Tertiary Volcanic Rocks and Uranium in the Thomas Range and Northern Drum Mountains, Juab County, Utah

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By DAVID A. LINDSEY

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The geologic setting and controls of uranium mineralization in a volcanic environment

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TERTIARY VOLCANIC ROCKS AND URANIUM IN THE THOMAS RANGE AND NORTHERN DRUM MOUNTAINS, JUAB COUNTY, UTAH

By DAVID A. LINDSEY

ABSTRACT

The Thomas Range and northern Drum Mountains have a history of volcanism, faulting, and mineralization that began about 42 m.y. (million years) ago. Volcanic activity and mineralization in the area can be divided into three stages according to the time-related occurrence of rock types, trace-element associations, and chemical composition of mineral deposits. Compositions of volcanic rocks changed abruptly from rhyodacite-quartz latite (42–39 m.y. ago) to rhyolite (38–32 m.y. ago) to alkali rhyolite (21 and 6–7 m.y. ago); these stages correspond to periods of chalcophile and siderophile metal mineralization, no mineralization(?), and lithophile metal mineralization, respectively. Angular unconformities record episodes of cauldron collapse and block faulting between the stages of volcanic activity and mineralization. The youngest angular unconformity formed between 21 and 7 m.y. ago during basin-and-range faulting.

Early rhyodacite-quartz latite volcanism from composite volcanoes and fissures produced flows, breccias, and ash-flow tuff of the Drum Mountains Rhyodacite and Mt. Laird Tuff. Eruption of the Mt. Laird Tuff about 39 m.y. ago from an area north of Joy townsite was accompanied by collapse of the Thomas caldera. Part of the roof of the magma chamber did not collapse, or the magma was resurgent, as is indicated by porphyry dikes and plugs in the Drum Mountains. Chalcophile and siderophile metal mineralization, resulting in deposits of copper, gold, and manganese, accompanied early volcanism.

The middle stage of volcanic activity was characterized by explosive eruption of rhyolitic ash-flow tuffs and collapse of the Dugway Valley cauldron. Eruption of the Joy Tuff 38 m.y. ago was accompanied by subsidence of this cauldron and was followed by collapse and sliding of Paleozoic rocks from the west wall of the cauldron. Landslides in The Dell were covered by the Dell Tuff, erupted 32 m.y. ago from an unknown source to the east. An ash flow of the Needles Range(?) Formation was erupted 30–31 m.y. ago from an unknown source. Mineralization probably did not occur during the rhyolitic stage of volcanism.

The last stage of volcanism was contemporaneous with basin-and-range faulting and was characterized by explosive eruption of ash and pumice, forming stratified tuff, and by quiet eruption of alkali rhyolite as viscous flows and domes. The first episode of alkali rhyolite volcanism deposited the beryllium tuff and porphyritic rhyolite members of the Spor Mountain Formation 21 m.y. ago. After a period of block faulting, the stratified tuff and alkali rhyolite of the Topaz Mountain Rhyolite were erupted 6–7 m.y. ago along faults and fault intersections. Erosion of Spor Mountain, as well as explosive eruptions through dolomite, provided abundant dolomite detritus to the beryllium tuff member. The alkali rhyolite of both formations is fluorine rich, as is evident from abundant topaz, and contains anomalous amounts of lithophile metals. Alkali rhyolite volcanism was accompanied by lithophile metal mineralization which deposited fluorite, beryllium, and uranium.

The structure of the area is dominated by the Thomas caldera and the younger Dugway Valley cauldron, which is nested within the Thomas caldera; the Thomas caldera is surrounded by a rim of Paleozoic rocks at Spor Mountain and Paleozoic to Precambrian rocks in the Drum Mountains. The Joy fault and Dell fault system mark the ring-fracture zone of the Thomas caldera. These structural features began to form about 39 m.y. ago during eruption of the Mt. Laird Tuff and caldera subsidence. The Dugway Valley cauldron sank along a series of steplike normal faults southeast of Topaz Mountain in response to collapse of the magma chamber of the Joy Tuff. Caldera structure was modified by block faulting between 21 and 7 m.y. ago, the time of widespread extensional faulting in the Basin and Range Province. Vents erupted alkali rhyolite 6–7 m.y. ago along basin-and-range faults.

Uranium mineralization was associated with the stage of alkali rhyolite volcanism, extensional basin-and-range faulting, and lithophile metal mineralization; it occurred at least 11 m.y. after the end of the caldera cycle. Uranium, derived from alkali rhyolite magma, was concentrated in trace amounts by magmatic fluids and in potentially economic amounts by hydrothermal fluids and ground water. Hydrothermal fluids deposited uraniferous fluorite as pipes in carbonate rocks of Paleozoic age on Spor Mountain and uranium-bearing disseminated deposits of fluorite and beryllium in the beryllium tuff member of the Spor Mountain Formation. Uranium of hydrothermal origin is dispersed in fluorite and opal. Uranium in fluorite may be tetravalent(?) but that in opal is probably hexavalent; no primary minerals of tetravalent uranium are known to occur. Ground water has concentrated significant ores of hexavalent uranium minerals in the beryllium tuff member of the Spor Mountain Formation at the Yellow Chief mine and is probably also responsible for widespread low concentrations (0.0X percent) of uranium that occur separately from beryllium ore in the beryllium tuff member. More deposits of the Yellow Chief type may occur in down-faulted sections of beryllium tuff beneath the Thomas Range. The ground-water ores show no evidence of a reducing environment; instead, precipitation of hexavalent uranium minerals occurred by evaporation, by decline in concentration of complexing ions such as carbonate, or by some other mechanism. Reducing environments for hydrothermal deposits must be sought around rhyolite vents and in a hypothesized pluton of alkali rhyolite composition beneath Spor Mountain; for ground-water deposits, reducing environments may occur in basin fill such as that of the Dugway Valley cauldron.

INTRODUCTION

The Thomas Range (fig. 1) contains important deposits of fluorspar, beryllium, and uranium. These mineral deposits are associated with a sequence of volcanic rocks that extends into the northern Drum

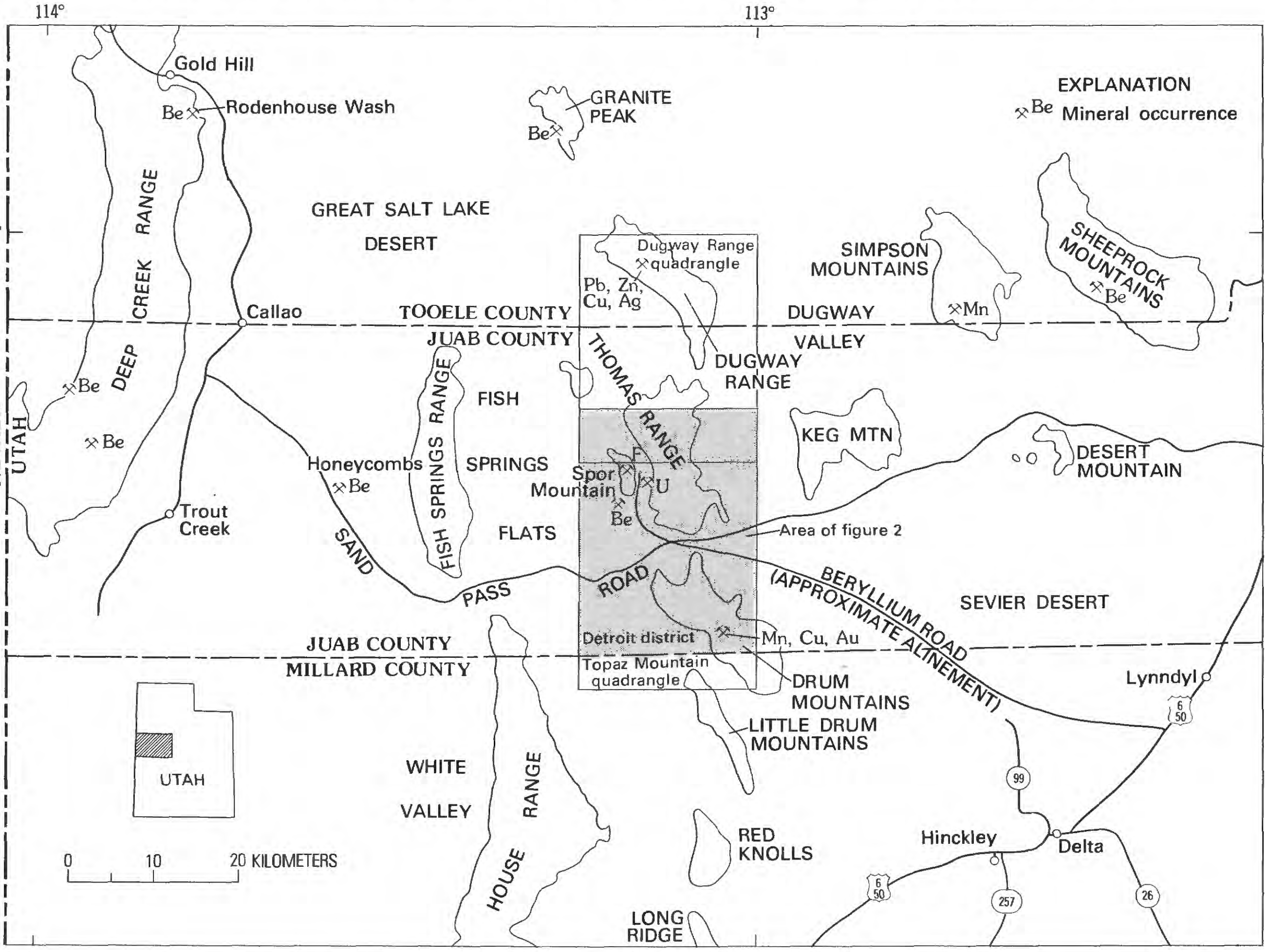

FIGURE 1.—Map showing location of the Thomas Range and Drum Mountains, other geographic features, and mineral occurrences shown by a pick and hammer and the following symbols: U, uranium; Be, beryllium; F, fluorite; Mn, manganese; Cu, copper; Pb, lead; Zn, zinc; Au, gold; and Ag, silver.

Mountains and contains intermediate-composition flow rocks and tuffs, rhyolitic ash-flow tuffs, and large volumes of alkali rhyolite. The area is part of an east-west belt of mineral deposits, volcanic and intrusive rocks, and aeromagnetic high anomalies called the Deep Creek–Tintic mineral belt (Shawe and Stewart, 1976; Stewart and others, 1977), which also contains the beryllium belt of western Utah (Cohenour, 1963). A similar sequence of volcanic rocks, but with no known mineral deposits, crops out in the Keg Mountains, east of the Thomas Range.

The volcanic rocks of the Thomas Range were first mapped and divided into two groups by Staatz and Carr (1964). Shawe (1972) reclassified the volcanic rocks of the Thomas Range into three assemblages, (1) flows and agglomerates, (2) ash-flow tuffs, and (3) rhyolite flows and tuff, all of which he was able to map throughout the area of the Drum Mountains, Keg Mountain, and Desert Mountain. Geochronologic studies (Lindsey and others, 1975) confirmed much of Shawe's (1972) three-fold classification of the volcanic rocks of the region. Shawe also concluded that eruption of voluminous ash-flow tuffs of his middle assemblage was followed by caldera collapse in the Thomas Range and at Keg Mountain and Desert Mountain. The Joy fault was interpreted as part of the ring fracture of the Thomas caldera, and such ring fractures were believed to have provided conduits that localized the deposits of ore-forming fluids. The northern Drum Mountains also were mapped by Newell (1971), who confirmed the general outline of the caldera model there. Recent mapping in southwestern Keg Mountain by Staub (1975) did not confirm the Thomas caldera ring fracture that was projected there by Shawe (1972).

The mineral deposits of the Thomas Range were studied by Staatz and Osterwald (1959) and Staatz and Carr (1964), who described the fluorspar pipes and uranium occurrences there. Beryllium deposits in tuff were discovered at Spor Mountain in 1959, and studies of these deposits related them to fluorspar mineralization and rhyolite volcanism in the Thomas Range (Staatz and Griffitts, 1961; Shawe, 1968; Park, 1968; Lindsey, 1977). The manganese deposits of the Detroit district in the Drum Mountains have been studied by Crittenden and others (1961), and the area's potential for gold, copper, and other mineral deposits has been examined by mapping and geochemical surveys (Newell, 1971) and geochemical studies of jasperoid found there (McCarthy and others, 1969).

This report describes the geology of Tertiary rocks and uranium occurrences of the Thomas Range and northern Drum Mountains in detail, and proposes a model relating volcanism, tectonism, and mineralization for the area. The present study was conducted in response to the current (1978) high interest in uranium exploration in the Thomas Range and vicinity. Reconnaissance studies of the uranium potential of the area have been made (Leedom and Mitchell, 1978; Texas Instruments Incorporated, 1977), and the uranium potential of the area has been evaluated by drilling (Morrison, 1980), but recent geologic investigations (Lindsey, 1978a) indicated that the history of volcanism and tectonism in the Thomas Range and Drum Mountains was still not sufficiently understood to relate it to uranium mineralization and to provide reliable guides for uranium exploration. A new stratigraphic framework, resembling that of Shawe (1972) in general outline but differing in many details, was developed from field mapping, geochronologic, petrographic, and trace-element studies, and a new geologic map of the area was prepared (Lindsey, 1979a). The results of the new mapping are summarized in figure 2 for reference here, but the reader should consult Lindsey (1979a) for details. The present report supersedes an earlier open-file report (Lindsey, 1979b).

