2O_5	0.09	0.08	0.03	0.02	0.10	0.04	0.01	0.01	0.10	0.01	---	0.01	0.84
Total	96.71	97.96	98.63	98.47	98.87	97.74	96.80	97.90	98.1	99.13	98.42	95.18	99.82
F	2,800	2,100	1,100	500	520	300	2,000	520	810	800	---	900	---
Be	20	7	15	20	20	15	15	20	10	20	---	10	---
Mo	5	7	10	10	5	L	500	10	20	L	---	10	---
Rb	500	700	500	500	700	500	100	500	---	700	270	700	---
Li	150	150	200	150	150	200	N	70	---	200	---	70	---
Nb	50	50	70	50	50	100	70	50	70	20	85	70	---
U	1.7	---	6.3	2.6	3.6	1.2	2.3	3.4	---	2.7	---	0.15	---
Y	100	70	100	50	70	100	100	70	100	50	---	100	---
La	20	N	L	N	50	L	20	20	100	L	---	20	---
Ba	N	N	50	20	20	L	20	L	L	20	15	N	---

SAMPLE DESCRIPTIONS

1* Vitrophyre from Steamboat Mountain quadrangle, probably equivalent to vitrophyre of Broken Ridge.
2* Mugearite flow, 13 m.y. old.
3* Flow-layered, felsic, topaz-bearing flow at The Tetons in The Tetons quadrangle.
4* Felsic, porphyritic rhyolite at the Staats mine.
5* Strongly porphyritic felsic dike, east side of Needle Range, 6 km south of Indian Peak, Buckhorn Spring quadrangle, Utah.
6* Felsic, porphyritic flow (23 m.y. old) 5 km west of Miners Hill Reservoir on east flank of Wah Wah Mountains in the Frisco quadrangle, Utah.
7* Trachyandesite flow in Frisco quadrangle.
8* Trachyandesite flow in Willow Creek southeast of Baudino Ranch in the Frisco quadrangle.

older volcanic rocks, as well as geochemical data of the Steamboat Mountain Formation. Table 4 lists whole-rock major- and trace-element chemistry of 18 fresh and altered rhyolitic rocks of the Steamboat Mountain Formation and 2 samples of the Lund Formation. Also included are analyses from Best and others (1987) of a mugearite lava flow (orthoclase-bearing oligoclase basalt) from the east side of the Wah Wah Mountains dated at 13.3 Ma, and a vitrophyre from the Steamboat Mountain quadrangle to the west. Analyses of four fresh rhyolitic rocks and two trachyandesite flow rocks of the Blawn Formation (23–18 Ma) from Best and others (1987) are included (samples 3–8). Only fresh rocks will be considered in this discussion.

The rhyolitic rocks of the Steamboat Mountain Formation have greater than 74 percent SiO_2, except for the rhyolite member of Pine which has between 72 and 74 percent SiO_2 (table 4). Aluminum content is about 12 percent and total alkali content is high, averaging 8–10 percent. Average CaO content is low (0.6 percent), but leaders (---), not analyzed. Oxides in weight percent; all whole-rock analysis by A.E. Hubert, X-ray fluorescence spectroscopy. Elements in parts per

Argillized rhyolite Steamboat Mountain Formation					Alunite alteration	Blawn Formation						Lund Formation	
83K027	83K037	83K088	83K116	83K115	83K265	3*	4*	5*	6*	7*	8*	83K143	83K264
73.2	74.2	73.1	73.6	77.5	74.9	75.8	75.8	74.5	76.1	60.5	58.7	65.4	65.3
0.11	0.11	0.11	0.05	0.06	0.2	0.06	0.06	0.28	0.05	0.96	0.94	0.7	0.61
12.4	10.8	11.6	7.4	10.8	12.1	12.4	12.8	12.8	12.5	15.9	15.4	13.5	13.5
1.5	2.4	1.33	1.38	1.17	0.9	1.1	1.3	1.78	1.17	7.42	7.2	4.9	5.5
0.3	0.2	0.2	0.1	0.1	0.1	0.05	0.11	0.21	0.05	3.9	3.8	1.7	1.3
1.2	2.4	1.7	0.63	0.31	1.7	0.62	0.67	0.69	0.62	6.01	6.65	2.4	3.2
1.5	1.8	3.1	0.89	1.55	0.6	3.7	4.06	3.7	4.2	2.9	3.44	2.7	2.6
5.4	4.0	4.4	3.76	6.63	3.2	4.72	4.60	5.41	4.64	3.32	3.10	3.4	3.6
0.03	0.04	0.05	0.07	0.05	0.09	---	---	---	---	0.33	0.34	0.17	0.21
95.64	93.95	95.56	87.88	98.17	93.79	98.56	99.43	99.42	99.47	101.29	99.65	94.87	95.82
820	710	500	700	420	1500	---	---	---	---	---	---	600	400
5	10	50	50	20	5	---	---	---	---	---	---	2	2
L	10	150	150	5	N	---	---	---	---	---	---	N	N
---	---	700	700	700	50	690	572	200	645	---	---	100	150
---	---	150	150	30	15	---	---	---	---	---	---	20	50
100	100	150	150	100	70	170	---	40	115	---	---	N	N
---	---	2.5	2.5	0.6	---	---	---	---	---	---	---	.45	.45
20	70	100	100	30	15	---	---	---	---	---	---	200	20
N	70	L	L	N	L	---	---	---	---	---	---	50	50
N	L	N	50	50	300	25	---	395	25	---	---	1000	1500

the concentration ranges from 0.2 to 1.7 weight percent. The rocks have very low MgO (mostly <0.1 percent), TiO_2 (<0.2 percent), and P_2O_5 (<0.15 percent) contents. Of the trace elements, Be, Rb, Li, Nb, Mo, and Y are high and Ba is low. Beryllium averages 5–10 ppm, with 500 ppm Rb, 150 ppm Li, 50–100 ppm Nb, 10–20 ppm Mo, and 50–100 ppm Y.

The partially hydrated and devitrified green glass contains high K_2O and low Al_2O_3, MgO, Na_2O, Li, and U relative to the other rhyolitic units. This can be attributed to the addition of K^+ and subtraction of the other elements that is common during hydration and devitrification of glass (Zielinski and others, 1977).

Fluorine content of the rhyolitic rocks is high where topaz is present, but the average fluorine values of 500–1,000 ppm are low in comparison with other high-F rhyolites. For example, vitrophyres from Spor Mountain, Utah, contain as much as 1 weight percent F (Christiansen and others, 1984). The scarcity of fresh vitrophyre in the Broken Ridge area makes it difficult to determine the fluorine content of the parent magma, inasmuch as fluorine is lost during eruption and high-temperature devitrification of the rhyolite lava flow.

Whole-rock major-element chemistry of the Blawn Formation (SiO_2 contents between 74 and 76 percent, high alkalies and low MgO, TiO_2, and P_2O_5), is very similar to that of the Steamboat Mountain Formation. Calcium is low, but this element does not show the large range of values as seen in the Steamboat Mountain Formation.

The characteristic high silica and alkalies, low magnesium, calcium, titanium and phosphorus, and enrichment of lithophile elements is typical of other topaz-bearing rhyolite lava flows in the Western United States and northern Mexico. (See for example Burt and others, 1982; Huspeni and others, 1984; Christiansen and others, 1984; and Eggleston and Norman, 1984.) These high-silica and high-fluorine rhyolites commonly have associated beryllium and tin mineral deposits: the beryllium deposit at Spor Mountain, Utah (Staatz and Carr, 1964; Christiansen and others, 1984), the tin deposits in the Black Range, N. Mex. (Eggleston and Norman, 1984), and the tin hosted by rhyolite lava flows in the Sierra Madre Occidental, Mexico (Huspeni and others, 1984).

Alkali, iron, and magnesium contents of the Steamboat Mountain Formation, the Blawn Formation, and the Lund Formation are plotted on ternary diagrams (fig. 8); SiO_2 variation diagrams of CaO, Na_2O, and K_2O contents for the volcanic rocks are shown in figure 9. For comparison, analyses of rhyolitic rocks from the Sierra Madre Occidental, Mexico (Huspeni and others, 1984; table 3) and Spor Mountain, Utah (Christiansen and others, 1984; table 1) are also plotted.

The AFM (Na_2O+K_2O–Fe_2O_3–MgO) ternary diagram (fig. 8*A*) shows the Steamboat Mountain Formation and Blawn Formation to be strongly alkaline, magnesium poor, and very similar in terms of alkalies (K_2O+Na_2O), Mg, and Fe to rhyolite lava flows of the Spor Mountain area and the Sierra Madre Occidental. The mugearite lava flow of the Steamboat Mountain Formation is more iron rich and less alkaline than is trachyandesite of the Blawn Formation.

The Na_2O–K_2O–CaO ternary diagram (fig. 8*B*) and the SiO_2–CaO variation diagram (fig. 9*A*) show the wide range in calcium for the Steamboat Mountain Formation compared to the Blawn Formation, even though the averages are similar. Calcium is variable in rhyolitic rocks from Sierra Madre Occidental and Spor Mountain, but K_2O increases with CaO in the Sierra Madre rocks and NaO_2 increases with increasing CaO at Spor Mountain. There is no apparent relation of alkalies to calcium in the Steamboat Mountain Formation. The linear trend toward higher calcium from the Steamboat Mountain Formation to the Lund Formation to the mafic rocks (fig. 8*B*) suggests that the calcium content is related to the primary composition of the rock rather than to secondary alteration. In general, calcium in the Steamboat Mountain Formation and the Blawn Formation increases with decreasing silica (fig. 9*A*).

