Oligocene and Miocene Volcanic Rocks in the Central Pioche-Marysvale Igneous Belt, Western Utah and Eastern Nevada

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Stratigraphy of the Volcanic Oligocene Needles Range Group in Southwestern Utah and Eastern Nevada

By MYRON G. BEST *and* S. KERRY GRANT

Miocene Magmatism and Tectonism in and near the Southern Wah Wah Mountains, Southwestern Utah

By MYRON G. BEST, HARALD H. MEHNERT, JEFFREY D. KEITH,
and CHARLES W. NAESER

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U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1433-A

Several ash-flow cooling units with a total volume of more than 6,600 km^3 make up two compositional cycles, each of which began with rhyolite and terminated with dacite

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ABSTRACT

Dominantly explosive mid-Oligocene magmatic activity 33–28 m.y. ago along the southern Utah-Nevada border produced several ash-flow cooling units with a total volume of at least 6,600 km^3 and formed the large Indian Peak caldera complex. These units constitute two eruptive-compositional cycles, each of which began with crystal-poor, lithic, low-silica rhyolite tuff and culminated with a larger volume of crystal-rich, mostly nonlithic dacite tuff. Pyroxene andesite flows were erupted from many widely scattered vents contemporaneously with first-cycle rhyolite flows and tuffs, and locally with second-cycle tuffs. Five major pyroclastic units deposited during the two eruptive cycles are here accorded formation rank (some were previously assigned member rank) within the revised Needles Range Group (formerly the Needles Range Formation). From the base upward, these formations are the Escalante Desert Formation (newly added to group), the Cottonwood Wash Tuff (formerly a member), and the Wah Wah Springs Formation (formerly a member) in the older cycle, and the Ryan Spring Formation (new unit) and the Lund Formation (formerly a member) in the younger cycle. The Wallaces Peak Tuff (formerly a member in the Needles Range Formation) is herein abandoned because of synonymy with the Three Creeks Tuff Member of the Bullion Canyon Volcanics, whose source lies far to the east in south-central Utah.

The Escalante Desert Formation consists of at least two low-silica rhyolite ash-flow tuff cooling units, rhyolite and pyroxene andesite lava flows, and local lenses of epiclastic deposits. The crystal-poor, lithic rhyolite tuff units are given formal status as the older Marsden Tuff Member (new unit) and the younger Lamerdorf Tuff Member. The source of the Marsden, whose total volume is about 300 km^3, was the Pine Valley caldera, a poorly defined collapse structure extending from the Indian Peak Range (southern Needle Range of older usage) to the southern Wah Wah Mountains in Utah. The source of the Lamerdorf may also have been the same caldera, but direct evidence is lacking. The Beers Spring Member is assigned to the Escalante Desert as the upper member.

The 500-km^3, 30.6-m.y.-old Cottonwood Wash Tuff, deposited after the Escalante Desert Formation, is essentially a simple cooling unit of crystal-rich dacite tuff. Like all of the crystal-rich dacite tuff units of the Needles Range Group, it has about 40 percent phenocrysts, about half of which are plagioclase. In the Cottonwood Wash Tuff, large phenocrysts of biotite and lesser quartz are characteristic. The source of the Cottonwood Wash Tuff appears from indirect evidence to be concealed beneath a broad, mostly alluviated area immediately west of the Utah-Nevada State line.

The first eruptive-compositional cycle of the Needles Range Group culminated 29.5 m.y. ago with the eruption of at least 1,500 km^3 of crystal-rich dacite tuff of the outflow tuff member of the Wah Wah Springs Formation, which spread over an area of at least 22,000 km^2 in Utah and Nevada. The tuff is distinctively rich in hornblende and poor in quartz, and it is the only reversely magnetized tuff in the Needles Range Group. The Indian Peak caldera produced by this eruption had an estimated area of at least 1,200 km^2 and is partly filled by 2,400 km^3 or so of the intracaldera member of the Wah Wah Springs Formation, which comprises landslide and fault debris that sloughed off the topographic wall as well as lithic dacite tuff.

Two cooling units of crystal-poor, lithic-rich rhyolite ash-flow tuff—the Greens Canyon and Mackleprang Tuff Members of the Ryan Spring Formation, all newly named in this report—initiated the second cycle. The more than 200 km^3 of ash-flow tuff is almost entirely confined within the Indian Peak caldera, where its source was located. The pattern of deposition implies that the core of the older caldera had been resurgently uplifted and block faulted before the Ryan Spring Formation was deposited. Andesitic and rhyolitic lava flows of the Ryan Spring Formation occur locally.

The 27.9-m.y.-old crystal-rich dacite tuff of the Lund Formation completely filled the resurgently domed Indian Peak caldera to depths of several hundred meters and spilled beyond to cover an area of about 11,000 km^2 in Utah and Nevada with a volume of about 1,600 km^3. It is the most quartz-rich unit in the Needles Range Group and the only one that contains trace amounts of sphene. The tuff is a compound cooling unit within the Indian Peak caldera and within the younger White Rock caldera, which partly eclipses the Indian Peak caldera on the southwest and is the source of the Lund. Perhaps as much as 2 km of tuff and intercalated landslide breccia are exposed along the northwest margin of the White Rock caldera, whose estimated area was 2,000 km^2. Pyroxene andesite lava flows very locally cap the tuff.

INTRODUCTION

Since the pioneering efforts of J. Hoover Mackin and his students in the 1950's and early 1960's, the crystal-rich, dacitic tuffs[1] of the Needles Range Group of Oligocene age have been recognized as one of the most widespread and voluminous sequences of Cenozoic ash-flow deposits in the Western United States. Mackin (1960; see also 1963) and Cook (1965) noted that these lithologically distinctive rocks crop out from the central High Plateaus of Utah westward across the eastern Great Basin into central southern Nevada (fig. A1). Their areal extent was estimated to be at least 34,000 km^2 and their volume to be 6,500 km^3.

A direction for future investigations of the Needles Range tuffs was indicated in a statement by Mackin (1963, p. 77): "* * * the significant point is differences in thickness, lithology, and distribution of different Needle Range ignimbrites suggest that they may have been erupted in different places. The answer to this and most other problems relating to the Needles Range Formation depends on member-by-member mapping." Virtually all areas in Utah where Needles Range units occur have now been mapped, mostly at a scale of 1:24,000, under the auspices of the U.S. Geological Survey. Thomas A. Steven, Peter D. Rowley, John J. Anderson, and Charles G. Cunningham have been responsible for much of the effort in the High Plateaus and into the easternmost Great Basin, and we, along with Lehi F. Hintze, have had responsibility in western Utah. Adjacent parts of Nevada have not been mapped in comparable detail, but reconnaissance work in these areas by Cook (1965), Grommé and others (1972), Ekren and others (1977), and Best (unpublished) provides important clues to the distribution and types of tuff and their possible sources. Available isotopic ages bracket the age of the Needles Range units between about 33 and 28 m.y., and paleomagnetic studies have shown that all but one of the tuff sheets—the Wah Wah Springs—have normal magnetic polarity (Grommé and others, 1972; Shuey and others, 1976).

The purpose of this report is to summarize what is currently known regarding the lithologic character, thickness, distribution, and source of the units in the Needles Range Group, and to revise their stratigraphic nomenclature.

ACKNOWLEDGMENTS

This study would have been impossible without the fruitful insights, patient encouragement, and unflagging logistical efforts of Thomas A. Steven. Lehi F. Hintze first introduced the senior author to the geology of the eastern Great Basin in the late 1960's and has continued to provide valuable assistance and a listening ear ever since. Bart J. Kowallis of Brigham Young University kindly provided fission-track ages. Many other geologists too numerous to mention here have provided assistance and constructive discussions over the years.

GENERAL GEOLOGY

The inception of Cenozoic volcanism in southwestern Utah approximately 34 m.y. ago followed a long period of erosion that had begun with the warping, folding, and thrusting of pre-Tertiary sedimentary strata during the Sevier and Laramide orogenies (Rowley and others, 1979). The rocks from this earliest volcanic episode have calc-alkalic affinities and are discontinuous and widely scattered; locally they occur in east-west paleovalleys carved into sedimentary strata to depths of a few hundred meters, rarely to as much as a kilometer. Into one of these paleovalleys, at Sawtooth Peak in the southern Mountain Home Range, 300 m of ash-flow tuff with abundant phenocrysts of quartz, plagioclase, biotite, and minor sanidine and hornblende was deposited. This tuff was designated the Sawtooth Peak Formation by Conrad (1969). The location of his type section, Sawtooth Peak (Best and Hintze, 1980a), is here clarified as in NE¼ sec. 15, T. 28 S., R. 18 W. A potassium-argon age on biotite determined in 1983 by S. H. Evans, Jr., at the University of Utah is 33.5±1.2 m.y., and a fission-track age on zircon from the same sample is 33.6±1.8 m.y. as determined in 1984 by Bart Kowallis at Brigham Young University. The sample was collected at lat 38°25′38″ N. and long 113°51′13″ W.

Volcanic rocks of the Needles Range Group, deposited next, flooded the landscape to depths as great as a kilometer and filled source calderas to depths of at least three kilometers. After deposition of these volcanic rocks, much of southwestern Utah and southeastern Nevada must have been a rather featureless plain, because densely welded trachytic tuffs of the Isom Formation generally only a few tens of meters thick overlie the Needles Range Group throughout the region. However, along the northern margin of the Escalante Desert these Isom tuffs (average K-Ar age about 26.0 m.y.; Fleck and others, 1975, adjusted for new decay constants of Dalrymple, 1979) are hundreds of meters thick and locally contain large compacted pumice blocks with secondary flowage features, suggesting a nearby source (Rowley and others, 1979; Best, 1987).

Early Miocene ash-flow tuffs of the Quichapa Group (Williams, 1967) are virtually absent north of lat. 38° N.,

[1]Unless otherwise indicated, the term "tuff" in this chapter implies lapilli ash-flow tuff.

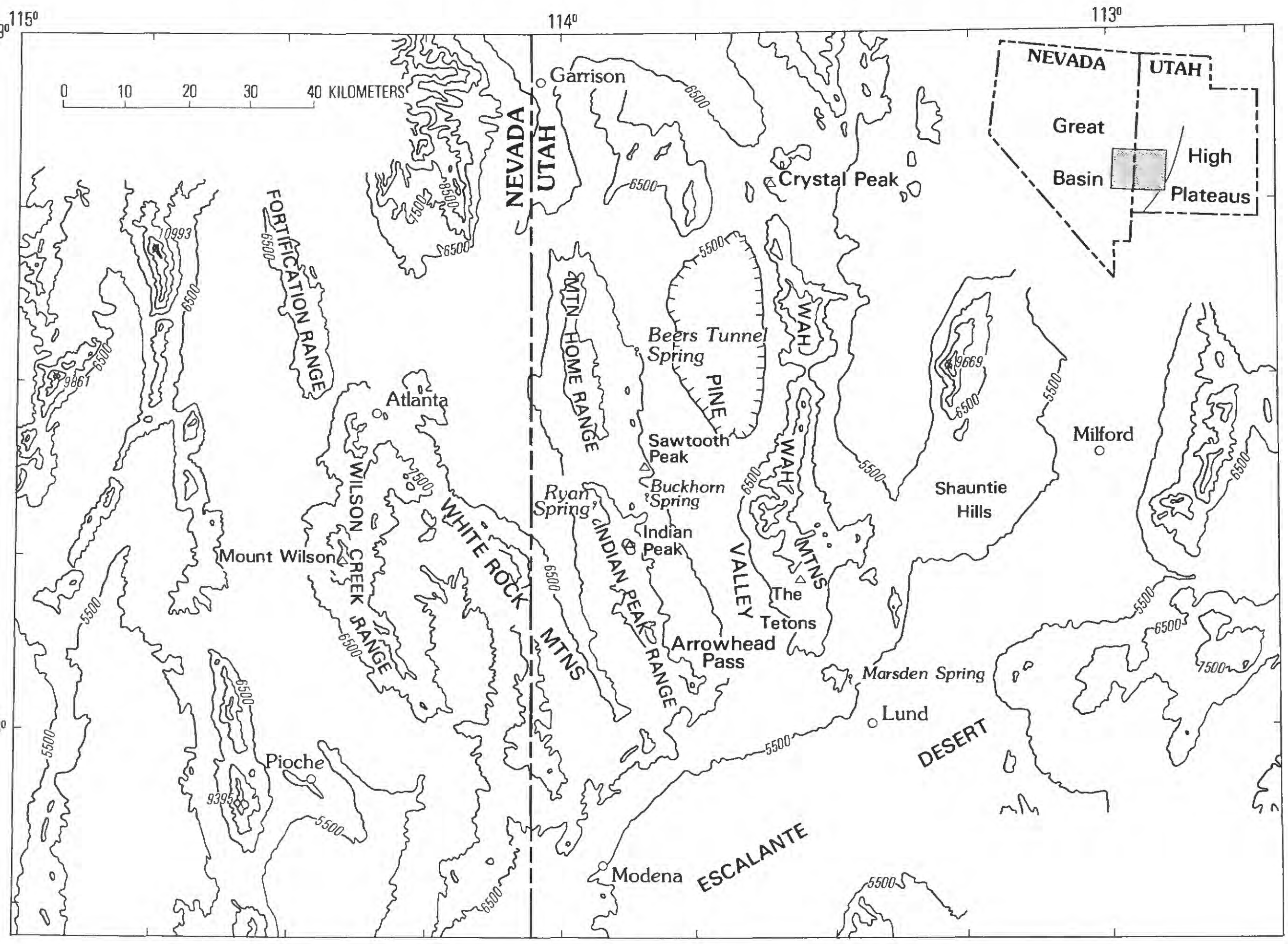


FIGURE A1.—Location of features referred to in text. Elevations in feet (1 ft = 0.3048 m).

except for the densely welded Bauers Tuff Member of the Condor Canyon Formation, which is a thin but widespread sheet. However, the Quichapa Group and other associated Miocene rocks form a thick sequence to the south and especially to the southwest, where the sources of the regional ash-flow sheets probably lay in the Caliente cauldron complex (Ekren and others, 1977; Williams, 1967). North of the Escalante Desert, episodic Miocene magmatism erupted two bimodal silicic-mafic associations from many local vents without forming a caldera (Best and others, this volume, chap. B). A period of east- to northeast-trending extensional block faulting accompanied the early Miocene bimodal activity 23–18 m.y. ago.

STRATIGRAPHIC NOMENCLATURE

Crystal-rich dacite tuffs of Oligocene age have long served as key stratigraphic markers in southwestern Utah and southeastern Nevada because of their wide geographic extents and distinctive compositions. Mapping by many geologists in southwestern Utah has distinguished four widespread crystal-rich ash-flow units, which were included as members in the Needles Range Formation of Mackin (1960). As summarized by Best and others (1973), these stratigraphic units are, from oldest to youngest, Cottonwood Wash, Wah Wah Springs, Lund, and Wallaces Peak. In southeastern Nevada, Cook (1965) recognized as many as five distinctive Needles Range units, three of which are the Cottonwood Wash, Wah Wah Springs, and Lund.

As originally described by Mackin (1960), the type locality of the Needles [sic] Range Formation was the Needle Range in western Utah. This geographic designation was used on all maps published by the U.S. Geological Survey until 1974. Since that time, the southern part of the Needle Range has been called the Indian Peak Range, and the northern part the Mountain Home Range. We will use the former name when the whole mountain range is being discussed, and the newer names in referring to specific parts.

CHANGE IN STRATIGRAPHIC RANK

Although Mackin's original definition of the Needles Range Formation included only crystal-rich dacite tuffs (Best and others, 1973), one of us (Grant) realized in the late 1970's that associated crystal-poor rhyolite tuffs were integral parts of the Needles Range magma system; some are interstratified with the crystal-rich tuffs and all share source areas with the crystal-rich tuffs. Two compositional cycles can be recognized in the erupted parts of the Needles Range magma system, each beginning with crystal-poor rhyolite and culminating with a greater volume of crystal-rich dacite (fig. A2). It is now apparent that the stratigraphic rank of the whole assemblage of apparently cogenetic tuffs and minor lava flows should be that of a group, so that each major unit is a formation that has its own interpretable history of origin and emplacement.

The Needles Range Group thus defined consists in ascending order of the Escalante Desert Formation (newly assigned to group), the Cottonwood Wash Tuff, the Wah Wah Springs Formation, the Ryan Spring Formation (new name), and the Lund Formation. Our justification for omitting the Wallaces Peak Tuff from the Needles Range Group is outlined in the next section. The new formational status of the Cottonwood Wash, Wah Wah Springs, and Lund applies wherever they are exposed. The type locality and the upper and lower boundaries of the Cottonwood Wash Tuff are those given by Best and others (1973) for its prior status as a member unit. Type sections and boundaries of the chiefly rhyolitic Escalante Desert and Ryan Spring Formations are described in later sections.

The development of the Indian Peak caldera, which was the source of the Wah Wah Springs Formation, can be traced by dividing this formation into two members. The outflow tuff member of the formation is here defined as the ash-flow tuff sheet that lies almost entirely outside the limits of the caldera and whose catastrophic eruption led to initial caldera collapse. Only a few remnants of this member are found inside the topographic rim of the caldera. The outflow tuff member includes all of those rocks formerly assigned by Best and others (1973) to the Wah Wah Springs Tuff Member of the Needles Range Formation of Mackin (1960); definitions of the type locality, upper and lower boundaries, and lithologic character of the previous member now apply to the newly defined outflow tuff member. The intracaldera member of the formation will be defined and described in a later section.

The White Rock caldera, the source of the Lund Formation, has only recently (1984) been discovered; most of its definition, as well as detailed elucidation of constituent members of the Lund Formation, must await

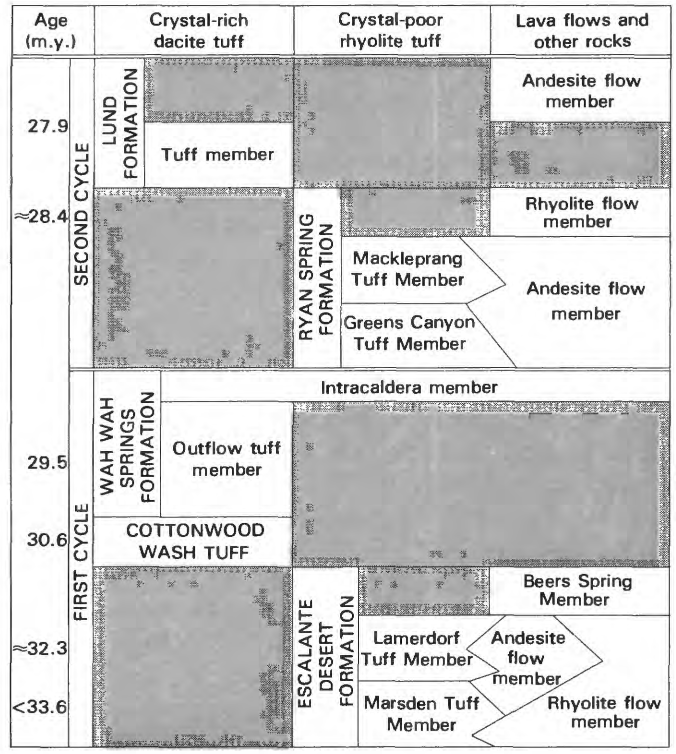


FIGURE A2.—Stratigraphic relations and nomenclature of the Oligocene Needles Range Group.

future mapping in Nevada. The tuff member of the Lund Formation encompasses rocks formerly assigned by Best and others (1973) to the Lund Tuff Member of the Needles Range Formation of Mackin (1960); the type section, the definitions of upper and lower boundaries, and the lithologic character of the previous member now apply to the newly defined tuff member of the Lund Formation. The andesite member will be defined in a later section in this chapter.

ABANDONMENT OF THE WALLACES PEAK TUFF MEMBER

Best and others (1973) named the youngest member of the Needles Range Formation of Mackin (1960) the Wallaces Peak Tuff Member for exposures at Wallaces Peak on the east flank of the Wah Wah Mountains, 45 km west of Milford. It is a crystal-rich dacite tuff with unusually large (as much as 4 mm long), euhedral plagioclase phenocrysts and is mineralogically similar to the newly defined outflow tuff member of the Wah Wah Springs Formation, except that it has less quartz and no augite. Unlike the outflow tuff member, though, it has normal magnetic polarity. Although the Wallaces Peak is not isotopically dated, its stratigraphic position in western Utah between the Lund Formation and the Isom Formation fixes its age between 27.9 and 26.0 m.y.

Unlike the other Needles Range units, it appears to have a source well east of the Indian Peak caldera complex. Indeed, westernmost exposures of the Wallaces Peak Tuff are along the eastern flank of the Wah Wah Mountains. Its easternmost known exposure is in Minersville Canyon, 25 km southeast of Milford, where it lies between the Lund and Isom Formations.

Examination of the Three Creeks Tuff Member of the Bullion Canyon Volcanics, which is widely exposed in the Marysvale volcanic field of south-central Utah (Cunningham and others, 1983), indicates that the Wallaces Peak Tuff Member is the same unit. The type area of the Three Creeks Tuff Member is in Clear Creek Canyon, 20 km northwest of Marysvale, where it forms a thick compound cooling unit in and near its source trapdoor caldera (Steven and others, 1979; Steven, 1981). This thick section of tuff was believed by Mackin (1963) to be his Needles Range Formation. Subsequently, Caskey and Shuey (1975) showed that only the lowermost part had the requisite reverse magnetic polarity and mineralogical composition to be the then recognized Wah Wah Springs Tuff Member. Most of the overlying section, with normal polarity, was perceived by Caskey and Shuey (1975) to be of local derivation and was named by them the Clear Creek Tuff Member. As this name was preempted by prior use, Steven and others (1979) renamed the unit the Three Creeks Tuff Member of the Bullion Canyon Volcanics.

The most striking megascopic similarity between the Wallaces Peak Tuff Member, recognized in western Utah, and the Three Creeks Tuff Member, in central Utah, is their content of abundant large, euhedral plagioclase phenocrysts. Both have normal magnetic polarity and similar mineralogical composition (table A1). Seven isotopic ages on the Three Creeks Tuff scatter widely between 31.4 and 26.2 m.y. (Steven and others, 1979) but do show that the unit is older than the 26.0-m.y.-old Isom Tuff, which overlies the Wallaces Peak Tuff in western Utah.

Because the Wallaces Peak Tuff Member of western Utah and the Three Creeks Tuff Member of central Utah appear to be the same unit and because the latter has a demonstrated source far distant from the sources of the other units of the Needles Range Group, the Wallaces Peak Tuff is abandoned.

GENERAL COMMENT ON CRYSTAL-RICH DACITE TUFF UNITS

All three of the crystal-rich dacite ash-flow tuff units of the Needles Range Group (table A1) contain approximately 40 percent crystals, and about one-half of these are complexly zoned, twinned plagioclase from 0.5 to 3 mm long. Combinations of quartz, biotite, and hornblende constitute most of the remaining crystals. All of the tuffs contain generally less than 3 percent total augite and equant Fe-Ti oxides, and trace amounts of apatite and zircon. Foreign lithic fragments in the tuffs are rare, except for volcanic clasts in tuff of the intracaldera member of the Wah Wah Springs Formation. Lapilli and local blocks of light-colored pumice are prominent and contrast with the gray, red, pink, or brown ashy matrix of the dacite tuffs. On an anhydrous basis, the rocks contain 65–69 weight percent SiO_2.

TABLE A1.—*Modal composition of samples of the Three Creeks Tuff Member of the Bullion Canyon Volcanics*

[About 1200 points were counted through one thin section per sample. All samples contain trace amounts of apatite and zircon. Multiple samples from one locality are listed in order of ascending stratigraphic position. The relatively crystal-poor sample from south of Wallaces Peak is from the basal vitrophyre]

Constituent	Clear Creek Canyon near type area			Minersville Canyon[1]	Wallaces Peak[1] [2]			South of Wallaces Peak[1]	
Matrix[3]----	47	52	51	61	55	60	58	66	49
Plagioclase	40	33	33	26	26	23	29	17	36
Hornblende	8	10	10	9	11	11	6	12	8
Biotite----	3	3	3	2	5	4	5	3	4
Fe-Ti oxide	1	2	2	2	1	1	1	2	1
Quartz-----	<1	<1	1	<1	2	1	1	<1	1

[1]Locality of formerly designated Wallaces Peak Tuff.
[2]Best and others (1973).
[3]Includes lithic fragments.