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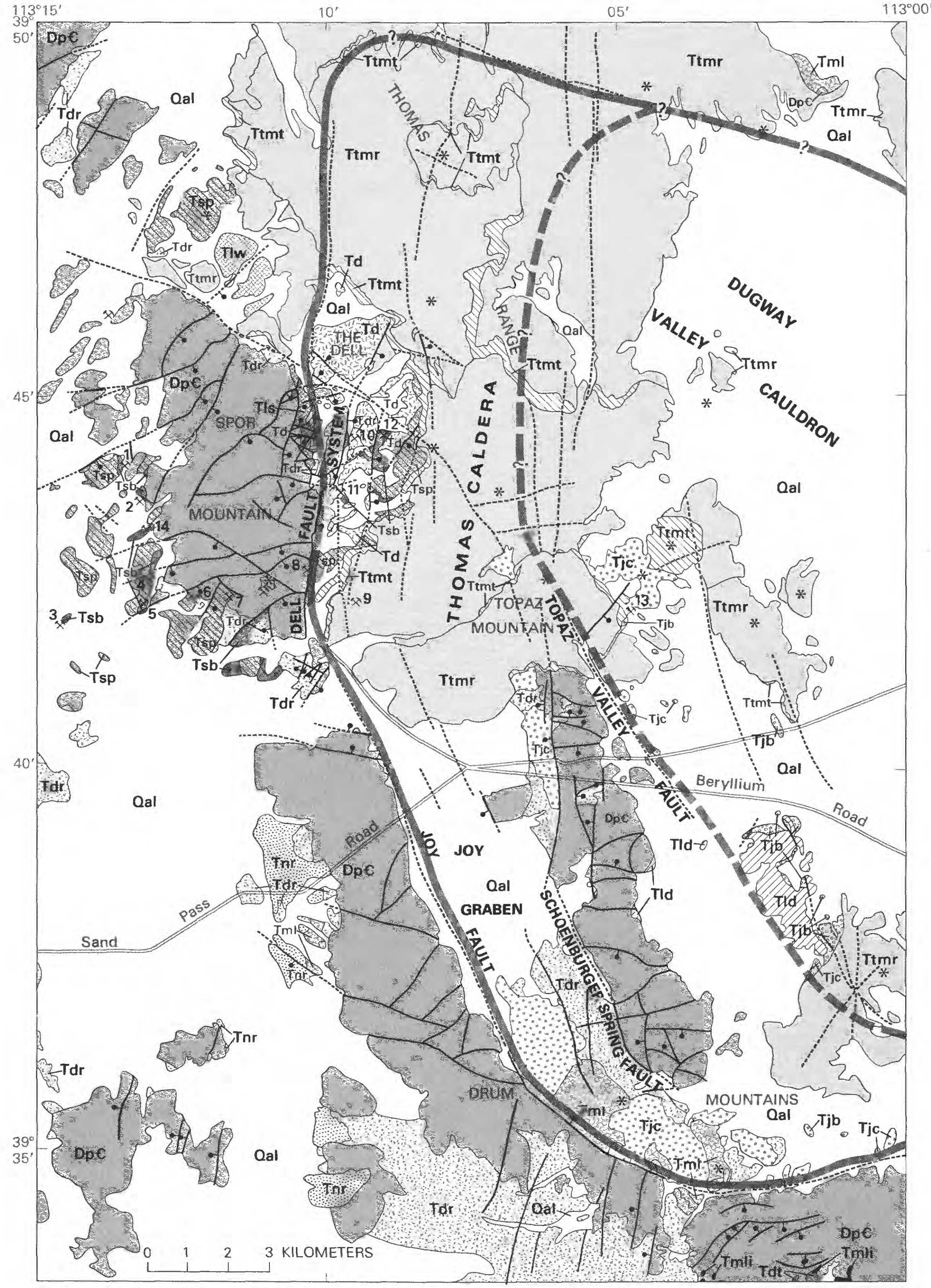
STRATIGRAPHY

STRATIGRAPHIC SECTION

The Tertiary rocks of the Thomas Range and northern Drum Mountains are divided into nine formations (table 1). As revised here, the stratigraphy corresponds generally to the former subdivision of stratigraphic units into oldest (flows and agglomerates), middle (ash-flow tuffs), and youngest (rhyolite flows and tuffs) assemblages or groups (Shawe, 1972; Lindsey and others, 1975). Each of these groups is characterized by a particular style of volcanism and is separated by an angular unconformity. Minor unconformities occur between some formations, also.

All of the volcanic rocks with the possible exception of the Needles Range(?) Formation have local sources. Flows of the Drum Mountains Rhyodacite were probably extruded from local fissures and from central volcanoes in the Black Rock Hills and Little Drum Mountains (Leedom, 1974) about 42 m.y. ago. Quiet eruption of rhyodacite gave way to explosive eruption of ash-flow tuff from vents north of Joy townsite in the Drum Mountains and east of Topaz Mountain in the Thomas Range. The first explosive eruptions, from the Drum Mountains vent, deposited tuff of intermediate composition (Mt. Laird Tuff), whereas all later eruptions, from 38 m.y. to 32 m.y. ago, deposited rhyolitic tuff. One or more of these eruptions deposited the crystal tuff member of the Joy Tuff over an area that extends from Fish Springs Flat to Desert Mountain, a distance of 60 km (kilometers). Collapse of cauldron walls 39–32 m.y. ago left landslide deposits of megabreccia and breccia interbedded with lava flows and ash-flow tuffs. Near the end of explosive rhyolite volcanism, about 30–31 m.y. ago, an ash-flow tuff of the Needles Range(?) Formation was deposited in part of the area. All later volcanism consisted of explosive eruption of ash and quiet extrusion of alkali rhyolite lava as flows and domes 21 m.y. ago (Spor Mountain Formation) and 6–7 m.y. ago (Topaz Mountain Rhyolite).


113°15′
39° 50′
10′
05′
113°00′
45′
40′
39° 35′
DUGWAY VALLEY CAULDRON
THOMAS CALDERA
THOMAS RANGE
THE DELL
SPOR MOUNTAIN
DELL FAULT SYSTEM
TOPAZ MOUNTAIN
TOPAZ VALLEY FAULT
JOY GRABEN
JOY FAULT
SCHOENBURGER SPRING FAULT
DRUM MOUNTAINS
Beryllium Road
Sand Pass Road
Qal
Ttmr
Ttmt
Tml
DpC
Tdr
Tsp
Tlw
Td
Tls
Tsb
Tjc
Tjb
Tld
Tnr
Tmli
Tdt
0 1 2 3 KILOMETERS

Qal — Alluvium and colluvium (Quaternary)

Topaz Mountain Rhyolite (Upper Miocene)

Ttmr — Flows and domes of alkali rhyolite

Ttmt — Stratified tuff

Angular unconformity D

Spor Mountain Formation (Lower Miocene)

Tsp — Porphyritic rhyolite member

Tsb — Beryllium tuff member

Angular unconformity C

Tnr — Needles Range(?) Formation (Oligocene)

Td — Dell Tuff (Oligocene)

Tld — Landslide breccia (Oligocene?)—Megabreccia in northern Drum Mountains, Age relations with other landslide breccias unknown

Tls — Landslide breccia (Oligocene?)—Breccia at Spor Mountain

Tlw — Landslide breccia (Oligocene?)—Breccia at Wildhorse Spring

Joy Tuff

Tjb — Black glass tuff member (lower Oligocene)

Tjc — Crystal tuff member (lower Oligocene and upper Eocene)

Angular unconformity B

Tml — Mt. Laird Tuff (upper Eocene)—Ash-flow tuff and breccia

Tmli — Mt. Laird Tuff equivalent (upper Eocene)—Intrusive dike and plugs

Tdt — Diorite (upper Eocene?)—Intrusive plugs

Tdr — Drum Mountains Rhyodacite (upper Eocene)—Flows and breccias

Angular unconformity A

DpC — Undifferentiated rocks (Devonian to Precambrian)—Limestone, dolomite, quartzite, and shale

Contact—Dashed where approximately located

Fault, dotted where concealed, ball and bar on downthrown side; concealed faults located from aerial photographs (Lindsey, 1979a)

* Probable vent area

Structural margin of Thomas caldera—Queried where location uncertain

Structural margin of Dugway Valley cauldron—Queried where location uncertain

Mines and prospects in Tertiary rocks

1 North End (Be)
2 Taurus (Be)
3 Monitor (Be)
4 Roadside mine (Be)
5 Fluro mine (Be)
6 Rainbow (Be)
7 Blue Chalk mine (Be)
8 Oversight (Be, U)
9 Buena no. 1 (U)
10 Claybank (Be, U)
11 Hogsback (Be)
12 Yellow Chief mine (U)
13 Autunite no. 8 (U)
14 Sigma Emma (Be)

FIGURE 2.—Geologic map of Tertiary rocks in the Thomas Range and northern Drum Mountains (modified from Lindsey, 1979a).

Four angular unconformities record periods of cauldron collapse, faulting, and erosion in the Tertiary section; these unconformities have regional extent throughout the volcanic field of the Thomas Range, Drum Mountains, and Keg Mountain. Unconformity A, at the base of the section, records some prevolcanic period or periods of uplift and erosion of uncertain age. Unconformity B lies beneath the 38 m.y.-old crystal tuff member of the Joy Tuff, and records subsidence of the Thomas caldera that accompanied eruption of the Mt. Laird Tuff about 39 m.y. ago. Erosional detritus is lacking above the unconformity, indicating that it is mainly constructional. Cauldron collapse resulting from eruption of the Joy Tuff 38 m.y. ago was followed by deposition of the Dell Tuff 32 m.y. ago and the Needles Range(?) Formation about 30-31 m.y. ago. Unconformity C represents a 9-m.y. period of quiescence after ash-flow eruption; it is partly constructional and partly erosional, as indicated by erosional detritus in the Spor Mountain Formation of 21 m.y. ago. Unconformity D, between the Spor Mountain Formation and the Topaz Mountain Rhyolite, formed during basin-and-range faulting between 21 and 6-7 m.y. ago.

TABLE 1.—*Revised stratigraphy of Tertiary rocks in the Thomas Range and northern Drum Mountains*

[Leaders (—), information not available or not relevant; <, less than; ~, about]

Description of rocks[1]	Age (m.y.)[2]	Map symbol (fig. 2)
Alluvium and colluvium (Quaternary): Alluvial pediments and stream deposits of poorly sorted gravel, sand, and clay; colluvium covering slopes; playa sediments; beach sand and gravel deposits and lake-bottom clays deposited by Lake Bonneville at elevations below about 1,580 m elevation.	<1	Qal
Unconformity		
Topaz Mountain Rhyolite (Upper Miocene): Flows and extrusive domes of gray to red, topaz-bearing alkali rhyolite, black vitrophyre, and interbedded units of tan stratified tuff. Tuff units (Ttmt) seldom exceed 30 m in thickness, are local in extent, and have unconformable bases. Rhyolite contains sparse cryatals of quartz, aanidine, biotite, and plagioclase except locally at Antelope Ridge and lower part of Pismire Wash, where phenocrysts are abundant. Maximum thickness of rhyolite about 700 m.	6.3-6.8	$Ttm_{1,2,3}$
Angular unconformity D		
Spor Mountain Formation, porphyritic rhyolite member (Lower Miocene): Flows, domes, and plugs of gray to red porphyritic alkali rhyolite; rhyolite contains abundant phenocrysts of dark quartz, sanidine, plagioclase, and biotite and abundant microscopic topaz in groundmasa. Maximum thickness about 500 m.	21.3	Tsp
Spor Mountain Formation, beryllium tuff member (Lower Miocene): Stratified tan vitric tuff and tuffaceous breccia with abundant clasts of carbonate rocks. Tuff includes thin beds of ash-flow tuff, bentonite, and epiclastic tuffaceous sandatone and conglomerate in The Dell. Hydrothermal alteration of tuff to clay, fluorspar, and potassium feldspar widespread. Maximum thickness about 60 m.	(21.3)	Tsb
Angular unconformity C		
Needles Range(?) Formation (Oligocene): Simple cooling unit of pink to gray to red-brown ash-flow tuff with abundant small crystals of plagioclase, hornblende, and biotite. Partially welded. Tuff fills paleovalleys on northwest side of Drum Mountains. Maximum thickness about 30 m.	31.4[3]	Tnr
Dell Tuff (Oligocene): Gray to pink rhyolitic ash-flow tuff that contains abundant crystals of euhedral quartz, sanidine, biotite, and plagioclase in poorly welded to unwelded matrix of devitrified shards and pumice. Tuff resembles older Joy Tuff but may be distinguished from Joy by presence of abundant large quartz bipyramids and loose, ashlike weathering aspect. Maximum thickness about 180 m at north end of The Dell.	32.0	Td
Landslide breccia, megabreccia of the northern Drum Mountains (Oligocene?): Megabreccia of Cambrian limestone and dolomite overlying Joy Tuff in northern Drum Mountains. Megabreccia retains original stratigraphy of Cambrian strata but contains intensely brecciated and rotated clasts of Cambrian rocks locally. Maximum thickness about 60 m.	(<37)	Tld
Landslide breccia, breccia at Spor Mountain (Oligocene?): Breccia of Ordovician and Silurian dolomite, limestone, and quartzite. Breccia retains original stratigraphy of Paleozoic rocks near breakaway zone at crest of Spor Mountain but passes east into breccia with clasts of various strata mixed together and faintly stratified. Maximum thickness estimated very approximately at 80 m.	(32-42)	Tls
Landslide breccia, breccia at Wildhorse Spring (Oligocene?): Breccia of mixed angular to subround clasts of Paleozoic rocks and Drum Mountains Rhyodacite in a matrix of rhyodacite fragments. Breccia underlies and passes laterally into breccia at Spor Mountain and is stratified at top. Maximum thickness estimated very approximately at about 20 m.	(32-42)	Tlw
Unconformity		
Joy Tuff, black glass tuff member (Lower Oligocene): Simple cooling unit of rhyolitic ash-flow tuff with sparse crystals of sanidine, quartz, plagioclase, and biotite, and lithic fragments of limestone and volcanic rock. Most of tuff intensely welded, with abundant compacted black pumice in lower part. Upper unwelded part is tan and contains abundant light-colored pumice. Maximum thickness about 30 m.	~37	Tjb
Joy Tuff, crystal tuff member (Lower Oligocene and Upper Eocene): Gray-pink to red-brown rhyolitic ash-flow tuff with abundant euhedral and broken crystals of quartz, sanidine, plagioclase, and biotite in moderately welded matrix of devitrified shards. Lower 10 m of tuff contains abundant compacted black pumice; light-colored pumice present higher in section. Tuff contains abundant accessory sphene and rare cognate inclusions of lathlike plagioclase, biotite, and sphene that aid in distinguishing it from Dell Tuff. Welding strong near probable vents east of Topaz Mountain, where foliation near vertical and breccia occurs. Maximum thickness about 180 m at the type locality.	38.0	Tjc
Angular unconformity B		
Mt. Laird Tuff (Upper Eocene): Pink quartz latitic ash-flow tuff with abundant euhedral crystals of white plagioclase (10 mm long), bronze biotite (5 mm across), and hornblende. Quartz phenocrysts with resorbed outlines occur in tuff northeast of Thomas Range. Pumiceous breccia and hydrothermally altered tuff occur near probable vent north of Joy townsite. Dikes and plugs of porphyry (Tmli) very similar to Mt. Laird Tuff crop out 3 km south of Joy townsite are included in unit. Maximum exposed thickness about 80 m, but 500 m of tuff interbedded with tuffaceous lacustrine sediments in subsurface of Dugway Valley.	~39[4]	Tml
Diorite (Upper Eocene): Plugs of dark-gray, massive, fine-grained diorite intrude Paleozoic strata 3 km southeast of Joy townsite. Diorite contains abundant calcic plagioclase and hornblende.	(39-42)	Tdi
Drum Mountains Rhyodacite (Upper Eocene): Rusty weathering black rhyodacite flows and breccias with phenocrysts of intermediate composition to calcic plagioclase and pyroxene in an aphanitic to glassy matrix. Modally, rock is hypersthene andesite, but chemical analyses show rock to be rhyodacite in classification of Rittmann (1952). Unit includes some interbedded tuffaceous sandstone and laharic debris flows in Black Rock Hills and some aphanitic flow or dike rocks near Joy townsite. Maximum thickness about 240 m in Black Rock Hills.	~42	Tdr

TABLE 1.—Continued

Description of rocks[1]	Age (m.y.)[2]	Map symbol (fig. 2)
Angular unconformity A		
Undifferentiated rocks (Devonian to Precambrian): Limestone, dolomite, quartzite, and shale. Formations are differentiated on maps of Staatz and Carr (1964) for Thomas Range and Newell (1971) and Crittenden and others (1961) for Drum Mountains. Maximum thickness exceeds 1,200 m.	--	Dp€

[1]Many units have unconformable tops, so that the original thickness has been reduced by erosion.
[2]Ages are averages of all valid potassium-argon and fission-track dates (table 3); ages in parentheses are inferred from stratigraphic relationships.
[3]Average of two ages of Needles Range(?) Formation of Little Drum Mountains is 31.4 m.y.; average age of the Needles Range Formation is 30.4 m.y. (Armstrong, 1970).
[4]A single age of 36.4±1.7 m.y. on the Mt. Laird Tuff was determined (table 3), but the true age of the Mt. Laird Tuff is estimated at about 39 m.y., because it underlies the 38.0-m.y.-old crystal tuff member of the Joy Tuff.