Steamboat Mountain rhyolitic rocks average 3.4 weight percent Na_2O contents, lower than the Blawn rhyolites (average 3.9 percent) but similar to the Sierra Madre Occidental (fig. 9*B*). Spor Mountain rhyolites are extremely high in sodium and somewhat lower in silica compared with the other rhyolites. The mugearite has more sodium than the trachyandesite flow rocks. Generally, sodium decreases with decreasing silica, to around 65 percent SiO_2; sodium increases with a further decrease in silica (fig. 9*B*).

Average K_2O contents in the Steamboat Mountain and Blawn rhyolitic rocks are nearly identical, at about 4.8 weight percent, and the range of K_2O values falls well within the range for the Sierra Madre Occidental and Spor Mountain rocks (figs. 8*B* and 9*C*). With an increase in SiO_2, K_2O increases slightly for the Steamboat Mountain Formation, but K_2O decreases with increasing SiO_2 for the Blawn Formation (fig. 9*C*), though the scarcity of data for the Blawn Formation weakens this observation. The mugearite of the Steamboat Mountain Formation is less potassic than the trachyandesite of the Blawn Formation. Overall, K_2O increases with increasing SiO_2.

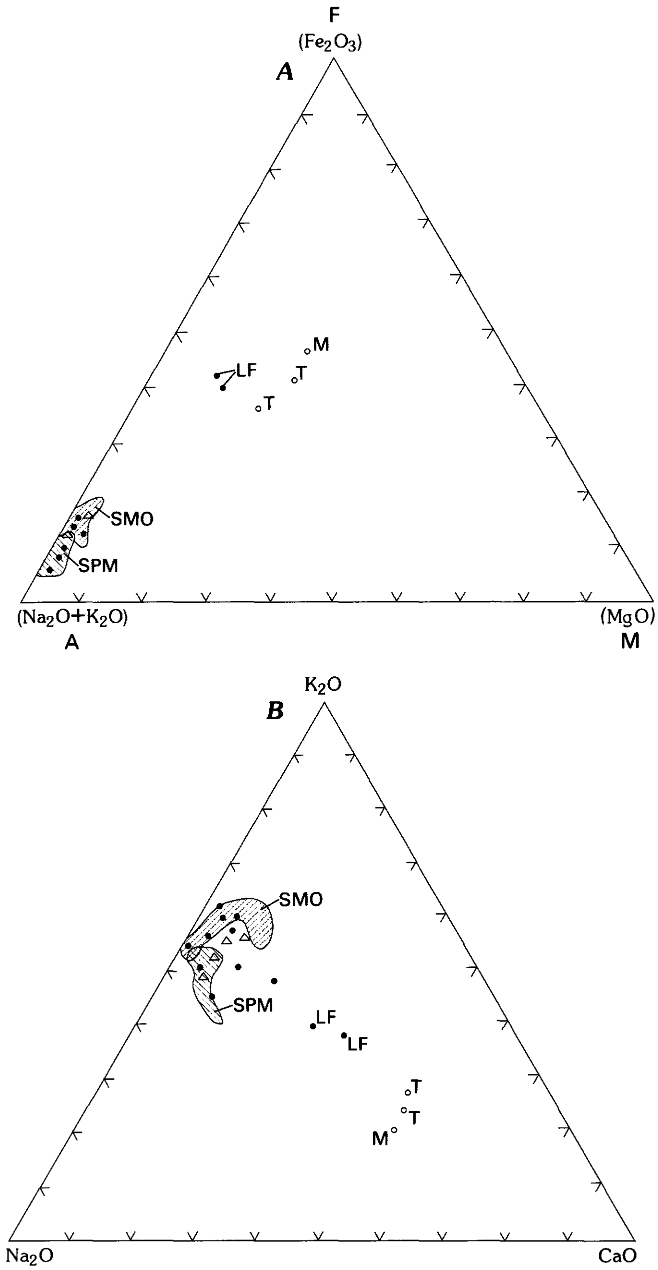

Figure 8. Ternary diagrams for volcanic rocks, southern Wah Wah Mountains. *A*, AFM diagram; *B*, Na_2O-K_2O-CaO diagram. Open triangle, analysis of silicic rocks of the Blawn Formation from Best and others (1987); open circle, analysis of mafic rocks from Best and others (1987); dot, analysis from this study. M, mugearite flow; T, trachyandesite flow; LF, Lund Formation; SMO, Sierra Madre Occidental, Mexico (Huspeni and others, 1984; table 3); SPM, Spor Mountain, Utah (Christiansen and others, 1984; table 1).

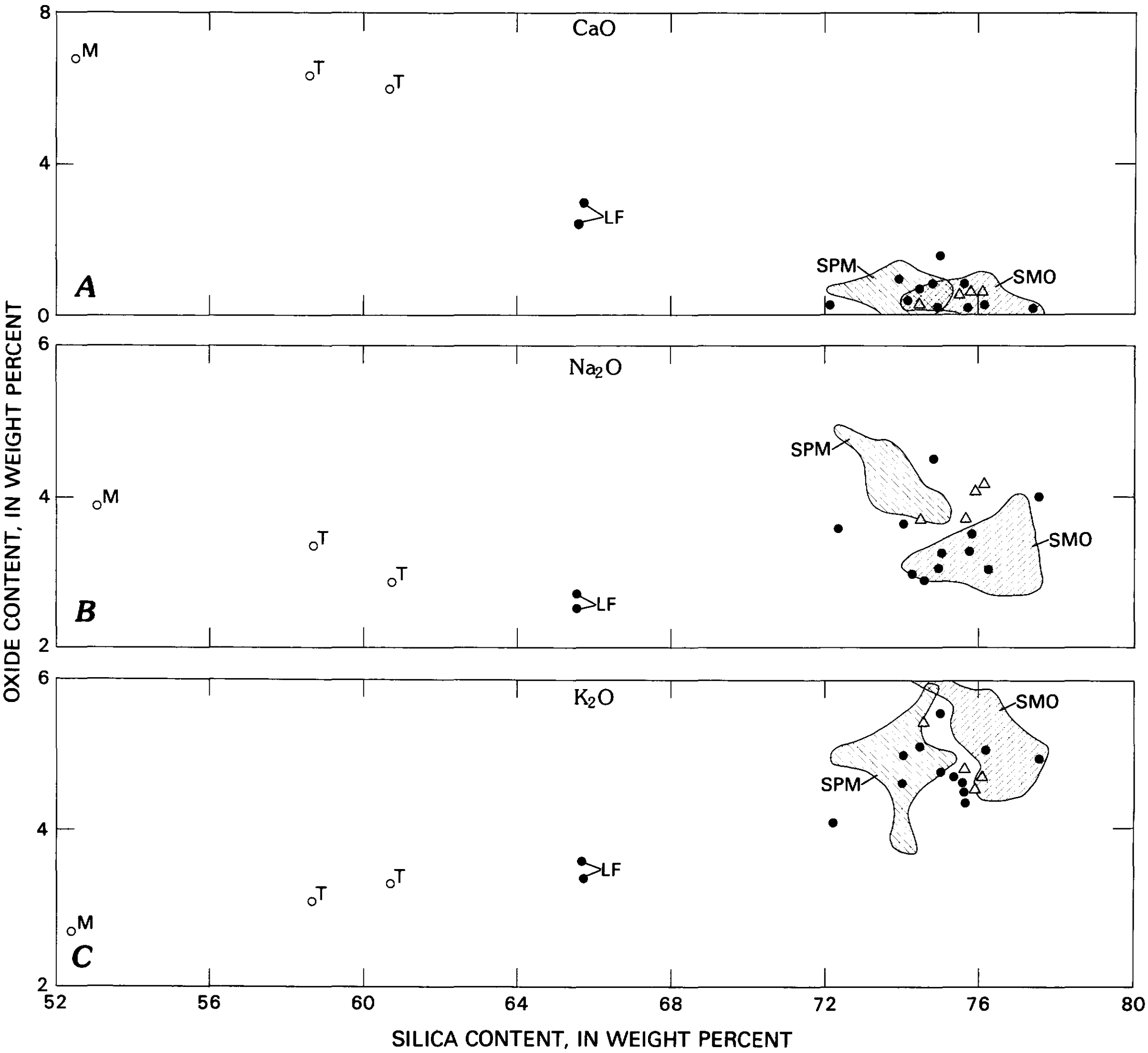

Figure 9. Silica variation diagrams of *A*, CaO; *B*, Na_2O; and *C*, K_2O for volcanic rocks, southern Wah Wah Mountains. Open triangle, analysis of silicic rocks of the Blawn Formation from Best and others (1987); circle, analysis of mafic rocks from Best and others (1987); dot, analysis from this study; M, mugearite flow; T, trachyandesite flow; LF, Lund Formation; SMO, Sierra Madre Occidental, Mexico (Huspeni and others, 1984; table 3); SPM, Spor Mountain, Utah (Christiansen and others, 1984; table 1).

Topaz rhyolites from the Thomas Range, Utah, and Spor Mountain, Utah (Christiansen and others, 1984), as well as rhyolitic rocks from the Sierra Madre Occidental, Mexico (Huspeni and others, 1984) and from the Black Range, N. Mex. (Eggleston and Norman, 1984), are thought to form by extreme differentiation of magmas at shallow crustal levels (Hanson, 1978, from Huspeni and others, 1984). The similarity of major-element characteristics of the Steamboat Mountain Formation and Blawn Formation to those of other topaz rhyolites suggests that they also formed from highly differentiated magmas.

Burt and others (1982) have suggested that U.S. topaz rhyolites are equivalent to Soviet ongonites. Ongonites are topaz-bearing dikes, or the subvolcanic equivalents of the topaz rhyolites (Kovalenko and Kovalenko, 1976). Glassy portions of ongonites contain up to 3.2 percent fluorine. The lower fluorine content of topaz rhyolites, particularly the Steamboat Mountain Formation, is attributed to loss during initial eruption and during high-temperature devitrification and crystallization.