Thick, simple cooling units of the Needles Range dacite tuffs near their sources typically have a gray to black, densely welded vitrophyre from 1 to 10 m thick near the base. This is overlain by red-brown, slightly devitrified tuff, whose degree of welding and compaction decreases upward. Porous, partially welded tops of the tuffs are pink, buff, or light gray. The actual base of any ash-flow deposit is rarely exposed, and the interval below the vitrophyre is generally only a few meters thick, at most. Where exposed, the base is generally a nonstratified tuff containing phenocrysts that are finer than those in other parts of the unit.

ESCALANTE DESERT FORMATION

The Escalante Desert Formation is herein made a part of the Needles Range Group because the magmas that created it were derived from essentially the same area, and, we believe, from the same magma system that produced the other formations in the group. The Escalante Desert Formation was named and described by Grant (1978) for a sequence of crystal-poor, lithic-rich, rhyolite ash-flow tuff units underlying the Needles Range Formation of Mackin (1960) and overlying a local unnamed conglomerate at the type section on the northeast flank of hill 6535, sec. 6, T. 32 S., R. 14 W., in the Lund, Utah, 7½-minute quadrangle (Grant and Best, 1979b). At this locality near the southeastern end of the Wah Wah Mountains, the Cottonwood Wash Tuff is absent and the outflow tuff member of the Wah Wah Springs Formation rests directly on a local bed of volcanic conglomerate included within the Escalante Desert Formation.

Mapping in nearby areas has disclosed the presence of andesite and rhyolite lava flows that interfinger with the rhyolite tuffs of the Escalante Desert Formation (table A1). Accordingly, the Escalante Desert Formation is here expanded to include a local unnamed andesite flow member, a rhyolite lava flow member, and minor epiclastic deposits. Because the type section of Grant (1978) for the formation does not include the lava flow units, a principal reference section for the formation is established about 8 km northwest of his type section in secs. 21, 22, 27, and 28, T. 31 S., R. 15 W., in the northeast corner of the Mountain Spring Peak, Utah, 7½-minute quadrangle (Best, 1979; Best, Morris, and others, 1987), where the Escalante Desert Formation is several hundred meters thick and overlies Cambrian carbonate rocks and local unnamed Tertiary conglomerates and underlies the outflow tuff member of the Wah Wah Springs Formation. An additional reference section that is designated here contains the upper, clastic member as well as the two rhyolite tuff members but lacks the andesite and rhyolite lava flow members. It lies in the SW¼ sec. 1, T. 29 S., R. 19 W., along the unimproved dirt road between Ryan Spring and Indian Peak in the Miners Cabin Wash, Utah, 7½-minute quadrangle in the northern Indian Peak Range (fig. A3) (Best and others, 1979; Best, Hintze, and Holmes, 1987). Here, the Escalante Desert Formation overlies Ordovician carbonate rocks and is overlain by landslide and fault breccias of the intracaldera member of the Wah Wah Springs Formation formed during subsidence of the Indian Peak caldera.

MARSDEN TUFF MEMBER

The basal member of the Escalante Desert Formation is herein named the Marsden Tuff Member for its occurrence at Marsden Spring (fig. A1), which is also designated the type section, in sec. 25, T. 31 S., R. 15 W., in the Lund, Utah, 7½-minute quadrangle (Grant and Best, 1979b). There, the member rests on a local unnamed conglomerate and consists of three cooling units that formed the lower member of the Escalante Desert of Grant (1978) and are altogether about 110 m thick. It is overlain by the Lamerdorf Tuff Member. The Marsden consists of white to pale-gray, green, orange, and pink, densely welded ash-flow tuff with less than 6 percent phenocrysts (decreasing downward) of sodic plagioclase, quartz, and a trace of biotite, hornblende, and iron-titanium oxides. The tuff is generally easily eroded and poorly exposed because of pervasive, closely spaced fractures. Weak alteration to sericite and to carbonate and epidote minerals is widespread. Fragments of gray carbonate rock, green phyllite, and white, red, pink, and purple orthoquartzite are characteristic of these rocks and increase in abundance downward to as much as 12 percent near the base of the member. The quartzite clasts were probably derived from the thick upper Precambrian to Lower Cambrian quartzites that underlie much of southwestern Utah. At Marsden Spring the lithic fragments in the member are as much as 6 cm in diameter. In the reference section for the member—designated in this report as north of Indian Peak (fig. A3) in SW¼ sec. 1 and sec. 12, T. 29 S., R. 19 W.—clasts of carbonate rock and quartzite are locally as much as 15 cm across. At the type section of the member and westward for a few kilometers a local crystal-rich, plagioclase-biotite tuff several meters thick forms the base of the unit.

RHYOLITE FLOW MEMBER

The Marsden Tuff Member is generally overlain by either rhyolite or andesite lava flow members. Locally, the rhyolite flows interfinger with the tuff, as between Ryan Spring and Indian Peak (fig. A3). The rhyolite flow member consists of flow-layered lava that is variegated red, purple, brown, or rarely gray and contains 5–10 percent phenocrysts of plagioclase, quartz, and minor biotite and hornblende. The rhyolitic rocks contain about 73 weight percent SiO_2 on an anhydrous basis.

ANDESITE FLOW MEMBER

Andesite lava flows extruded from many vents throughout the Needle Range and southern Wah Wah Mountains generally lie above the Marsden Tuff Member and the rhyolite flow member but locally intertongue with them. These lava flows are here informally designated as the andesite flow member of the Escalante Desert Formation. Locally, the lava flows are as much as 350 m thick, as in SE¼ sec. 15, T. 31 S., R. 15 W., in the Mountain Spring Peak, Utah, 7½-minute quadrangle in the southeastern Wah Wah Mountains (Best, 1979; Best, Morris, and others, 1987), where the member lies between the Marsden and

Lamerdorf Tuff Members of the Escalante Desert Formation. The andesitic rocks have phenocrysts of plagioclase, augite, and hypersthene in a partly glassy matrix containing the same minerals plus iron-titanium oxides; they have a low Mg/Fe ratio and about 59 weight percent SiO_2.

LAMERDORF TUFF MEMBER

The Lamerdorf Tuff Member of the Escalante Desert Formation was named and described by Campbell (1978). As used here, the member consists of as many as three cooling units that are somewhat more crystal-rich than the Marsden Tuff Member. The type locality of the member lies in the central part of the Lamerdorf Peak, Utah, 7½-minute quadrangle (Abbott and others, 1983), in secs. 1, 2, and 12, T. 29 S., R. 16 W., and secs. 5, 7, and 8 in T. 29 S., R. 15 W., where two cooling units are separated by lava flows of the andesite flow member and have a total thickness of about 100 m. The densely to partially welded tuffs of the Lamerdorf are mottled gray, orange, red, purple, or buff and contain 10–15 percent plagioclase, 1–3 percent biotite and trace amounts of hornblende, quartz, sanidine, and Fe-Ti oxides. Light-colored pumice lapilli and dark volcanic fragments, which compose 5–25 percent of the tuff, cause the mottling. The upper cooling unit has about 69 weight percent SiO_2, and the lower has about 71 percent, on an anhydrous basis. A biotite from the Lamerdorf has a potassium-argon age of 32.3±1.1 m.y., determined by H. H. Mehnert in the U.S. Geological Survey's Denver laboratories; the sample was collected at lat 38°18′45″ N. and long 113°29′47″ W.

BEERS SPRING MEMBER

Based on his work in the central Needle Range, Conrad (1969) defined a heterogeneous sequence of tuffs, sandstones, and conglomerates lying below the Needles Range Formation of Mackin (1960) as the Beers Spring Formation. Constituent units, in ascending order, were (1) a densely welded ash-flow tuff with phenocrysts of plagioclase and pyroxene, (2) a coarse sandstone and conglomerate, and (3) crystal-poor tuff overlain by sandstone and conglomerate. Subsequent mapping by Best (1976) and Campbell (1978; see also Best, Hintze, and Holmes, 1987) showed that Conrad's member 1 is the Isom Formation and member 2 is a local epiclastic deposit that contains clasts of the Isom Formation and therefore cannot predate the Needles Range Formation of Mackin (1960). Hence, Campbell (1978) abandoned Conrad's members 1 and 2 and made his member 3 the Beers Spring Member of the Escalante Desert Formation. This revision is adopted here.

The type section of the Beers Spring Member lies in secs. 15 and 16, T. 26 S., R. 18 W., around Beers Tunnel Spring (fig. A1) in the Halfway Summit, Utah, 7½-minute quadrangle (Best and Hintze, 1980b). The Beers Spring Member here underlies the Cottonwood Wash Tuff and overlies the Sawtooth Peak Formation or the Lamerdorf Tuff Member of the Escalante Desert Formation. At its type section, the Beers Spring Member is about 50 m thick. The lower part of the member is a loosely welded, white to pink, somewhat lithic-rich, ash-flow tuff with about 10 percent phenocrysts of plagioclase, quartz, and biotite; the top is a conglomerate or volcanic debris flow with clasts of greenish-brown porphyritic andesite.

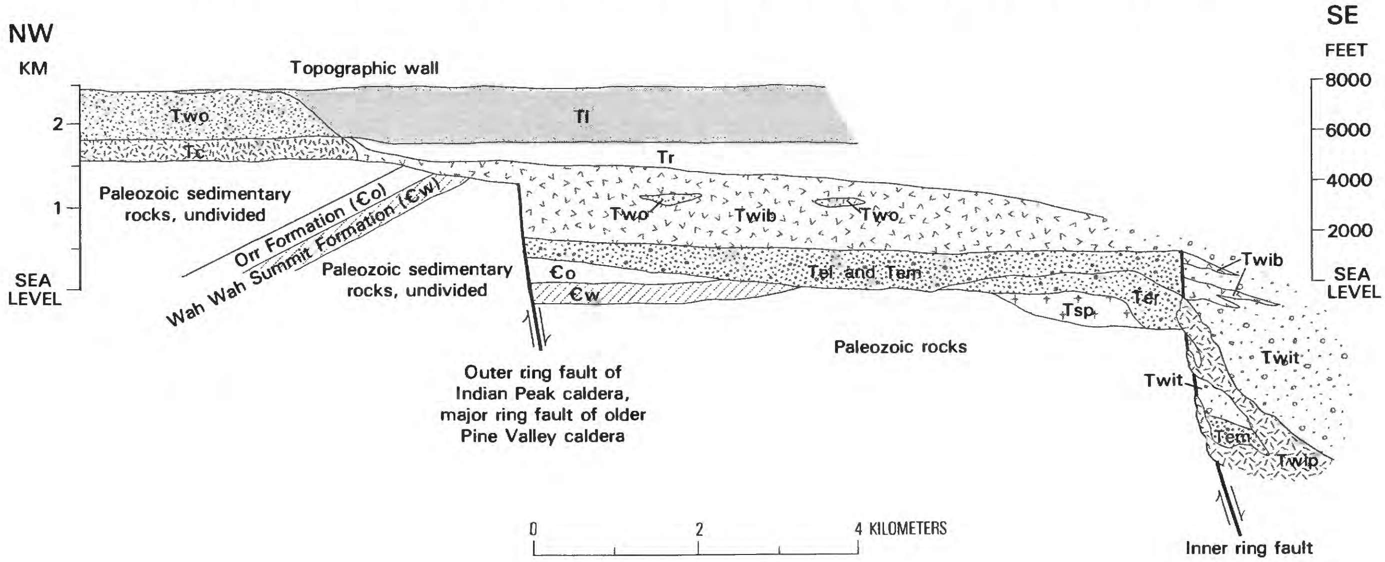
Elsewhere in the Needle Range and the Wah Wah Mountains, the Beers Spring Member consists chiefly or exclusively of well-sorted, evenly bedded, friable, greenish-gray sandstone, which is generally several meters thick but locally ranges up to more than 100 m. A reference section for this member is selected 1–2 km south of Ryan Spring, just east of and along an unimproved road leading to Indian Peak in sec. 1, T. 29 S., R. 19 W., where the sandstone is about 60 m thick and lies between the Lamerdorf Tuff Member of the Escalante Desert Formation and breccias of the intracaldera member of the Wah Wah Springs Formation.

COTTONWOOD WASH TUFF

The Cottonwood Wash Tuff was formally defined by Best and others (1973) as a member of the Needles Range Formation of Mackin (1960) but is here elevated to formation rank within the Needles Range Group.

The Cottonwood Wash Tuff appears to be a simple cooling unit of crystal-rich, dacitic lapilli ash-flow tuff containing about 25 percent plagioclase; large books of biotite as much as 6 mm in diameter; sparse broken, embayed quartz phenocrysts that are almost as large; and minor hornblende, green augite, and equant iron-titanium oxides.

Exposures of moderately welded ash-flow tuff near the northern distal margin of the Cottonwood Wash Tuff, northeast of Crystal Peak, Utah, are locally underlain by compositionally similar air-fall and surge deposits several meters thick, which are also included in the unit. Tuffaceous sedimentary deposits in the Mercury quadrangle in southwestern Nevada include as much as 9 m of reworked tuff, which contains abundant phenocrysts of plagioclase, quartz, and biotite as much as 5 mm in diameter, has a revised potassium-argon age



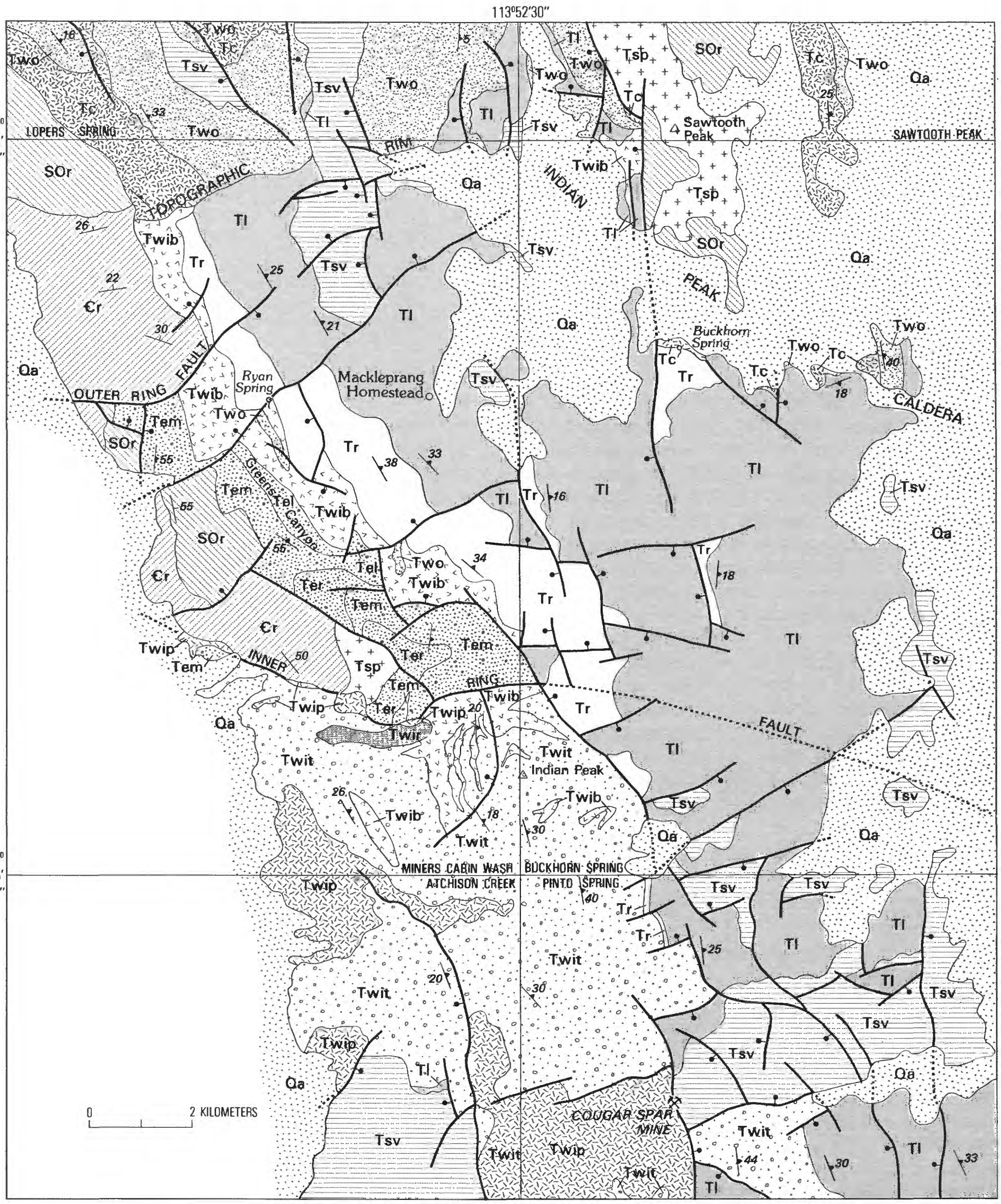
EXPLANATION

- Qa — **Quaternary alluvium**
- Tsv — **Tertiary sedimentary and volcanic rocks**—Mostly volcanic in southeast and sedimentary in north
- Tl — **Lund Formation**
- Tr — **Ryan Spring Formation**
- **Wah Wah Springs Formation**
  - Twip, Twib, Twit, Twir — **Intracaldera member**
    - **Twip, granodiorite porphyry**
    - **Twib, breccia**
    - **Twir, rhyolite**
    - **Twit, tuff**
  - Two — **Outflow tuff member**
- Tc — **Cottonwood Wash Tuff**
- **Escalante Desert Formation**
  - Tel — **Beers Spring and Lamerdorf Tuff Members**
  - Tem — **Marsden Tuff Member and andesite flow member**
  - Ter — **Rhyolite flow member**
- Tsp — **Sawtooth Peak Formation**
- SOr — **Silurian and Ordovician rocks**
- €r — **Cambrian rock**

The Lund Formation, Ryan Spring Formation, Wah Wah Springs Formation, Cottonwood Wash Tuff and Escalante Desert Formation make up the **Needles Range Group**. Lund Formation through Sawtooth Peak Formation: **OLIGOCENE**.

- **Contact**
- **Fault**—Dotted where concealed; bar and ball on downthrown side
- **Strike and dip of bedding**
- **Strike and dip of foliation**

FIGURE A3.—Geologic map (facing) and idealized cross section (above) of the northeastern segment of the Indian Peak caldera in the east-tilted northern Indian Peak Range and southernmost Mountain Home Range (central Needle Range) showing topographic rim and shelf, ring faults, and caldera fill. Cross section is more or less parallel to the strike of the volcanic units and shows the topographic wall, ring faults, and caldera fill prior to resurgent uplift. Minor faulting that is possibly related in part to resurgence is omitted.


113°52'30"
38° 22' 30"
38° 15' 00"
LOPERS SPRING
SAWTOOTH PEAK
Sawtooth Peak
TOPOGRAPHIC RIM
INDIAN PEAK CALDERA
OUTER RING FAULT
INNER RING FAULT
Ryan Spring
Mackleprang Homestead
Buckhorn Spring
Greens Canyon
Indian Peak
MINERS CABIN WASH
ATCHISON CREEK
BUCKHORN SPRING
PINTO SPRING
COUGAR SPAR MINE
0 2 KILOMETERS
Qa
Tl
Tr
Tsv
Two
Twib
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of 30.1±0.9 m.y. (Barnes and others, 1982), and is probably correlative with the Cottonwood Wash Tuff. These are the only two localities known where the Cottonwood Wash Tuff includes deposits not formed from ash-flows.

The Cottonwood Wash Tuff has an average age of 30.6 m.y. based on four potassium-argon determinations (table A2).

WAH WAH SPRINGS FORMATION

The Wah Wah Springs Tuff Member of the Needles Range Formation was named by Mackin (1960) and was retained with that stratigraphic rank by Best and others (1973). Subsequent mapping in the Needle Range and White Rock Mountains has shown that the unit consists of two cogenetic units related to evolution of the source caldera of the formation. Accordingly, the Wah Wah Springs Tuff Member is here elevated in rank to formation, the appellation "Tuff" is dropped, and the formation is made part of the Needles Range Group. The two informal members within the Wah Wah Springs Formation are here defined to be the outflow tuff member and the intracaldera member.

No single exposure or group of nearby exposures shows both members of the Wah Wah Springs Formation together. The nature of the large Indian Peak caldera precludes their close juxtaposition. Accordingly, a type locality for the formation showing stratigraphic relations of constituent members is the entire Miners Cabin Wash, Utah, 7½-minute quadrangle and secs. 21, 27, and 28, T. 29 S., R. 18 W., in the adjoining Buckhorn Spring 7½-minute quadrangle (figs. A1 and A3; Best and others, 1979; Best, Hintze, and Holmes, 1987).

OUTFLOW TUFF MEMBER

The type locality of the Wah Wah Springs Tuff Member of the Needles Range Formation of Mackin (1960) and Best and others (1973) represents only the newly defined informal outflow tuff member of the Wah Wah Springs Formation. The stratigraphic boundaries of the new informal member are the same as those of Mackin's Wah Wah Spring Tuff Member. The deposit is generally a simple cooling unit, wherever exposed.

In addition to abundant plagioclase, the outflow member contains prominent hornblende, lesser biotite, and minor quartz, green augite, and equant iron-titanium oxides (Dinkel, 1969).

The average of 16 potassium-argon ages for the outflow tuff member is 29.5 m.y., which is only slightly less than the widely quoted age of 29.7 m.y. from the study of Armstrong (1970), which used fewer determinations and older decay constants (table A2).

TABLE A2.—*Isotopic ages of dacite tuffs in the Needles Range Group*

[Older determinations adjusted to new decay constants (Dalrymple, 1979). All ages are by K-Ar method except for one fission-track age on zircon]

Source of data	Material	Age±2σ (m.y.)
Lund Formation		
Armstrong (1970); sample 834B	Biotite--------	27.9±1.2
H. H. Mehnert (unpub. data, 1982).[1]	Biotite--------	27.9±1.0
M. G. Best and B. J. Kowallis (unpub. data, 1984).	Zircon---------	27.8±1.0
Average----------------------------------		27.9
Wah Wah Springs Formation		
J. D. Obradovich (unpub. data, 1965).[2]	Biotite--------	30.5±1.2
	Hornblende-----	30.6±1.2
	Biotite--------	28.7±1.1
	Hornblende-----	29.8±1.2
	Hornblende-----	27.2±1.1
Armstrong (1970):		
Sample 159B-------------	Biotite--------	30.0±1.2
Sample 159G-------------	Glass----------	28.4±1.2
Sample 102C-------------	Biotite with hornblende.	31.5±1.2
Sample 170B-------------	Biotite--------	30.4±1.2
Sample 183B-------------	Hornblende with biotite.	29.2±1.6
Lemmon and others (1973)-----	Biotite--------	30.1±1.2
	Hornblende-----	30.0±1.2
Fleck and others (1975)------	Biotite--------	29.5±1.0
T. A. Steven (unpub. data, 1981).[3]	Biotite--------	28.4±1.0
	Hornblende-----	28.3±1.7
Noble and McKee (1972)-------	Biotite--------	28.7±1.3
Average----------------------------------		29.5
Cottonwood Wash Tuff		
Armstrong (1970):		
Sample 158--------------	Biotite--------	30.4±1.2
Sample 101E-------------	Biotite--------	31.5±1.2
Sample 834AB------------	Biotite--------	29.2±1.2
Sample 834AH------------	Hornblende-----	31.4±1.8
Average----------------------------------		30.6

[1]Sample from east flank of Wah Wah Mountains at lat 38°21'32" N., and long 113°31'40" W.

[2]Determined on three samples collected by R. D. Hose in the Confusion Range. See Fleck and others (1975).

[3]Analyses by H. H. Mehnert on a sample from the Crystal Peak area, Utah.