AGE AND CORRELATION

An attempt was made to date each rock unit in the Thomas Range and Drum Mountains, using both old and new data (table 2). The ages have been revised to reflect additional dating and recently adopted decay constants used in calculating ages by the potassium-argon and fission-track methods. Methods used for fission-track dates reported here are described by Naeser (1976) and Naeser and others (1978).

The new fission-track ages extend the history of volcanism in western Utah to almost 42 m.y. ago (tables 2 and 3). A single age of 41.8±2.3 m.y. on zircon from the Drum Mountains Rhyodacite is somewhat older than two whole-rock potassium-argon ages of 38.2±0.4 m.y. (revised from 37.3±0.4 m.y., reported by Leedom (1974), to account for change in constants) for flow rocks that overlie the rhyodacite in the Little Drum Mountains. The zircon age is considered reliable because it is not subject to the effects of weak alteration that pervades much of the rhyodacite; also, uranium and the resultant fission tracks are distributed uniformly in the zircon dated so that counting errors that may attend dating of zoned grains are not a problem.

The age of the crystal tuff member of the Joy Tuff is estimated at 38.0±0.7 m.y. (table 2) by eight fission-track dates on sphene, zircon, and apatite. The date of the Joy Tuff marks the onset of extensive eruptions of rhyolitic ash-flow tuff. A single zircon age of 36.4±1.6 m.y. on the Mt. Laird Tuff, which unconformably underlies the Joy Tuff, is probably not significantly different from the age of the Joy Tuff. Accordingly, the true age of the Mt. Laird Tuff is believed to be about 39 m.y. The age of the black glass tuff member of the Joy Tuff, which overlies the crystal tuff member, was checked by a single determination of 37.0±4.1 m.y. on sphene. The age is supported by the close chemical and spatial association of the two members of the Joy Tuff and sets them apart from the younger Dell Tuff, which has an average age of 32.0±0.6 m.y. as determined by 10 fission-track dates on zircon, sphene, and apatite.

The age of the ash-flow tuff correlated with the Needles Range(?) Formation (Pierce, 1974) was determined to test that correlation. Tuff of the Needles Range(?) Formation was described from outcrops south of the Little Drum Mountains (Leedom, 1974; Pierce, 1974), and mapped by me (Lindsey, 1979a) along the northwest side of the Drum Mountains. Fission-track ages of 30.6±1.2 m.y. on zircon and 32.2±3.6 m.y. on apatite are in accord with assignment of the tuff to the Needles Range Formation, which was estimated by Armstrong (1970) to be 30.4 m.y. old (age adjusted to account for different decay constants).

The 21-m.y. age of the Spor Mountain Formation is confirmed by a new zircon date of 21.5±1.1 m.y. on the dome of porphyritic rhyolite near Wildhorse Spring. H. H. Mehnert dated the porphyritic rhyolite flow at the Roadside mine at 21.2±0.9 m.y. by the potassium-argon method on sanidine (Lindsey, 1977). An age of 18.1±4.6 m.y. was obtained for porphyritic rhyolite at the east side of The Dell but was not used in estimating the average age (table 2) because only a single grain of zircon could be dated.

An attempt to date zircon from bentonite in the Yellow Chief mine, a facies of the beryllium tuff member of the Spor Mountain Formation, was not successful. Detrital zircon from the bentonite makes up about 10 percent of the total zircon and is dated as 28.3±1.8 and 40.0±7.0 m.y. old; it reflects the ages of the older volcanic rocks. The remaining 90 percent of the zircon has high track densities and could not be dated; it contains 3,700–7,500 ppm (parts per million) uranium, which is well above that of zircon from the older volcanic rocks and within the range of high uranium content typical of zircon in the overlying porphyritic rhyolite member. Field relationships pre-

TABLE 2.—*Summary of radiometric ages for volcanic formations of the Thomas Range and northern Drum Mountains*

[Ages determined from some formations in nearby areas are included. All fission-track ages on zircon, sphene, and apatite have been recalculated using λ_D=1.551×10^{-10}yr^{-1} and λ_F=7.03×10^{-17}yr^{-1}. All K-Ar ages on sanidine have been recalculated using decay constants for ^{40}K of λ_ϵ=0.581×10^{-10}yr^{-1} and λ_B=4.962×10^{-10}yr^{-1} and ^{40}K/K=1.167×10^{-4}]

Rock unit	Sample No.	Mineral dated	Age ±2σ (millions of years)	Average age (± standard error of the mean)
Topaz Mountain Rhyolite:				
Younger flow, Topaz Mountain--	177[1]	Sanidine	6.1±0.4	
Do---------------------------	T40-TRA[2]	--do---	6.3±0.4	6.3±0.1 m.y.
Do---------------------------	T40-TRA[3]	Zircon	6.3±0.3	
Older flow, Topaz Mountain----	T52-TR-A[3]	--do---	6.2±0.3	
Do---------------------------	T52-TR-B[3]	--do---	6.4±0.3	6.3±0.1 m.y.
Older flow, Pismire Wash------	T50-TR-A[3]	--do---	6.8±0.3	
Spor Mountain Formation:				
Porphyritic rhyolite member---	T53-TR-B[4]	Sanidine	21.2±0.9	
Do---------------------------	U26	Zircon	21.5±1.1	21.3±0.2 m.y.
Needles Range(?) Formation, Little Drum Mountains.	U229	--do---	30.6±1.2	31.4±0.8 m.y.
Do---------------------------	U229	Apatite	32.2±3.6	
Dell Tuff--------------------------	T43-A[3]	Zircon	30.7±6.3	
Do---------------------------	T43-A[3]	Sphene	28.5±1.2	
Do---------------------------	T43-A[3]	Apatite	32.8	
Do---------------------------	T42-A[3]	Zircon	33.0±1.3	32.0±0.6 m.y.
Do---------------------------	T42-A[3]	Sphene	32.4±1.4	
Do---------------------------	T42-A[3]	Apatite	33.3	
Do---------------------------	T54-A	Zircon	29.4±1.3	
Dell Tuff, Keg Mountain Pass---------------	K20-A[3]	Sphene	33.6±1.8	
Do---------------------------	K48-A[3]	--do---	32.5±1.6	
Do---------------------------	K48-A[3]	Zircon	33.8±1.3	
Joy Tuff:				
Black glass tuff member-------	U141	Sphene	37.0±4.1	
Crystal tuff member-----------	T51-A[3]	Apatite	40.0	
Do---------------------------	T51-A[3]	Sphene	38.5±2.0	
Do---------------------------	U18B	--do---	39.7±3.4	
Do---------------------------	U32	--do---	39.4±2.8	38.0±0.7 m.y.
Do---------------------------	U34	--do---	38.4±4.0	
Do---------------------------	U56	--do---	36.4±2.8	
Crystal tuff member, Desert Mountain-------------	U238	Zircon	34.5±1.3	
Crystal tuff member, Picture Rock Hills----------	U240	--do---	36.9±1.7	
Mt. Laird Tuff--------------------	U57	--do---	36.4±1.6	
Drum Mountains Rhyodacite---------	U10A	--do---	41.8±2.3	

[1]Armstrong (1970, table 3).
[2]E. H. McKee, oral commun., 1975.
[3]Lindsey and others (1975).
[4]H. H. Mehnert, oral commun., 1976, 1978.

sented in following sections of this report indicate that the age of the bentonite and the rest of the beryllium tuff member is close to that of the overlying porphyritic rhyolite.

The history of igneous activity is approximately the same in the Thomas Range, Drum Mountains, Keg Mountain, and Desert Mountain (Shawe, 1972; Lindsey and others, 1975). Each range has local intrusive and volcanic rocks, however, and only the ash-flow tuffs provide stratigraphic markers that extend into all of the ranges. The "Keg Spring andesite and latite" of Erickson (1963) is 39.4±0.7 m.y. old and is confined to the northwest part of Keg Mountain. The "Keg Spring" is overlain by the Mt. Laird Tuff north of Keg Pass; thus, it occupies the same stratigraphic position at Keg Mountain as the Drum Mountains Rhyodacite does in the Thomas Range. A newly recognized stock of granodiorite (Staub, 1975; H. T. Morris, oral commun., 1976), dated here at 36.6±1.6 m.y. by the fission-track method on zircon, intrudes the "Keg Spring andesite and latite" west of Keg Pass. Both of these rocks are unconformably overlain by the crystal tuff member of the Joy Tuff in the Picture Rock Hills, which suggests that the zircon age of the granodiorite stock may be about 1–2 m.y. too young. The Dell Tuff unconformably overlies the "Keg Spring andesite and latite" and the Mt. Laird Tuff north of Keg Pass, where three fission-track ages yield an average of 33.1±0.4 m.y. (Lindsey and others, 1975). The crystal tuff member of the Joy Tuff is well exposed on the east side of Desert Mountain, where it has been dated at 34.5±1.3 m.y. by the fission-track method. This age may be too young because the tuff has been intruded by the stock of Desert Mountain (Shawe, 1972); the

TABLE 3.—*Analytical data for new fission-track ages of igneous rocks in western Juab and Millard Counties*

[All ages determined by author by external detector method. Neutron dose determined by C. W. Naeser]

Sample No.	Rock unit	Geographic area	Sample location	Mineral	Number of grains	Fossil tracks: Number counted	Fossil tracks: Density (tracks/cm^2)	Induced tracks in detector: Number counted	Induced tracks in detector: 2X density (tracks/cm^2)	Neutron dose (Neutrons/cm^2)	Age ±2 σ (m.y.)[1]
U26-------	Spor Mountain Formation, porphyritic rhyolite member.	North of Spor Mountain.	NE1/4 sec. 9, T. 12 S., R. 12 W.	Zircon---	5	730	1.13×10^{7}	463	1.41×10^{7}	4.56×10^{14}	21.5±1.1
U7A-------	--do--------------------	The Dell-----	SW1/4 sec. 36, T. 12 S., R. 12 W.	--do-----	1	156	7.22×10^{6}	119	1.10×10^{7}	4.60×10^{15}	18.1±4.6
U128-1----	Spor Mountain Formation, beryllium tuff member (bentonite at Yellow Chief mine).	--do---------	NW1/4 sec. 36, T. 12 S., R. 12 W.	--do[2]----	4	321	4.57×10^{6}	338	9.63×10^{6}	9.97×10^{14}	28.3±1.8
				--do[2]----	2	346	9.62×10^{6}	257	1.43×10^{7}	9.97×10^{14}	40.0±7.0
U229------	Needles Range(?) Formation	South of----- Little Drum Mountains.	NE1/4 sec. 23, T. 16 S., R. 11 W.	--do-----	10	919	5.87×10^{6}	861	1.10×10^{7}	9.61×10^{14}	30.6±1.2
U229------	--do----------------------	--do---------	--do-------------	Apatite--	15	234	2.63×10^{5}	1,002	2.25×10^{6}	4.62×10^{15}	32.2±3.6
T54-A-----	Dell Tuff-----------------	The Dell-----	SE1/4 sec. 26, T. 12 S., R. 12 W.	Zircon---	5	1,031	1.05×10^{7}	1,047	2.13×10^{5}	1.00×10^{15}	29.4±1.3
U141------	Joy Tuff, black glass----- tuff member.	Northeastern Drum Mountains.	NE1/4 sec. 36, T. 13 S., R. 11 W.	Sphene---	12	262	1.01×10^{6}	1,017	7.85×10^{6}	4.81×10^{15}	37.0±4.1
U18B------	Joy Tuff, crystal tuff---- member.	East of Topaz Mountain.	SW 1/4 sec. 10, T. 13 S., R. 11 W.	--do-----	12	488	1.88×10^{6}	350	2.70×10^{6}	9.55×10^{14}	39.7±3.4
U32-------	--do----------------------	South of----- Topaz Mountain.	NW1/4 sec. 22, T. 13 S., R. 11 W.	--do-----	11	436	1.83×10^{6}	311	2.62×10^{6}	9.43×10^{14}	39.4±2.8
U34-------	--do----------------------	--do---------	NE1/4 sec. 20, T. 13 S., R. 11 W.	--do-----	10	366	1.70×10^{6}	1,384	1.28×10^{7}	4.86×10^{15}	38.4±4.0
U56-------	--do----------------------	Northwest of- Joy townsite.	NE1/4 sec. 21, T. 14 S., R. 11 W.	--do-----	10	369	1.72×10^{6}	1,466	1.36×10^{7}	4.84×10^{15}	36.4±2.8
U238------	--do----------------------	East of Desert Mountain.	NW1/4 sec. 29, T. 12 S., R. 6 W.	Zircon---	10	789	5.03×10^{6}	656	8.38×10^{6}	9.61×10^{14}	34.5±1.3
U240------	--do----------------------	Picture Rock- Hills.	NW1/4 sec. 23, T. 13 S., R. 10 W.	--do-----	8	1,005	8.80×10^{6}	782	1.37×10^{7}	9.61×10^{14}	36.9±1.7
U57-------	Mt. Laird Tuff------------	Northwest of- Joy townsite.	NE1/4 sec. 21, T. 14 S., R. 11 W.	--do-----	8	966	6.63×10^{6}	886	6.08×10^{6}	1.12×10^{15}	36.4±1.6
U29B------	Granodiorite of Keg------- Mountain (Staub, 1975).	Western Keg-- Mountain.	SE1/4 sec. 24, T. 12 S., R. 10 W.	--do-----	6	727	6.48×10^{6}	598	1.07×10^{7}	1.01×10^{15}	36.6±1.6
U10A------	Drum Mountains Rhyodacite	The Dell------	SW1/4 sec. 35, T. 12 S., R. 12 W.	--do-----	8	518	3.00×10^{6}	345	4.00×10^{6}	9.33×10^{14}	41.8±2.3

[1]Computed using $\lambda_D=1.551\times10^{-10}$/yr and $\lambda_F=7.03\times10^{-17}$/yr. λ_D, total decay constant for ^{238}U; λ_F, decay constant for spontaneous fission of ^{238}U.
[2]Zircon believed to be detrital; abundant (90 percent) zircon with high U content could not be dated.

granitic facies of the stock was emplaced about 28–31 m.y. ago (Lindsey and others, 1975; Armstrong, 1970), and that event may have reset slightly the zircon age of the tuff. Stratified tuff and rhyolite considered to be equivalent in part to the Topaz Mountain Rhyolite were erupted from Keg Mountain about 8–10 m.y. ago. Alkali rhyolite and basalt north of Fumarole Butte were erupted about 6–7 m.y. ago (Mehnert and others, 1978; Peterson and others, 1978). The last volcanic activity in the region was the eruption of basaltic lava at Fumarole Butte 0.88 m.y. ago (Peterson and others, 1978).