The geochemistry of high-fluorine rhyolites is similar to that of anorogenic or A-type granites (Loiselle and Wones, 1979), which are distinct from I or S-type granites as defined by Chappel and White (1974). The petrogenesis of A-type granites occurs late in an orogenic cycle (hence the name "anorogenic"), prior to rifting and after subduction ceases. They are derived from partial melting of water-depleted lower crustal rocks from which an earlier partial melt was produced. White and others (1981) proposed a similar origin for Climax-type

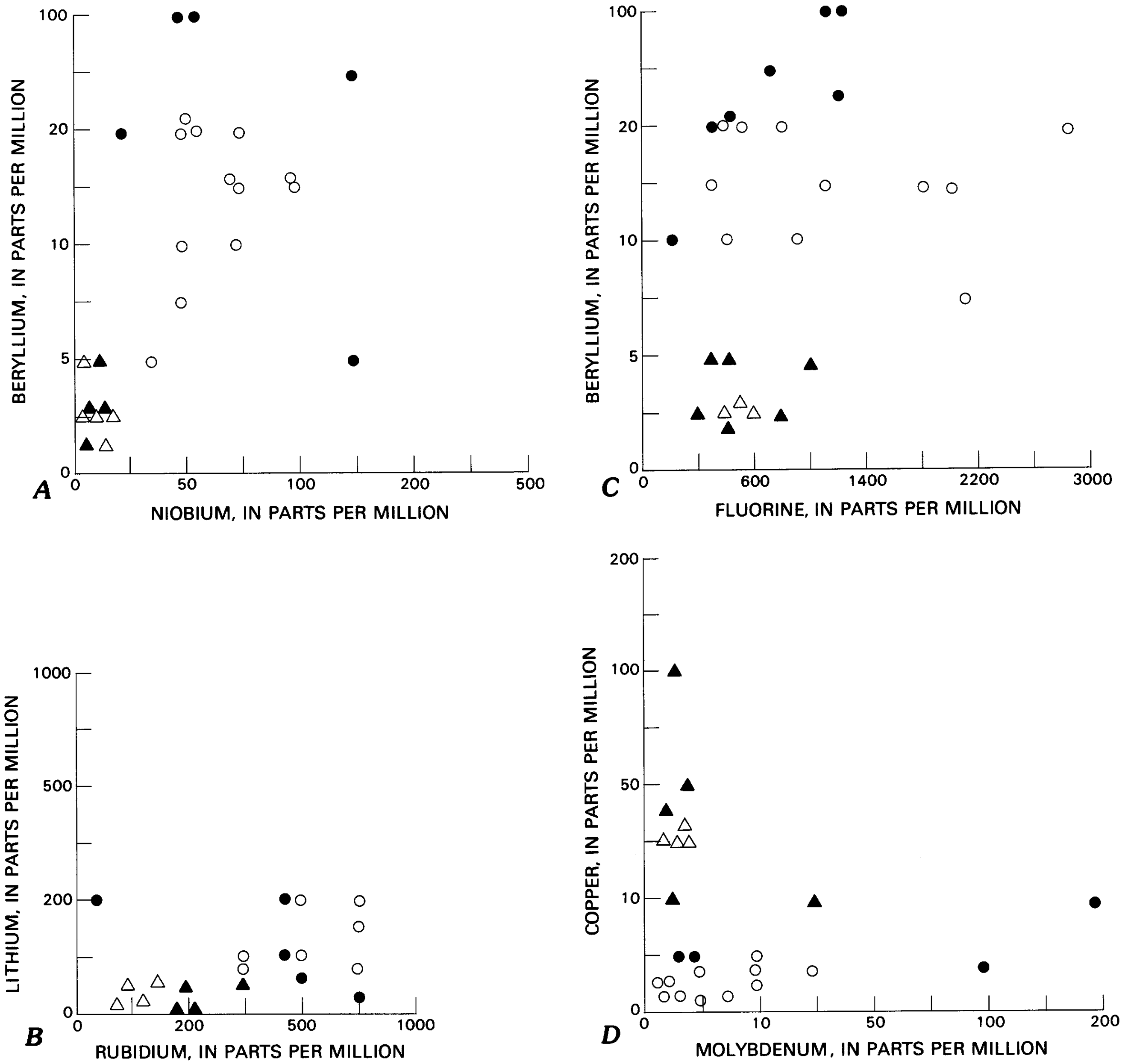

Figure 10. Correlation diagrams of selected elements in volcanic rocks from the Broken Ridge area. *A*, Be and Nb; *B*, Li and Rb; *C*, F and Be; *D*, Cu and Mo. Circle, rhyolite of the Steamboat Mountain Formation; triangle, Oligocene volcanic rock; open symbol, fresh rock; closed symbol, altered rock.

porphyry molybdenum deposits. Both the geochemistry of the Steamboat Mountain Formation and the extensional tectonic setting in the Broken Ridge area support a link between topaz rhyolites and A-type granites.

Regional Trace-Element Geochemistry of Rocks

Two hundred and four rock samples were collected for geochemical analyses in the area of Broken Ridge and Fourmile Wash and south-southwestward along the Bible Spring fault zone. Analytical results for these samples are given by Duttweiler (1985).

Beryllium, fluorine, tin, niobium, uranium, and thorium vary sympathetically, and their distribution reflects compositional variation within the Steamboat Mountain Formation. The highest values occur along the Bible Spring fault zone and other faults and associated areas of altered rocks. High values of molybdenum, copper, and lead accompany the lithophile elements in some altered areas, but these high values are more widely dispersed and not restricted to rhyolitic rocks. For the most part, barium is low in fresh rhyolitic rock, but is high in alunitized clastic rocks and Oligocene volcanic rocks.

Correlation diagrams of beryllium and niobium, lithium and rubidium, fluorine and beryllium, and copper and molybdenum are shown in figure 10. Rubidium, lithium, beryllium, niobium, and fluorine are higher in rhyolitic rocks than in Oligocene volcanic rocks, and a high correlation exists between beryllium and niobium, and lithium and rubidium in fresh rock. Beryllium and niobium contents in altered rhyolitic rocks differ from that of fresh rhyolite. Beryllium contents of 50–100 ppm in altered rocks are nearly five times greater than the beryllium content of fresh rock. Niobium increases only slightly in altered rocks. In contrast, beryllium and niobium change little between fresh and altered Oligocene rocks.

Lithium content increases slightly with increasing rubidium in rhyolitic rocks, and both elements are higher in rhyolites than in Oligocene rocks. In Oligocene rocks, rubidium increased during alteration whereas lithium remained fairly constant. One altered sample contains twice as much lithium as the average fresh rock. There was a slight loss of lithium and rubidium during alteration of rhyolitic rocks.

Fluorine varies widely, and fluorine does not systematically change with beryllium in fresh rhyolite. Altered samples show a strong correlation between beryllium and fluorine, indicating that beryllium and fluorine are transported and precipitated together by hydrothermal solutions. Beryllium is commonly carried in solution as BeF_4^- (Griffitts, 1982); if fluorine reacts with calcium to form fluorite or substitutes for OH to form topaz, beryllium would precipitate out of solution.

The copper content of intermediate-Si Oligocene rocks is higher than that of the high-silica rhyolite of the Steamboat Mountain Formation. Copper averages <5 ppm in the rhyolitic rocks and 20 ppm in the Oligocene rocks. Molybdenum by contrast is consistently <5 ppm in the Oligocene rocks but <5 to 20 ppm in the rhyolite. Copper was very mobile during alteration of Oligocene rocks; altered rocks contain from 10 to 100 ppm Cu, whereas molybdenum generally remains low. In altered rhyolitic rocks, both copper and molybdenum are highly variable; Mo ranges from 5 ppm to 200 ppm and Cu from 5 to 100 ppm. The two metals vary independently, however, suggesting that they were precipitated by different processes.

The geochemical data indicate that tin and barium also increased during alteration of the rhyolitic rocks of the Steamboat Mountain Formation. The type of alteration strongly influenced the behavior of these elements. Figures 11 and 12 are histograms of tin, molybdenum, beryllium, niobium, barium, and copper abundances in 18 fresh rhyolitic rocks, 25 argillically altered, 6 silicified,

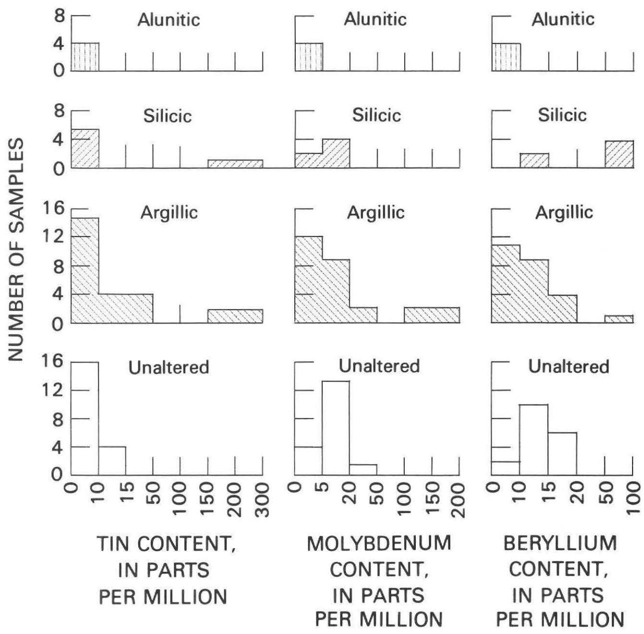

Figure 11. Histograms of Sn, Mo, and Be abundances in fresh (unaltered) and altered rhyolitic rocks.