INTRACALDERA MEMBER

The informal intracaldera member of the Wah Wah Springs Formation includes dacite tuff, breccia, intrusive granodiorite porphyry, and minor rhyolite and andesite, which were emplaced within the Indian Peak caldera during and just after its collapse. The type locality for the member is near Indian Peak in secs. 19–21 and 27–30, T. 29 S., R. 18 W., in the southern Miners Cabin Wash and Buckhorn Spring 7½-minute quadrangles (fig. A3; Best and others, 1979; Best, Hintze, and Holmes, 1987) and secs. 8–10, T. 30 S., R. 18 W., in the adjacent Atchison Creek and Pinto Spring 7½-minute quadrangles (Grant and Best, 1979a; Best, Grant, and others, 1987). Tuff and lava flows of the Escalante Desert Formation underlie the intracaldera member; tuff of the Ryan Spring Formation overlies the member. In the Indian Peak Range the intracaldera member is at least 2 km thick.

The intracaldera member is a compound cooling unit consisting of crystal- and lithic-rich, dacite ash-flow tuff. It is orange brown to olive gray, densely welded, and generally contains about 10 percent lapilli-size clasts of dark volcanic rock; locally near the northeastern segment of the inner caldera ring fault (fig. A3) these clasts are as much as 2 m in diameter and compose half or more of the tuff. Phenocrysts constitute almost half of the tuff and are mostly plagioclase with lesser amounts of hornblende, biotite, quartz, augite, and iron-titanium oxides. The amount of quartz is slightly more than in the outflow tuff member.

Breccias south of the inner ring fault, near Indian Peak, are mostly monolithologic accumulations of volcanic fragments, chiefly of the Lamerdorf Tuff Member and Cottonwood Wash Tuff, whereas near Arrowhead Pass (fig. A1) clasts are Paleozoic sedimentary rocks and tuff from the Sawtooth Peak Formation. These breccias represent debris slides and talus deposits shed off the unstable scarp of the ring fault. Between the northeastern segment of the ring fault at Indian Peak and the topographic wall of the caldera 10 km to the north the intracaldera member consists of commonly cataclastic monolithologic breccias that were pervasively sheared and pulverized. These breccias are believed to have formed in slabs that slid from the northward-retreating caldera wall into the depression along low-angle detachment surfaces.

Local bodies of rhyolite and andesite occur within the sequence of tuff and breccia that fills the inner part of the caldera; they may be sills, lava flows, or landslide breccias.

Granodiorite porphyry that intrudes the intracaldera tuff is olive to brownish gray and has the same phenocrysts as the tuff, except that they are somewhat larger and unbroken. Propylitically altered rocks are widespread. The main body of intrusive rock, 7 km south of Indian Peak (fig. A3), crops out over an area of at least 12 km² as described by Grant (1979). The porphyry locally forms dikes and plugs along the inner ring fault of the Indian Peak caldera where, in places, it is vertically foliated and appears to grade texturally into intracaldera tuff. In other places, where the intrusions cut Paleozoic carbonate rocks, the rock is more leucocratic and variable in texture.

RYAN SPRING FORMATION

Two cooling units of crystal-poor, lithic-rich rhyolite ash-flow tuff, as well as local pyroxene andesite and rhyolite lava flows, lie between the intracaldera member of the Wah Wah Springs Formation and the younger Lund Formation within the topographic depression of the Indian Peak caldera. The two rhyolite cooling units are quite similar in composition to the ash-flow tuff units in the older Escalante Desert Formation; only differences in color, nature of lithic fragments, and stratigraphic position allow the two doublets to be distinguished in the field. As proposed by Rauch (1975), these younger rhyolite tuff units and associated lava flows are here formally designated the Ryan Spring Formation. At its type section west and north of Ryan Spring in NE¼ sec. 35, and NW¼ sec. 36, T. 28 S., R. 19 W., in the Miners Cabin Wash quadrangle (fig. A3; Best and others, 1979; Best, Hintze, and Holmes, 1987), the formation consists of the two tuff members and is as much as 560 m thick, overlies breccias of the intracaldera member of the Wah Wah Springs Formation, and underlies the Lund Formation. Because this type section does not include the rhyolite and andesite lava flow members, a principal reference section for the formation is designated 2–8 km south of Arrowhead Pass in secs. 19, 30, and 31, T. 31 S., R. 17 W., and secs. 24 and 25, T. 31 S., R. 18 W., in the central part of the Steamboat Mountain, Utah, 7½-minute quadrangle (Best, Grant, and others, 1987). In this locality the formation is a discontinuous sequence consisting of the tuff members, pyroxene andesite flows, and capping altered rhyolite flows of the andesite and rhyolite flow members; the formation is underlain by altered rocks of the intracaldera member of the Wah Wah Springs Formation and to the south is overlain by the Lund Formation.

GREENS CANYON AND MACKLEPRANG TUFF MEMBERS

The lower simple cooling unit of the Ryan Spring Formation is here named the Greens Canyon Tuff Member for Greens Canyon, in the Miners Cabin Wash quadrangle, whose north and east slopes are in part underlain by the member. This unit resembles the Marsden Tuff Member of the Escalante Desert Formation in the small size (generally <1 mm) and abundance of crystals (12 percent plagioclase, 2 biotite). However, in the Greens Canyon Member volcanic clasts predominate over carbonate and quartzite; lapilli- to small block-size pieces of red tuff from the Wah Wah Springs Formation are common. Weathered surfaces on the member typically have holes a centimeter or so in diameter surrounded by haloes lighter in color than the orange- to pink-brown matrix. These holes apparently formed by weathering of baked carbonate inclusions. The upper part of the member is a crystal-poor tuff containing no pumice lapilli or lithic fragments and locally is overlain by several meters of volcanic debris flow and sandstone. The type section is in sec. 6, T. 29 S., R. 18 W., where the member overlies breccias and tuffs of the intracaldera member of the Wah Wah Springs Formation and is overlain by the younger Mackleprang Tuff Member of the Ryan Spring Formation.

The younger simple cooling unit or tuff member of the Ryan Spring Formation is here named the Mackleprang Tuff Member for the old Mackleprang Homestead 3 km due east of Ryan Spring (fig. A3). This member is virtually identical in most respects to the Lamerdorf Tuff Member of the Escalante Desert Formation—only position in the stratigraphic sequence positively distinguishes them. It is distinguished from the Greens Canyon Member by its larger (up to 2 mm) and slightly more abundant phenocrysts of plagioclase and biotite (14 and 3 percent, respectively) and by a more strongly developed compaction foliation defined by varicolored, flattened pumice lapilli. The member is a thin (less than 50 m), densely welded simple cooling unit at its type section, just northeast of Ryan Spring in NW¼ sec. 36, T. 28 S., R. 19 W. In the clifflike exposures just south of Buckhorn Spring in the quadrangle of that same name (fig. A3; Best and others, 1979; Best, Hintze, and Holmes, 1987), 8 km east of the type section, the member is somewhat thicker and is a variably welded compound cooling unit. This locality, in secs. 34 and 35, T. 28 S., R. 18 W., is designated as a reference section for the Mackleprang. Here, the unit is sandwiched between the lilac gray, almost wholly vitric tuff of the Greens Canyon Tuff Member and the overlying Lund Formation. Locally, the Mackleprang includes well-sorted sandstone below and above the tuff.

LAVA FLOW MEMBERS

Nonvesicular, gray to black andesite lava flows are widespread in the principal reference locality for the Ryan Spring Formation, 2–8 km south of Arrowhead Pass in the central part of the Steamboat Mountain quadrangle. These flows, containing phenocrysts of plagioclase, augite, hypersthene, and locally, near the base of the unit, hornblende, are informally designated as the andesite flow member of the Ryan Spring Formation. Well sorted brown sandstone occurs locally in the sequence of flows. The unit overlies altered tuff of the intracaldera member of the Wah Wah Springs Formation and interfingers with tuffs of the Ryan Spring Formation (fig. A2).

The andesite flow member is locally overlain in the area south of Arrowhead Pass by rhyolite lava flows that are informally designated as the rhyolite flow member of the Ryan Spring Formation. The rhyolite is varicolored and locally strongly flow layered and has sparse phenocrysts of plagioclase, biotite, potassium-rich feldspar, and quartz. Zircon from the rhyolite yielded a fission-track age of 28.4±1.2 m.y. This determination, on a sample from lat 38°6′25″ N. and long 113°47′27″ W., was made by Bart J. Kowallis at Brigham Young University in 1984.

LUND FORMATION

The Lund Tuff was formally defined by Best and others (1973) as a member of the Needles Range Formation of Mackin (1960) but is here raised in stratigraphic rank to a formation within the Needles Range Group, and the appellation "Tuff" is dropped because other rock types occur. Much has yet to be learned about the formation and its source—the White Rock caldera—through future mapping in eastern Nevada. A reference section for the formation, designated in this report, is in the southern Steamboat Mountain, Utah, 7½-minute quadrangle (Best, Grant, and others, 1987) in secs. 6 and 7, T. 32 S., R. 17 W., and secs. 11 and 12, T. 32 S., R. 18 W., where the formation lies between the Ryan Spring and Isom Formations. There, two informal members can be recognized, a tuff member and an andesite flow member.

TUFF MEMBER

The tuff member of the Lund Formation is here defined to be equivalent to the Lund Tuff Member of Best and others (1973). The type section, stratigraphic boundaries, and lithologic description of the former Lund Tuff Member now apply to the new tuff member. A reference section designated for the member is in secs. 9 and 10 and the N½ sec. 16, T. 5 N., R. 67 E., in the Schoolmarm Basin, Nevada, 7½-minute quadrangle, where it is a thick intracaldera compound cooling unit locally intercalated with lenses of breccia that formed as landslides sloughed off the nearby topographic wall of the White Rock caldera. Clasts in the breccias are of Paleozoic carbonate rocks and granite of unknown age. The base of this thick unit is not exposed, but it is overlain by the Isom Formation. Thick sections of the tuff member within the older Indian Peak caldera are also compound cooling units, but outside the White Rock and Indian Peak calderas it is essentially a simple cooling unit.

The tuff member of the Lund Formation is distinguished from the other crystal-rich dacite tuffs of the Needles Range Group by relatively abundant (5–10 percent) quartz, more biotite than hornblende, and most diagnostic of all, trace amounts of sphene (Kreider, 1970). Fragments of volcanic rock are only locally conspicuous in the tuff. The average isotopic age is 27.9 m.y. (table A2).

ANDESITE FLOW MEMBER

A thick section of pyroxene andesite lava flows occurs in the type section of the Lund Formation and is here designated as an informal member. The lava flows are gray to black, nonvesicular, and locally flow-layered and have phenocrysts of plagioclase, augite, and hypersthene. Tuff of similar composition and lenses of brown, well sorted sandstone appear locally in the member. This unit is juxtaposed against the Ryan Spring Formation and the tuff member of the Lund Formation along the topographic wall of the White Rock caldera. An unusually thick section of the Isom Formation overlies the andesite flow member within the caldera depression.

DISTRIBUTION, VOLUME, AND SOURCES OF NEEDLES RANGE GROUP

Data concerning the distribution and volume of formations in the Needles Range Group have a high degree of uncertainty because the formations are concealed by younger volcanic deposits, especially in the southern part of the area of figure A1 (see Stewart and others, 1977), and by alluvial valley fill in at least half of the area of the Great Basin. Uneven pre-eruption topography and local post-Oligocene uplifts, which led to local nondeposition and erosion of Needles Range rocks, are additional hinderances in determining original areal extents and volumes of the tuff sheets. Thicknesses of formations in the Needles Range Group in Nevada are still more uncertain because of the paucity of detailed mapping and because of possible difficulties in stratigraphic correlation. Correcting the estimated areal extents and volumes of the formations for post-Oligocene east-west crustal extension during development of the Basin and Range province reduces numerical values; local estimates of extension range from 100 percent or more to 20–30 percent for the Great Basin area of Nevada and Utah (Stewart, 1980). Tilts of Oligocene volcanic deposits in the Needle Range and Wah Wah Mountains of southwestern Utah average close to 25°, which implies an extension there of 50 percent. Crustal thicknesses of the eastern Great Basin and adjacent Colorado Plateaus (summarized in Wannamaker, 1983) indicate an extension of 50 to 75 percent. We will assume 40 percent in the discussion that follows.

TABLE A3.—*Presently exposed, known areal extents and estimated volumes of ash-flow tuffs of the Needles Range Group*

[From figures A4 to A10 (corrected for an assumed 40 percent east-west crustal extension since the Oligocene). Volume of Cottonwood Wash Tuff does not include the unknown amount in its source caldera]

Unit	Area (km^2)	Volume (km^3)
Lund Formation:		
Inside caldera-------------	2,000	Unknown
Outside caldera------------	11,000	1,600
Ryan Spring Formation:		
Mackleprang Tuff Member----	400	100
Greens Canyon Tuff Member--	400	150
Wah Wah Springs Formation:		
Intracaldera member--------	1,200	2,400
Outflow tuff member--------	22,000	1,500
Cottonwood Wash Tuff---------	5,000	500
Escalante Desert Formation:		
Lamerdorf Tuff Member------	2,000	100
Marsden Tuff Member--------	1,000	300
Total--------------------	*	>6,650

*The area of the outflow tuff member of the Wah Wah Springs Formation eclipses that of all other tuffs.

The areal extents of the tuffs shown on figures A4–A7 are conservatively drawn around known exposures. Areas listed in table A3 are reduced 40 percent from those measured on the figures, to correct for east-west crustal extension. Volume estimates in table A3 have been made by dividing the known areas of distribution into sectors in which the thickness has been estimated or taken from measured sections.

ESCALANTE DESERT FORMATION

The two rhyolite ash-flow tuff sheets in the Escalante Desert Formation are exposed in the Needle Range and the Wah Wah Mountains. Thick sections of propylitically altered tuff of the Marsden Tuff Member (fig. A4), containing abundant lapilli- and block-sized clasts of

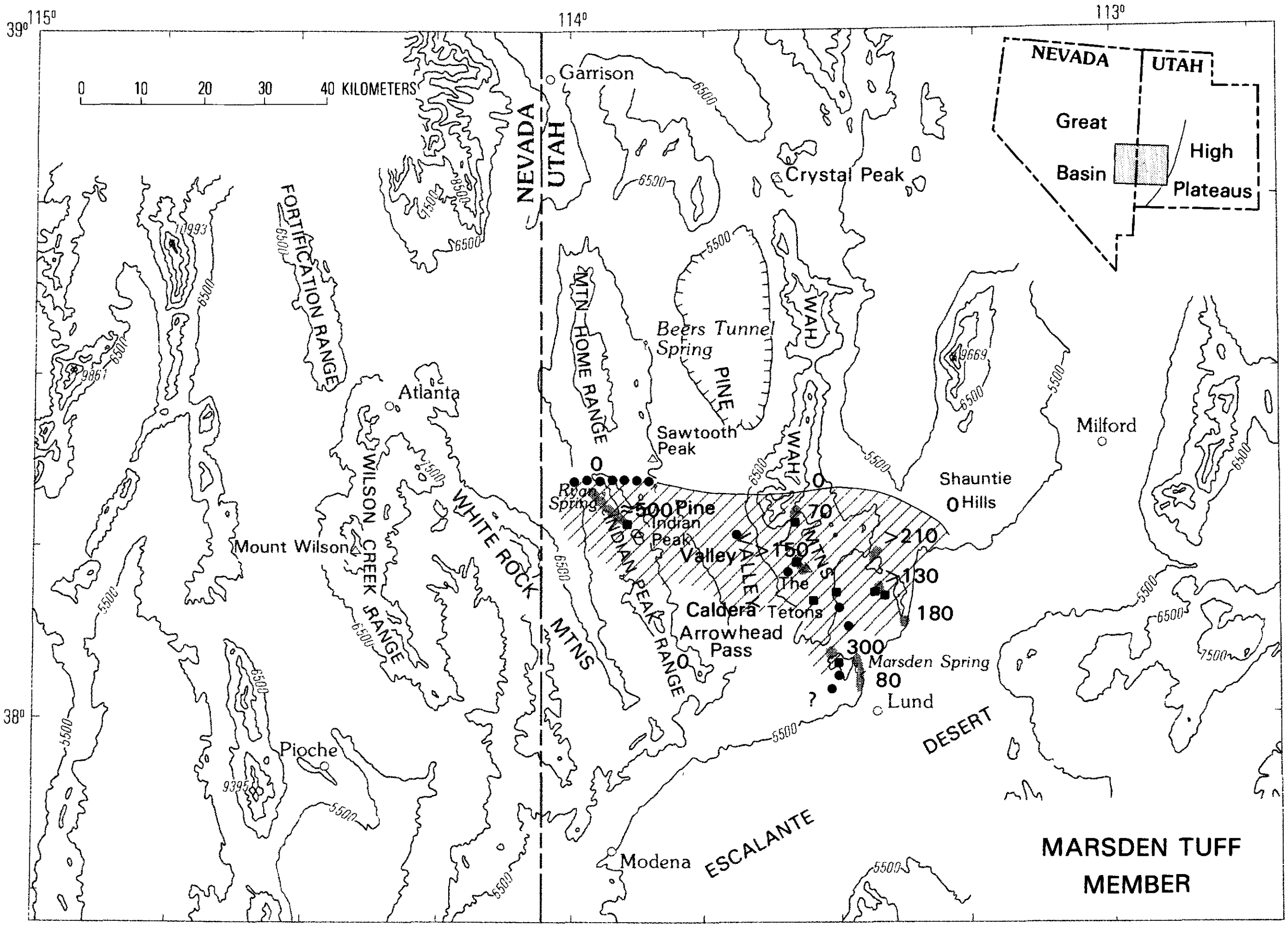

FIGURE A4.—Distribution and thickness of the Marsden Tuff Member of Escalante Desert Formation. Solid squares show occurrences of rhyolite flow member. Gray pattern shows known exposures; numbers indicate thickness in meters. Diagonally ruled area is inferred original distribution of tuff. Zeros indicate absence of member. Filled circles show structural margin of Pine Valley caldera from which tuff erupted. (See also cross section on fig. A3.)

sedimentary rocks, occur immediately north of Indian Peak and also at the southeastern end of the Wah Wah Mountains. These sections probably lie within a source caldera, whose northern margin seems to be represented in part by a major east-west fault that lies west of Ryan Spring (figs. A3 and A4). About 600 m of vertical movement took place along this fault during subsidence of the younger Indian Peak caldera, but the Paleozoic rock units across it are offset about 1,900 m. The 1,300-m difference in displacement is believed to reflect collapse of the earlier caldera during eruption of the Marsden Tuff Member. This conclusion is supported by deposits found just south of the fault: here, wedges of sandstone, breccia, and poorly bedded debris flows, containing clasts of Ordovician sedimentary rocks within matrices rich in volcanic material, overlie but also interfinger with the Marsden Tuff Member. These wedges of clastic material are thickest near the postulated ring fault and pinch out 4 km to the south; they are interpreted to consist of debris wasted off the unstable wall of the caldera, where Ordovician rocks were exposed. No Marsden Tuff Member is exposed north of the fault.

The source caldera for the Marsden Tuff Member of the Escalante Desert Formation is here named the Pine Valley caldera because it straddles the valley of that name between the Indian Peak Range and Wah Wah Mountains (fig. A1).

The known areal extent of the Lamerdorf Tuff Member of the Escalante Desert Formation (fig. A5) is about the same as that of the Marsden Tuff Member, but its measured thicknesses and apparent volume are less. No direct evidence for the location of its source exists. However, the tuff partly covers the Pine Valley caldera, so its source could be that caldera or, possibly, one nested within it and now lying beneath alluvium-covered Pine Valley.

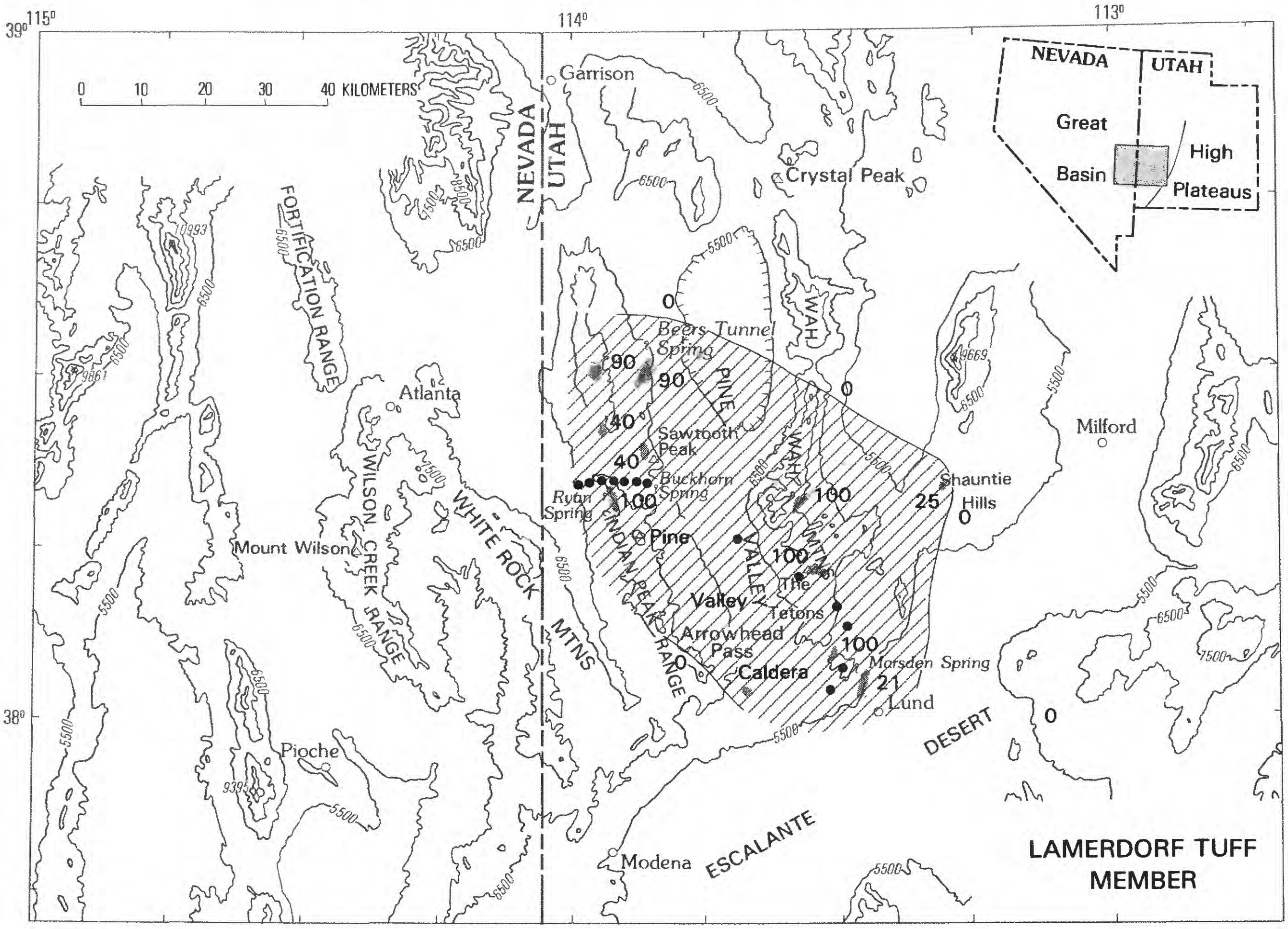

FIGURE A5.—Distribution and thickness of the Lamerdorf Tuff Member of Escalante Desert Formation. Symbols as on figure A4.

COTTONWOOD WASH TUFF

Ash flow tuff of the crystal-rich Cottonwood Wash Tuff (fig. A6) has an estimated volume of about 500 km^3, based on known areal extent (table A3). For this volume, a fairly large caldera would be expected, but no direct evidence points to its specific location. In the Mountain Home Range, where the Cottonwood Wash and its basal vitrophyre are thickest, no breccias or even lithic clasts occur within the tuff, and no system of faults compatible with a fault-bounded caldera depression have been recognized. To the west, across a 40-km-wide alluvial valley, sections of the Cottonwood Wash in the Fortification Range are about 200 m thick, have a basal vitrophyre several meters thick, and are unique in containing sparse lapilli and small blocks of volcanic xenoliths. Characteristics of the Cottonwood Wash in both the Fortification Range and the Mountain Home Range indicate proximity to the source, as does their more or less central location within the known area of the tuff sheet. It appears likely, therefore, that the source lies concealed beneath the intervening broad alluvial valley, but whether it is a fault-bounded caldera or a downwarped sag (compare Steven and others, 1984) cannot be said. In either case, an additional volume of tuff possibly equal to that outside the source lies buried within it.