DESCRIPTION OF ROCK UNITS

DRUM MOUNTAINS RHYODACITE

The oldest formation of volcanic rocks in the mapped area consists of dark, rusty-brown-weathering flows and flow breccias having the chemical composition of rhyodacite and, to a lesser extent, quartz latite[1]. Named the Drum Mountains Rhyodacite for exposures in the Drum Mountains (Lindsey, 1979a), the rhyodacite crops out discontinuously around Spor Mountain and is well exposed in the Black Rock Hills, where it is believed to have been erupted from a small central volcano. It is about 240 m (meters) thick in the Black Rock Hills and about 150 m thick in the southern part of The Dell. Volcaniclastic sandstone and laharic breccias are interbedded with the lower part of the rhyodacite in the Black Rock Hills. Some dark, aphanitic flow rocks were mapped with the more porphyritic rhyodacite near Joy townsite; these are seen under the microscope to have similar petrographic features. Much rhyodacite in the northern Drum Mountains and

[1]Nomenclature of Rittmann (1952) is used throughout this report, unless otherwise stated.

around Spor Mountain is broken into blocks about 100–300 m across of diverse orientation; these blocks may reflect shattering of the formation as it subsided into the Thomas caldera. The rhyodacite everywhere unconformably overlies rocks of Paleozoic age and is overlain by the Mt. Laird Tuff locally, by the Joy Tuff at many localities, and by landslide breccia, Dell Tuff, and the Spor Mountain Formation around Spor Mountain.

The rhyodacite contains an average of 35 percent euhedral phenocrysts of plagioclase and pyroxene as large as 3–4 mm (millimeters) in a groundmass of plagioclase microlites and glass (table 4, fig. 3). Plagioclase is mainly andesine and labradorite, but sodic rims are common; pyroxene is mainly hypersthene, but lesser amounts of augite are present, and pigeonite has been reported (Staatz and Carr, 1964). Euhedral magnetite is abundant, traces of quartz occur at a few localities, and very small amounts of accessory apatite and zircon also occur locally. Along the east side of Spor Mountain, the mafic minerals in the rhyodacite are commonly altered to chlorite and brown hydromica(?).

The texture of the rhyodacite indicates that the phenocrysts were not in equilibrium with the magma at the time of eruption and cooling of the groundmass. Intratelluric crystallization of the phenocrysts evidently proceeded in an andesitic magma; somehow, either by addition of another magma, contamination with wall rocks, or differentiation, the melt became more silicic and alkalic than the original magma, so that plagioclase phenocrysts were partially resorbed and overgrown with sodic rims. The interiors of some plagioclase have a sieve texture of holes filled with glass; this texture may indicate change in composition of the melt or, alternatively, of temperature and pressure. When erupted, the remaining lava cooled quickly to form microlites and glass. Chemical analyses confirm that the groundmass of the rhyodacite is much more silicic (60–67 percent SiO_2) than the phenocrysts would indicate. The modal phenocryst content suggests the rock is a hypersthene andesite, but most chemical analyses show it to be rhyodacite and quartz latite in the classification of Rittmann (1952).

DIORITE

Plugs of diorite crop out in the Drum Mountains 3 km southeast of Joy townsite; they were first mapped by Crittenden and others (1961) as quartz diorite and were examined only briefly by me. Fresh specimens of the rock are dark brown in color, like the Drum Mountains Rhyodacite, but the rock is phaneritic, unlike the aphanitic-porphyritic texture of the rhyodacite. In thin section, the rock is seen to contain about 56 percent elongate, subparallel grains of calcic plagioclase and about 22 percent hornblende that is highly altered. Other minerals include about 7 percent anhedral brown biotite, about 9 percent anhedral potassium feldspar, 5 percent magnetite, and accessory apatite. Although Crittenden and others (1961) called the rock quartz diorite, no quartz could be identified with certainty. The diorite is assigned a probable Eocene age on the basis of overall compositional similarity to other rocks of that age and on the basis of crosscutting by dikes considered equivalent to the Mt. Laird Tuff. Crittenden and othrs (1961, pl. 20) mapped dikes of quartz monzonite porphyry cutting the diorite. Reexamination of their quartz monzonite dikes 2–3 km south and southwest of Joy townsite showed them to be nearly identical to the Mt. Laird Tuff. Similar but hydrothermally altered dikes cut one diorite plug, indicating that the diorite is older than the Mt. Laird Tuff.

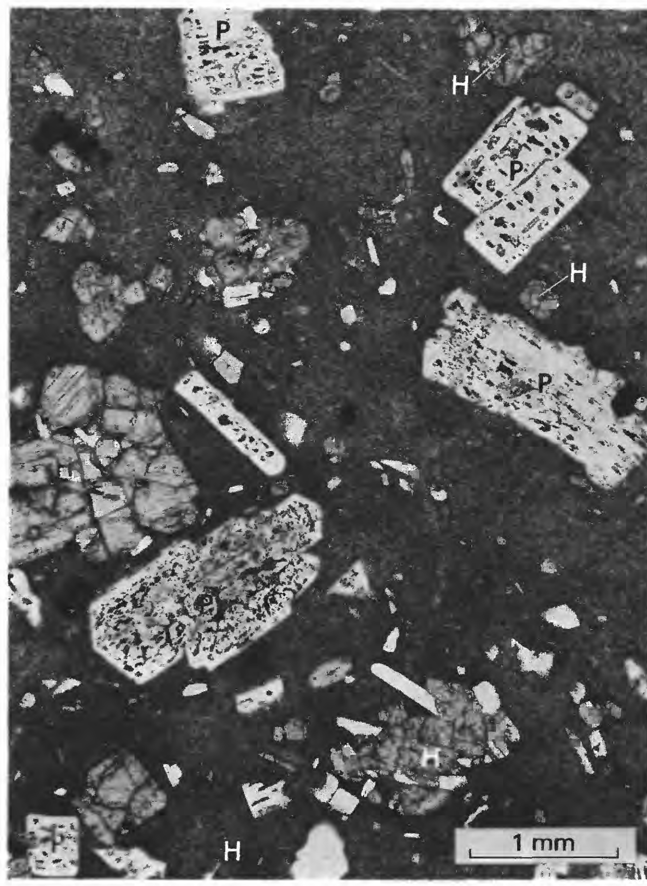


FIGURE 3.—Photomicrograph of Drum Mountains Rhyodacite showing partially resorbed plagioclase (P) and clusters of hypersthene (H) and plagioclase in a groundmass of microlites. Crossed polars. Sample from sec. 20, T. 13 S., R. 11 W.

TABLE 4.—*Comparison of the mean and range of mineral composition and the occurrence of accessory minerals in volcanic rocks in the Thomas Range and northern Drum Mountains*

[Mineral composition estimated from point counts on three to six thin sections and cobaltinitrite-stained slabs of each rock type by C. A. Brannon. Accessory minerals identified by binocular microscope and X-ray methods by the writer using mineral concentrates prepared by heavy-liquid and electromagnetic separation. Range of values are in parentheses. Tr, trace; x, present; leaders (—), not present; <, less than]

Rock unit----------	1	2	3	4	5	6	7	8	9
				Mineral composition, in percent					
Quartz-------------	0.1(0-0.6)	0.3(0-1)	29(22-34)	5(3-7)	20(14-25)	3(0-5)	18(13-27)	6(4-10)	16(12-19)
Potassium-feldspar	--	--	24(15-35)	3(2-6)	21(16-26)	--	19(12-29)	7(3-10)	13(11-14)
Plagioclase--------	25(20-27)	17(9-29)	8(3-14)	5(1-7)	8(5-11)	31(26-37)	2(0-3)	<1(0-1)	3(1-3)
Biotite------------	--	3(1-5)	3(0-8)	<1(0-1)	3(1-5)	7(2-11)	1(0-3)	Tr.	Tr.
Hornblende---------	--	6(0-11)	Tr.	--	--	9(6-13)	--	--	--
Hypersthene and---- augite.	10(1.5-13)	4(1-5)	--	--	--	0.7(0-1)	--	--	--
Rock fragments-----	--	Tr.	1(0-13)	8(6-11)	<1(0-1)	<1(0-1)	--	--	--
Opaque minerals----	2(1-6)	1.5(0-3)	Tr.	<1(0-1)	Tr.	2.6(1-4)	Tr.	<1(0-1)	<1(0-1)
Other accessory---- minerals.	Tr.	0.8(0-2.4)	1.0(0-2)	<1(0-1)	Tr.	Tr.	Tr.	Tr.	Tr.
Matrix-------------	63(52-74)	68(61-72)	34(26-49)	79(77-89)	68(40-54)	46(47-52)	60(46-72)	87(74-96)	68(63-73)
Matrix------------- composition.	Glass and crystals.	Devitrified shards and pumice.	Devitrified shards and pumice.	Glassy to devitrified shards and pumice.	Devitrified shards and pumice.	Glassy to devitrified shards and pumice.	Devitrified glass.	Devitrified glass.	Devitrified glass.
				Occurrence of accessory minerals					
Magnetite----------	x	x	x	x	x	x	x	--	--
Specular hematite--	--	--	--	--	--	--	--	x	x
Allanite-----------	--	--	x	x	x	--	--	--	--
Sphene-------------	--	--	x	x	x	--	--	--	--
Zircon-------------	Tr.	x	x	x	x	x	Tr.	Tr.	Tr.
Apatite------------	Tr.	x	x	x	x	x	--	--	--
Topaz--------------	--	--	--	--	--	--	x	x	x

Rock units

1. Drum Mountains Rhyodacite
2. Mt. Laird Tuff.
3. Crystal tuff member of Joy Tuff.
4. Black glass tuff member of Joy Tuff.
5. Dell Tuff.
6. Needles Range(?) Formation.
7. Porphyritic rhyolite member of Spor Mountain Formation.
8. Flows and domes of alkali rhyolite, Topaz Mountain Rhyolite.
9. Local flows and domes of porphyritic alkali rhyolite, Topaz Mountain Rhyolite.

MT. LAIRD TUFF

The Mt. Laird Tuff, called plagioclase crystal tuff by Staatz and Carr (1964, p. 78–79), is about 80 m thick in the type locality near Mt. Laird in the north-central Drum Mountains. It overlies the Drum Mountains Rhyodacite and is unconformably overlain by the Joy Tuff. The Mt. Laird Tuff has a wide but scattered distribution: it crops out northeast of the Thomas Range, where it overlies rocks of Paleozoic age (Staatz and Carr, 1964), and in the northern part of Keg Mountain, where it overlies the "Keg Spring andesite and latite" of Erickson (1963). The formation is more than 500 m thick in the subsurface 2–3 km east and northeast of Topaz Mountain, where drilling has revealed a section consisting of (1) 95 m of ash-flow tuff, (2) 62 m of tuffaceous sediments, (3) 75 m of ash-flow tuff, (4) 85 m of tuffaceous sediments, and (5) 199 m of ash-flow tuff to the bottom of the hole (table 5). The drilled section contains three major intervals of ash-flow tuff, and variation in size and type of lithic inclusions within these suggests that each may consist of more than one ash flow. Much of the tuff is partly welded, devitrified and further altered to clay and calcite.

Outcrops of the Mt. Laird Tuff vary from gray to pink to lavender, and the tuff can be recognized easily in the field by conspicuous white plagioclase phenocrysts as much as 10 mm long and bronze-colored bio-

TABLE 5.—*Section of Mt. Laird Tuff in drill hole east of Topaz Mountain*

[Revised, after study of core and thin sections, from log by Charles Beverly of hole 7 drilled for Bendix Field Engineering Corp. Drill hole is in SW1/4NW1/4 sec. 3, T. 13 S., R. 11 W. Ground elevation, 1,669 m; total depth, 608 m]

Top of unit (m below surface)	Formation	Description of core and thin sections
0------	Topaz Mountain Rhyolite------	Crystal-poor alkali rhyolite flow.
70------	Joy Tuff; crystal tuff member	Crystal-rich (quartz, sanidine, biotite, and plagioclase) rhyolitic welded ash-flow tuff.
90------	Mt. Laird Tuff (top---------- approximate).	Crystal-rich (plagioclase, biotite, hornblende) quartz latitic welded ash-flow tuff. Thin sections at 98 m show glassy, perlitic matrix; at 152 m, matrix is devitrified and crystals are euhedral and mostly unbroken. At 158 m, matrix is devitrified but contains relict pumice, and broken crystals are common.
185------	Mt. Laird Tuff---------------	Fault(?) breccia.
187------	Mt. Laird Tuff---------------	Tuffaceous sediments of probable lacustrine origin include carbonaceous laminated mudstone, siltstone, sandstone, and minor conglomerate. Ash-flow tuff interbedded with sediments below 239 m. Thin sections at 202 m are of tuffaceous sandstone containing altered pumice, plagioclase, biotite, quartz, and lithic fragments of rhyodacite, tuffaceous siltstone, quartzite, and carbonate rock; all fragments are angular. At 210 m, same as at 202 m but has birefringent clay or sericite. At 240 m, unwelded ash-flow tuff containing broken plagioclase, biotite, quartz, hornblende altered to calcite, altered pumice, and lithic fragments of flow rock.
249------	Mt. Laird Tuff---------------	Crystal-rich (plagioclase, biotite, quartz, and hornblende), latitic ash-flow tuff containing abundant lithic fragments of carbonate rock and volcanic rocks to 292 m and below 305 m. Minor to no welding. Thin sections at 277 m and 306 m contain many broken crystals, relict pumice, and an altered matrix.
324------	Mt. Laird Tuff---------------	Tuffaceous sediments of probable lacustrine origin include black laminated carbonaceous mudstone containing pyrite, siltstone, sandstone, minor conglomerate and some interbedded ash-flow tuff. Sediments contain abundant graded bedding, flame structure, mud chips, and cross-lamination. Thin sections at 335 and 392 m contain abundant angular quartz, plagioclase, biotite, carbonate rock, and altered volcanic rock fragments.
409------	Mt. Laird Tuff---------------	Crystal-rich (plagioclase, biotite, altered hornblende) quartz latitic welded ash-flow tuff. Large lithic clasts to 433 m. Thin sections at 514 m show euhedral and unbroken crystals accompanied by relict pumice in a devitrified matrix. At 575 m, many crystals are broken and large resorbed quartz crystals are common.
608------	Mt. Laird Tuff---------------	Bottom of hole.