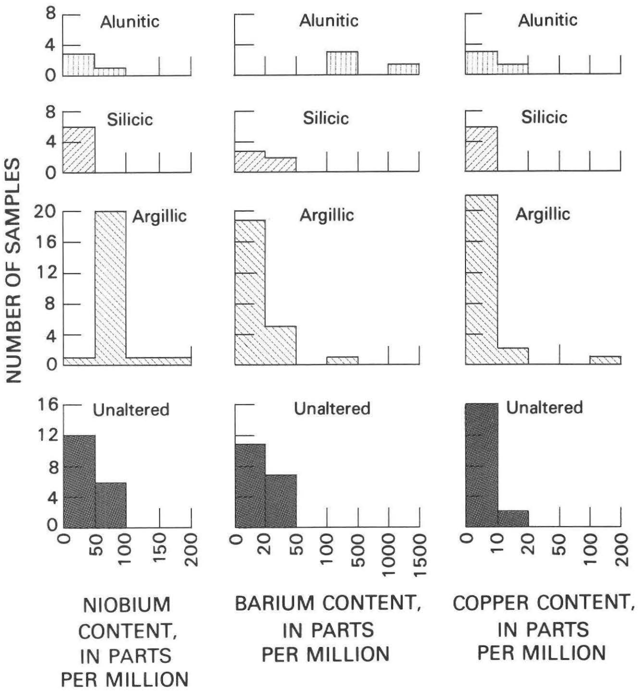

Figure 12. Histograms of Nb, Ba, and Cu abundances in fresh (unaltered) and altered rhyolitic rocks.

and 4 alunitically altered rocks. Argillic alteration resulted in up to thirtyfold increases in tin, up to twentyfold for molybdenum, and about twofold for niobium.

Although one sample contains 50 ppm Be, Be contents decreased during argillic alteration; most argillic rocks contain < 10 ppm. Barium is also low (< 20 ppm) in argillized rock. Silicification, however, resulted in a tenfold increase in beryllium, and up to thirtyfold in tin with little change in molybdenum, niobium, or barium. Alunitically altered rocks are depleted in all metals except barium, which increased twentyfold, and copper, which increased slightly.

Map plots of Be, F, Sn, Nb, U, Th, Mo, Cu, Pb, and Ba are shown in figures 13 through 17. The two contour intervals plotted for each element combine to represent approximately the upper 25 percent of the values (75th percentile). Concentrations represented by the uppermost interval are considered anomalous because they are within the 95th percentile. Sample localities, analytical results for rock samples, and details in plotting are given in Duttweiler (1985).

The distribution of these elements relative to the zones of alteration and associated faults is apparent from figures 13–17. Three areas have anomalous concentrations of metals: the Bible Spring fault zone, the area of altered rocks around the margins of the eroded dome north of Mountain Spring, and faulted areas in Fourmile Wash.

Bible Spring Fault Zone

It is significant that the higher concentrations of beryllium, molybdenum, copper, lead, silver, fluorine, tin, and uranium in the Steamboat Mountain rhyolite are along the trend of the Bible Springs fault zone, even though the extrusion of the rhyolite postdates most of the movement on the fault. The total amount of metal in the overall depositional system probably is much larger than the amount that could be "sweated out" of the exposed pile of rhyolite on Broken Ridge. The fault thus controlled influx of metals into the rhyolite from below, and the geochemical anomalies we detect in fractures at the present surface are a result of nearly exhausted solutions that deposited most of their dissolved metal below our level of observation. The fault zone at depth where Paleozoic carbonate strata form the walls is therefore a possible host for mineral deposits. The most striking geochemical feature is the similarity in distribution of anomalous concentrations of beryllium and fluorine, which are clustered together along strike of the fault zone (fig. 13). Average beryllium and fluorine contents in the northeast-trending zone are 30 ppm and 5,000 ppm, respectively, whereas north of Broken Ridge, fresh rhyolite contains < 10 ppm Be and < 1,450 ppm F. West of Broken Ridge, the rhyolitic rocks are extensively argillized and silicified and contain 50–100 ppm Be and 400–11,000 ppm F. East of Broken Ridge, where tin mineralization occurs and we suspect an intrusion at depth, silicified and fluoritized rhyolite contains up to 100 ppm Be and 3,200 ppm F, grading northeastward to

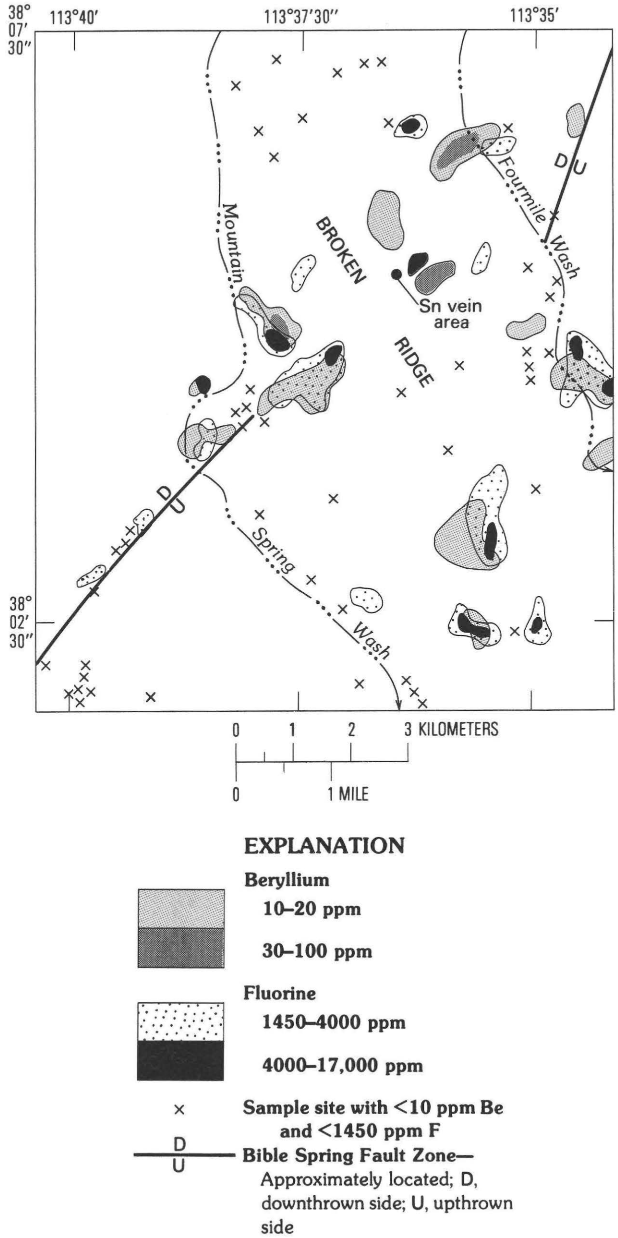

Figure 13. Distribution of Be and F in rocks.

unaltered rhyolite averaging 15 ppm Be and 1,500 ppm F—values that are generally higher than for fresh rhyolite outside the Bible Spring fault zone.

High concentrations of tin and niobium also mark the trend of the Bible Springs fault zone (fig. 14), although the anomalies are not as continuous as those of beryllium and fluorine. Fresh rhyolite north of Broken Ridge contains 10 ppm Sn and 100 ppm Nb, whereas southwest of Broken Ridge, Sn and Nb are both high (150–200 ppm Nb and 30–300 ppm Sn). East of Broken Ridge, where tin minerals occur, silicified rhyolite contains 300 ppm Sn. Further northeastward, slightly argillized and fresh rhyolite contains 10–20 ppm Sn.

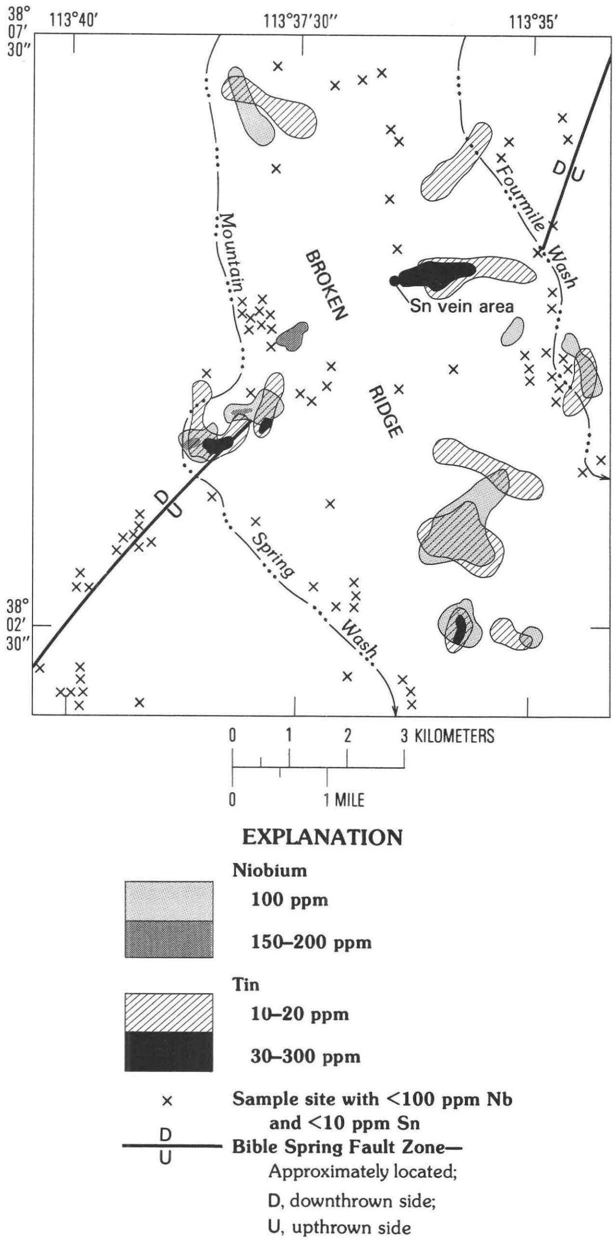

Figure 14. Distribution of Sn and Nb in rocks.