WAH WAH SPRINGS FORMATION

Eruption of the widespread and voluminous outflow tuff member of the Wah Wah Springs Formation led to subsidence of the Indian Peak caldera. The minimum area of exposure of the outflow tuff member, as shown on figure A7, is about 22,000 km^2; this is surely less than the original extent of the ash-flow deposit, because a significant part of the sheet is obscured by younger volcanic cover southwest of the Indian Peak caldera. The known volume (table A3) is on the order of 1,500 km^3.

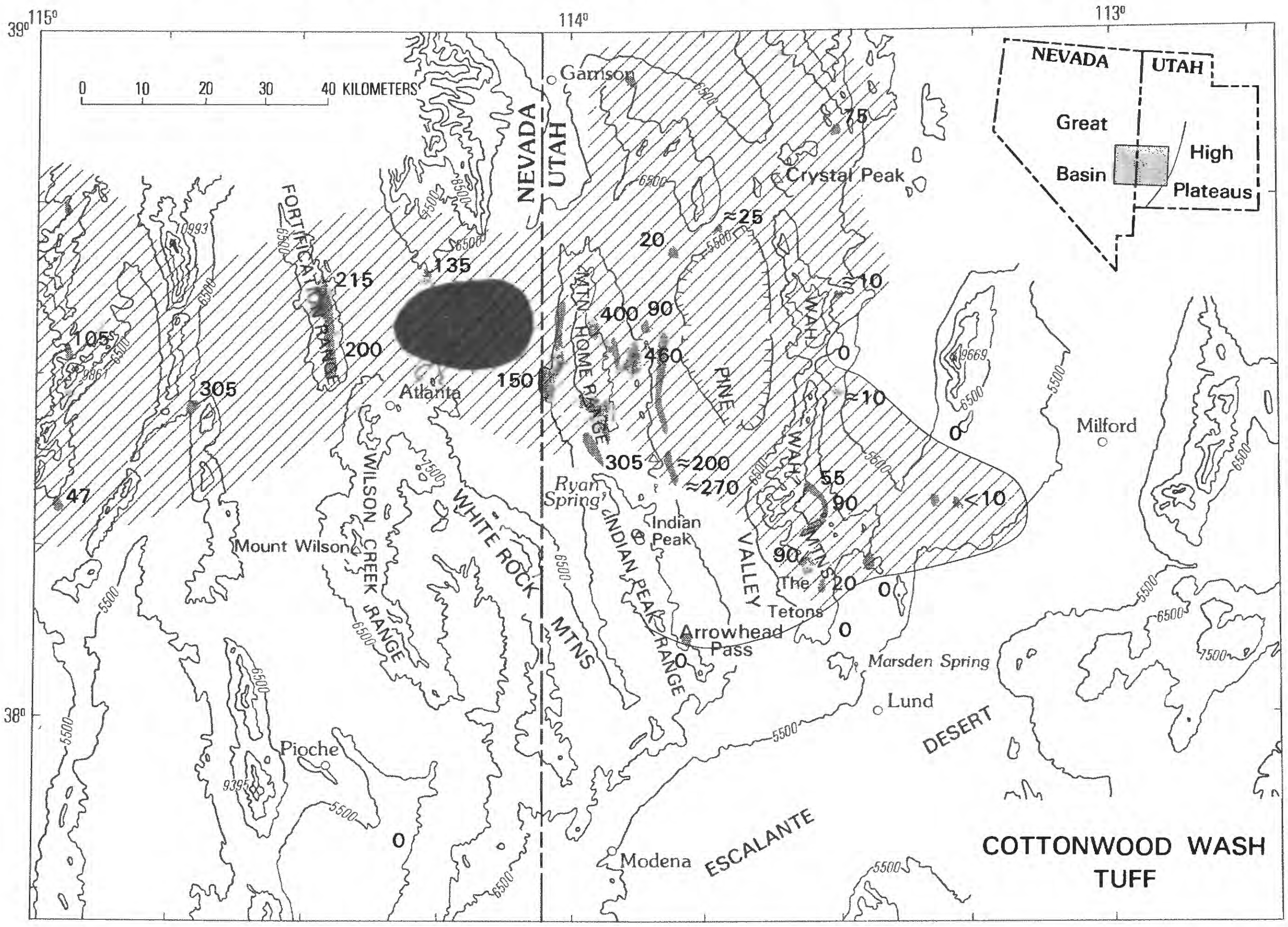

FIGURE A6.—Distribution and thickness of the Cottonwood Wash Tuff. Dark-gray area is probable location of source of the tuff. Symbols as on figure A4.

In areas to the southeast and south of the Indian Peak caldera, partially welded outflow tuff is thin to locally absent. South of the Escalante Desert the outflow tuff is only 10–17 m thick and lies immediately below the Isom Formation or occurs within a sequence of clastic sediments and lacustrine limestones that has been included within the upper part of the Claron Formation (Blank, 1959; Rowley and others, 1979, p. 5). An unpublished fission-track date of 29.0±1.7 m.y. on zircon by C. W. Naeser confirms these remote exposures as outflow tuff member, a conclusion previously drawn on the basis of phenocryst composition by Blank.

The original size and shape of the Indian Peak caldera cannot be determined accurately from present exposures. The northeast segment of the caldera is exposed in the central Needle Range, where an east-tilted and somewhat faulted section of rocks several kilometers thick around Indian Peak and northward to Sawtooth Peak reveals the details of the northeastern ring fault zone, topographic shelf and rim, and caldera fill (figs. A3 and A7). The southeast and northwest segments of the caldera are indirectly constrained by exposures of tuff and breccia of the intracaldera member, by the distribution of pre-Oligocene sedimentary rocks, and by permissive structural relations. No control exists for its southwestern and western perimeter.

The Indian Peak caldera as defined by its inferred ring fault zone is about 70 km across east-west. Prior to east-west crustal extension, assumed to be 40 percent, the original east-west dimension was about 50 km; inasmuch as the north-south dimension was at least 30 km, the area of the caldera was about 2,000 km². Accommodating crustal extension makes the original outline of the caldera more nearly equant.

INDIAN PEAK CALDERA

This section summarizes what is known about the evolution and present characteristics of the source caldera of the Wah Wah Springs Formation.

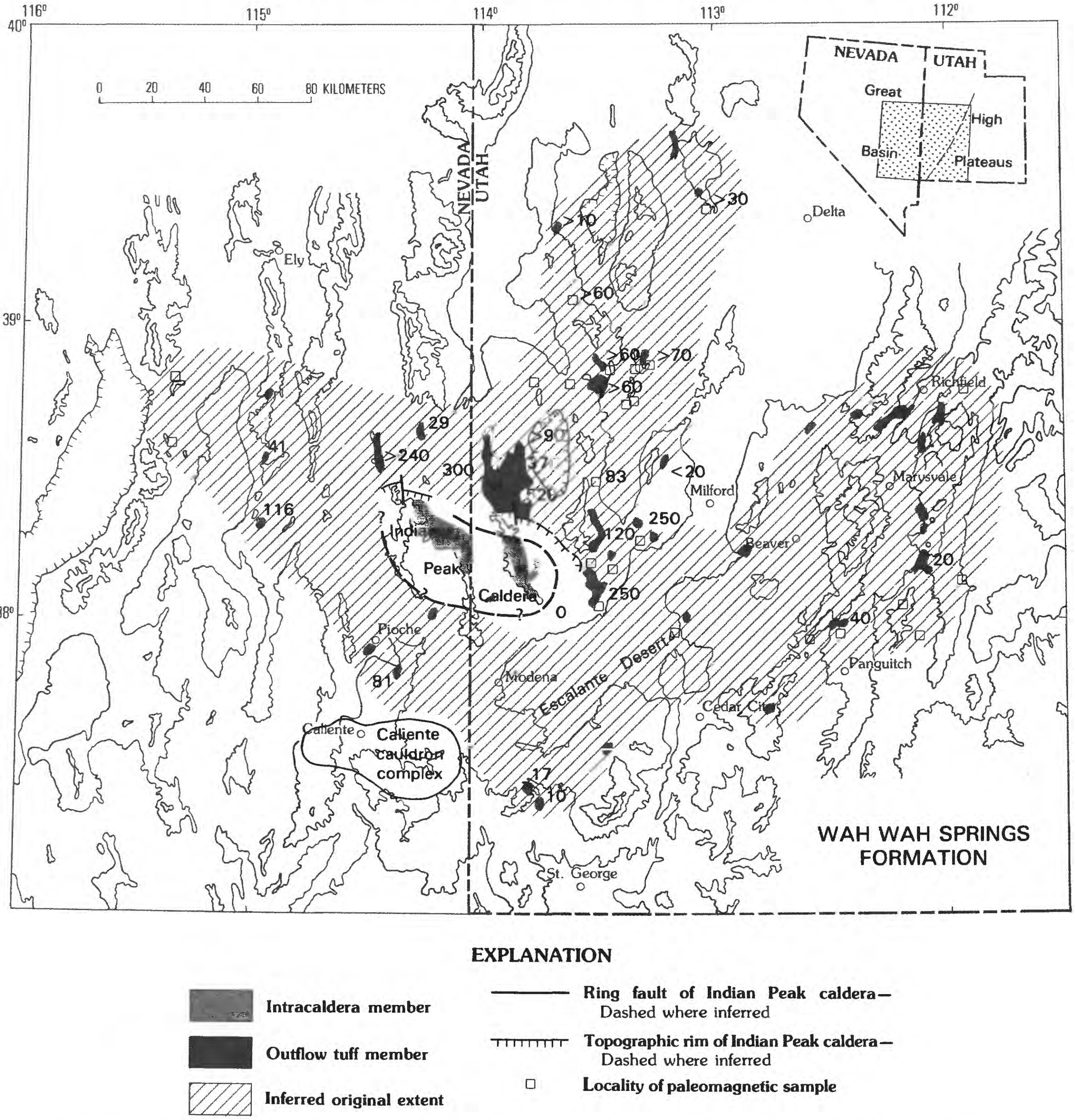

FIGURE A7.—Distribution and thickness of Wah Wah Springs Formation and location of Indian Peak caldera. Thickness values in meters. Open squares are sites where paleomagnetic samples were collected in Nevada by Grommé and others (1972) and in Utah by Shuey and others (1976). Location of the Miocene Caliente cauldron complex after Ekren and others (1977). Elevation contours at 5,500, 7,500, 9,500, and 11,500 feet (1,676, 2,286, 2,896, and 3,505 m).

UTAH SECTOR

The most direct evidence for the Indian Peak caldera lies in the east-tilted central Needle Range, around Indian and Sawtooth Peaks and the area to the west (fig. A3). North of a generally east-west line through Sawtooth Peak, the Lund Tuff is no more than 55 m thick and is locally absent between the underlying outflow tuff member of the Wah Wah Springs Formation and the overlying Isom Formation. To the south of this line, in this same stratigraphic interval, is a 2-km-thick section of breccias of the intracaldera member of the Wah Wah Springs Formation and overlying ash-flow tuffs of the Ryan Spring Formation and Lund Formation. This 2-km-deep depression, which formed after eruption of the outflow tuff member but before deposition of the Ryan Spring Formation, must represent the topographically enlarged source caldera of the Wah Wah Springs Formation. Although a significant normal fault, exposed west of Ryan Spring (fig. A3), parallels the east-west topographic rim, it had only about 600 m of offset during subsidence of the caldera. The major ring fault that controlled most of the caldera subsidence in this area lies farther to the south, 2 km north of Indian Peak, where Paleozoic sedimentary rocks and an overlying thick sequence of volcanic rocks of the Sawtooth Peak and Escalante Desert Formations are juxtaposed against a section of the intracaldera member of the Wah Wah Springs Formation that is at least 2.5 km thick. The intracaldera member is similarly thick for as much as 14 km farther south through the Indian Peak Range.

Breccias of the intracaldera member of the Wah Wah Springs Formation exposed north of the inner, major caldera ring fault document sloughing of landslide and fault masses off the unstable topographic wall of the deepening caldera as this escarpment retreated some 10 km northward from the major ring fault (figs. A3 and A7). This topographic shelf, which was cut into older rock units and covered by intracaldera breccias, probably sloped into the caldera, but later resurgent uplift (see below) and post-Oligocene faulting have modified its original attitude. The breccias of the intracaldera member are mostly monolithologic rock types of volcanic units normally occurring between the outflow tuff member of the Wah Wah Springs Formation and the Marsden Tuff Member of the Escalante Desert Formation; breccia of the Cottonwood Wash Tuff is especially prominent. Widespread cataclastic fabrics in these breccias show that not all of the masses caving off the caldera wall were landslides or loose talus falls: many must have been fairly intact fault slices capable of generating sufficient frictional drag to create throughgoing seams of finely pulverized cataclastic material.

Within the sequence of breccias north of the inner ring fault are lenses of Wah Wah Springs tuff. Some of these lenses are apparently of the outflow tuff member, are densely welded, and lack the common complementary less welded upper part of the deposit; these may be decapitated fault slices derived from the northward-retreating escarpment. Other lenses of lithic-free tuff are neither typical outflow tuff nor intracaldera member and may represent local accumulations of Wah Wah Springs type ejecta that were intermittently expelled during caldera collapse and were quickly buried and densely welded during accompanying breccia emplacement.

The intracaldera member of the Wah Wah Springs Formation is well exposed for 18 km south of the inner ring fault in the horst that forms the backbone of the Indian Peak Range. In the horst, the intracaldera member consists of a compound cooling unit of ash-flow tuff with intercalated wedges of essentially monolithologic breccia, intrusive granodiorite porphyry, and minor rhyolite and andesite. The wedges of breccia generally pinch out southward within a kilometer or so of the inner ring fault. Collapse of the caldera, slope failure along the fault escarpment, and expulsion of ejecta were obviously episodic. The clasts in the breccia consist chiefly of recognizable pre-Wah Wah Springs rock types, although some wedges of breccia near the fault contain clasts of exotic volcanic rock several meters across (compare the megabreccias of Lipman, 1976). Breccias south of the inner ring fault are not cataclastic and must therefore represent accumulations of landslide and loose talus debris that fell off the unstable scarp of the fault. Intrusions of porphyry within the intracaldera member appear to have formed from Wah Wah Springs magma rising into higher levels of the hot pile of tuff filling the caldera. At least part of this intrusion may have caused the resurgent uplift of the caldera floor (described below).

The topographic rim of the Indian Peak caldera is mostly concealed in the area 4 km south of Sawtooth Peak (fig. A3). Exposures of locally brecciated rock of the Cottonwood Wash Tuff and of strongly welded but unusually thin outflow tuff member of the Wah Wah Springs Formation are barely visible on the northern margin of an extensive area covered by the thick, caldera-filling Lund Formation. This compound cooling unit and the overlying Ryan Spring Formation conceal the inner ring fault on the east flank of the Indian Peak Range.

The topographic rim and ring fault system of the Indian Peak caldera are buried beneath late Cenozoic basin fill in southern Pine Valley (fig. A1). In the southern Wah Wah Mountains a normal extracaldera sequence of Needles Range rocks overlies Paleozoic sedimentary rocks, and no intracaldera member of the Wah Wah Springs Formation is exposed. However, stratigraphic thickness relations in the Lund Formation around The Tetons are such that the topographic rim could have been located just to the west.

The perimeter of the Indian Peak caldera probably swings southwestward across the southern tip of the Indian Peak Range, but its exact location is obscured by Miocene magmatic units (Best and others, this volume, chap. B) and other more recent deposits. A northeast-striking normal fault through Arrowhead Pass (fig. A1) separates a section at least 2 km thick of tuff and breccia of the intracaldera member on the north from a section mainly of tuff only one-tenth as thick to the south (Best, Grant, and others, 1987). Breccia near but north of the fault has clasts of tuff of the Sawtooth Peak Formation, but a slab of shattered Ordovician and Silurian sedimentary rocks, a square kilometer or so in area, also lies north of the fault, within the caldera. The fault through Arrowhead Pass appears to have had a complex history and was not the outermost ring fault. The 200-m-thick section of intracaldera tuff south of the fault is overlain by discontinuous lava flows and tuffs of the Ryan Spring and Lund Formations, and by Miocene volcanic rocks, indicating post-caldera uplift, partly during resurgence of the caldera but also during block faulting and magmatic activity in the Miocene (Best and others, this volume, chap. B).

NEVADA SECTOR

Only reconnaissance field work has been done in the northern White Rock Mountains and Wilson Creek Range in Nevada, building upon the 1:250,000 map of Ekren and others (1977). Although Miocene rocks cover much of this area, tuffs of the Lund and Ryan Spring Formations are exposed together with almost 100 km^2 of tuff and minor breccia of the intracaldera member of the Wah Wah Springs Formation.

Southeast of the Atlanta gold mining district, intensely silicified Paleozoic carbonate rocks are juxtaposed against tuffs of the intracaldera member of the Wah Wah Springs and the Ryan Spring Formation to the south. Nearby unaltered Paleozoic rocks are overlain by latite flows containing phenocrysts of plagioclase and smaller amounts of pyroxene, biotite, and hornblende. One biotite specimen collected at lat 38°27′38″ N. and long 114°15′10″ W. has a potassium-argon age of 31.8±1.2 m.y. (determination by S. H. Evans, Jr., at the University of Utah in 1982). West of Atlanta, latite flows are juxtaposed against altered rocks, in part of the Ryan Spring Formation, to the south. These relations indicate the topographic margin of the Indian Peak caldera lies near Atlanta. Until more study is made it is impossible to tell whether the widespread hydrothermal activity around Atlanta is related to a ring-fault system bounding the caldera or to a later north-striking fault system. Five to six kilometers southeast of Atlanta, slabs of brecciated lower Paleozoic carbonate rocks and quartzite rest on tuff of the Wah Wah Springs Formation; at the base of the slabs the clasts are separated by a matrix of the tuff. These "jostled" slabs are interpreted to have fallen from the nearby wall of the caldera into the depression during collapse and now rest as erosionally resistant caps on the tuff. The tuff appears to be of the outflow member, but more or less continuous exposures of the formation southward lead into more typical tuffs of the intracaldera member. There are obviously significant variations in the type of tuff in the intracaldera member within the caldera and it is not unlikely that some of it could closely resemble the outflow tuff member.

No direct evidence for the location of the ring fault or topographic wall of the caldera has been found elsewhere in Nevada, so its western and southwestern perimeter is conjectural.

RESURGENCE

At no place within the Indian Peak caldera have any lake beds or significant areas and thicknesses (more than a few meters) of any other sedimentary material been recognized between the Wah Wah Springs Formation and the caldera-filling volcanic deposits of the Ryan Spring and Lund Formations. If such sediments were ever deposited they must have been eroded away prior to emplacement of the younger volcanic rocks because of resurgent uplift of the floor of the caldera.

Evidence that is more direct for resurgence in the Utah sector of the caldera can be seen in the distribution and thickness of the Ryan Spring Formation (figs. A8 and A9). The Greens Canyon Tuff Member lies in a small basin bounded to the north by the topographic wall and to the south by another topographic high, which was probably the margin of the resurgent core of the caldera. A moat between the resurgent core and topographic wall is also expressed in the younger Mackleprang Tuff Member (fig. A9), and variations in its thickness on the order of several hundred meters south of Indian Peak reflect deposition on the block-faulted uplift. South of the fault through Arrowhead Pass, post-caldera uplift appears to have locally exceeded 2 km, inasmuch as Paleozoic basement rocks are exposed beneath an unusually thin intracaldera member. Part of this uplift may have coincided with the extrusion of lava flows in the Ryan Spring Formation onto the thin intracaldera member.

The intrusive porphyry of the intracaldera member was probably emplaced during resurgence and may have caused the resurgence. The main intrusion of porphyry is exposed west of the Cougar Spar Mine (fig. A3). South of this intrusion, as far as Arrowhead Pass, compaction foliation in tuff of the intracaldera member dips southward from 20° to 60°. These dips presumably reflect tilting of the tuff over a large buried mass of porphyry.

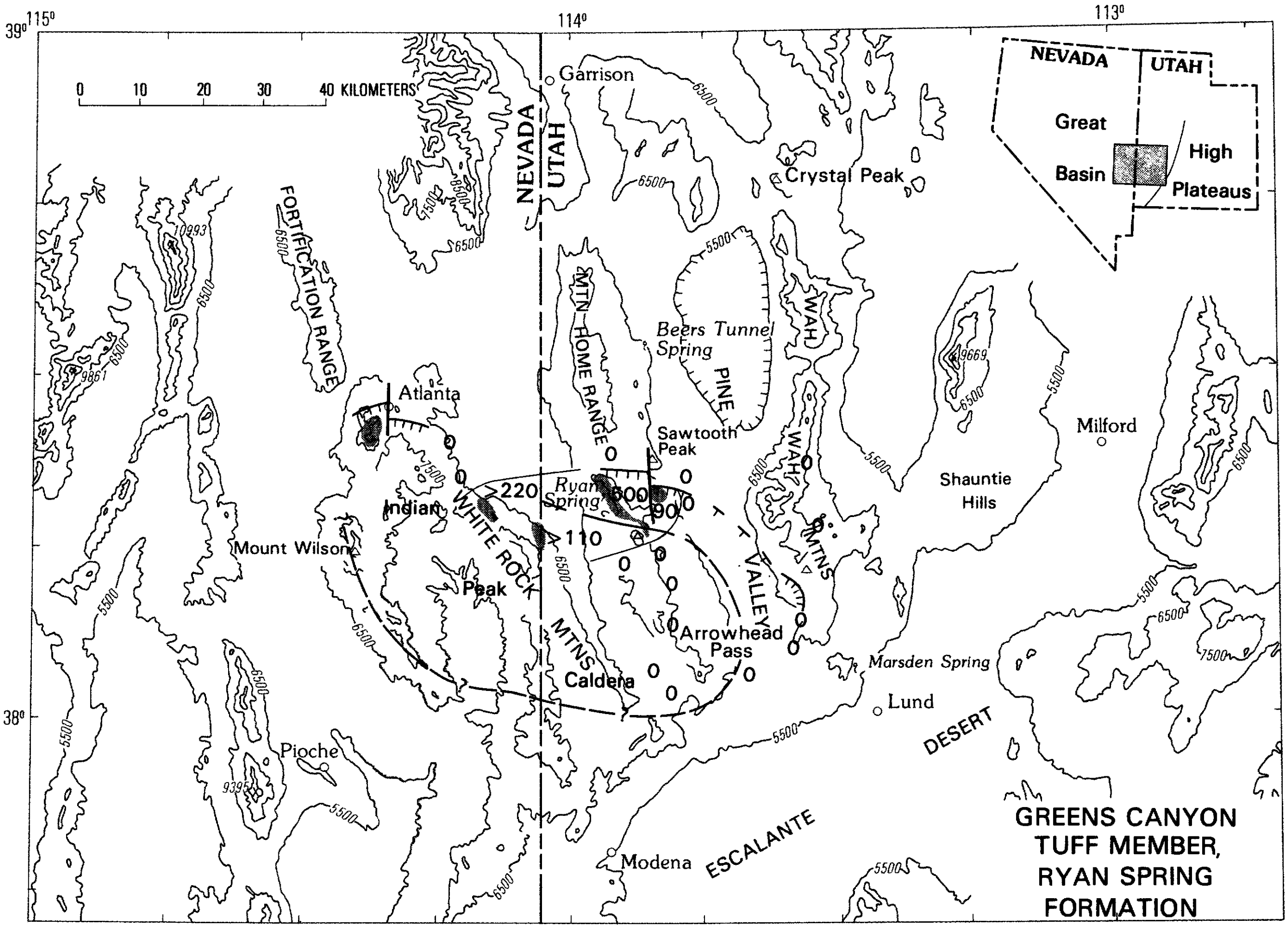

FIGURE A8.—Distribution and thickness of the Greens Canyon Tuff Member of the Ryan Spring Formation. The tuff was confined on the north by the topographic wall of the Indian Peak caldera, on the south by its resurgent uplift, and on the east by a north-striking fault escarpment (heavy line). Symbols as on figure A4.