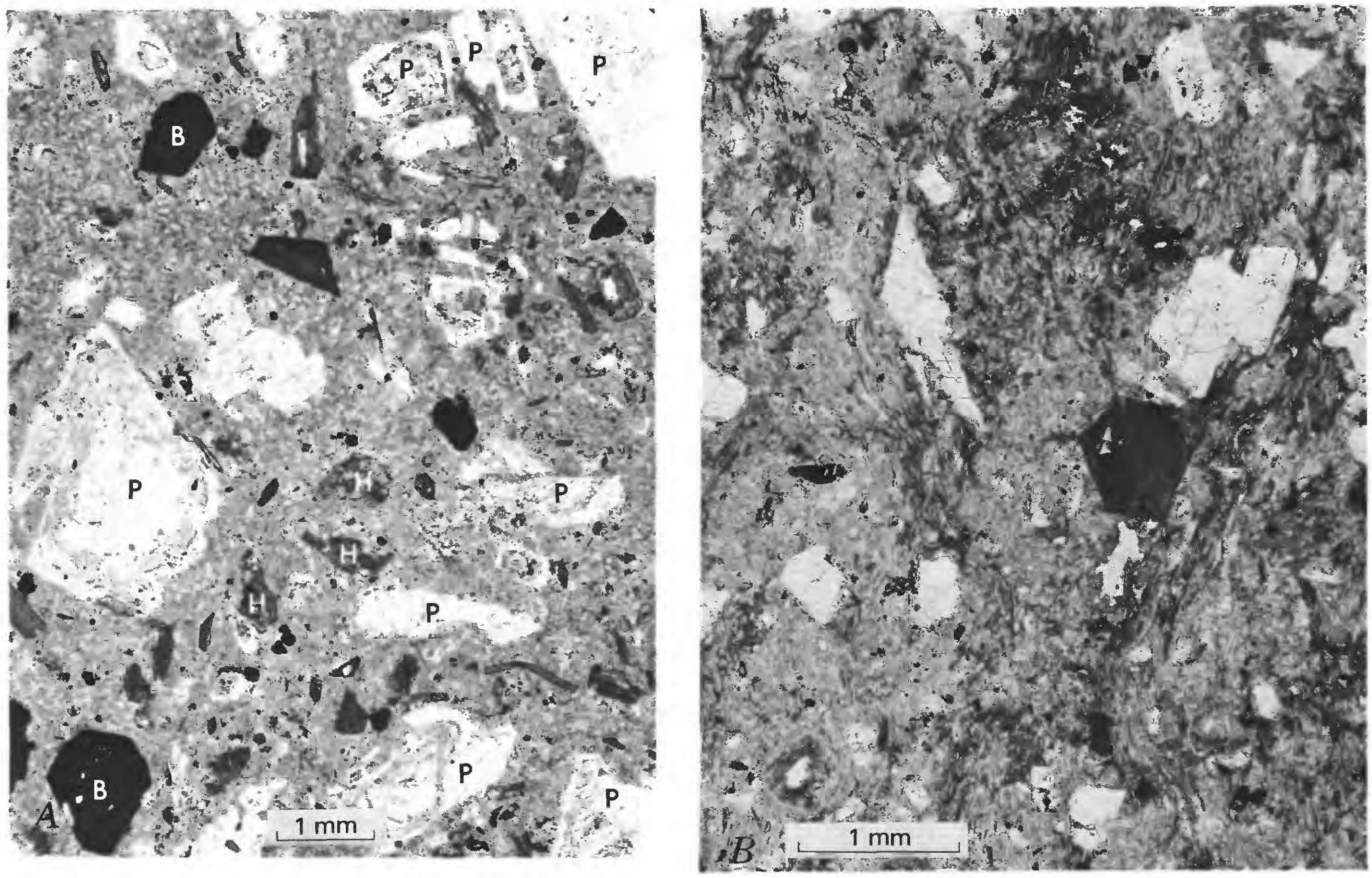
tite phenocrysts as much as 5 mm across. As seen under the microscope, the tuff contains 9–29 percent plagioclase, 1–5 percent red-brown biotite, and as much as 11 percent hornblende and 5 percent pyroxene (table 4, fig. 4*A*). Crystals in the upper part of the Mt. Laird, at both the type locality and the drilled section, are remarkably euhedral and unbroken for an ash-flow tuff, and some of this rock, with no preserved vitroclastic texture, may possibly be flow rock instead of tuff. Broken crystals and relict pumice and shards are common in the rest of the tuff (fig. 4*B*). Northeast of the Thomas Range, the tuff differs from the type locality in that it contains conspicuous quartz. Plagioclase (labradorite) in the Mt. Laird Tuff is typically zoned; some is euhedral but other crystals have sieve texture and rounded, resorbed boundaries and zones and overgrowths that follow these boundaries. Hornblende is partly to completely altered to iron oxide minerals, and locally, plagioclase is altered to chlorite and sericite. Accessory magnetite and traces of apatite and colorless zircon are present. The groundmass of the tuff near Joy townsite contains abundant plagioclase microlites and small hornblende crystals that are altered to iron oxide minerals; all are set in a matrix that was probably glassy, but evidence of vitroclastic texture has been destroyed by alteration.

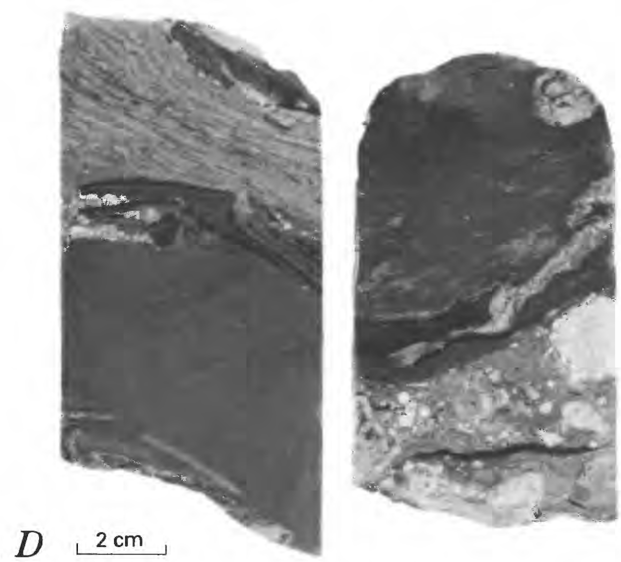
Study of core and thin sections from a drill hole (table 5) that penetrated the Mt. Laird Tuff east of Topaz Mountain confirms the abundance of ash-flow tuff in the formation. Only the upper 70 m contains large, euhedral crystals with little or no vitroclastic texture preserved. The matrix is perlitic glass at 8 m but is completely devitrified at 62 m below the top of the Mt. Laird Tuff. The devitrified matrix resembles the upper part of the Mt. Laird 3–4 km northwest of the type locality. Perhaps the uppermost part of the Mt. Laird is a flow, but more likely it formed by eruption of a very hot, viscous ash flow. Below the top 70 m of Mt. Laird Tuff the drilled section contains much ash-flow tuff distinguished by broken crystals and relict pumice and shards (fig. 4*B*). At 485 m below the top of the tuff, near the bottom of the drill hole, large crystals of resorbed quartz are common, as also in tuff northeast of the Thomas Range.

Two intervals of tuffaceous sediments are interbedded with the Mt. Laird Tuff in the subsurface east of Topaz Mountain (table 5). The sediments contain laminated carbonaceous mudstone, siltstone, sandstone, and conglomerate (figs. 4C, D) derived mainly from the Mt. Laird ash flows and Drum Mountains Rhyodacite. The sediments contain abundant graded bedding, flame structures, mud chips, and cross lamination; conglomerates are matrix supported, indicating a probable mud-flow origin. Such features, taken together, indicate rapid sedimentation. Mudstones contain small amounts of organic carbon and pyrite, indicating that they may have been deposited in stagnant water. Samples of mudstone were searched for pollen and microfossils that might reveal evidence about the depositional environment, but only abundant pollen of conifers was found; such pollen is not diagnostic of age or depositional environment (D. J. Nichols, written commun., 1980). The Mt. Laird sediments were probably deposited in a lake that formed during eruption of the Mt. Laird Tuff and attendant cauldron subsidence.

Three features of the Mt. Laird Tuff indicate that it was erupted from the vicinity of Mt. Laird in the Drum Mountains. (1) At the type locality and also 3–4 km northwest of Mt. Laird, the lower part of the tuff contains a distinctive breccia of abundant large (30 cm or centimeters) pumiceous tuff clasts in a similar matrix (fig. 4*E*). Such monolithologic breccias may represent fallback into the vent during eruption. (2) Massive to layered porphyritic rock of Mt. Laird mineralogy but resembling flow rock overlies the breccia at Mt. Laird and nearby; layers in the porphyritic rock are inclined gently and consist of dark-gray lenses 1–5 cm thick (fig. 4*F*) that extend many meters. In thin section, the porphyritic rock is seen to contain many euhedral crystals but also layers of small broken crystals and lenses of devitrified matrix with sparse phenocrysts; these features and the layering seen in outcrops are undoubtedly the product of flowage, but it is unclear whether such flowage features formed by eruption as a flow or as a hot, viscous ash flow that became densely welded and flowed after eruption. In either case, proximity to the source of the Mt. Laird magma is indicated. (3) An area of kaolinitic and pyritic alteration, now oxidized, occurs around a small breccia pipe on the northwest side of Mt. Laird; alteration affected the Mt. Laird Tuff but did not affect the Joy Tuff, which overlies the Mt. Laird Tuff nearby. Intrusion of breccia and alteration evidently represent late venting of fluids from the source magma of the Mt. Laird Tuff.

An area of porphyry intrusion and mineralization in the Detroit mining district of the Drum Mountains may be part of the Mt. Laird magma chamber that did not collapse or may represent resurgence and shallow intrusion of the Mt. Laird magma after eruption of the tuff. Small dikes and plugs of porphyritic rock, mapped as quartz monzonite porphyry by Crittenden and others (1961), resemble the Mt. Laird Tuff. Most intrude rocks of Cambrian and Precambrian age, but one dike intrudes a diorite plug of probable Eocene age. The westernmost group of dikes retains most of their original plagioclase phenocrysts, but mafic minerals and matrix have been hydrothermally altered. The eastern group contains only relict textures of feldspar and biotite phenocrysts. Study of X-ray diffraction patterns and thin sections show that the eastern intrusions are altered to quartz, kaolinite, well-





crystallized sericite and minor pyrophyllite; such alteration is typical of the phyllic zone of the Lowell and Guilbert porphyry copper model (Hollister, 1978). The easternmost plug contains a stockwork filled with jarosite and is partly surrounded by quartzite pebble breccias derived from the country rock of the Precambrian and Cambrian Prospect Mountain Quartzite. The intrusions of porphyritic rock are believed to be apophyses from a buried pluton (Newell, 1971) that is the uncollapsed or resurgent part of the magma chamber of the Mt. Laird Tuff. The area of porphyry intrusion and mineralization is only 4–6 km south of the probable vent breccias of the Mt. Laird Tuff, and

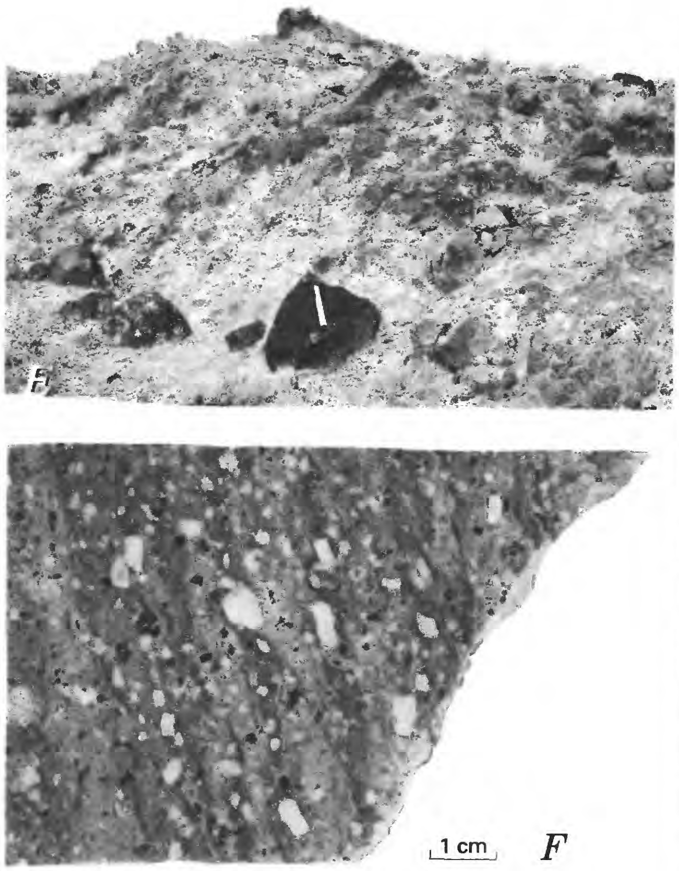


FIGURE 4.—Mt. Laird Tuff. *A*, Photomicrograph of ash-flow tuff showing crystals of plagioclase (P), hornblende (H), and biotite (B) in a devitrified matrix; vitroclastic texture is poorly preserved. Sample is from drill core from 158 m below surface at SW$\frac{1}{4}$ NW$\frac{1}{4}$ sec. 3, T. 13 S., R. 11 W. *B*, Photomicrograph of ash-flow tuff showing broken crystals and vitroclastic texture, from drill core from 216 m below surface at same locality as *A*. *C*, Core of tuffaceous sandstone and siltstone from 391 m below surface at same locality as *A*; note flame structure, graded bedding (top), and carbonaceous laminae. *D*, Core showing carbonaceous siltstone and mudstone with mud chips and matrix-supported conglomerate of probable mudflow origin (right core). Left core is from 401 m below surface; right core is from 334 m below surface; both from same locality as *A*. *E*, Probable vent breccia in the Mt. Laird Tuff northwest of Joy townsite, NE$\frac{1}{4}$ sec. 21, T. 14 S., R. 11 W. *F*, Layered porphyry that overlies vent breccia northwest of Joy townsite, same locality as *E*; porphyry contains large euhedral crystals of white plagioclase and dark biotite in a layered, foliated matrix.

the original mineralogy of the porphyry so closely matches that of the tuff that the two are considered to have been derived from the same magma.