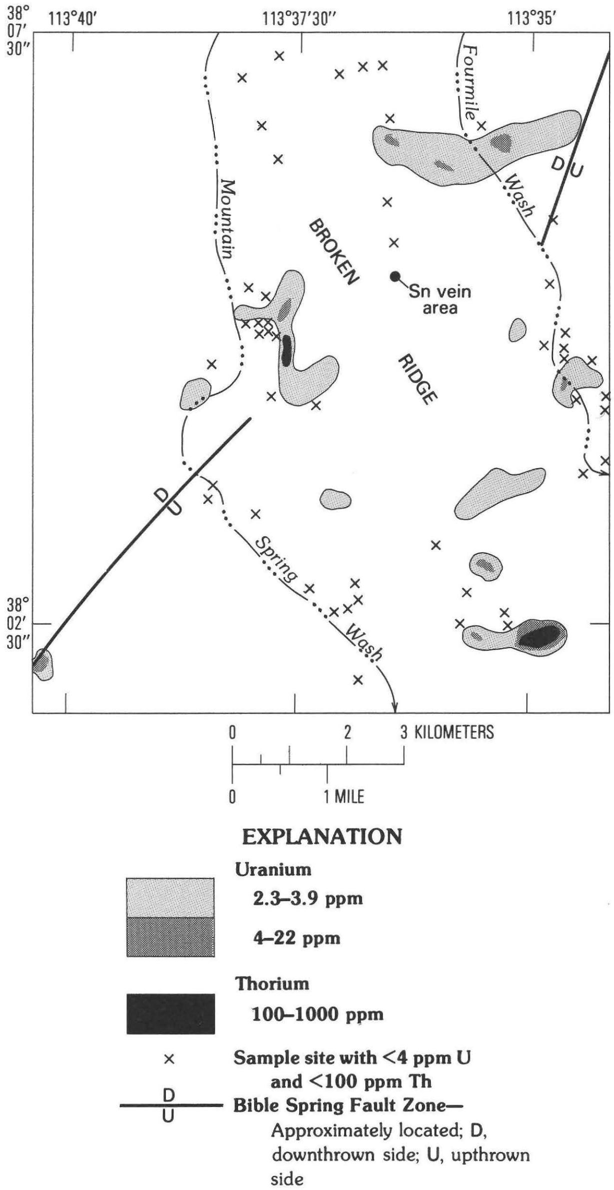

Figure 15. Distribution of U and Th in rocks.

Data for uranium are not available for all samples, and the detection limit for thorium is so high that thorium was not detected in most samples. Nonetheless, available data show that uranium and thorium along the Bible Spring fault zone (fig. 15) are distributed in patterns similar to those of beryllium, fluorine, tin, and niobium (figs. 12–14). West of the dome of Fourmile Wash and northeast of Broken Ridge, the rhyolite contains 4–10 ppm U. Argillized and silicified rhyolite west of Broken Ridge contains abundant Th (100–200 ppm) with moderately high U (2.3–3.9 ppm). In the southwesternmost part of the map area, 22 ppm U occurs in silicified volcanic rocks containing very low Th.

Anomalous concentrations of molybdenum and copper occur along the trend of the Bible Spring fault zone, but they are not as restricted to rhyolitic rocks as the lithophile elements are: they extend southwestward from the rhyolitic rocks into Oligocene volcanic rocks (fig. 16). The distribution of copper clearly marks the trend of the Bible Spring fault zone. In the far southwesternmost part of the map area, faulted and silicified Oligocene volcanic rocks contain 30–100 ppm Cu and 10–20 ppm Mo. Northeastward along the fault zone in alunitized clastic rocks, Mo content is generally less than 10 ppm, but Cu content is consistently 10–20 ppm. Southwest of Broken Ridge but east of Mountain Spring Wash, rhyolitic rocks with anomalous Be, F, Sn, Nb, U,

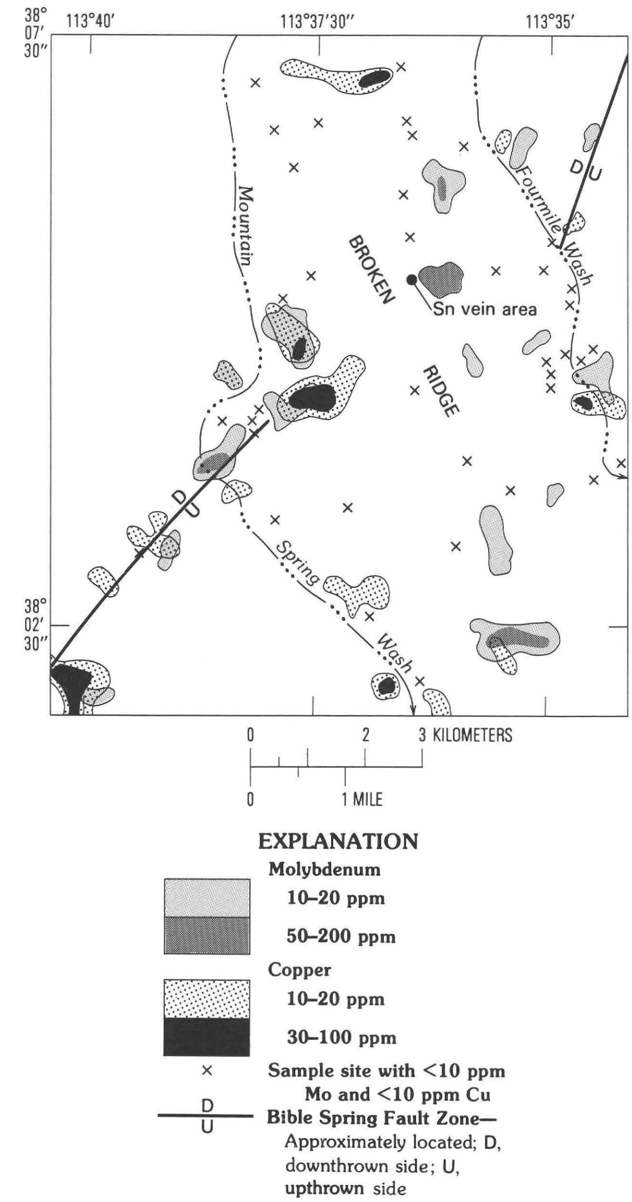

Figure 16. Distribution of Mo and Cu in rocks.

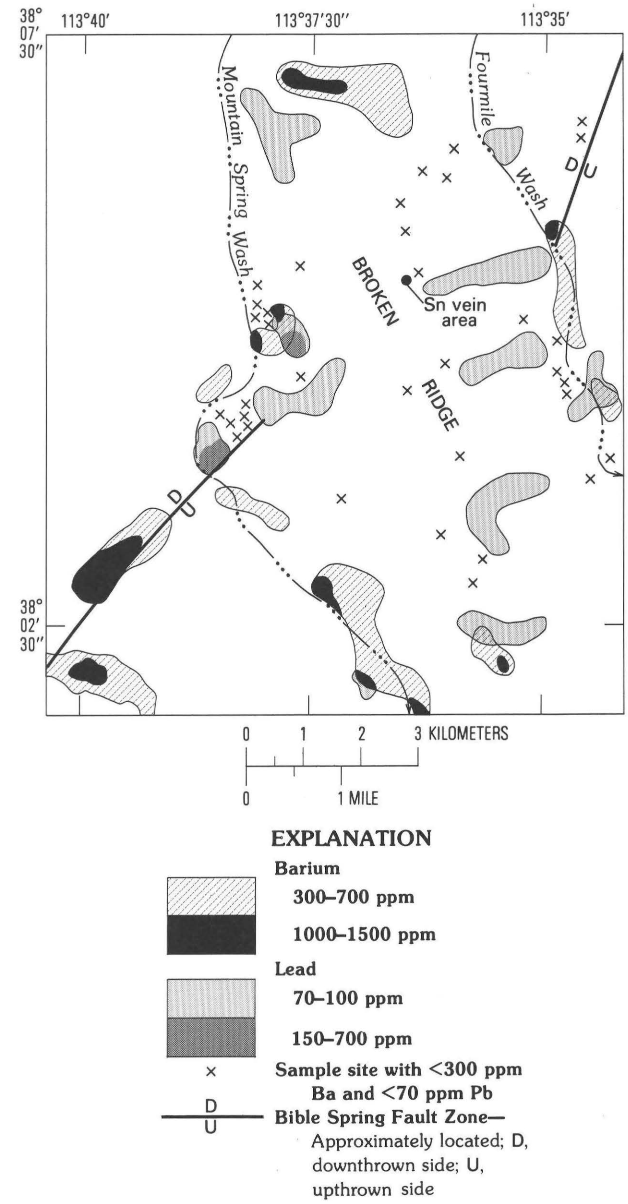

Figure 17. Distribution of Ba and Pb in rocks.

and Th also contain 50–100 ppm Mo and 70–100 ppm Cu. Three samples with up to 100 ppm Cu also contain 200–500 ppm Zn. Just east of Broken Ridge and the tin-rich area, rhyolitic rocks contain anomalous concentrations of Mo (50–200 ppm). East-northeast of Broken Ridge and in the dome of Fourmile Wash, Mo and Cu contents decrease to 10–20 ppm or less.

Altered rhyolite southwest of Broken Ridge containing high Sn, Nb, Be, F, Cu, and Mo also contains 150–700 ppm Pb (fig. 17). Elsewhere in scattered areas around Broken Ridge, lead remains moderately high at 70–100 ppm.