TOTAL VOLUME OF WAH WAH SPRINGS FORMATION

Minimum measured thicknesses of tuff and minor breccia in the intracaldera member in the Indian Peak Range and the northeastern Wilson Creek Range are 2–3 km. If a conservative value of 2 km is used for the entire caldera, the volume of tuff in the intracaldera member is about 2,400 km^3. The calculated total volume of ash-flow tuff in the Wah Wah Springs Formation, including both outflow and intracaldera members, is therefore about 4,000 km^3.

Relations shown on figure A3 along the northeastern segment of the caldera indicate a total drawdown of roughly 3 km, or perhaps more, depending on how much resurgent uplift was compensated for, as magma was withdrawn from the underlying magma chamber. If this drawdown is applied to the entire caldera, the volume of extruded magma must have been at least 3,600 km^3. The estimated volumes of extruded magma and tuff are in close agreement. Unevaluated factors, such as the amount of subsidence on subsidiary faults outside the main ring fault, the location of the western and southern margins of the caldera and therefore its area, the porosity of partially welded tuff, the volume of the landslide debris in the intracaldera member, and the volume of air-fall deposits far from the caldera, all enter into the volume considerations.

RYAN SPRING FORMATION

The Ryan Spring Formation (figs. A8 and A9) lies almost wholly within the Indian Peak caldera, which probably includes its source. The Greens Canyon Tuff Member in the lower part of the formation is confined to an area along the northern margin of the caldera where a moat existed between a resurgently uplifted core and the topographic wall. The member thins

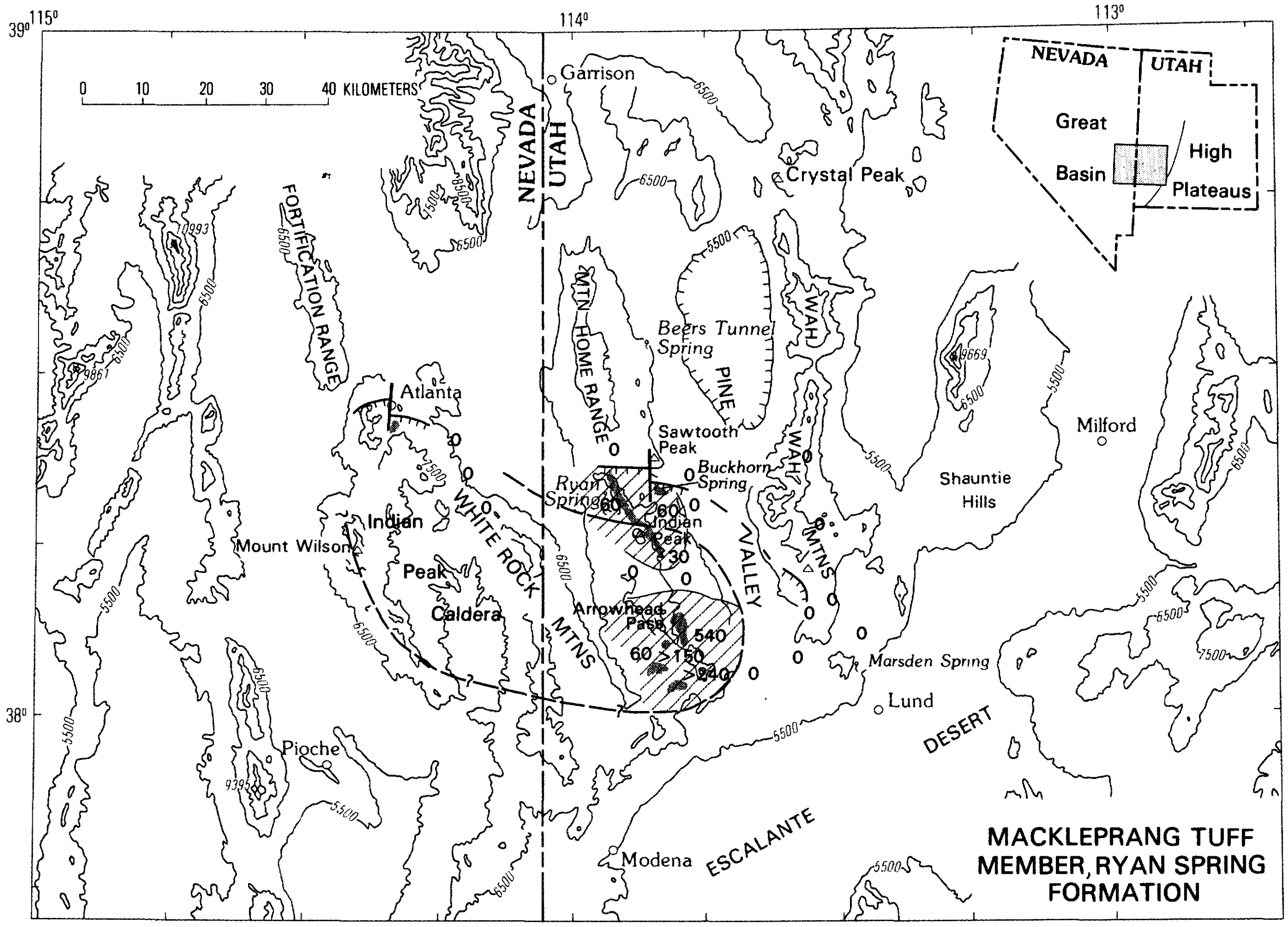

FIGURE A9.—Distribution and thickness of the Mackleprang Tuff Member of the Ryan Spring Formation. The tuff pinched out over the resurgent uplift of the Indian Peak caldera. Symbols as on figure A4.

significantly eastward across a north-south fault near Sawtooth Peak, which offsets the topographic wall of the caldera about 4 km north-south (fig. A3). Although some displacement along this fault postdates deposition of the Lund Formation and thus is also younger than the Ryan Spring Formation, some could have preceded deposition of the Greens Canyon Tuff Member, or even been contemporaneous with its eruption, in which case the fault could be a bounding fault for a segment of a source caldera. Preliminary mapping of areas in the northern White Rock Mountains has disclosed thick sections of the Greens Canyon, suggesting proximity to a caldera wall.

The Mackleprang Tuff Member of the Ryan Spring Formation does not thin across the north-south fault near Sawtooth Peak but wedges out a short distance to the south; the member is absent a few kilometers east and south of Indian Peak. The Mackleprang Tuff Member reappears farther south of Indian Peak and thickens to as much as several hundred meters east and south of Arrowhead Pass. These thickening and thinning relations probably reflect deposition of the tuff in a moat between the resurgently uplifted and block faulted core and the topographic wall of the Indian Peak caldera.

LUND FORMATION

The Lund Formation (fig. A10) is almost as extensive east-west as the outflow tuff member of the Wah Wah Springs Formation, but is more restricted north and south. The thickest sections of this compound cooling unit, which commonly have a basal black vitrophyre several meters thick, are in the northeastern moat of the Indian Peak caldera and the northwestern part of the White Rock source caldera. Had the earlier depression of the Indian Peak caldera not existed, the Lund Formation would undoubtedly have spread far to the north, as did the outflow tuff member of the Wah Wah Springs Formation (fig. A7).

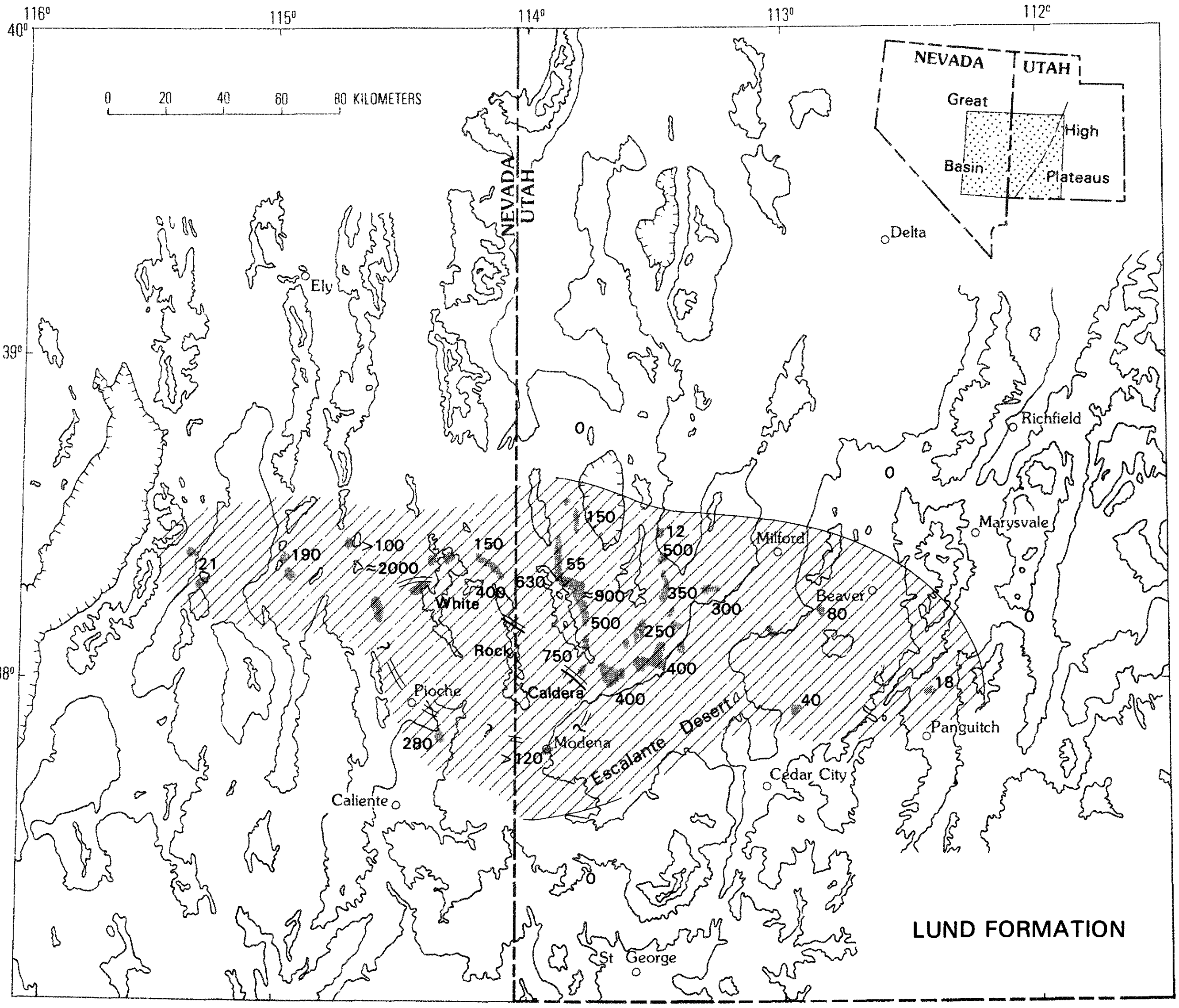

FIGURE A10.—Distribution and thickness of the Lund Formation. Heavy, hachured double line indicates known location of topographic wall of the White Rock caldera; lighter, plain double line shows inferred approximate location. Other symbols as on figure A4.

The tuff of the Seaman Range in southern Nevada (Ekren and others, 1977) is similar to the Lund in composition and occupies the same stratigraphic position. Whether the Lund Formation and tuff of the Seaman Range are actually parts of the same sheet or are similar, virtually contemporaneous deposits from separate sources can only be decided by future investigations.

WHITE ROCK CALDERA

The catastrophic eruption of about 1,600 km^3 of the dacite tuff member of the Lund Formation caused the collapse of the White Rock caldera. Only small segments of its eastern and northwestern margins are clearly exposed.

A segment of the topographic wall is exposed just west of Wilson Canyon in the southern Indian Peak Range, 8–9 km south of Arrowhead Pass. A caldera-filling sequence about 1.2 km thick of the andesite flow member of the Lund Formation and Isom Formation is banked against older rocks of the Lund, Ryan Spring, and Wah Wah Springs Formations (Best, Grant, and others, 1987). A lens of brecciated tuff member of the Lund Formation that is completely out of stratigraphic position lies beneath the caldera fill along the topographic wall. Ash flows of the Isom Formation spilled northward beyond the topographic rim, where their thickness is an order of magnitude less than inside the caldera depression. A thick section of post-Isom, early Miocene lava flows conceals older units southward beyond Modena, so the nature of the rocks filling the eastern segment of the White Rock caldera is unknown.

Preliminary mapping in the White Rock Mountains discloses an unusually thick section of the Isom Formation just south of about lat 38°15′ N.; this is permissive evidence for the approximate location of the topographic wall of the White Rock caldera.

Field relations 8 km northwest of Mount Wilson, in the reference locality of the tuff member of the Lund Formation, clearly indicate proximity to the structural margin of the White Rock caldera. A northeast-tilted compound cooling unit of the tuff member, which may be as much as 2 km thick, contains intercalated lenses of breccia whose clasts are of Paleozoic carbonate rocks and granite of unknown age. Generally, in this well-exposed reference locality, the tuff member has sparse clasts, locally almost a meter across, that have generally the same composition as the tuff but are finer grained or flow-layered, or have other textural contrasts.

Many drill holes in the Pioche mining district encountered volcanic rocks beneath Cambrian sedimentary rocks, or an alternation of the two (Park and others, 1958; Gemmill, 1968). Tschanz and Pampeyan (1970, p. 125, 127) interpret these rocks to be a "megabreccia composed of slices and blocks of Tertiary volcanic rocks and Cambrian limestone" that "is either a thrust breccia, a chaotic sedimentary megabreccia, or a megabreccia produced by gravity sliding. Small dikes or dikelike masses of volcanic rocks with the microscopic characteristics of welded tuff occur * * *. These are believed to be downfaulted remnants of blocks dragged beneath a postvolcanic thrust plate. This * * * has since been eroded or else it has slid off the flanks of the range to form the megabreccia." Alternatively, these puzzling relations can be interpreted to indicate the close proximity of the Pioche district to the unstable wall of a caldera along which Cambrian rocks sloughed into the depression to cover and intermingle as breccias with either precaldera volcanic rocks or concurrently erupting tuff. Only a few churn-drill cuttings of volcanic rocks from these holes, drilled in the late 1940's and early 1950's, have been located. The volcanic cuttings are outflow tuff of the Wah Wah Springs Formation and a slightly altered tuff whose petrographic character and fission-track age on zircon are most compatible with the Lund Formation. Until additional drill-hole material can be examined and detailed mapping of volcanic rocks done around Pioche, there is some uncertainty whether the postulated caldera is the White Rock.

SUMMARY

Ash-flow tuffs of the newly revised Needles Range Group cover an area of at least 22,000 km^2 and probably much more; they have an aggregate volume of at least 6,600 km^3 and possibly as much as 10,000 km^3. They were erupted from clustered, overlapping sources (fig. A11) along the southern Utah-Nevada border between 33 and 28 m.y. ago. The group consists of seven cooling units in two compositional cycles. Each cycle began with crystal-poor, lithic-rich rhyolite and culminated with more voluminous crystal-rich dacite. Andesite lavas were extruded more or less contemporaneously.

The first cycle began about 33 m.y. ago with eruption of the rhyolitic Marsden and Lamerdorf Tuff Members of the Escalante Desert Formation. The Pine Valley caldera collapsed during the extrusion of the Marsden and, possibly, Lamerdorf Tuff Members. Many compositionally similar rhyolite flows were extruded from vents near the margin of the caldera at about this same time. More widely scattered vents throughout the Needle Range and the Wah Wah Mountains were the source of an even greater number of contemporaneous pyroxene andesite lava flows. Thin, widely scattered deposits of sand and local thick lenses of gravel accumulated in topographic lows between the lava flows, forming the Beers Spring Member of the Escalante Desert Formation. Then followed two voluminous eruptions of crystal-rich dacite tuff. At least 500 km^3 of the 30.6-m.y.-old Cottonwood Wash Tuff was erupted from a source that appears to be concealed beneath a broad alluvial valley near the northern margin of the younger Indian Peak caldera.

Dacite tuffs of the Wah Wah Springs Formation were erupted 29.5 m.y. ago from the Indian Peak caldera, which straddles the Utah-Nevada border. Although this caldera is mostly concealed by younger deposits, it appears to have had an area of at least 1,200 km^2 at the time of collapse and its northeastern perimeter generally coincides with the northeastern perimeter of the smaller, earlier Pine Valley caldera. The Indian Peak caldera collapsed after the expulsion of about 1,500 km^3 of the outflow tuff member, which spread over an area of at least 22,000 km^2 in Nevada and Utah to depths as great as 500 m. Continued eruption of the Wah Wah Springs tuffs and intermittent caving of the unstable caldera wall produced tuff and breccia in the intracaldera member that filled the depression inside the major ring fault to a depth of at least 2 km. The northeastern segment of the topographic shelf and wall of the caldera retreated as much as 10 km back from the major ring fault as the central floor of the depression subsided about 3 km. The total volume of

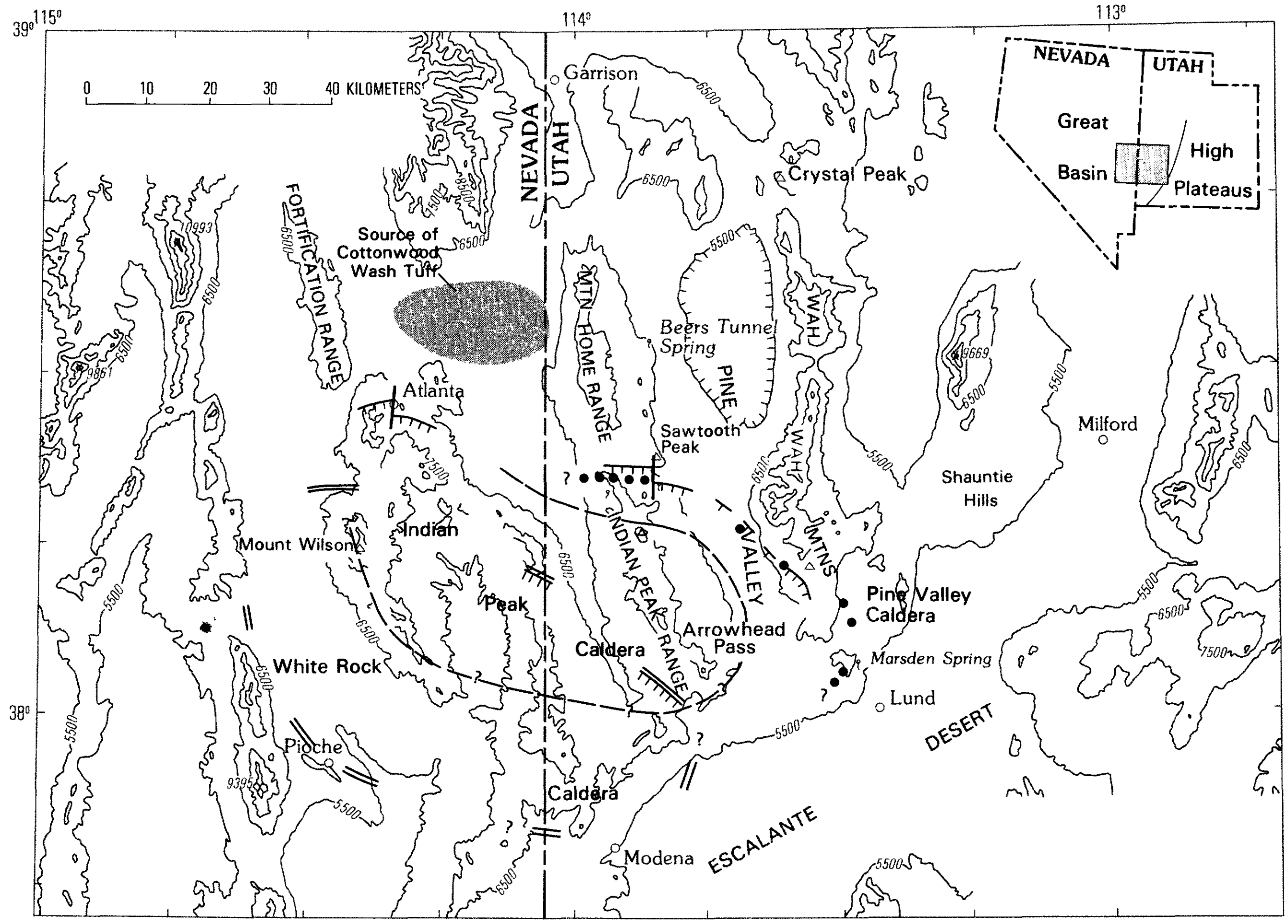

FIGURE A11.—Nested sources of tuff cooling units in the Needles Range Group from figures A4 to A10. The Marsden Tuff Member and possibly the Lamerdorf Tuff Member of the Escalante Desert Formation were derived from the Pine Valley caldera. Tuffs of the Wah Wah Springs and the Ryan Spring Formations were derived from the Indian Peak caldera. The Lund Formation originated from the White Rock caldera. Approximate location of the source of the Cottonwood Wash Tuff is shown by shaded area.

the Wah Wah Springs Formation is estimated to be on the order of 4,000 km³, which ranks this unit among the great pyroclastic sheets in the world.

The second cycle of eruptive activity began sometime after the core of the Indian Peak caldera had risen resurgently at least several hundred meters. Two small-volume cooling units of rhyolite ash-flow tuff of the Ryan Spring Formation had sources within the area of the older Indian Peak caldera; rhyolite and andesite lava flow members of the Ryan Spring Formation occur in the southeastern part of the caldera.

Crystal-rich dacite ash-flows of the 27.9-m.y.-old Lund Formation then ponded as a compound cooling unit to depths of at least 600 m within the northeastern moat of the Indian Peak caldera and spread widely to the east and west in Utah and Nevada, covering an area of about 11,000 km². The source of this 1,600 km³ volume of tuff was the White Rock caldera, which had an estimated area of about 2,000 km² and partly eclipses the southwestern part of the older Indian Peak caldera. The volume of the Lund Formation within the White Rock caldera is unknown but possibly equals the outflow.

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Miocene Magmatism and Tectonism in and near the Southern Wah Wah Mountains, Southwestern Utah

By MYRON G. BEST, HARALD H. MEHNERT,
JEFFREY D. KEITH, *and* CHARLES W. NAESER

OLIGOCENE AND MIOCENE VOLCANIC ROCKS IN THE CENTRAL PIOCHE-MARYSVALE IGNEOUS BELT, WESTERN UTAH AND EASTERN NEVADA

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1433-B

Radiometric ages and field and chemical data document two episodes of bimodal magmatism and one accompanying pulse of block faulting

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MIOCENE MAGMATISM AND TECTONISM IN AND NEAR THE SOUTHERN WAH WAH MOUNTAINS, SOUTHWESTERN UTAH

By MYRON G. BEST, HARALD H. MEHNERT, JEFFREY D. KEITH, and CHARLES W. NAESER

ABSTRACT

Magmatic and tectonic activity in the central part of the Pioche-Marysvale igneous belt in southwestern Utah during the Miocene contrasts sharply with that during the Oligocene. Great volumes of chiefly intermediate calc-alkalic magma erupted to form large calderas in the Oligocene, but beginning about 23 million years (m.y.) ago, smaller volumes of bimodal mafic-silicic magmas erupted from many local centers. This first pulse of bimodal magmatism lasted until 18 m.y. ago and was characterized by potassic trachyandesite lava flows associated with mostly younger rhyolite tuffs and lava flows (some topaz bearing) and shallow porphyritic intrusions, one of which hosts disseminated molybdenum and tungsten. After a hiatus of about 5 m.y., bimodal magmatism resumed for about a million years (13–12 m.y. ago), when mafic lava flows containing less potassium and silicon than the earlier mafic flows were emplaced along with uniformly high-silica, lithophile-rich, topaz-bearing rhyolite flows and tuffs. These mid-Miocene rhyolites form a northeast-trending belt just south of the similarly trending belt containing early Miocene rhyolitic rocks. Hydrothermal activity accompanied both episodes of silicic magmatism.