JOY TUFF

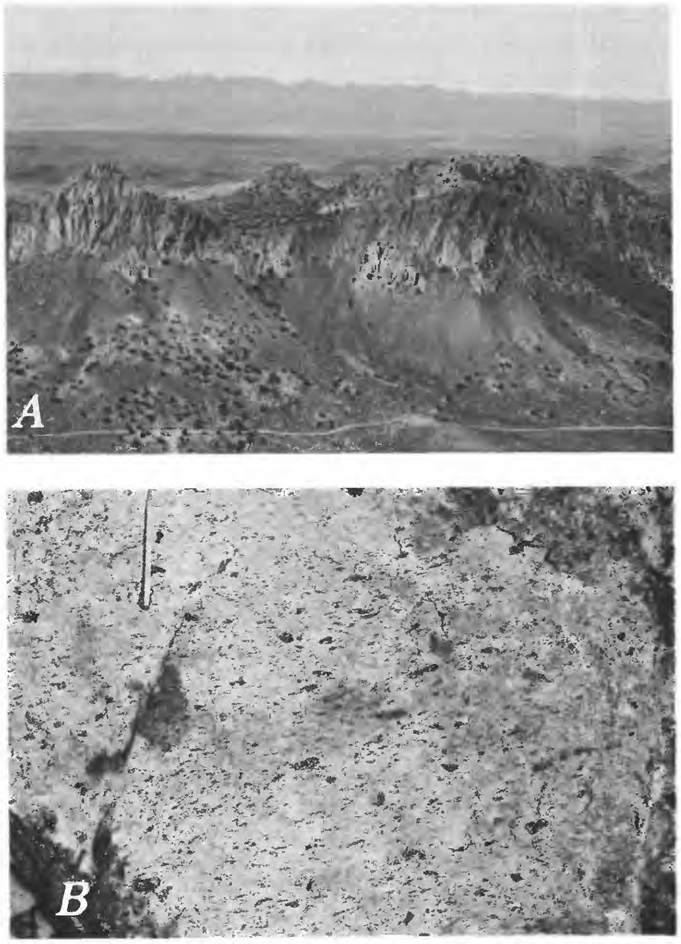
The Joy Tuff was named for excellent exposures in hills 3–5 km northwest of Joy townsite in the Drum Mountains (Lindsey, 1979a). The tuff consists of two members: a lower crystal tuff member about 180 m thick and an upper black glass tuff member about 30 m thick. In the type locality, the crystal tuff member overlies the Mt. Laird Tuff and the Drum Mountains Rhyodacite along angular unconformity B. The black glass tuff member is present only in the northeastern part of the Drum Mountains and southeast of Topaz Mountain; it overlies the crystal tuff member.

CRYSTAL TUFF MEMBER

The crystal tuff member of the Joy Tuff extends from Fish Springs Flat to the east side of Desert Mountain, a distance of 60 km (fig. 1). It is well exposed in the Joy graben (fig. 5*A*), where it is 180 m thick in hills northwest of Joy townsite and 70 m thick on the south side of Topaz Mountain, in the Picture Rock Hills of southwestern Keg Mountain, where it is about 150–200 m thick, and on the east side of Desert Mountain (fig. 1). Locally, the lowermost 10 m contains abundant compacted black pumice fragments (fig. 5*B*); the degree of welding and amount of black pumice decrease upward. Sections of the tuff in cliffs northwest of Joy townsite have a distinct parting that may be a partial cooling break within a compound cooling unit (fig. 5*A*). No compositional zoning of the crystal tuff is evident.

The source of the Joy Tuff is believed to be the Dugway Valley cauldron, which is generally east of Topaz Mountain and perhaps in the subsurface northeast of Topaz Mountain. The tuff east of Topaz Mountain is strongly welded and contains steeply dipping (60°–90°) foliation of somewhat variable northeasterly strike, in contrast to the more friable and less welded tuff with gentle dips in the Joy graben. Monolithologic tuff breccia having unrotated and slightly rotated clasts in a welded matrix occurs east of Topaz Mountain (fig. 5*C*), and similar breccia was penetrated by drill holes 3 and 5 km north of Topaz Mountain. One small outcrop of crystal tuff in the northeast Drum Mountains has near-vertical foliation. Such welded tuff breccia and tuff with steep foliation may indicate vents; possibly, the north-south distribution of such occurrences along faults may indicate a system of eruption fissures. Alternatively, it is possible that the tuff breccias formed by collapse of the ash flow into the cauldron during eruption. Such might be the explanation for large areas of steeply dipping foliation in the tuff; these could be large blocks that fell into the cauldron.

The crystal tuff member ranges from gray to reddish brown in outcrop; it contains abundant broken crystals of sanidine and quartz, and lesser quantities of



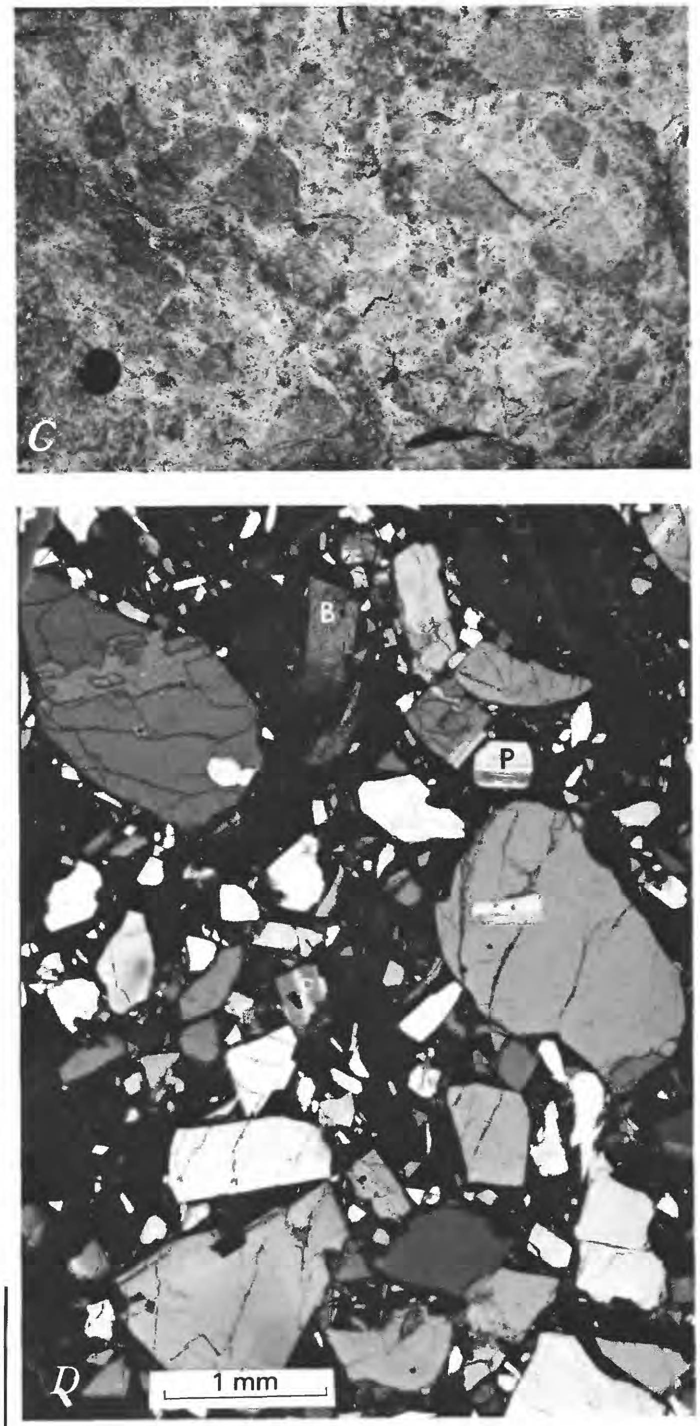
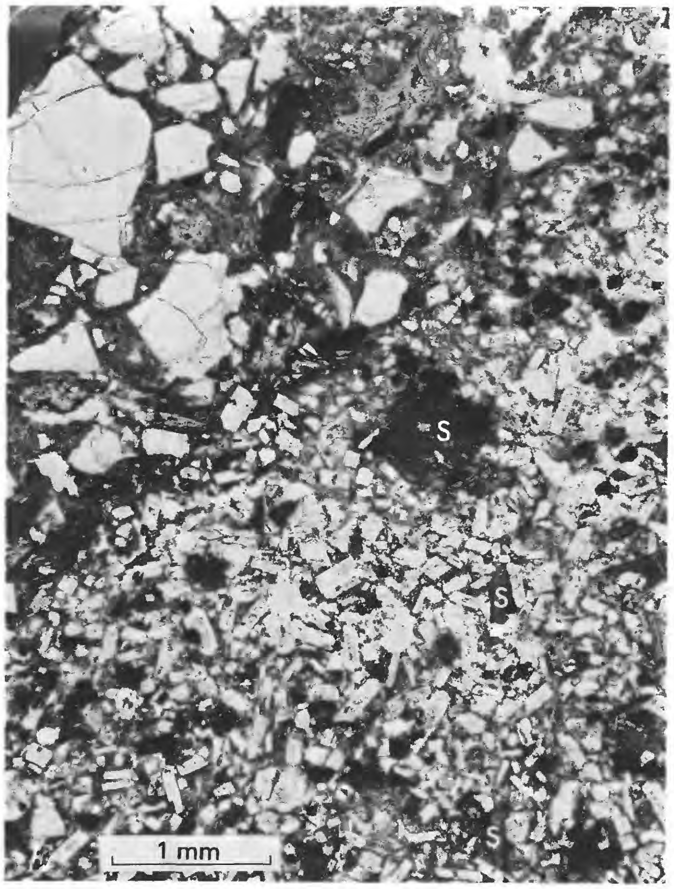


FIGURE 5.—Crystal tuff member of Joy Tuff. *A*, Section of crystal tuff in the type locality (sec. 22, T. 14 S., R. 11 W.). *B*, Compacted black pumice in lower 10 m of tuff (sec. 29, T. 13 S., R. 11 W.). *C*, Probable vent breccia of crystal tuff fragments in welded matrix of the same. *D*, Photomicrograph showing broken crystals of quartz and sanidine with lesser plagioclase (P) and biotite (B). *E*, Photomicrograph of cognate inclusion (lower right half of photograph) containing abundant sphene (S). Photomicrographs (crossed polars) of sample from sec. 5, T. 13 S., R. 11 W.

plagioclase (oligoclase-andesine), brown biotite, and euhedral magnetite (table 4, fig. 5*D*). The crystals are as much as 4 mm across and average about 65 percent of the tuff. Sphene, apatite, allanite, and colorless zircon occur as accessory minerals, but large euhedral crystals of sphene are so abundant and conspicuous that they can be seen in some hand specimens. Abundant sphene and the darker, more compact appearance of outcrops are the most reliable characteristics that can be used to distinguish the Joy Tuff from the Dell Tuff, which it resembles closely. The matrix of the Joy Tuff consists of welded shards that have been devitrified and altered to potassium feldspar and cristobalite. Lithic inclusions of the Drum Mountains Rhyodacite occur in the crystal tuff member east of Topaz Mountain, and distinctive cognate inclusions consisting of normally zoned plagioclase, brown biotite, sphene, and interstitial glass occur in the tuff in the canyon north of Topaz Mountain (fig. 5*E*). The cognate inclusions contain smaller, unbroken phenocrysts, in contrast to the tuff, and evidently represent an early stage of crystallization of the Joy Tuff within the magma chamber. Chemical analyses show that the crystal tuff member is a rhyolite.



BLACK GLASS TUFF MEMBER

The upper member of the Joy Tuff is a simple cooling unit of ash-flow tuff. It consists of three zones that show differing degrees of welding (fig. 6*A*): a densely welded lower zone consisting almost entirely of black, glassy pumice, a partly welded middle zone of gray, glassy tuff containing locally abundant compacted black pumice (fig. 6*B*), and an upper zone of unwelded tan, glassy tuff. At some localities the welded zones are more readily divisible into a lower black, glassy zone and an upper gray-brown, devitrified zone; both are overlain by unwelded tan tuff. The tuff crops out east of Topaz Mountain (Staatz and Carr, 1964, p. 84) and in the northeastern Drum Mountains. A section about 30 m thick is well exposed in sec. 36, T. 13 S., R. 11 W., where all three of the welding zones occur in approximately equal thickness, and where the tuff is overlain by a landslide of Tertiary age. The limited local extent of the black glass tuff, together with its small thickness and densely welded lower zone, indicate that it was a local hot ash flow erupted from the Dugway Valley cauldron.

The black glass tuff contains an average of only 13 percent small inconspicuous crystals of quartz, sanidine, zoned plagioclase, brown biotite, and magnetite (table 4, fig. 6*C*). Sphene is a conspicuous accessory mineral, as it is in the underlying crystal tuff member. Inclusions of the crystal tuff, Mt. Laird Tuff, Drum Mountains Rhyodacite, and Paleozoic rocks are common in all zones. Glass shards and pumice compose the rest of the tuff; these are highly compacted and deformed in the welded zones (figs. 6*B*, 6*C*) but are uncompacted, porous, and partly altered to clinoptilolite in the upper, unwelded zone.

The correct stratigraphic assignment of the upper unwelded zone of the black glass tuff is critical to the age of the overlying landslide megabreccias and their role in the volcanic and tectonic history of the area. The unwelded zone resembles tuff that is interbedded with younger rhyolite flows and was mapped as waterlaid tuff of the youngest volcanic group by Shawe (1964). The unwelded zone is not clearly stratified, however, and its contact with the underlying welded zone is conformable and sharply gradational. Chemical analyses show the composition of the unwelded zone to be consistent with leached tuff that had the same composition as the underlying welded zones. Stratified tuffs interbedded with young alkali rhyolite have a distinct trace-element signature comprised of anomalous beryllium, lithium, niobium, uranium, thorium, and yttrium that is not present in any of the black glass tuff, including the upper, unwelded tuff. The unwelded zone has been partly altered to clinoptilolite and leached of alkali and alkaline-earth elements, and perhaps some trace elements, but such leaching does not remove the distinctive trace-element signature of the younger tuffs (Lindsey, 1975).

LANDSLIDE BRECCIAS

Large masses of breccia interpreted by me as landslide deposits and related debris flows occur at Spor Mountain and in the northeastern part of the Drum Mountains; they are associated with the time of ash-flow eruption and probably record collapse of caldera walls. The breccias were mapped as three lithologically and geographically distinct informal units: breccia at Spor Mountain, breccia at Wildhorse Spring, and megabreccia of the northern Drum Mountains.