Silver contents range from 0.5 to 3 ppm in rocks west of Broken Ridge and southwest along the trend of the Bible Spring fault zone. Silicified Oligocene volcanic rocks in the southwesternmost part of the map area contain 0.5–1 ppm Ag. Rock samples exhibit a weak positive correlation between silver and lead contents.

Barium, generally low in fresh rhyolite (fig. 17), is enriched in altered copper-rich rocks. An extensive area along the the Bible Spring fault zone in the southwestern part of the map area contains 300–1,000 ppm Ba. Alunitically altered silicic clastic rocks with 10–20 ppm Cu, but depleted in Mo and Pb, contain up to 1,000 ppm Ba. Barium exceeds 1,000 ppm west of Broken Ridge, in an area containing high concentrations of Be, F, U, Th, Nb, Mo, Cu, and Pb.

The close association between anomalous Be, F, Sn, Nb, Mo, U, and Th is characteristic of disseminated porphyry molybdenum deposits (Boyle, 1974), which suggests the possibility that these surface anomalies may reflect a disseminated molybdenum deposit beneath Broken Ridge, though perhaps at a great depth.

Southern Broken Ridge Area

The deeply eroded dome of Mountain Spring, about 1–1½ km north of Mountain Spring Peak, is truncated on the north by an east-trending normal fault and on the east by north- to northwest-trending faults. Rocks along the margins of the dome have undergone silicification and argillic alteration and are partly oxidized. Unusually abundant caliche along the western margin suggests that calcium carbonate was brought up along the structure from subjacent Paleozoic carbonate rocks.

Altered rocks from the fault-bounded eastern margin of this dome contain 200 ppm Mo, 150–200 ppm W, 4–10 ppm U, 500–1,000 ppm Th, 500 ppm Zn, 4,000–9,000 ppm F, and 30 ppm Sn. A small prospect pit 1 km northeast of Mountain Spring exposes vertical joints in silicified rhyolite. One silicified rock sample from the pit contains 0.05 ppm Au, and argillized rhyolitic rocks about ½ km south of the prospect contain 0.1 to 0.4 ppm Au (Duttweiler, 1985). Except for one rock sample containing 0.5 ppm Ag, the rocks are virtually free of silver. The eroded dome area is the only area around Broken Ridge with detectable gold in rock samples. North of the dome area, fresh rhyolite over an area of about 2 km^2 contains 10–20 ppm Sn, 100 ppm Nb, 10–20 ppm Mo, and 3,000 ppm F. Enrichment of the lithophile elements in this area has resulted from migrating hydrothermal fluids that deposited the Mo, W, U, Th, Zn, F, and Sn in the altered rock to the south.

Quartz-alunite rock at Mountain Spring Peak contains 1,500 ppm Ba and 300 ppm Pb; this rock thus contrasts with the virtually lead-free alunitically altered clastic rocks in the southwestern part of the map area. Barium is consistently 1,000–1,500 ppm west and northwest of Mountain Spring Peak in faulted and altered Oligocene volcanic rocks.

Fourmile Wash

A northwest-trending normal fault juxtaposes rhyolite of the Steamboat Mountain Formation against Oligocene volcanic rocks west of Broken Ridge and south of the dome of Fourmile Wash. Quartz- and fluorite-bearing altered rock in the green glass at the fault grades north and south into extensive argillically altered rock. Fluorine contents of the altered rhyolite are 4,500–8,800 ppm, and most samples have 20 ppm Be. Slight enrichments of Sn (20 ppm), U (10 ppm), Mo (20 ppm), and Cu (30 ppm) have also been detected in the rhyolite. Oligocene volcanic rocks south of the fault contain 2,000 ppm Zn and 500 ppm Ba.

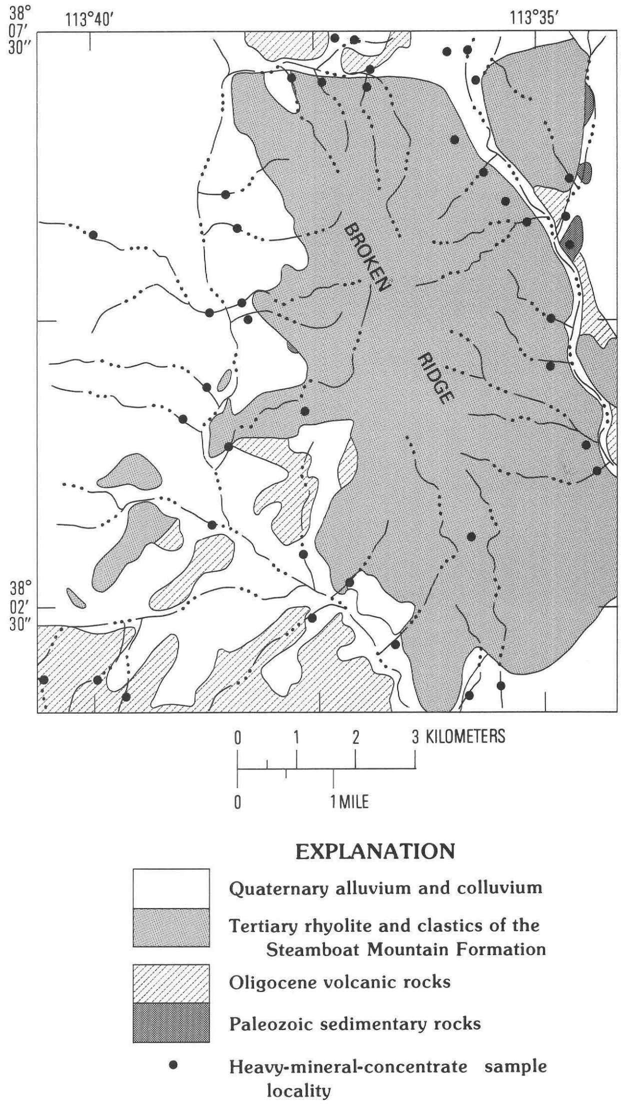

Figure 18. Heavy-mineral-concentrate sample localities, with simplified geology. Geology from Best and Davis (1981) and plate 1 (this report).

Heavy-Mineral-Concentrate Geochemistry

Localities of 41 heavy-mineral-concentrate samples are shown with generalized geology on figure 18. Only the major washes draining the area are shown.

Each sample site represents a drainage area of about 2 km^2. Most are within the Steamboat Mountain Formation; those in the southwestern part of the area represent older volcanic rocks along the Bible Spring fault zone.

The heavy-mineral concentrates were collected primarily for use in mineralogical studies to evaluate the distribution of ore-forming minerals. Minor mineral constituents of rocks that are often not seen in hand specimen examination are readily apparent in such concentrates.

Distribution of Barite and Garnet

Barite in the NM (nonmagnetic at 1 ampere) fraction and garnet in the M.5 (magnetic at 0.5 ampere) fraction are among the minerals unobserved in rocks but abundant in concentrates. Barite occurs in concentrates from washes draining Oligocene volcanic rocks or alunitically altered silicic clastic rocks. Both areas have high barium contents in rocks (fig. 17). Garnet is in concentrates from areas of rhyolite lava flows and silicic clastic rocks of the Steamboat Mountain Formation. Analyses of four garnet separates show >1 percent Mn and 20–30 percent Fe. Magnesium and calcium contents are low, suggesting that the garnet is spessartine-almandine in composition. Keith and others (1986, p. 13) have described a garnet-bearing ash-flow tuff that completely surrounds the Pine Grove pluton in the northern Wah Wah Mountains. Microprobe analyses of garnets from ash-flow and intrusive units in the Pine Grove area demonstrate that both are yttrium-rich almandine-spessartine garnets of identical composition (Keith and others, 1986). The garnet-bearing ash-flow tuff is considered to be the extrusive facies of the granitic porphyry system in Pine Grove that hosts disseminated Mo-W at depth. The widespread and abundant garnet in the Broken Ridge area may have similar significance. More detailed sampling is needed to identify the exact source areas for the garnet.

Distribution of Tin and Cassiterite

Because the Steamboat Mountain Formation is highly silicic and contains abundant lithophile-element minor constituents including tin, special attention was given to determine the distribution of tin and cassiterite in the heavy-mineral concentrates.

The distribution of tin and that of cassiterite are shown in figure 19. Tin is particularly abundant and widespread in concentrates from the high-silica, topaz-bearing rhyolite of the Steamboat Mountain Formation.