During the Oligocene, southwestern Utah and the adjacent part of Nevada appear to have been tectonically inactive; successive ash-flow deposits progressively smoothed the prevolcanic topography, and so the latest Oligocene (26-m.y.-old) Isom Formation now forms a thin sheet no more than a few tens of meters thick throughout most of the area. However, in the early Miocene, northeast-trending normal faulting began in the central part of the Pioche-Marysvale igneous belt. At the same time, many northeast-trending, subvertical rhyolite dikes were emplaced, indicating local northwest-southeast extension of the crust in contrast to the east-west directed extension of the last 10 m.y. or so that has produced northerly trending basins and ranges in the eastern Great Basin.

INTRODUCTION

Recent papers have focused attention on the geophysical and tectonomagmatic character of broad, generally east-trending belts of mineralization in western Utah and eastern Nevada that cut across boundaries of major geologic provinces, including the Colorado Plateaus, the Basin and Range province, the Sevier orogenic belt, and the Mesozoic metamorphic belt (fig. B1, inset; see Rowley and others, 1978; Shawe and Stewart, 1976; Stewart and others, 1977). These mineral belts are noted for valuable deposits of gold, silver, lead, zinc, copper, iron, molybdenum, and tungsten and are associated with east-trending belts of Tertiary igneous rocks that decrease in age from north to south. Broad aeromagnetic highs with superimposed short-wavelength anomalies characterize the igneous and mineral belts (fig. B2).

In southwestern Utah and adjacent parts of Nevada, one of these belts has been called the Pioche mineral belt by Shawe and Stewart (1976); this name earlier had been applied only to the Nevada portion of the belt by Roberts (1966), and the Utah portion had been designated the Wah Wah-Tushar belt by Hilpert and Roberts (1964). The zone of magmatic rocks that was designated the Pioche-Marysvale igneous belt by Rowley and others (1979) generally coincides with the mineral belt. This belt, however defined, trends east-northeasterly from a point west of Pioche, Nev., through the southern Wah Wah Mountains of western Utah, the Tushar Mountains between Beaver and Marysvale, to the western part of the Colorado Plateaus (fig. B1; compare the aeromagnetic map of fig. B2). A subparallel belt of igneous rocks and mineral deposits lies about 50 km south of the Pioche-Marysvale belt and includes near its eastern end the Iron Springs district west of Cedar City.

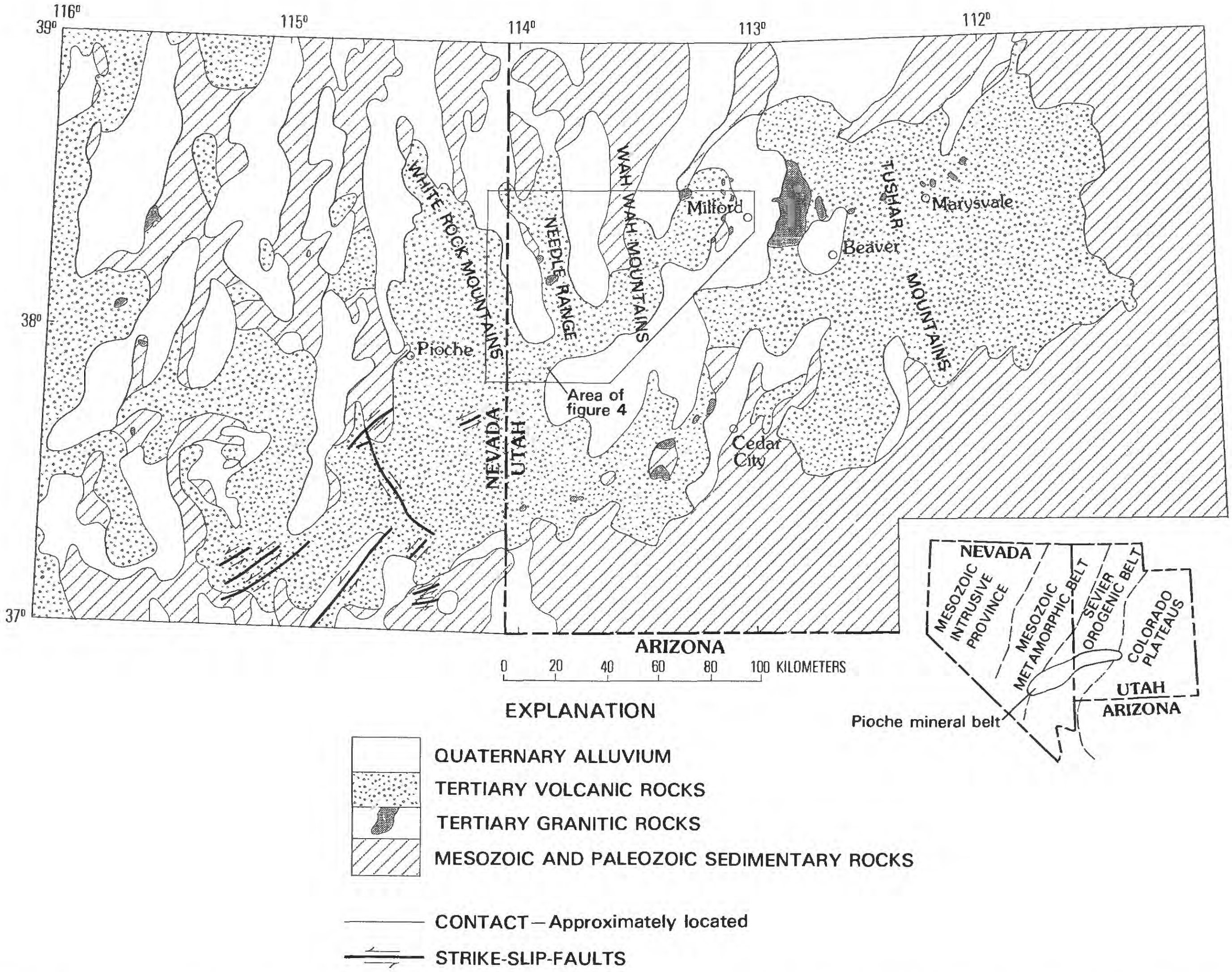

FIGURE B1.—Generalized geology of the Pioche-Marysvale igneous belt of Rowley and others (1978) and surrounding areas. Note the northeast-striking, left-lateral strike-slip faults and the single northwest-striking, right-lateral fault south of Pioche. Geology based on Hintze (1980) and Stewart and Carlson (1978); inset after Shawe and Stewart (1976).

Shawe and Stewart (1976, p. 226) drew attention to major northeast- to east-northeast-striking high-angle faults in the Nevada segment of the Pioche-Marysvale belt that are clearly oblique to the northerly oriented normal faults that bound most of the present basins and ranges. These oblique faults tend to be en echelon and stepped to the right as though produced by a left-lateral shear couple. Strike-slip faults with left lateral displacement occur south of Pioche (fig. B1; see also Ekren and others, 1977).

Rowley and others (1978) defined the east-trending Blue Ribbon lineament, which largely overlaps the Pioche-Marysvale belt and is based in part upon the distribution of Tertiary rhyolite bodies and deposits of fluorspar, uranium, and tungsten.

Recent mapping at a scale of 1:24,000 and compilations at 1:50,000, combined with radiometric dating in the southern Wah Wah Mountains and the Indian Peak Range,[1] has established a framework of tectonic, magmatic, and hydrothermal events that sheds light on the character and evolution of at least the central part of the Pioche-Marysvale belt. This framework also clarifies broader aspects of the Cenozoic tectono-magmatic development of the Colorado Plateaus–Basin and Range transition zone.

[1] The Indian Peak Range is the southern part of what was called the Needle Range on maps published prior to 1974. The northern part of the Needle Range is now called the Mountain Home Range.

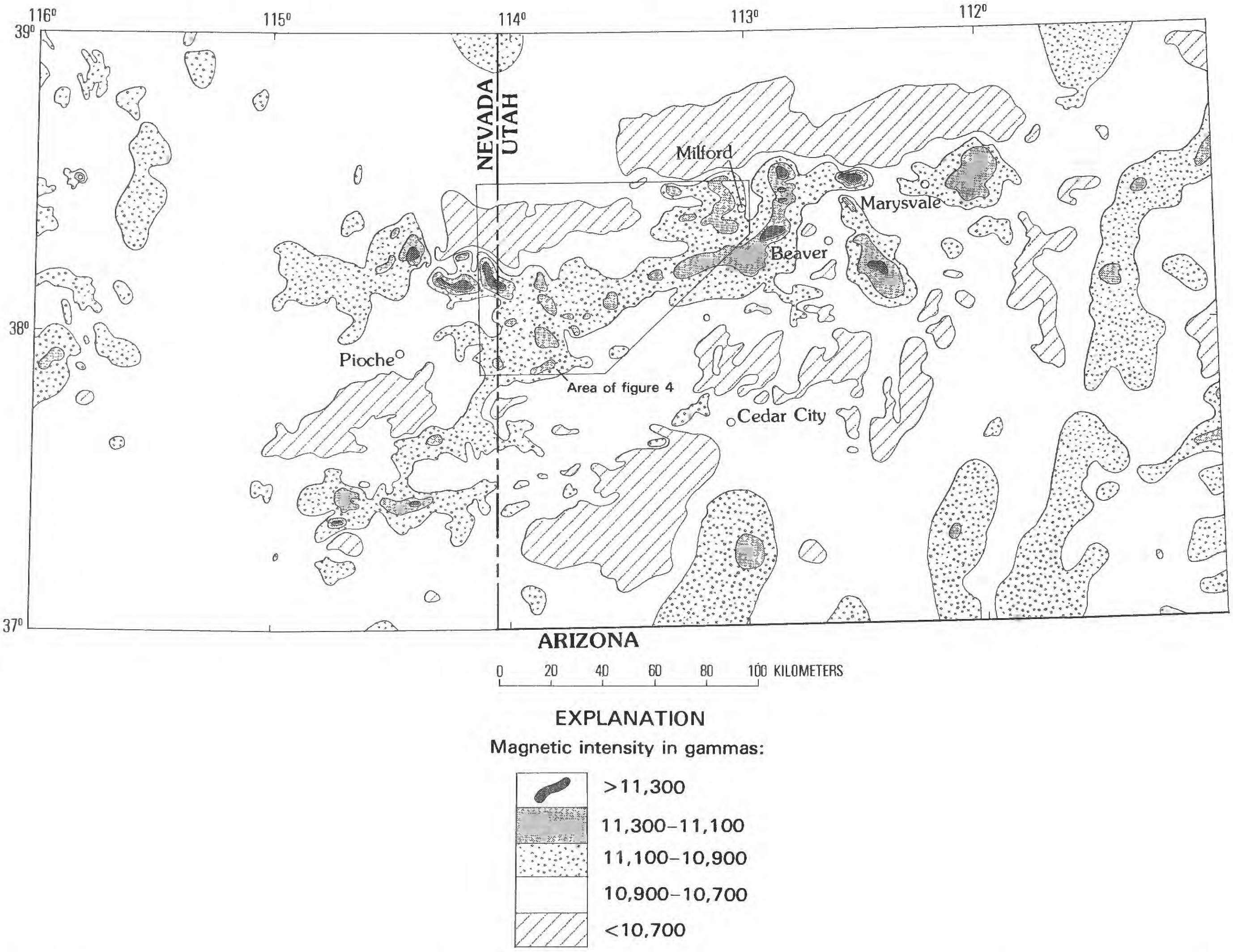

FIGURE B2.—Generalized aeromagnetic map of the Pioche-Marysvale igneous belt and surrounding area. Modified from Zietz and others (1976, 1978).

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GENERALIZED VOLCANIC HISTORY

In the region between Pioche and Marysvale, regional ash-flow sheets and locally derived lava flows and volcaniclastic deposits of Tertiary age rest on a surface of moderate relief, generally less than a few hundred meters, carved into Paleozoic and Mesozoic sedimentary strata that were deformed during the latest Cretaceous Sevier orogeny (fig. B3). Paleovalleys now filled with thick volcanic deposits are generally aligned more or less east-west; one of these on the west flank of the Wah Wah Mountains was especially deep—about 1,200 m (Abbott and others, 1981). Another deep paleovalley cut into Ordovician carbonate rocks at Sawtooth Peak in the southern Mountain Home Range contains 300 m of the Sawtooth Peak Formation.

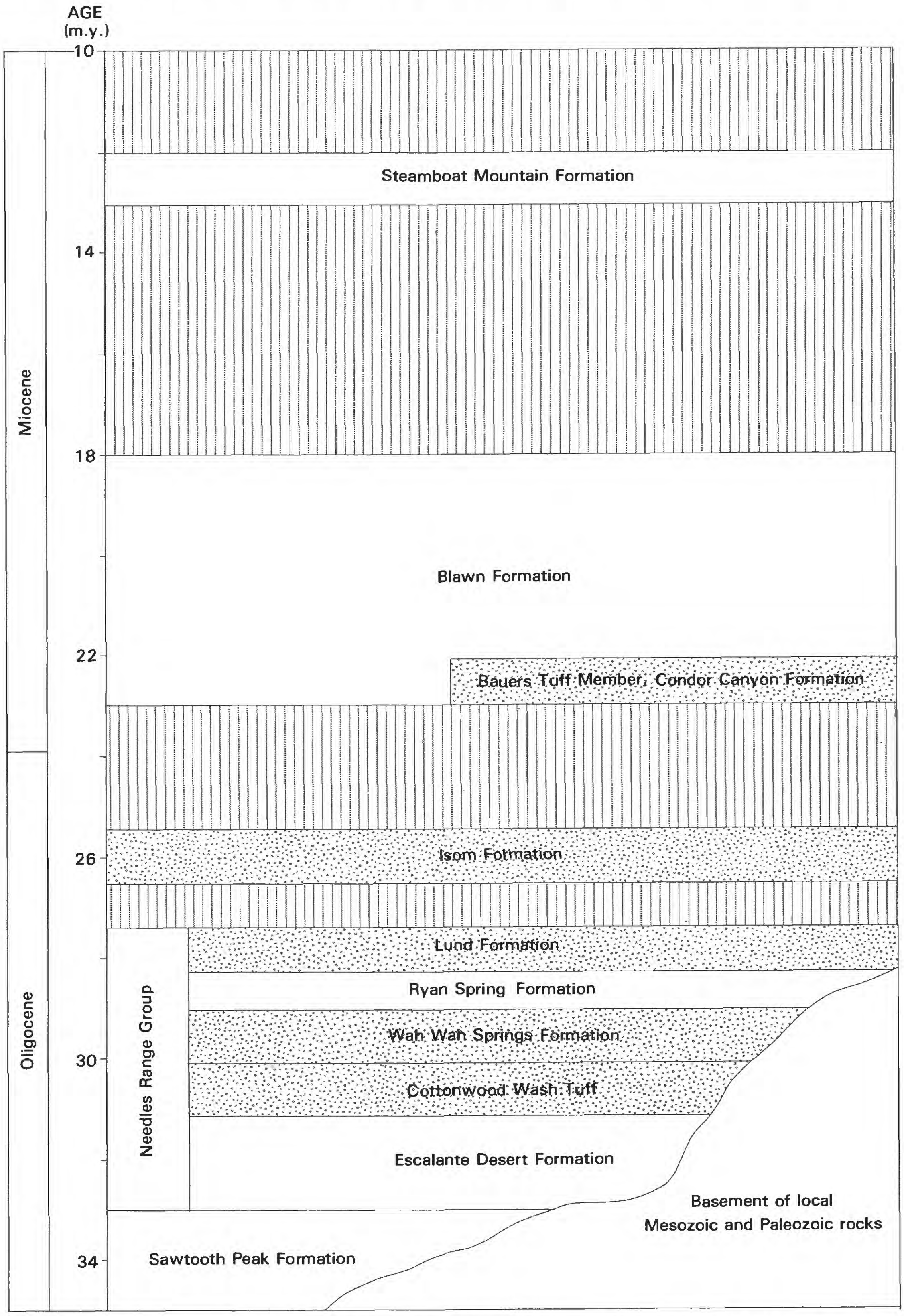

FIGURE B3.—Tertiary stratigraphy of the southern Wah Wah Mountains and the Indian Peak Range, southwestern Utah. Regional ash-flow sheets are stippled. The Condor Canyon Formation comprises regional ash-flow sheets whose source may have been south of Pioche, Nev. (Williams, 1967); in the southern Wah Wah Mountains and the Indian Peak Range, only the Bauers Tuff Member of the Condor Canyon is present.

Volcanic rocks of the Needles Range Group, deposited next after the Sawtooth Peak, flooded the landscape in southwestern Utah and the adjacent part of Nevada to depths as great as a kilometer and filled nested source calderas that straddle the State line to much greater depths. This group, which has been newly revised in chapter A of this volume, consists of more than 6,600 km^3 of ash-flow tuffs and minor lava flows representing two eruptive-compositional cycles. Each cycle began with eruption of crystal-poor, low-silica rhyolites followed by greater volumes of crystal-rich dacite. First-cycle rhyolite tuffs and lava flows of the Escalante Desert Formation erupted about 33 m.y. ago were succeeded by dacite ash flows 30.6 and 29.5 m.y. ago that formed the Cottonwood Wash Tuff and the Wah Wah Springs Formation. Second-cycle rhyolite ash-flow tuffs of the Ryan Spring Formation followed by dacite of the Lund Formation were emplaced by 28 m.y. ago.

The 26-m.y.-old[2] (Fleck and others, 1975) Isom Formation consists of a sequence of trachytic ash-flow tuffs that is generally less than a few tens of meters thick yet crops out over much of southwestern Utah and extends into Nevada. It is thus apparent that extrusion of the Needles Range tuffs had produced a flat terrain outside the Indian Peak caldera and that negligible tectonic disturbance and erosion had occurred by the end of the Oligocene.

Elsewhere in southwestern Utah and the adjacent part of Nevada, regional ash-flow sheets of the Quichapa Group were deposited 25–22 m.y. ago (Armstrong, 1970; Fleck and others, 1975) on tuffs of the Isom Formation. Their source was probably the Caliente cauldron complex south of Pioche, Nev. (Williams, 1967; Ekren and others, 1977). However, only the northeastern part of the most widespread sheet—the Bauers Tuff Member of the Condor Canyon Formation (22.3 m.y., Fleck and others, 1975)—is found in the Wah Wah Mountains and the mountain ranges on either side. The Bauers sheet of low-silica rhyolite tuff is generally less than 20 m thick but firmly welded.

In early Miocene time, volcanic activity shifted from eruption of the earlier, generally intermediate composition magmas to a more bimodal assemblage of mafic and silicic compositions. Between 23 and 18 m.y. ago, many local magmatic centers were active in the central part of the Pioche-Marysvale belt, producing the mafic lava flows and rhyolite lava flows and tuffs of the Blawn Formation, named and described in this report. After a hiatus of about 5 m.y., bimodal magmatic activity was renewed and mafic lava flows and topaz-bearing rhyolite extrusions of the 13- to 12-m.y.-old Steamboat Mountain Formation (adopted as proposed by Thomson and Perry in 1975) were erupted. Alteration and mineralization accompanied both episodes of silicic acitivity. These two bimodal associations and related early Miocene tectonism in the central part of the Pioche-Marysvale belt are the main subject of this paper.

[2]Potassium-argon ages published prior to 1977 have been adjusted for new radiometric constants (Dalrymple, 1979).

EARLY MIOCENE BLAWN FORMATION

In contrast to the dominantly intermediate-composition calc-alkalic magmas extruded chiefly as regionally extensive ash flows during Oligocene time, extruded Miocene magmas in the central part of the Pioche-Marysvale belt have smaller volumes and more restricted compositions and comprise an essentially bimodal assemblage of silicic and mafic rocks emplaced around many local magmatic centers. No caldera formed during this Miocene activity.

A bimodal assemblage of silicic intrusive and extrusive rocks and potassium-rich mafic lava flows emplaced between 23 and 18 m.y. ago (table B1) is here designated the Blawn Formation. The unit is named from Blawn Wash, a major drainage through the southern Wah Wah Mountains (fig. B4), where a nearly complete sequence of the Blawn Formation overlies the Isom Formation and underlies unaltered mid-Miocene mafic lava flows of the 13- to 12-m.y.-old Steamboat Mountain Formation. (See later section.) Silicic rocks of the formation are also exposed in the nearby Blawn Mountain area; these and some older rocks in the area have been altered to alunite and clay minerals and may also contain small deposits of uranium, tin, molybdenum, and beryllium (Lindsey and Osmonson, 1978). The type section for the formation lies near the intersecting corners of the Lamerdorf Peak, Frisco, The Tetons, and Blue Mountain quadrangles at 38°15′ N. and 113°30′ W. in sec. 35, T. 29 S., R. 15 W. (Abbott and others, 1983; Best, Morris, and others, 1987; Weaver, 1980), where it is about 600 m thick. Well-exposed sections are found along the southeast flank of the Wah Wah Mountains northeast of Blawn Wash (Abbott and others, 1983).

RHYOLITIC TUFFS AND TRACHYANDESITIC LAVA FLOWS

Early Miocene bimodal volcanic activity that produced the Blawn Formation in the southern Wah Wah Mountains began with deposition of rhyolitic volcaniclastic rocks. At the base, 3–20 m of stratified volcanic

TABLE B1.—*Radiometric ages of igneous rocks in the Wah Wah Mountains and nearby areas, southwestern Utah*

[See appendix for descriptions of samples and localities. Potassium analyses by X-ray fluorescence at Brigham Young University, Provo, Utah. Ages determined by H. H. Mehnert at U.S. Geological Survey laboratory, Denver, Colo., except as noted. Decay constants: ^{40}K $\lambda_\epsilon=0.581\times10^{-10}$/yr; $\lambda_\beta=4.962\times10^{-10}$/yr; $^{40}K/K_{total}=1.167\times10^{-4}$. Leaders (---), not determined]

Sample No.	Rock type	*	Locality: North latitude	Locality: West longitude	K_2O (wt. pct)	Radiogenic ^{40}Ar: Moles/g $\times10^{-10}$	Radiogenic ^{40}Ar: Percent of total Ar	Age ± 2σ (m.y.)
			Steamboat Mountain Formation					
1	Rhyolite--------	s	38°04'02"	113°38'43"	7.03, 7.19	1.317	82.2	12.8±0.5
2	----do----------	s	38°05'17"	113°41'22"	7.66, 7.67	1.383	79.8	12.5±0.4
3	----do----------	s	38°00'20"	113°42'43"	7.66, 7.60	1.317	81.3	11.9±0.5
4	----do----------	s	38°02'18"	113°43'26"	6.60, 6.57	1.214	48.5	12.8±0.5
5	----do----------	s	38°05'10"	113°44'45"	7.79, 7.73	1.411	82.4	12.6±0.4
6	----do----------	s	38°04'30"	113°34'30"	5.92, 5.85	1.069	61.5	12.6±0.5
7	----do----------	s	38°01'08"	113°46'10"	5.49	1.097	18.9	13.8±1.5
8	Trachyandesite--	w	38°19'57"	113°27'04"	3.76, 3.73	.666	73.9	12.3±0.5
9	Mugearite-------	w	38°15'38"	113°27'52"	2.68, 2.68	.498	62.0	12.9±0.5
[1] 10	----do----------	w	38°18'53"	113°26'22"	2.68, 2.85	.5422	49.2	13.3±0.3
			Alunitic alteration					
11	Alunite-------------		38°16'	113°31'	6.09, 6.09	1.818	42.4	20.6±0.9
12	----do-------------		38°18'	113°18'	4.54, 4.55	1.480	8.4	22.5±5.7
			Blawn Formation					
13a	Rhyolite--------	s	38°15'00"	113°48'10"	7.72, 7.82	2.457	70.8	21.8±0.9
13b	----do----------	s	38°15'00"	113°48'10"	8.09, 8.05	2.452	76.2	21.0±0.8
14	----do----------	s	38°12'50"	113°33'45"	4.38, 4.25	1.146	84.6	18.3±0.7
[2] 15	----do----------	z	38°26'47"	113°13'50"	(2)	(2)	(2)	18.9±1.0
[2] 16	----do----------	z	38°12'45"	113°51'00"	(2)	(2)	(2)	19.0±1.1
[2] 17	----do----------	z	38°12'50"	113°48'15"	(2)	(2)	(2)	20.6±1.3
18	----do----------	s	38°12'50"	113°48'15"	7.35, 7.30	2.187	81.4	20.6±0.7
19	----do----------	b	38°12'50"	113°48'15"	8.47, 8.52	2.688	74.0	21.8±0.8
[2] 20	----do----------	z	38°10'20"	113°50'30"	(2)	(2)	(2)	21.5±1.1
21	----do----------	s	38°16'16"	113°25'47"	5.47, 5.78	1.847	81.2	22.1±0.8
22	----do----------	b	38°15'59"	113°31'01"	8.37, 8.36	2.687	74.9	22.2±0.8
[1] 23	----do----------	b	38°18'41"	113°33'35"	5.44, 5.50	1.697	29.6	21.5±0.8
24	----do----------	s	38°14'45"	113°34'45"	8.86, 8.84	2.582	74.0	20.2±0.9
25	----do----------	p	38°28'30"	113°18'55"	1.98	.6122	66.0	[3] 21.3±0.4
26	----do----------	b	38°28'30"	113°18'55"	7.60	2.534	80.0	[3] 23.0±0.4
27	----do----------	s	37°59'19"	114°03'43"	4.62, 4.68	---	38.0, 42.5	21.0±1.3
[1] 28	Trachyandesite--	w	38°22'55"	113°29'57"	3.28, 3.35	1.118	23.4	23.2±1.0
[4] 29	----do----------	w	37°59'00"	113°47'39"	4.70	1.5259	32.0	22.5±1.1
[2] 30	Granite---------	z	38°20'30"	113°09'13"	(2)	(2)	(2)	21.6±2.3

*Type of material dated: w = whole rock; s = sanidine; b = biotite; z = zircon; p = plagioclase.