BRECCIA AT SPOR MOUNTAIN AND BRECCIA AT WILDHORSE SPRING

These breccias are spatially and genetically associated. The breccia at Spor Mountain consists of angular clasts of Paleozoic rocks as large as 1 m across in a matrix of the same material (fig. 7*A*). Breccia at Wildhorse Spring contains subrounded clasts (0.5 m or less) of Paleozoic rocks and rhyodacite in a matrix of

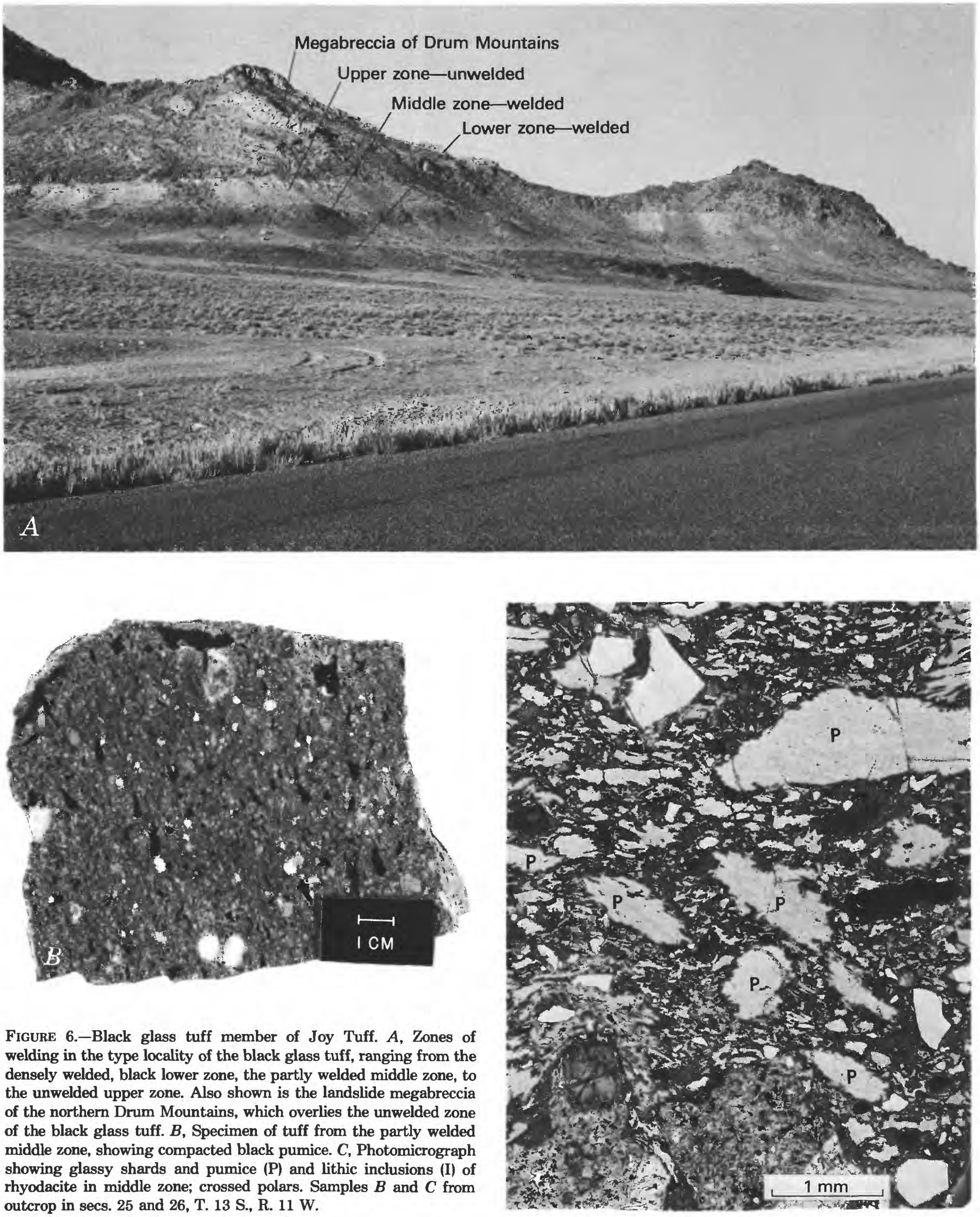


FIGURE 6.—Black glass tuff member of Joy Tuff. *A*, Zones of welding in the type locality of the black glass tuff, ranging from the densely welded, black lower zone, the partly welded middle zone, to the unwelded upper zone. Also shown is the landslide megabreccia of the northern Drum Mountains, which overlies the unwelded zone of the black glass tuff. *B*, Specimen of tuff from the partly welded middle zone, showing compacted black pumice. *C*, Photomicrograph showing glassy shards and pumice (P) and lithic inclusions (I) of rhyodacite in middle zone; crossed polars. Samples *B* and *C* from outcrop in secs. 25 and 26, T. 13 S., R. 11 W.

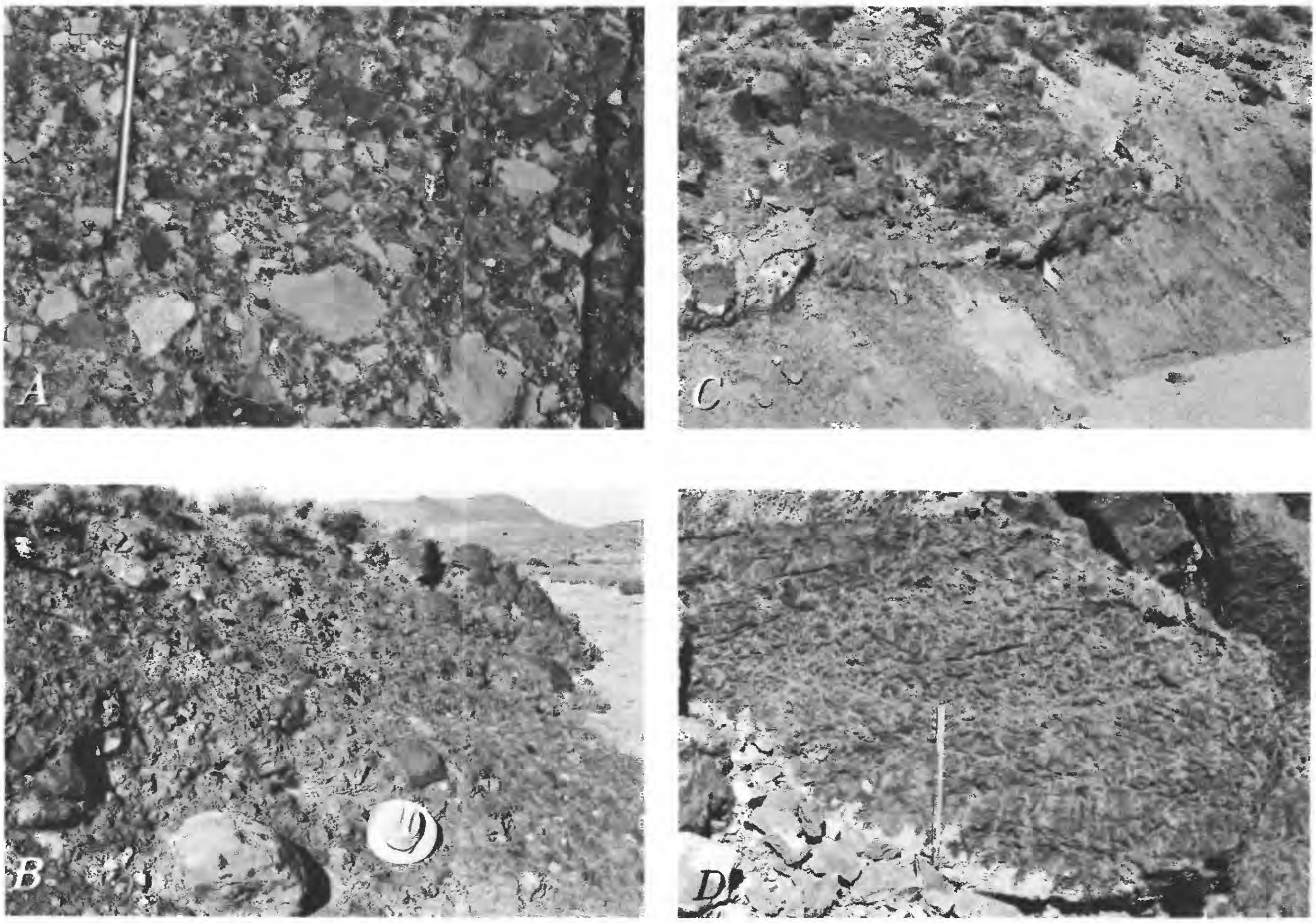


FIGURE 7.—Landslide breccia. *A*, Breccia at Spor Mountain, showing clasts of mixed lithologies derived from rocks of early Paleozoic age on Spor Mountain (sec. 27, T. 12 S., R. 12 W.). *B*, Breccia at Wildhorse Spring, showing large clasts of rhyodacite and Paleozoic rocks in a matrix of pulverized rhyodacite (sec. 15, T. 12 S., R. 12 W.). *C*, Contact between breccia at Wildhorse Spring and overlying breccia at Spor Mountain, which contains clasts 1 m in diameter. Note layering defined by concentration of clasts along the contact between breccias, above map case and pick (sec. 16, T. 12 S., R. 12 W.). *D*, Breccia at Spor Mountain, showing monolithologic crackle breccia of dark dolomite in the breakaway zone (sec. 27, T. 12 S., R. 12 W.).

pulverized rhyodacite (fig. 7*B*). The two units are associated locally but can be distinguished readily in the field. The breccia at Spor Mountain overlies the Drum Mountains Rhyodacite along the east side of Spor Mountain and overlies the breccia at Wildhorse Spring 1 km southwest of that locality (fig. 7*C*). The breccia at Spor Mountain is overlain by the Dell Tuff in the northern part of The Dell and probably west of the Yellow Chief mine, although relations near the mine may be complicated by faulting. Thus, stratigraphic relationships indicate that the age of the breccias is between 42 and 32 m.y., the ages of the rhyodacite and Dell Tuff, respectively (table 2).

The breccias have long been considered to be of intrusive origin (Staatz and Carr, 1964, p. 85), but new evidence presented here indicates that they formed from landslides and related debris flows along a steep escarpment that followed the present north and east sides of Spor Mountain. Three types of evidence support my view that the breccias are landslide deposits: (1) The breccia at Spor Mountain contains rotated and mixed clasts of Paleozoic dolomite and limestone and Ordovician Swan Peak Quartzite in a nonigneous matrix (fig. 7*A*); it can be traced continuously westward from the east side of Spor Mountain to monolithologic dolomite breccia having healed fractures between unrotated and slightly rotated fragments (fig. 7*D*). Both of these facies were mapped as breccia at Spor Mountain (Lindsey, 1979a). The monolithologic dolomite breccia retains the original stratigraphy of the Paleozoic rocks and resembles the "crackle breccia" of Tertiary landslides in Arizona described by Krieger (1977). All stages of brecciation from bedded but fractured dolomite to breccia of mixed Paleozoic lithologies are present in a small area about 2 km north-south and less than 0.3 km east-west that extends along the east side of the crest of Spor Mountain; I interpret this area as the breakaway zone for a landslide. (2) Both the breccias at Spor Mountain and at Wildhorse Spring are for the most part massive and unsorted, but they are faintly bedded locally, and the contact between the breccias southwest of Wildhorse Spring is distinctly bedded (fig. 7*C*). Massive structure and clasts of mixed lithology, set in abundant fine material, indicate turbulent mass transport, but bedding in the breccias indicates a transport mechanism capable of partial sorting of fragments. Massive breccias may represent landslides that moved when on steep slopes or when saturated by moisture, and faintly bedded breccias may represent water-saturated debris flows deposited during heavy rainfall. (3) Only Paleozoic rocks are present as clasts and matrix of the breccia at Spor Mountain; Paleozoic rocks and rhyodacite are both present as clasts and matrix of the breccia at Wildhorse Spring; nowhere is an ingeneous matrix other than fragments of rhyodacite present. A few areas of breccia occur in small plugs of intrusive alkali rhyolite on Spor Mountain, such as at the Blowout mine, but these are related to later faulting and to intrusion of the rhyolite.

The breccias at Spor Mountain were formed by sliding and flowage off a northerly trending breakaway zone on Spor Mountain, west of Eagle Rock Ridge; the slides traveled east and northeast over a valley floor covered by rhyodacite. Somewhat similar breccias form by collapse of caldera walls (Lipman, 1976), by landsliding along upthrown fault blocks (Krieger, 1977), and by sliding along scarps of erosional origin (Shreve, 1968); the geologic environment of ash-flow eruption and cauldron collapse in the Thomas Range favors an origin by collapse of caldera walls. The breccia at Spor Mountain probably began moving as coherent masses (fractured and brecciated dolomite) that disintegrated into landslides (breccia with rotated clasts of mixed lower Paleozoic lithologies) and debris flows during heavy rainfall. Where slides and debris flows traveled over rhyodacite, they incorporated rhyodacite detritus into them, forming the breccia at Wildhorse Spring. Evidently, the two most important agents responsible for formation of the breccias were steep scarps and abundant moisture. There is no reason to believe that the slides traveled on a cushion of air, as was concluded for the Blackhawk slide described by Shreve (1968), in part because the total distance traveled was probably not more than 5 km. Localization of sliding and flowage along north- and northwest-trending scarps that follow the Dell fault system suggests that these faults originated during times of ash-flow eruption and cauldron collapse 42 to 32 m.y. ago, even though the faults now displace rocks as young as 21 m.y. old.

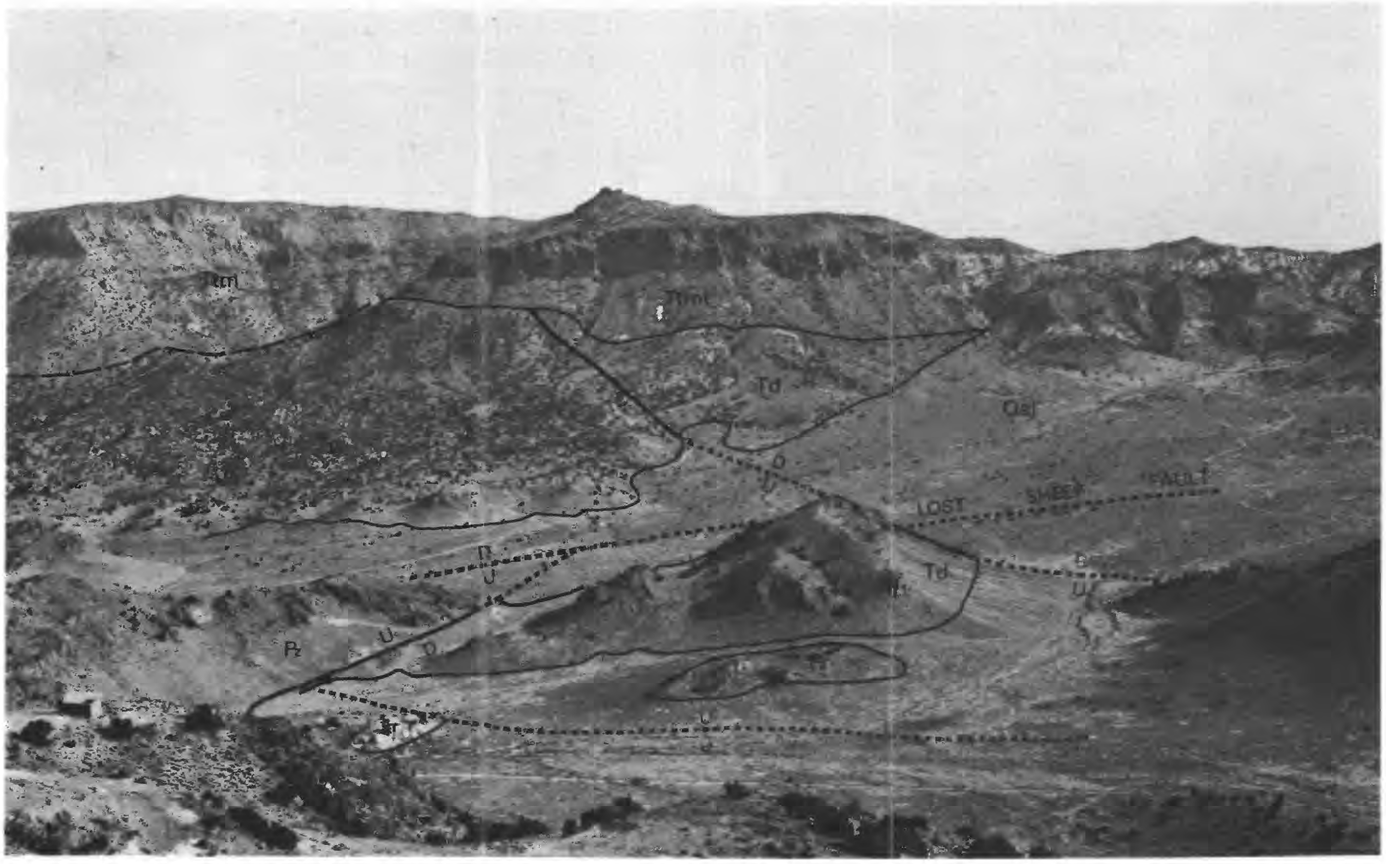
MEGABRECCIA OF THE NORTHERN DRUM MOUNTAINS

This megabreccia overlies the upper, unwelded zone of the black glass tuff member of the Joy Tuff in an area of about 5 km^2 (square kilometers) (fig. 6*A*). It occurs as more or less coherently bedded slabs, some hundreds of meters across in size, of Cambrian limestone and dolomite; locally, the slabs show large-scale contortion (fig. 6*A*) and intense brecciation. Breccia zones have been thoroughly recemented with fine particles of Cambrian rocks. The underlying tuff has not been appreciably disturbed. A breakaway zone may be preserved along the east side of the north-central Drum Mountains, where small amounts of breccia crop out in an upthrown fault block of Cambrian rocks that contains the same formations as the breccia.