About 40 percent of the samples contain 2,000 ppm or more of tin, and the mean is 700 ppm (fig. 19*A*). The occurrence of cassiterite in the concentrates correlates in general with the tin content (fig. 19*B*). The correlation is not precise, because cassiterite in trace amounts was commonly not recognized or was mistaken for other minerals such as rutile. Further, the cassiterite may not be uniformly distributed between the analytical

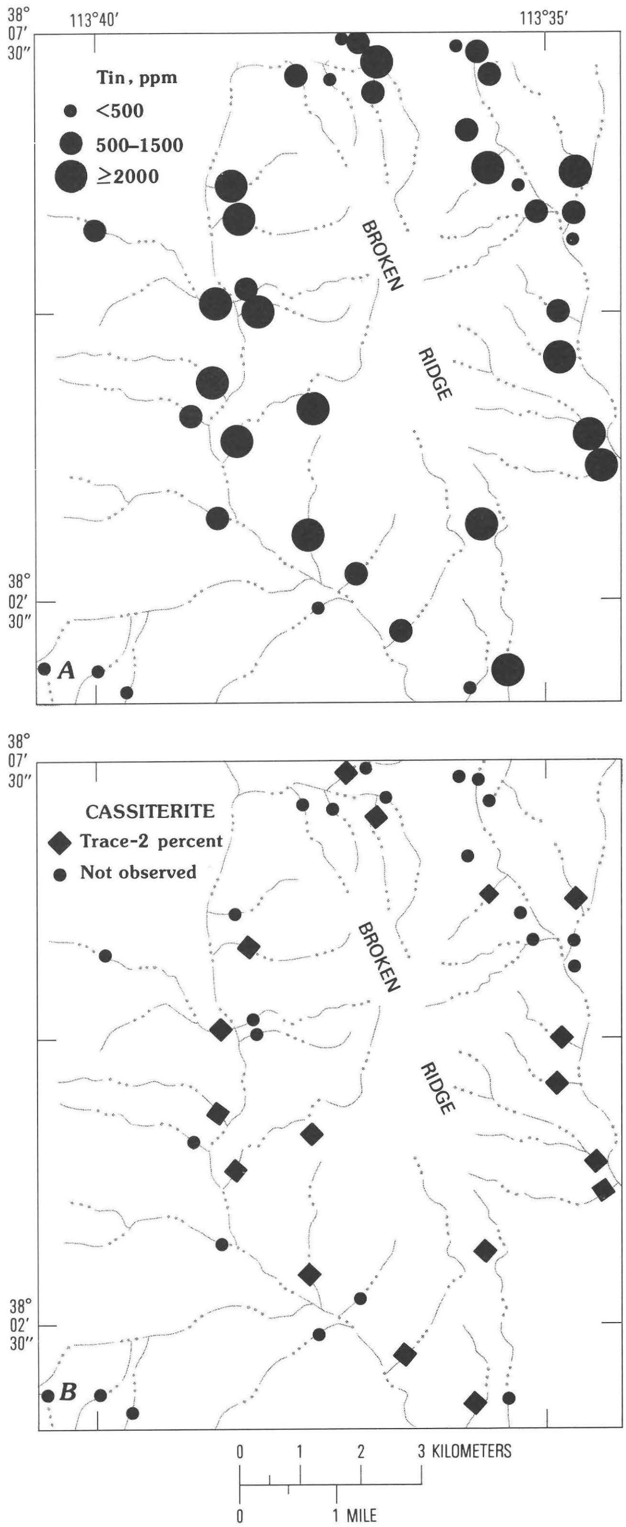

Figure 19. Distribution of Sn and cassiterite in heavy-mineral concentrates. *A*, Sn content; *B*, cassiterite distribution.

and mineralogical split. Therefore, some samples with anomalous tin contents have no recorded cassiterite. However, in nearly all samples containing >2,000 ppm

Sn, a trace to 2 percent cassiterite was observed in the concentrate.

Both single crystals of red-brown cassiterite and polycrystalline flakes of wood tin (botryoidal microcrystalline cassiterite) were recognized in heavy-mineral concentrates; single crystals are far more common than wood tin. It is possible that wood tin is more common in the bedrock but that during transportation it breaks into minute crystals that escape recognition or are lost during panning.

MINERAL DEPOSITS

No mines have been excavated in the Broken Ridge area, but several bodies of altered rock have been explored to shallow depths for uranium or alunite. The distribution of metals in rocks in the Broken Ridge area strongly suggests that geologic structures controlled influx of metals from below and that the geochemical anomalies at the surface are a product of nearly exhausted solutions. Skarn, vein, and replacement deposits in the carbonate strata at depth are therefore a good possibility. Our geochemical data suggest that molybdenum, beryllium, fluorine, tin, and tungsten with lesser amounts of lead, zinc, and copper are the likely metals to be concentrated in such deposits. Very low, undetectable levels of gold and silver in most rocks suggest that potential for precious-metal mineralization is low for most of the Broken Ridge area. However, detectable gold (0.05–0.4 ppm) and minor silver are reported in rocks south of Broken Ridge at the margins of the dome of Mountain Spring. It is possible that faulting and erosion in this area have exposed deeper parts of the pile of Miocene volcanic rocks and deeper levels of a hydrothermal system than elsewhere in the Broken Ridge area, where present exposures are near the top of the original volcanic accumulation. The detectable gold and silver and very high concentrations of numerous other metals in rocks from this southern area strongly indicate mineralization at depth.

The pre-Miocene and early Miocene rocks may also have been mineralized during the 35 to 25 Ma episode of calc-alkaline volcanism, as they were in the San Francisco Range 35 km to the northeast and the Star and Rocky Ranges 30 km to the east. Inasmuch as our samples were collected mainly in an area of late Miocene rocks, our data do not strongly reflect subjacent older mineralization. However, anomalous copper, zinc, and barium concentrations in rocks along the trend of the Bible Spring fault zone and in rocks older than the Steamboat Mountain Formation indicate that these metals migrated to some extent, possibly in large enough amounts to form ore deposits.

Near-Surface Mineralization

The strongest mineralization that took place at the surface yielded cassiterite dispersed in the rhyolite or in veins within the rhyolite. The dispersed cassiterite formed as a result of cooling from a vapor phase shortly after emplacement of the rhyolite, and it should thus favor some zone within the rhyolite. The location of this zone, the limits of which are arbitrary, would depend on the temperature of the fluids and porosity of the rock; but it is most likely to be in the upper parts of lava flows and domes. Vein tin may have formed during cooling, or from later hydrothermal fluids originating either in the lava flow or from an external source at depth that partly redistributed the dispersed cassiterite. Unlike the veins described in the next section, veins that form in the tops of flows and the carapaces of domes generally are thin and discontinuous.

Cassiterite-Bearing Veins

The Steamboat Mountain rhyolite is younger than most of the movement on the Bible Spring fault zone, but the rhyolite has nonetheless been affected by faulting. The three northeasterly trending valleys on the east side of Broken Ridge nearly parallel the fault zone. Their orientation can be attributed to slight, late movement on the fault.

A breccia body near the bottom of one of the northeast-trending washes in section 23 is thoroughly silicified and contains several ore minerals. The breccia body is at least 100 m long and at least 10 m wide, and trends N. 55° E., about parallel to the wash on its southeast side and to the trend of the Bible Spring fault zone. Exposures are discontinuous because the rock is strongly silicified in some places and soft in others. Much of the body, especially the softer parts, is covered by surficial material littering the valley floor. Where well exposed, about ⅔ of the body consists of gray to pink silicified rhyolite clasts 1 mm to 15 cm across set in a hard, dark-gray to black siliceous matrix. The matrix contains hexagonal plates of hematite as much as 2 mm across, cassiterite, purple fluorite, and tiny unidentified grains. The breccia contains several percent of cavities as much as 5 mm across, some of which are partly lined by crystals of cassiterite and hematite and radial aggregates of cristobalite (fig. 20*A*). In places hematite flakes 0.1–0.2 mm thick are coated on one or both sides by minute brown crystals of cassiterite. In other places, hematite is interlayered with coarser grained cassiterite, indicating alternating deposition (fig. 20*B*). Elements

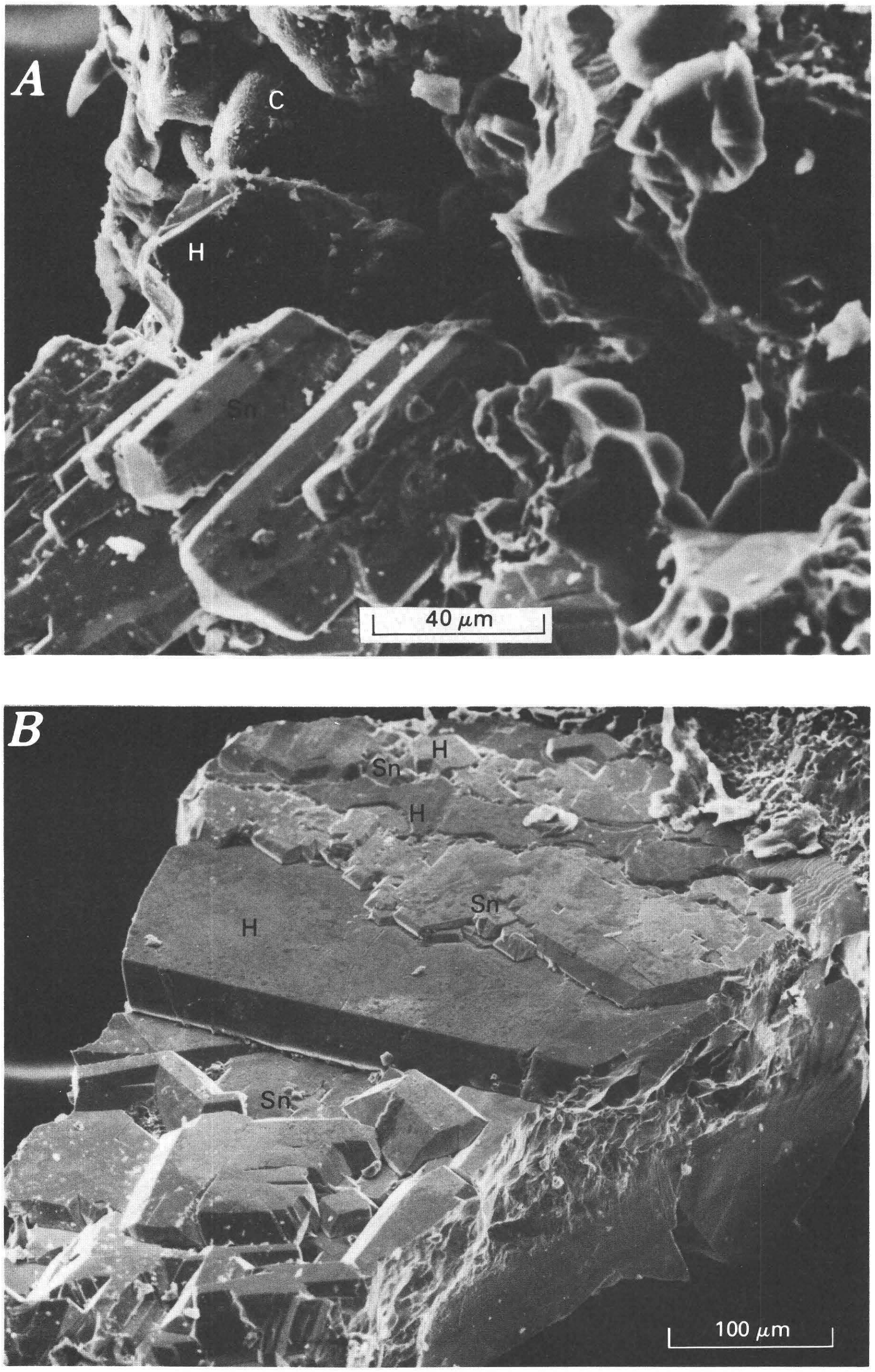

Figure 20. Photomicrographs of the cassiterite-bearing veins under a scanning electron microscope (SEM); H, hematite; Sn, cassiterite; C, cristobalite. *B* contrasts with *A* in that in *B* hematite and coarser grained cassiterite are interlayered.