[1]Age determined by M. G. Best at U.S. Geological Survey laboratory at Menlo Park, Calif.
[2]Fission-track age by C. W. Naeser, U.S. Geological Survey, Denver, Colo. K/Ar data not applicable.
[3]Age corrected for new decay constants (Dalrymple, 1979).
[4]Age determined by Stanley Evans, University of Utah, Salt Lake City.

sand and pumice and 0–4 m of crudely stratified air-fall tuff underlie a weakly welded, crystal-poor, somewhat lithic ash-flow tuff. Thickest sections (60–200 m) of the ash-flow tuff are exposed on the east flank of the Wah Wah Mountains (Abbott and others, 1983), and deposits a few meters thick have been recognized at two localities on the eastern slopes of the Indian Peak Range. The presently exposed extent of this tuff is an elliptical area of 800 km² surrounding Pine Grove in the southern Wah Wah Mountains; a conservative estimate of its original volume is 25 km³ (Keith, 1980). Large lithic fragments (20–60 cm) lie between the Plinian air-fall and

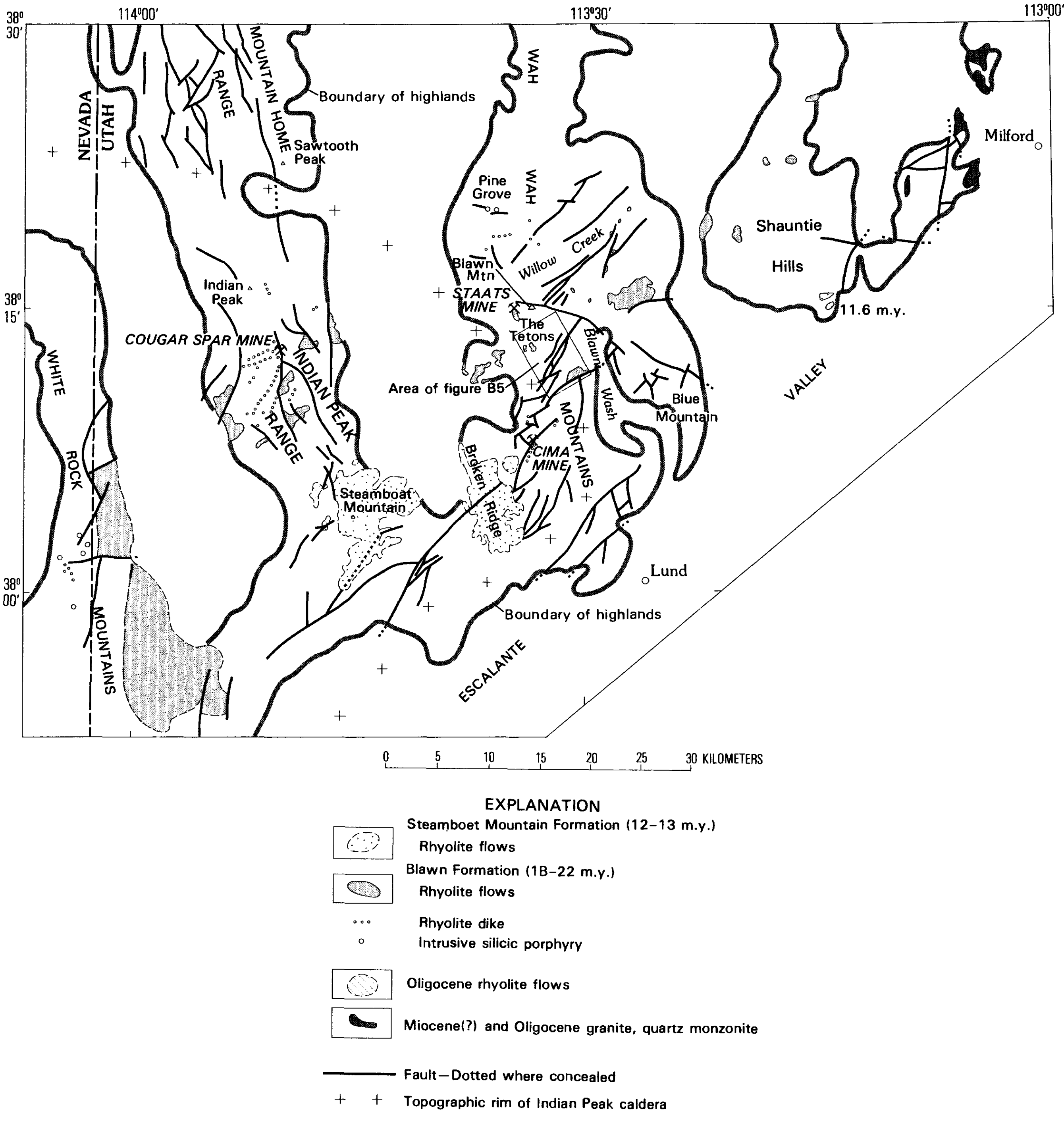

FIGURE B4.—Distribution of Miocene silicic rocks and major high-angle faults within ranges in the central part of the Pioche-Marysvale belt, southwestern Utah. Pluses enclose the Indian Peak caldera complex (chapter A of this volume). Data for White Rock Mountains from Keith (1980), Hintze (1980), and unpublished reconnaissance mapping by M. G. Best. Data for the Shauntie Hills-Milford area from Lemmon and Morris (1979a, b) and Felt (1981). Data for Indian Peak Range, Mountain Home Range, and Wah Wah Mountains from Abbott and others (1983); Best (1987); Best, Grant, and others (1987); Best, Hintze, and others (1987); Best, Morris, and others (1987); Grant and Best (1979); and Weaver (1980).

underlying deposits, whereas smaller (<10 cm) fragments occur in the ash-flow tuff. Fragments include conspicuous pieces of tuff from the Lund and Wah Wah Springs Formations and other volcanic rocks containing phenocrysts of plagioclase; less common fragments include quartzite, olive-colored phyllite, and varitoned gray carbonate rocks similar to Lower Cambrian units exposed in the Wah Wah Mountains.

The ash-flow tuff unit near the base of the Blawn Formation contains small (<2 mm) phenocrysts of quartz, sanidine, plagioclase, and biotite (in order of decreasing abundance) and trace amounts of hornblende, iron-titanium oxides, and dark-red almandine-spessartine garnet. The garnet is especially notable because it is indistinguishable in chemical composition, size, relative abundance, and nature of minute inclusions from garnets within intrusive rocks in Pine Grove (Keith, 1982; Abbott and others, 1983). These observations and the fact that the outcrops of the tuff surround Pine Grove led Keith (1982) to conclude that this ash-flow tuff represents an eruptive facies of the granitic intrusive system in Pine Grove that is host to a disseminated molybdenum-tungsten deposit at depth. Extrapolation of the east-dipping volcanic succession exposed on the east flank of the Wah Wah Mountains westward over Pine Grove indicates about 1.3 km of roof rock has been stripped off the intrusive complex since it vented to the surface.

The age of both the tuff and the Pine Grove intrusive rocks is bracketed by the 23.2±1.0-m.y. potassium-argon age of the overlying trachyandesite lava flow (see below) and the 26-m.y.-old Isom Formation beneath.

Overlying the garnet-bearing tuff in the southeastern part of the Wah Wah Mountains is a sequence of porphyritic trachyandesite lava flows. Phenocrysts include small, sparse olivine grains, almost invariably replaced by iddingsite, and more abundant crystals of augite, hypersthene, and plagioclase. Biotite occurs locally in glomeroporphyritic clots. Chemically, these potassium-rich mafic flows range from trachyandesite to latite (Le Maitre, 1976): their SiO_2 content ranges from 62 to 54 weight percent and their K_2O content ranges from 4.7 to 2.2 weight percent (table B2).

A sample from the base of the thick (200 m) section of potassium-rich mafic lava flows in the Blawn Formation on the east side of the Wah Wah Mountains has a potassium-argon age of 23.2±1.0 m.y. (table B1, sample 28). Three kilometers to the south, a lens of Bauers Tuff Member of the Condor Canyon Formation with an age of 22.3 m.y. appears to lie within the sequence of mafic flows of the Blawn Formation.

Overlying these potassium-rich mafic lava flows in the Blawn Formation of the southeastern Wah Wah Mountains are loosely consolidated rhyolitic deposits similar to those beneath the lavas but lacking garnet. Crystal-poor ash-flow tuffs dominate, but beds of air-fall ash and pumice, reworked water-laid tuffaceous sands, and base-surge deposits also occur. That these deposits were derived from local volcanic centers is indicated by the presence of abundant angular xenoliths, locally a meter or so in diameter, consisting of tuffs from the Lund and Wah Wah Springs Formations and assorted, probably cogenetic rhyolite flow rocks.

TABLE B2.—*Chemical composition of mafic to intermediate Miocene lava flows from the Wah Wah Mountains, southwestern Utah*

[Data in weight percent. Analyses by X-ray fluorescence spectrometry using the Norrish and Hutton (1969) method and several international rock standards. See appendix for descriptions of samples and localities]

Major oxide	Trachyandesite flows in Blawn Formation			Mugearite flow in Steamboat Mountain Formation, sample 10
	Sample 28	Sample 29	Sample 31	
SiO_2-----	60.5	55.0	58.7	52.6
TiO_2-----	.96	1.41	.94	1.89
Al_2O_3----	15.9	14.5	15.4	16.4
Fe_2O_3 [1]--	7.42	8.0	7.2	9.72
MnO------	.05	.13	.09	.16
MgO------	3.9	6.0	3.8	4.6
CaO------	6.01	6.50	6.65	6.92
Na_2O-----	2.9	3.3	3.44	3.9
K_2O------	3.32	4.70	3.10	2.79
P_2O_5-----	.33	.56	.34	.84
Total--	101.29	100.10	99.65	99.82

[1]Total iron expressed as Fe_2O_3.

In the Shauntie Hills, Indian Peak Range, and southern White Rock Mountains, sequences of rhyolitic tuffs and lavas and intermediate-composition lava flows similar to those in the Wah Wah Mountains occur in the same stratigraphic position above the Isom Formation (Lemmon and Morris, 1979a, b; Felt, 1981; Lemmon and others, 1973; Best, Grant, and others, 1987; Keith, 1980).

RHYOLITIC LAVA FLOWS AND INTRUSIONS

Rhyolitic lava flows mostly overlie but locally interfinger with garnet-free tuffs, and similar-appearing rhyolite intrusions are contemporaneous with or slightly older than the flows (table B1). All silicic bodies in the Blawn Formation have various combinations of phenocrystic quartz, sanidine, plagioclase, biotite, and, rarely, hornblende. Some also have clots of micrographic granite. Marginal vitrophyre and breccia are common around felsitic cores of several of the silicic extrusions.

A variety of flows and intrusions of the Blawn Formation is exposed in the southern Wah Wah Mountains. Plutons in Pine Grove are largely concealed granitic bodies that have combinations of phenocrysts of quartz, alkali feldspar, plagioclase, and biotite several millimeters in diameter set in a felsitic aphanitic matrix (Keith, 1982). Hydrothermal solutions have altered these rocks to assemblages of quartz, sericite, kaolinite, montmorillonite, carbonate minerals, and chlorite. A disseminated molybdenum-tungsten ore deposit lies at a depth of 900 m to more than 2,000 m in the intrusive complex (Abbott and others, 1983). South and east of Pine Grove, weakly porphyritic, flow-layered rhyolite containing biotite phenocrysts forms small dikes at the head of Willow Creek (fig. B4) and small flows east of the dikes. Small, commonly propylitically altered trachyandesite dikes and quartz-rich pebble dikes are present near rhyolite dikes. Biotite samples from two dikes have potassium-argon ages of about 22 m.y. (table B1, samples 22 and 23); a flow dome in the same area has a potassium-argon age on plagioclase of 21.3± 0.5 m.y. and on biotite of 23.0±0.5 m.y. (Lemmon and others, 1973). In the large pile of rhyolite lava flows east of Blawn Wash, phenocrysts range in abundance from approximately 20 percent to nil and in size from 1 cm to 1 mm. Gem quality red beryl is locally present, and one flow capping the pile has abundant vapor-phase topaz crystals several millimeters long. Sanidine from rhyolite in the lower part of the pile has a potassium-argon age of 22.1±0.8 m.y. (table B1, sample 21). Rhyolite dikes and some flows west, south, and southeast of The Tetons are characterized by abundant (25 percent) large phenocrysts of feldspar (up to 2 cm) and quartz; these bodies tend to be parallel to northeast-striking faults and are commonly altered.

Slightly porphyritic, gray to purple, flow-layered rhyolite of the Blawn Formation crops out near the Staats mine and at The Tetons (Lindsey and Osmonsen, 1978; Best, Morris and others, 1987). Exposures near the Staats mine are of a shallow intrusion, or intrusions, and associated pyroclastic deposits, whereas only lava flows are exposed at The Tetons. Phenocrysts in these rocks are small, generally 2 mm or less across, and consist of smoky quartz, sanidine, plagioclase, and sparse biotite. Lithophysal cavities and vugs contain quartz and, less commonly, topaz and fluorite; rare vapor-phase garnet occurs at The Tetons (E. H. Christiansen, oral commun., 1981). The rhyolite near the Staats mine has anomalously high concentrations of lithium, beryllium, niobium, molybdenum, and tin. Sanidines from these bodies give potassium-argon ages of about 20 and 18 m.y. (table B1, samples 24 and 14).

In the Indian Peak Range, strongly porphyritic flows and feeder dikes containing phenocrysts of sanidine (up to 6 cm across), quartz, plagioclase, biotite, and hornblende occur southeast of Indian Peak. The sanidine phenocrysts have an age of 21 m.y. (table B1, sample 13). South of Indian Peak the rhyolite occurs as flow domes in downdropped fault blocks that flank the central horst of the range. Feeder-dike swarms within the horst follow two different northeast trends (fig. B4); the northern lava flows and dike swarm trend east-northeast and have potassium-argon and zircon fission-track ages of 19 to 22 m.y. (table B1, samples 16–19). The southern flows and dike swarm trend northeast; a single fission-track age on zircon from one of the dikes is 21.5 m.y. (sample 20). Propylitized mafic rock containing xenocrysts of quartz and feldspar occurs locally along the margins of dikes in the northern swarm.

Only one of several small, flow-layered rhyolite flow domes and shallow intrusions of the Blawn Formation in the Shauntie Hills (fig. B4) has been dated (table B1, sample 15). Granitic intrusions farther to the east near Milford have discordant potassium-argon ages (Lemmon and others, 1973). Additional analytical work is currently under way by T. A. Steven, H. H. Mehnert, and C. W. Naeser to clarify chronologic relations in what appear to be older (Oligocene?) intrusions heated by Miocene magmatic activity. However, the Moscow granite pluton west-southwest of Milford is clearly of Blawn age (table B1, sample 30).

Shallow porphyritic intrusions in the Stateline area have been described by Keith (1980). One that cuts early Miocene rhyolite flows and tuffs and trachyandesite flows has an age of 21.0±1.3 m.y. (table B1, sample 27). Some intrusions are characterized by conspicuous layers of contrasting composition that may reflect mixing of compositionally contrasting magmas. Rhyolite to rhyodacite intrusions occur in and around Cottonwood Canyon. Phenocrysts range from 5 to 45 percent in abundance and include quartz, sanidine, plagioclase, biotite, and minor iron-titanium oxides, zircon, allanite, and sphene. Intrusions that have more abundant phenocrysts of plagioclase and biotite have less silica and weaker flow foliation—the same correspondences seen in silicic bodies in the Wah Wah Mountains.

MID-MIOCENE STEAMBOAT MOUNTAIN FORMATION

The Steamboat Mountain Formation is a bimodal assemblage of igneous rocks similar in some respects to those constituting the Blawn Formation. However, it is distinctly younger (13–12 m.y.); the topaz rhyolite lava flows that constitute its chief rock type lie farther south in the Indian Peak Range, Wah Wah Mountains, and Shauntie Hills (fig. B4); and the mafic and silicic compositions of its rocks are both more pronounced, so the assemblage is more truly bimodal.

The name Steamboat Mountain Formation was first used by Thomson and Perry (1975) for mid-Miocene rhyolite in their report on the Stateline mining district (fig. B4), and it is so used in this report. The type section designated in this report lies 4 km east of Steamboat Mountain, just north of Typhoid Spring in the Bible Spring quadrangle (Best, Grant, and others, 1987), where rhyolitic tuffs are overlain by topaz rhyolite lava flows. At Steamboat Mountain the aggregate thickness of these flows is about 500 m.

Compared to the fairly widespread potassium-rich mafic flows in the Blawn Formation, mafic flows of the Steamboat Mountain Formation are more restricted in extent; they occur chiefly on the eastern side of the southern Wah Wah Mountains and as scattered small remnants in the Shauntie Hills.

RHYOLITIC TUFFS AND FLOWS

Silicic volcanism of Steamboat Mountain age began with the explosive eruption of gas-charged magma that spread pyroclastic debris around many vents in the Steamboat Mountain and Broken Ridge areas. Most of these deposits are of weakly consolidated ash-flow tuffs, but local air-fall, base-surge, and water-reworked tuffs are also evident. Nearby sources for these volcaniclastic deposits are suggested by the local occurrence of abundant large (a meter or so in diameter) lithic fragments, most commonly of the Lund Formation and of flow-layered felsitic or vitrophyric rhyolites. Abundant, large, cognate fragments of rhyolite appear to have formed by the crumbling of extrusive flow and dome margins or by explosive disintegration at the vent. Petrographically, Steamboat Mountain tuffs are generally indistinguishable from Blawn tuffs.

Most rhyolite lava flows of the Steamboat Mountain Formation range from light gray and moderately porphyritic (phenocrysts compose 25 percent of rock) to purple-gray, strongly flow-layered, and nearly aphyric with felsitic, aphanitic groundmasses. Exposed margins of lava flows and rare feeder dikes around the flanks of Broken Ridge are red, black, and green perlitic vitrophyres. Phenocryst-poor flow-layered extrusions are commonly spherulitic; lithophysae and vugs are lined with quartz and less abundant topaz. Phenocrysts, generally less than 3 mm in diameter, are chiefly smoky quartz and sanidine; biotite and plagioclase are rare, and minute amphiboles were found in only one sample—a vitrophyre. Many Steamboat Mountain rhyolite lava flows are petrographically indistinguishable from Blawn lava flows at the Staats mine, The Tetons, and in the thick pile east of Blawn Wash,

Within the limits of analytical error, all dated Steamboat Mountain rhyolites (table B1, samples 1-7) are 12.4 m.y. old.

Slightly younger rhyolites (11.6 and 10.3 m.y.) described by Rowley and others (1978) occur in the southern Shauntie Hills (fig. B4) and on the southeast side of Escalante Valley.

MAFIC FLOWS

A mesa-capping sequence of mafic flows of the Steamboat Mountain Formation with ages of 13 to 12 m.y. (table B1, samples 8–10) overlies rhyolitic lava flows and tuffs of the Blawn Formation on the east flank of the southern Wah Wah Mountains in the southwestern quarter of the Frisco 15-minute quadrangle (Abbott and others, 1983). The northern, younger flows are of aphyric trachyandesite, whereas the southern, older flows are of somewhat potassic mugearite (table B2; see Le Maitre, 1976). Clotted phenocrysts of plagioclase, augite, and olivine are characteristic of the mugearite flows. Petrographically similar flow rocks occur as boulders in erosional remnants of alluvial fans on the east side of Steamboat Mountain, indicating that similar flows once existed in the southern Indian Peak Range. Basaltic rocks with ages of 13 to 11 m.y. crop out elsewhere in southwestern Utah and the adjacent part of Nevada (Best and others, 1980).

PETROCHEMISTRY OF RHYOLITES

The silicic lava flows of the Blawn and Steamboat Mountain Formations range in composition from near average rhyolite (Le Maitre, 1976) to high-silica rhyolite that contains topaz and generally lacks mafic minerals (table B3). Flows of the 23- to 18-m.y.-old Blawn Formation span the entire composition range, whereas all dated samples of 13- to 12-m.y.-old Steamboat Mountain rhyolite that have been analyzed have high silica content. Though not determined in our samples, Christiansen (1980) shows that fluorine occurs in concentrations of 0.25 to 0.50 weight percent in the high-silica topaz rhyolites of both early and middle Miocene age from Broken Ridge and the Staats pluton.

The high-silica rhyolites that have more than 75 weight percent SiO_2 have, as expected, significantly lower TiO_2, MgO, CaO, Sr, and Ba than the less silicic rhyolites in the Blawn Formation that contain more abundant phenocrysts of mafic minerals and plagioclase. In the almost wholly felsic high-silica rhyolites, titanium, manganese, and magnesium are present only in trace amounts, whereas rubidium and niobium are especially abundant.