present in anomalous concentrations in the breccia but not traced to specific minerals are antimony, arsenic, uranium, zinc, tungsten, beryllium, and manganese. Thorium and boron were found in a heavy-mineral-concentrate sample from a nearby wash.

Other bodies of altered rock are exposed adjacent to the cassiterite-bearing breccia body. Silicified rhyolite about ½ km west on strike from the tin-bearing breccia body contains minor garnet. Florite-bearing altered rhyolite is at the crest of the ridge south of the garnetiferous body. A trace of arsenopyrite was separated from a rhyolite sample collected about 1 km northeast of the cassiterite vein, and rhyolite is silicified along northwest-trending fractures nearby.

Potential for Deposits at Depth

The knowledge of regional structure is useful in evaluating potential mineral resources of the Broken Ridge area because persistent structures tap larger volumes of metalliferous solutions than would be available from solutions derived solely from lower parts of the rhyolite lava flows. The two areas with the greatest potential for deep mineral deposits are along the trend of the Bible Spring fault zone between Meadow Spring (sec. 33, T. 31 S., R. 16 W.) and the east edge of sec. 23, T. 31 S., R. 16 W., and at depth beneath the altered rocks around the margins of the eroded dome of Mountain Spring. Both areas have persistent structures to serve as channels for solutions that would pass through silicate and carbonate rocks at depth.

The presence of altered rocks and geochemical anomalies indicates that hydrous metalliferous solutions did indeed pass through the structures. Most of the altered rocks are localized along the Bible Spring fault zone or along its trend northeastward where it projects directly toward the Cima (Katie) sulfur-mercury deposit (fig. 3). The deposit at the Cima mine has been determined to be of Blawn age (23–18 m.y.), but the other areas of altered and mineralized rocks southwestward along the projection of the fault are of Steamboat Mountain age (12 m.y.). Alunitically altered rocks southwest of Meadow Spring are also clearly 12 m.y. old or younger, because alunite and kaolinite replace clastic rocks of the Steamboat Mountain Formation. Age relationships further southwest along the fault are unclear because silicification of volcanic rocks in this area may have resulted from hydrothermal activity associated with either the Blawn period of volcanic activity or with the 12 m.y. Steamboat Mountain Formation.

Alteration of the rhyolitic rocks probably took place in an acid-sulfate near-surface oxidizing environment over a limited vertical range. Deeper within the hydrothermal system lies potential for a wide range of mineral deposits, including sulfide deposits if the deeper solutions were not oxidized. Present exposures in the Broken Ridge area are near the top of the original volcanic accumulation, so potential ore deposits may be rather deep.

The relationship between the rhyolitic tuffs and lava flows of the Steamboat Mountain Formation and the types of mineral deposits possibly associated with them are depicted schematically in figure 21. On the surface, airfall and ash-flow tuffs alternate with lava flows and domes, indicating several episodes of volcanic activity separated by periods of erosion and weathering to produce epiclastic and water-deposited sediments. During or shortly after emplacement of the rhyolite domes and flows, vapor phase deposition of cassiterite, topaz, and fluorite occurred in lithophysae and vugs within the rhyolite. Later hydrothermal fluids concentrated metals along faults, producing alteration and geochemical anomalies.

If intrusive igneous rocks exist beneath Broken Ridge, possible deposit types include porphyry-type deposits near the tops of the intrusions, skarn and replacement deposits in carbonate rocks underlying the volcanic rocks, and near-surface vein deposits.

Potential for Porphyry Deposits

The close association of Be, F, Sn, Nb, Mo, U, and Th anomalies in altered rocks from the Broken Ridge area is characteristic of porphyry molybdenum deposits (Boyle, 1974). These data and data presented by Tucker and others (1981) suggest a possibility for such a deposit beneath Broken Ridge. This interpretation is also supported by Steven and Morris (1984).

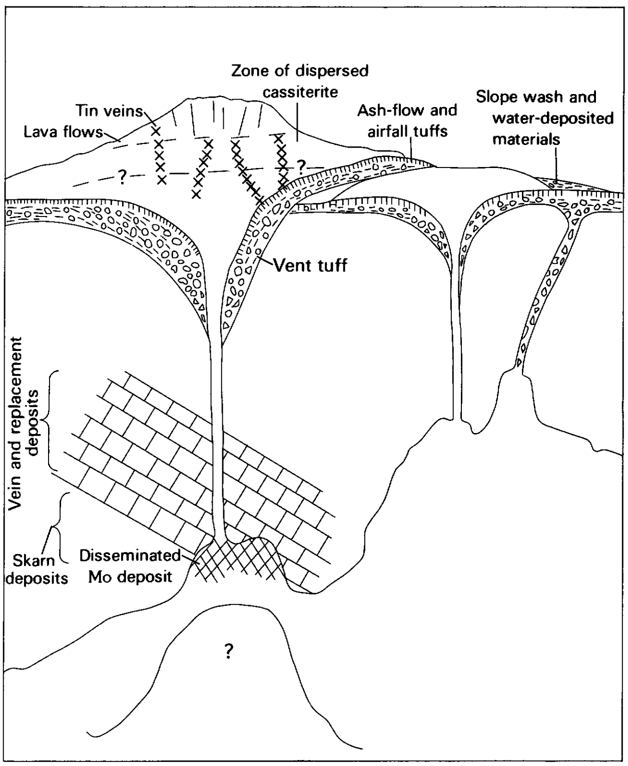

Figure 21. Schematic diagram showing relationship between rhyolite tuffs and lava flows in the Broken Ridge area, and possible mineral deposits related to them.

The Pine Grove district is only about 30 km north of Broken Ridge. Early mining activity produced gold, silver, copper, lead, and zinc from small replacement orebodies of Miocene age in carbonate strata. Subsequent to exploitation of these deposits, a large deeply buried stockwork molybdenum-tungsten deposit was discovered. The Pine Grove deposit has been classified as a typical stockwork climax-type porphyry molybdenum system (White and others, 1981; Keith and others, 1986). The top of the deposit is reported to lie at depths of 900–2,000 m below the surface (Abbott and others, 1983). Significant tonnage of high-grade ore (about 125 million tons of 0.3 percent MoS_2; Sillitoe, 1980, from Keith and others, 1986) is reported to characterize the deposit.

The geologic environment of the Broken Ridge area is similar in many respects to that of Pine Grove and is favorable for a comparable porphyry deposit, as well as comparable replacement deposits of base and precious metals.

Potential for Skarn and Replacement Deposits

In addition to potential for porphyry-type deposits, carbonate wall rocks surrounding such deposits are possible hosts to skarn, replacement, or vein-type deposits. Metals such as Mo, Be, F, W, and Sn, as well as base and precious metals, are concentrated in deposits of this sort. East of the Wah Wah Mountains in the San Francisco Mountains and adjacent areas, extensive erosion has cut to the lower volcanic or upper subvolcanic levels exposing the tops of intrusions. This is in contrast to the Broken Ridge area where equivalent levels of potentially mineralized areas are still largely buried. Widely exposed mineralized areas in the San Francisco Mountains and vicinity include skarn deposits of the Rocky district which have produced copper, tungsten, gold, and silver (Steven and Morris, 1984).

Replacement orebodies in the Pine Grove district, central Wah Wah Mountains, produced gold, silver, copper, lead, and zinc. Vein and replacement orebodies are especially important in the San Francisco and Star districts (Steven and Morris, 1984).

The Horn Silver replacement deposit in the southern San Francisco Mountains is unique among deposits in the Richfield 1° × 2° quadrangle in its size and richness (Steven and Morris, 1984). Lead, zinc, silver, gold, and minor copper were recovered from the deposit, which occurs in carbonate strata adjacent to the north-trending Horn Silver fault (Steven and Morris, 1984).

The material of low density along the northwestern side of the Bible Spring fault zone (see section, "Structure") may be a rubble of carbonate blocks fallen from the fault scarp to the south and embedded in a porous matrix. This would be excellent material in which to form replacement deposits, as in the Spor Mountain, Utah, beryllium district, and potentially as favorable as the fault breccia at the Horn Silver mine in the Frisco district, Utah.

The unusually strong development of caliche along the west edge of the dome of Mountain Spring may have resulted from carbonate that was carried upward along the dome margin during late Miocene replacement of underlying Paleozoic limestone or dolomite. The lithophile elements associated with altered rocks along this margin are beryllium, fluorine, tin, niobium, and uranium; the high concentrations of these elements at the surface may indicate that the metals were concentrated during replacement.

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