TECTONISM

The tectonic pattern of the central part of the Pioche-Marysvale belt is a composite of north-south- and northeast-southwest-trending features. The fault-bounded Wah Wah Mountains and Needle Range,

TABLE B3.—*Chemical composition of Miocene rhyolite from the southern Wah Wah Mountains and the Indian Peak Range, southwestern Utah*

[Analyses by X-ray fluorescence spectrometry using the Norrish and Hutton (1969) method for major and minor elements (except Na_2O) and using pressed pellets of pure rock powder for Na_2O and trace elements. Standards were GH, MIN-G, and G2. See appendix for descriptions of samples and localities]

Constituent	Steamboat Mountain Formation									Blawn Formation							Uncertain[2]
	1	2	3	4	5	6	7	[1] 32	[1] 33	14	[1] 34	13	21	35	36	37	38
	Major oxides (data in percent)																
SiO_2	76.2	76.0	75.4	75.2	75.7	75.3	76.4	76.8	77.3	75.8	75.8	74.5	76.1	73.9	69.3	71.3	74.5
TiO_2	.07	.09	.06	.08	.10	.09	.08	.11	.10	.06	.06	.28	.05	.20	.39	.22	.03
Al_2O_3	12.33	12.2	12.4	12.4	12.5	12.5	12.2	12.3	12.2	12.4	12.8	12.8	12.5	13.0	14.2	13.6	13.1
Fe_2O_3 [3]	1.2	1.2	1.2	1.1	1.1	1.1	1.2	1.16	1.19	1.1	1.3	1.78	1.17	1.36	1.99	1.39	1.06
MnO	.08	.09	.07	.03	.06	.07	.05	.09	.08	.11	.05	.05	.14	.05	.07	.07	.12
MgO	.03	.04	.03	.04	.06	.18	.03	.10	.06	.05	.11	.21	.05	.34	.55	.27	.10
CaO	.24	.05	.52	.54	.50	.64	.48	.91	.45	.62	.67	.69	.62	1.21	1.66	1.23	.62
Na_2O	4.0	4.0	3.8	3.7	3.85	4.0	3.2	4.21	3.63	3.7	4.06	3.7	4.2	4.1	2.5	3.0	4.7
K_2O	4.92	5.0	4.93	4.94	4.88	4.85	4.88	3.25	4.57	4.72	4.60	5.41	4.64	5.05	5.18	5.11	4.81
Total	99.07	98.67	98.41	98.03	98.65	98.73	98.42	98.83	99.58	98.56	99.43	99.42	99.47	99.21	95.84	96.19	99.03
	Trace elements (parts per million)																
Rb	555	415	515	275	375	515	270	595	---	690	572	200	645	530	235	240	840
Sr	15	10	10	10	15	10	20	17	---	20	18	65	5	75	280	235	20
Zr	225	205	185	180	200	165	200	530	---	215	---	310	155	214	180	165	150
Nb	125	90	110	60	85	85	85	---	---	170	---	40	115	---	30	30	155
Ba	20	20	15	15	30	20	15	---	---	25	---	395	25	340	955	895	50

[1]Analyses from Christiansen (1980). Sample 32 (his WW-9) also contains 0.47 weight percent F and the following, in ppm: U, 20; Hf, 7; Ta, 6; Th, 54; Cs, 87; La, 42; Ce, 94. Sample 33 (Christiansen's STC-4) also contains 0.53 weight percent F and the following, in ppm: U, 14; Hf, 6; Ta, 10; Th, 50; Be, 5; Cs, 5; La, 20; Ce, 50.

[2]Stratigraphic identity uncertain; flow lies immediately below 12.9±0.5-m.y.-old mugearite flow (sample 9, table B1) and at top of pile of Blawn-age rhyolite flows.

[3]Total iron expressed as Fe_2O_3.

aligned more or less north-south, are truncated at their southern ends by the northeast-trending northern margin of the Escalante Valley basin (figs. B1 and B4). The southern termini of these ranges are linked by a prominent zone of northeast-striking high-angle faults that coincides with a belt of early and middle Miocene silicic magmatic activity. Our data show the northeast-trending faulting was chiefly early Miocene. Development of the more conspicuous, northerly trending basins and ranges typical of this part of the Basin and Range province apparently followed the early Miocene event.

The pattern of northeast-striking faults of early Miocene age is displayed on figure B4. The virtually unfaulted segment of the Wah Wah Mountains north of Pine Grove, where few Tertiary volcanic rocks are exposed, contrasts sharply with the segment to the south, where numerous subvertical, northeast-striking faults cut voluminous Oligocene and Miocene volcanic rocks. This swarm of faults continues southwestward into the southernmost Indian Peak Range.

These northeast-striking faults, as well as the one northwest-striking fault zone extending from Blue Mountain to Blawn Mountain in the Wah Wah Mountains, have vertical displacements as great as 1 km. The northeast-striking faults are slightly oblique to the overall trend of the Pioche-Marysvale belt (fig. B1 inset) because of a more northerly strike. A crude en echelon pattern is apparent. Although no unequivocal strike-slip displacement of map units has been found, several well-exposed subvertical fault surfaces along the Bible Spring fault zone, in the low hills linking the southern termini of the Indian Peak Range and the Wah Wah Mountains, have strongly developed subhorizontal slickensides. The emplacement of the northeast-striking rhyolite dikes around the Cima mine in the Wah Wah Mountains and the Cougar Spar mine in the Indian Peak Range more or less contemporaneously with faulting (see below) indicates at least a local northwest-southeast direction of extension.

The age of the northeast-striking faults is well constrained. Oligocene volcanic rocks and overlying early Miocene Blawn Formation are cut and tilted, whereas 13- to 12-m.y.-old rhyolites of the Steamboat Mountain Formation are generally not faulted and lie unconformably on top of the older extrusions. At The Tetons (fig. B5) the constraints are even tighter because unfaulted 18-m.y.-old Blawn rhyolite rests unconformably on tilted, eroded Oligocene units; older Blawn units and the 22.3-m.y.-old Bauers Tuff Member of the Condor Canyon Formation are tilted in fault slices 4 km to the southeast.

Additional evidence for early Miocene block faulting is provided by deposits of chaotic megabreccia and associated coarse-cemented alluvium along the northeast-striking Bible Spring fault zone (fig. B4) that contain abundant clasts of 22.3-m.y.-old Bauers Tuff Member. These deposits, whose total area of exposure is about 4 km^2, appear to represent landslide debris that sloughed off uplifted fault blocks. The deposits underlie virtually unfaulted, subhorizontal, 13- to 12-m.y.-old rhyolite lava flows of the Steamboat Mountain Formation.

Locally, as at the northeast end of the Bible Spring fault zone, altered Steamboat Mountain rhyolite flows are cut by faults that might be reactivated early Miocene fractures. Minor structures on slickenside surfaces in the zone, indicating left-lateral movement, are well preserved in intensely silicified rocks, which apparently were produced by mid-Miocene hydrothermal activity that preceded the horizontal movement. Northeast-striking, left-lateral faults occur in the Star Range just west of Milford (Lemmon and Morris, 1979b) and in Lincoln County, Nevada (Ekren and others, 1977), south of Pioche (fig. B1).

ALTERATION AND MINERALIZATION

Hydrothermally altered and mineralized rocks are closely associated with silicic igneous rocks and with northeast-striking faults. Locally, Paleozoic carbonate rocks have been bleached and silicified, producing jasperoid. Rhyolitic tuffs are locally zeolitized or opalized. All volcanic units except the 13-m.y.-old mugearite flows are argillized or silicified at one place or another, either pervasively or selectively along fracture systems visible in single exposures. Considerable jasperoid occurs on Blawn Mountain (Lindsey and Osmonson, 1978; Whelan, 1965) and for a few kilometers east and northeast, where hills of alunitized tuffs stand in valleys underlain by less altered volcanic units. The more porous rocks in the upper part of the Lund Formation and the loosely consolidated tuffs and reworked deposits of the Blawn Formation are generally the most intensely altered, especially where they lie in graben wedges. Cinnabar and native sulfur occur in altered rhyolitic tuffs and fault-juxtaposed Paleozoic rocks at the Cima mine (fig. B4). Steeply dipping veins of quartz carbonate, some a meter or so wide, occur in many areas of argillically altered volcanic rocks, especially southeast of The Tetons (fig. B5).

Intracaldera tuff in the Wah Wah Springs Formation within the Indian Peak caldera in the Indian Peak

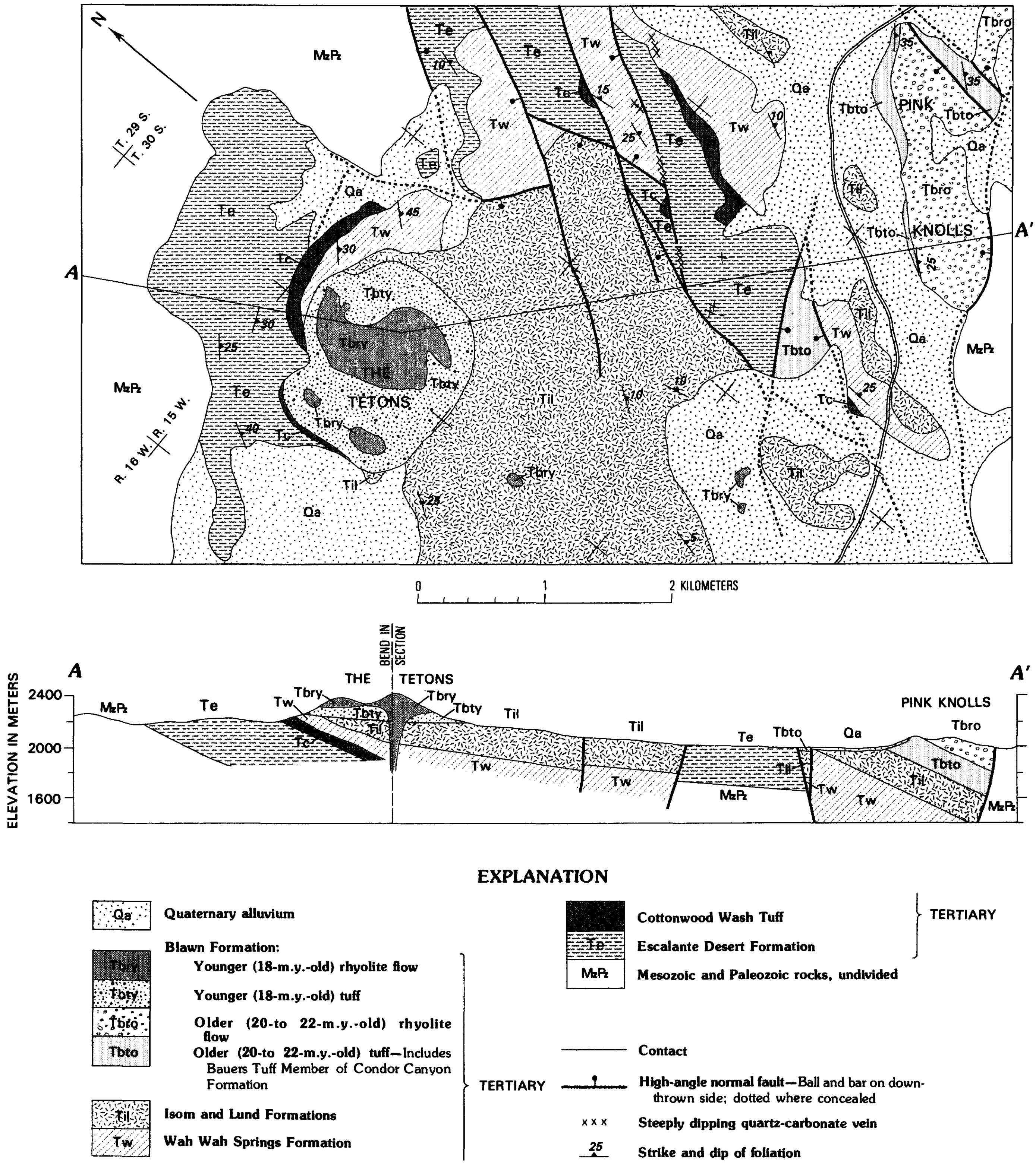

FIGURE B5.—Geologic map and cross section of the area around The Tetons, Beaver County Utah. Modified from Best, Morris, and others (1987).

Range was widely propylitized about 29.5 m.y. ago, shortly after the caldera subsided. These propylitized rocks were locally overprinted by Miocene alteration related to silicic magmatism.

Keith (1980) has reviewed the nature and distribution of mineralized rocks from the Wah Wah Mountains to the White Rock Mountains. Gold, silver, and lesser amounts of lead, copper, tellurium, mercury, molybdenum, and uranium occur in quartz-carbonate vein systems in the Stateline area; gangue minerals in these veins include adularia, fluorite, pyrite, and iron-manganese oxides. Fissure-replacement deposits of lead, zinc, copper, silver, and traces of gold have been mined from sedimentary rocks adjacent to Oligocene quartz monzonite intrusions related to the Indian Peak caldera in the Indian Peak Range and adjacent to late Miocene porphyritic granite intrusions in Pine Grove; disseminated molybdenum and tungsten have recently been discovered at depth in the Pine Grove plutonic rocks. Fluorite has been produced from the brecciated and argillized carbonate rocks at the margin of the topaz rhyolite intrusion at the Staats mine and from veins and breccia zones in igneous rocks at the Cougar Spar and other nearby mines. The only recorded production of uranium has come from the margin of the intrusion at the Staats mine, where Lindsey and Osmonson (1978) indicate a potential also exists for valuable concentrations of tin, molybdenum, and beryllium. Economic deposits of uranium, thorium, and molybdenum are possible in porous tuffs at the base of topaz rhyolite flows and in quartz-carbonate veins and their wall rocks in the Stateline district, where high concentrations of these elements (U, 1,300 ppm; Mo, 7,600 ppm) have been found.

Early Miocene potassium-argon ages have been obtained on alunite from the NG claims at the head of the Blawn Wash and from White Mountain in the Shauntie Hills (table B1, samples 11 and 12). Much of the alteration in the Indian Peak Range and Wah Wah Mountains took place during Blawn igneous activity because of the intimate association between altered rocks and extrusive and intrusive rhyolite centers of that age. A preliminary potassium-argon age on sericite from the porphyry of Pine Grove (J. T. Abbott, written commun., 1979) correlates with the Blawn igneous episode. The 13- to 12-m.y.-old rhyolite flows of the Steamboat Mountain Formation are generally unaltered and locally rest on altered older rocks, as east of Broken Ridge. Elsewhere, though, these younger flows are also altered, indicating that the younger silicic magmatism was also accompanied by hydrothermal activity.

DISCUSSION AND CONCLUSIONS

Early to middle Miocene magmatic, hydrothermal, and tectonic activity in the central part of the Pioche-Marysvale belt in southwest Utah was clearly confined to a northeast-trending belt about 30 km wide that extends from the Shauntie Hills southwestward at least 90 km into Nevada. All three types of activity were manifest in the early Miocene during emplacement of the Blawn Formation, whereas the middle Miocene magmatic-hydrothermal episode lacked conspicuous tectonism. The younger silicic activity that created the Steamboat Mountain Formation paralleled the northeast trend established some 5–10 m.y. earlier but was displaced a few kilometers to the south. Both magmatic pulses were bimodal.

TECTONISM

Zoback and others (1981) have proposed that a west-southwest to east-northeast direction of crustal extension prevailed uniformly throughout the Western United States 20–10 m.y. ago. This tensional direction conflicts with the orientation of the early Miocene (23–18 m.y. old) northeast-trending dikes and faults in the central part of the Pioche-Marysvale belt. Perhaps a slightly earlier period is represented in the belt, or perhaps there was a local spatial perturbation in the regional stress field. Such a local perturbation could be caused by the buttressing effect of a large Oligocene batholith of calc-alkalic affinity that must underlie the Indian Peak caldera complex (fig. B4). Alternatively, or in addition, a localized perturbation may have resulted because the central part of the Pioche-Marysvale belt is close to a northeast-trending Paleozoic-Mesozoic depositional hinge line, which roughly follows the western margin of the Colorado Plateaus (fig. B1, inset).

Anderson and Ekren (1977) and Zoback and others (1981) emphasize that since about 10 m.y. ago the direction of crustal extension in the Great Basin has been west-northwest to east-southeast. This deformation field has been chiefly responsible for the northerly trending basins and ranges of the eastern Great Basin. However, in the central part of the Pioche-Marysvale belt the early Miocene northeast trend appears to truncate the supposedly more recent northerly trending ranges.

It is obvious that "normal faults in the Basin and Range province form a complex geometry and history that cannot be accomodated by a single applied field of stress either in time or space" (Anderson and Ekren, 1977, p. 389).

MAGMATISM

Early and middle Miocene high-silica, high-alkali rhyolite flows and related intrusive porphyries in the central part of the Pioche-Marysvale belt are enriched in lithophile elements. Potentially economic deposits of molybdenum, tungsten, tin, beryllium, uranium, and niobium exist. (See, for example, Tucker and others, 1981).

Middle Miocene rhyolites of the Steamboat Mountain Formation have fairly uniform compositions, consisting almost wholly of felsic, topaz-bearing flows and minor tuffs. In contrast, the silicic rocks of the older Blawn Formation range in composition from highly evolved rhyolites identical to those in the Steamboat Mountain Formation (having very low strontium, barium, titanium, and magnesium) to less evolved rhyolites and, very locally in the Pine Grove intrusive rocks, dacitic rocks (Keith, 1982).

Christiansen (1981) shows that widespread topaz rhyolites in the Western United States are almost all of post-Oligocene age. They were emplaced in a bimodal association with mafic igneous rocks during crustal extension in areas underlain by a thick sialic crust that had been previously subjected to calc-alkalic magmatism. He argues that high-fluorine parental magmas were derived by partial melting of deep crustal rocks that had lost hydrous components during the earlier calc-alkalic activity. Subsequent differentiation of these fluorine-bearing magmas led to further enrichment of fluorine and other lithophile elements in apical parts of high-level magma chambers.

The aeromagnetic map (fig. B2) suggests that a large magmatic body (or bodies), now solidified and still deeply buried, once fed the many small silicic extrusions and shallow intrusions of Miocene age in the central part of the Pioche-Marysvale belt. It is impossible to decide what precluded an explosive, caldera-forming eruption of large volumes of this silicic magma (Hildreth, 1981), but it is tempting to speculate that the early Miocene extensional fracturing continuously permitted small amounts of magma to leak to the surface, thereby relieving pressure from a crustal magma chamber that otherwise might have erupted in large volume and collapsed (Bacon, 1982). However, there is little compelling evidence that major crustal extension continued during middle Miocene time, when extrusions of silicic lavas and pyroclastic material again formed at many centers not related to a caldera.

The difficulty in explaining, on the basis of available data, the southward shift to younger, more uniformly evolved silicic magma extrusions is a complementary problem to that of accounting for the space-time-composition pattern in Miocene mafic activity in southwestern Utah (Best and others, 1980). East- to northeast-trending belts of mafic extrusions dated at 24–20, 14–10, 9–5, and 2 m.y. that extend across the Great Basin and into the western part of the Colorado Plateaus shift southward about 120 km in the central to eastern part of the Pioche-Marysvale belt (Best and others, 1980). The early Miocene lava flows in the north are not strictly basalts but are relatively rich in potassium and have intermediate silica contents. In contrast, the younger, more southerly mafic extrusions span the range of compositions from tholeiitic to alkali olivine basalts and include mugearite and hawaiite as well as andesite. Generally, potassium concentrations are lower in younger mafic lavas. We have not determined whether any other mantle-incompatible elements are less common in the younger lavas.

We are just beginning to see some of the details of intriguing space-time-composition patterns in the episodic bimodal magmatism that accompanied a complicated period of tectonism along the border between the Colorado Plateaus and the Great Basin. The relationship of this Miocene tectonomagmatic activity and of the Pioche-Marysvale belt as a whole to other east-trending belts of magmatism and mineralization in the Western United States and to possible deep continental or upper mantle phenomena must be a subject for future speculation.

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APPENDIX.—*Descriptions of samples and sample localities in the Wah Wah Mountains and nearby areas, southwestern Utah*

[Sample numbers correspond to those used in tables B1, B2, and B3]

Sample No.	Field No.	Lithologic description	Locality description	Quadrangle
1	BBS-8-229-2	Felsic, porphyritic, topaz-bearing rhyolite flow.	Mountain Spring---------------	Bible Spring.
2	BBS-5-23-1--	----do-------------------------------------	S. side of Sawmill Canyon-----	Do.
3	BBS-5-25-5--	Perlitic, vitrophyric base of topaz-bearing rhyolite flow.	W. end of North Peaks---------	Do.
4	BBS-7-88-4--	Felsic, porphyritic rhyolite flow----------	NE. of White Cliff------------	Do.
5	BBS-7-93-1--	----do-------------------------------------	Ponderosa Park----------------	Do.
6	MSP-9-8-4---	Flow-layered, vuggy, topaz-bearing felsic rhyolite flow.	Four-Mile Wash----------------	Mountain Spring Peak.
7	STM-7-153-1	Perlitic, vitrophyric base of rhyolite flow	S. end of Wilson Canyon-------	Steamboat Mountain.
8	LAM-956-1---	Trachyandesite flow------------------------	Near Willow Creek, 4 km E. of Baudino Ranch.	Frisco.
9	LAM-9-103-3	Mugearite flow-----------------------------	E. side of Wah Wah Mts between Blawn Mtn and Miners Hill Reservoir.	Do.
10	WAH-65------	----do-------------------------------------	E. side of Wah Wah Mts, 4 km W. of Brimstone Reservoir.	Do.
11	M244--------	Alunitic alteration------------------------	NE. of Blawn Mtn in NG claims	Lamerdorf Peak.
12	80-S-31B----	----do-------------------------------------	E. end of White Mtn-----------	Frisco.
13	BUCK-8-179-2	Strongly porphyritic felsic dike containing amphibole phenocrysts.	E. side of Indian Peak Range, 6 km SE. of Indian Peak.	Buckhorn Spring.
14	TET-9-43-2--	Flow-layered felsic topaz-bearing rhyolite flow.	The Tetons--------------------	The Tetons.
15	82-S-16-----	Flow-layered rhyolite----------------------	SE. flank San Francisco Mts---	Milford.
16	M726--------	Altered rhyolite dike containing disseminated pyrite.	6 km S. of Indian Peak and 1 km NW. of Cougar Spar mine.	Pinto Spring.
17	PNT-8-137-1	Perlitic, vitrophyric rhyolite flow--------	2 km E. of Cougar Spar mine---	Do.
18	PNT-8-137-1	----do-------------------------------------	----do------------------------	Do.
19	PNT-8-137-1	----do-------------------------------------	----do------------------------	Do.
20	PNT-8-136-1	Argillized rhyolite dike-------------------	5 km S. of Cougar Spar mine---	Do.
21	LAM-1-38-2--	Felsic, porphyritic rhyolite flow----------	5 km W. of Miners Hill Reservoir, E. flank Wah Wah Mts.	Frisco.
22	LAM-9-74-9--	Flow-layered felsic rhyolite plug----------	3 km NE. of Blawn Mtn---------	Lamerdorf Peak.
23	WAH-PD------	Felsic rhyolite dike-----------------------	5 km SE. of Pine Grove--------	Do.
24	---([1])------	Intrusive plug feeder and extrusive rhyolite flow.	Staats mine-------------------	The Tetons.
25	---([2])------	Rhyolite flow------------------------------	Along Willow Cr, E. flank of Wah Wah Mts.	Frisco.
26	---([2])------	----do-------------------------------------	----do------------------------	Do.
27	---([3])------	Rhyolite intrusion-------------------------	Serviceberry Canyon-----------	Deer Lodge Canyon.
28	WAH-66------	Basal trachyandesite flow------------------	E. side of Wah Wah Mts--------	Frisco.
29	BAN-8-165-2	Lava flow----------------------------------	NE. side Escalante Desert-----	Bannion Spring.
30	83-3-1------	Slightly altered granite of Moscow Canyon--	In Moscow Canyon--------------	Milford.
31	LAM-9-104-5	Trachyandesite flow------------------------	In Willow Cr, 2 km SE. of Baudino Ranch.	Frisco.
32	WW-9--------	Green perlitic vitrophyre flow-------------	SE. end of Broken Ridge, SW¼ sec. 2, T. 32 S., R. 16 W.	Mountain Spring Peak.
33	WW-10-------	Felsic rock from same outcrop as 35--------	----do------------------------	Do.
34	STC-4-------	Felsic porphyritic rhyolite----------------	Near Staats mine--------------	The Tetons.
35	TET-9-77-1--	Strongly porpyhritic, felsic flow with phenocrystys of feldspar and smoky quartz as much as 1 cm across.	W. side of Blawn Wash, SW¼ sec. 14, T. 30 S., R. 15 W.	Do.
36	LAM-9-104-4	Biotite-bearing perlitic vitrophyre flow---	Near Willow Cr, E. side of Wah Wah Mts, SE¼ sec. 1, T. 29 S., R. 15 W.	Frisco.
37	LAM-2-------	----do-------------------------------------	Near Willow Cr on E. side of Wah Wah Mts, NE¼ sec. 31, T. 28 S., R. 14 W.	Do.
38	LAM-9-103-2	Felsic porphyritic, topaz-rich flow at top of pile of rhyolite just below 12.9-m.y.-old mugearite (sample 9).	E. flank of Wah Wah Mts-------	Do.

[1]From Rowley and others (1978).
[2]From Lemmon and others (1973).
[3]From Keith (1980).

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