The megabreccia of the Drum Mountains was first identified as a late Tertiary gravity slide (Shawe, 1964) and later as a Quaternary landslide (Newell, 1971). According to both interpretations, the megabreccia overlies water-laid tuff of the youngest volcanic group. The tuff is considered by me to be the upper unwelded zone of the black glass tuff member of the Joy Tuff; this interpretation permits the megabreccia to be as old as 37 m.y. and within the age range of the breccia at Spor Mountain and Wildhorse Spring. The top of the tuff is nearly flat and has not been eroded; thus, sliding must have taken place soon after deposition of the tuff so that it was protected from erosion.

DELL TUFF

The name "Dell Tuff" was given (Lindsey, 1979a) to slightly welded, gray to pink, rhyolitic ash-flow tuff that crops out extensively in The Dell; the tuff appears to be a simple cooling unit. A section about 180 m thick is exposed at the north end of The Dell (fig. 8*A*). The Dell Tuff unconformably overlies the Drum Mountains Rhyodacite and landslide breccia at Spor Mountain and is unconformably overlain by stratified tuff and tuffaceous sandstone of the beryllium tuff member of the Spor Mountain Formation at the Yellow Chief mine, by the beryllium tuff and porphyritic rhyolite members of the Spor Mountain Formation elsewhere in The Dell, and by the Topaz Mountain Rhyolite at the



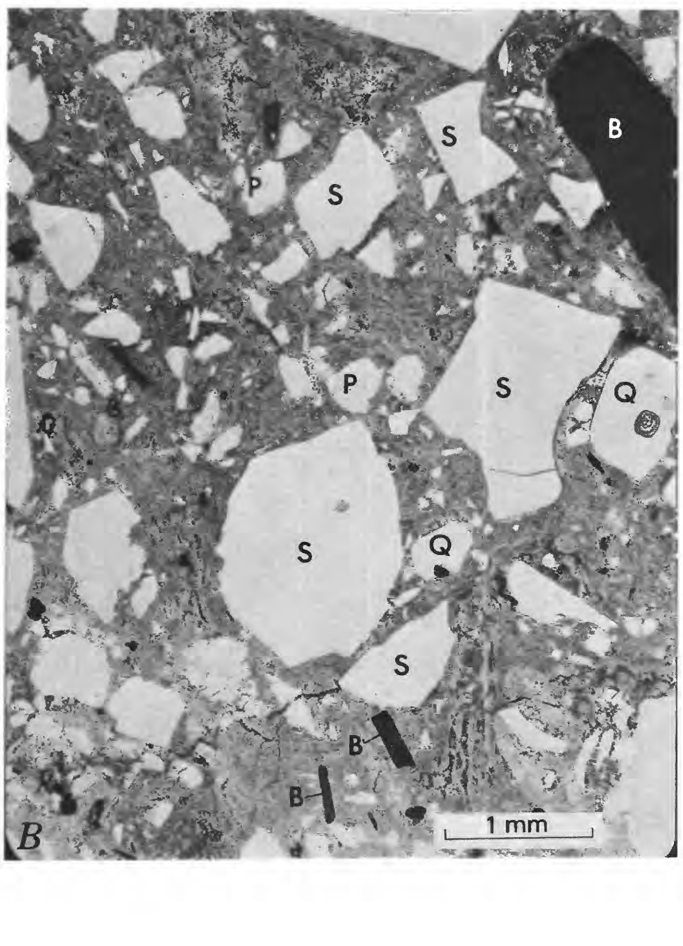


FIGURE 8.—The Dell Tuff. *A*, Type locality of the Dell Tuff, north end of The Dell (secs. 23 and 24, T. 12 S., R. 12 W.), showing Topaz Mountain Rhyolite unconformably overlying faulted Dell Tuff. Ttm, Topaz Mountain Rhyolite; Ttmt, stratified tuff in Topaz Mountain Rhyolite; Td, Dell Tuff; Pz, Paleozoic rocks; exposed faults shown by heavy solid lines; concealed faults shown by heavy dotted lines. *B*, Photomicrograph of the Dell Tuff, showing vitroclastic texture of devitrified shards and abundant crystals of quartz (Q), sanidine (S), plagioclase (P), and biotite (B). Plain light. Sample from SE$\frac{1}{4}$ sec. 2, T. 13 S., R. 12 W.

north end of The Dell. As much as 200 m of Dell Tuff crops out northeast of Keg Pass at Keg Mountain. There, it unconformably overlies the "Keg Spring andesite and latite" of Erickson (1963) and the Mt. Laird Tuff, and is unconformably overlain by stratified tuff and alkali rhyolite of the Topaz Mountain Rhyolite.

The source of the Dell Tuff has not been located. The tuff is limited to the Thomas Range and Keg Mountain, indicating that the source should be within or near these ranges. Intrusive rocks of about the same age and composition as the Dell Tuff occur as dikes northwest of Keg Mountain and in the granite facies of the stock of Desert Mountain.

The Dell Tuff was called quartz-sanidine crystal tuff by Staatz and Carr (1964, p. 80–81) because it contains large (5 mm or larger) euhedral crystals of quartz and sanidine and lesser amounts of plagioclase and brown biotite (fig. 8*B*). The tuff contains an average of 52 percent crystals (table 4). Minor euhedral magnetite and accessory allanite, sphene, apatite, and colorless zircon are present, also. The matrix consists of white pumice and shards that are only slightly welded. Tuff along the east side of The Dell and at Keg Pass is so poorly indurated that exposures weather to loose crystals in soft, ashy soil. Pumice and shards show both vapor-phase crystallization and devitrification textures, but hydrothermal fluids have partially altered some of the tuff to smectite and sericite and introduced minor amounts of fluorite. Chemical analyses show that the tuff has a rhyolitic composition.

NEEDLES RANGE(?) FORMATION

A simple cooling unit of ash-flow tuff that closely resembles the Wah Wah Springs Tuff Member of the Needles Range Formation crops out discontinuously along the west side of the Drum Mountains from the Sand Pass road southward to the Little Drum Mountains. It is also well exposed for 25 km south from the Little Drum Mountains through the Red Knolls and Long Ridge, where it forms long escarpments about 30 m high. The tuff was first identified in outcrops on the south flank of the Little Drum Mountains by Leedom (1974) and Pierce (1974), whose petrographic studies demonstrated its similarity to the Needles Range Formation. Ages reported here (table 3) are in accord with this correlation. Its thickness is difficult to judge but is probably near that of the 30 m estimated south of the Little Drum Mountains. The Needles Range(?) Formation is about 70 m thick in the subsurface south of The Dell, at the center of sec. 23, T. 13 S., R. 12 W., where it overlies about 25 m of Dell(?) Tuff and Drum Mountains Rhyodacite. The Needles Range(?) unconformably overlies lower Paleozoic rocks, Drum Mountains Rhyodacite, and Mt. Laird Tuff along the west side of the Drum Mountains, but it has not been observed in contact with the Joy and Dell Tuffs at the surface. The tuff fills valleys in Paleozoic dolomite and Drum Mountains Rhyodacite in secs. 23 and 26, T. 14 S., R. 12 W.

Tuff mapped as Needles Range(?) Formation is typically red brown and crystal rich, the crystals being small (1–2 mm) plagioclase (26–37 percent) of intermediate composition, conspicuous biotite (2–11 percent), small green-brown hornblende (6–13 percent), and minor resorbed quartz, magnetite, and hypersthene (fig. 9). Accessory minerals include apatite and colorless zircon; no sphene was observed. The matrix is glassy to devitrified pumice and shards that have been moderately welded. Collapsed black pumice and lithic inclusions of Mt. Laird Tuff occur in the lower part of the tuff as far south as the Little Drum Mountains and Long Ridge; the lithic inclusions are abundant in the drilled section of tuff south of The Dell. A few meters of tan, crudely stratified, loosely indurated tuff containing stones of Mt. Laird Tuff and Drum Mountains Rhyodacite crop out in the basal part of the Needles Range(?) Formation about 0.5 km south of the Sand Pass road.

The correct stratigraphic assignment of the tuff is still uncertain, although I assigned it to the Needles Range Formation (Lindsey, 1979a) because of the tuff's close resemblance, in petrography and age, to the Wah Wah Springs Tuff Member. The type locality of the Needles Range Formation is in southwestern Utah, about 150 km south of the Drum Mountains (Best and others, 1973; Cook, 1965). The Wah Wah Springs Tuff Member has been traced from its type locality as far north as the southern House Range (fig.

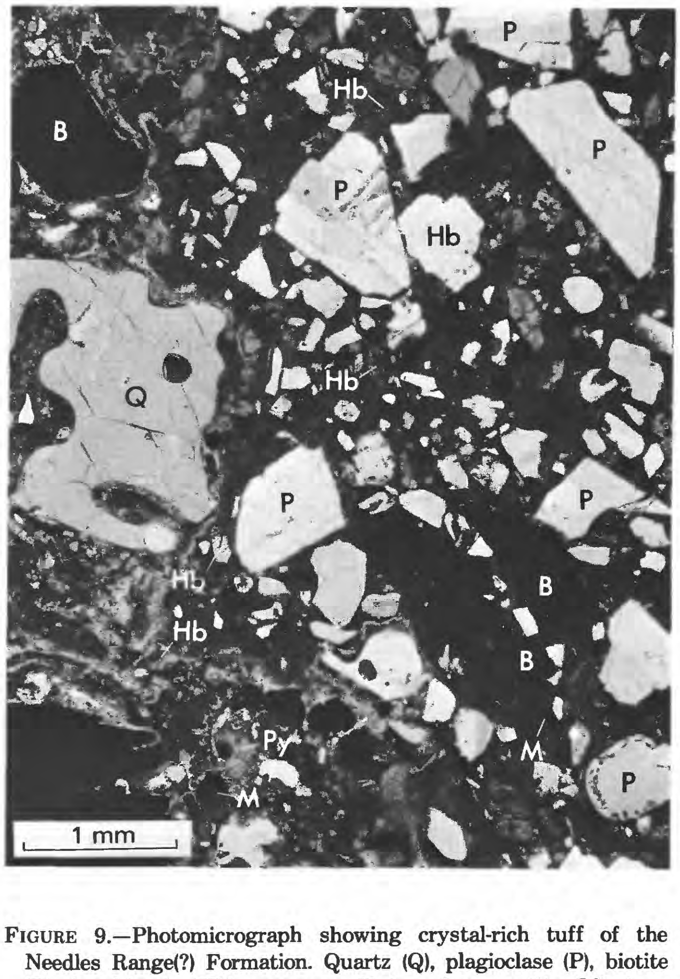


FIGURE 9.—Photomicrograph showing crystal-rich tuff of the Needles Range(?) Formation. Quartz (Q), plagioclase (P), biotite (B), hornblende (Hb), pyroxene (Py), and magnetite (M), in a matrix of devitrified shards. Crossed polars.

1), where I examined it in an effort to resolve the problem of correlation with tuff mapped as Needles Range(?) in the Drum Mountains. The two tuffs compare closely in general aspect and in petrography and mineralogy; only minor differences in lithic inclusions and preservation were noted. Lithic inclusions of Mt. Laird Tuff are, of course, not present in the tuff in the House Range, but they are noticeable at Long Ridge and in the Drum Mountains. The thickest section found to date by drilling just inside the Thomas caldera contains abundant inclusions of Mt. Laird Tuff, indicating a possible source within that structure. The possibility that the tuff is not Wah Wah Springs is also suggested by differences in paleomagnetic direction between the two tuffs (Shuey and others, 1976). Further study is needed to resolve the correlation of tuff mapped as Needles Range(?) in the Drum Mountains.

SPOR MOUNTAIN FORMATION

The Spor Mountain Formation consists of two informal members, the beryllium tuff and an overlying porphyritic rhyolite, both of which in most places occur together and are restricted to the vicinity of Spor Mountain. The beryllium tuff member contains all of the important deposits of beryllium and uranium discovered in the Spor Mountain area as of 1980, and the 21-m.y.-old porphyritic rhyolite is an important reference point for establishing the onset of alkali rhyolite volcanism, the maximum age of beryllium and uranium mineralization, and the maximum age of block faulting in this part of the Basin and Range Province. The close spatial association of the two members of the Spor Mountain Formation indicates that eruption of the porphyritic rhyolite followed soon after deposition of the beryllium tuff.

Angular unconformities separate the Spor Mountain Formation from older rocks (unconformity C) and from the younger Topaz Mountain Rhyolite (unconformity D) (table 1). The two members of the Spor Mountain Formation are conformable to one another. The beryllium tuff member unconformably overlies Paleozoic rocks, Drum Mountains Rhyodacite, and Joy Tuff (locally, in the subsurface only) west of Spor Mountain, and Drum Mountains Rhyodacite and Dell Tuff in The Dell. Unconformity C is partly of erosional origin as is evident from abundant detritus of older volcanic rocks in the beryllium tuff member in The Dell. Unconformity D is erosional as indicated by angular relationships in The Dell. There, the Spor Mountain Formation dips as much as 20° west along the east side of The Dell, where it is unconformably overlain by flat-lying Topaz Mountain Rhyolite.

BERYLLIUM TUFF MEMBER

About 60 m of the beryllium tuff member occurs beneath the porphyritic rhyolite member in drilled sections and beryllium mines south and west of Spor Mountain. In The Dell, about 60 m of the tuff, including bentonite and tuffaceous sandstone, is exposed beneath porphyritic rhyolite in the Yellow Chief mine, and a partial section of 22 m occurs at the Claybank prospect. Drilling in the southern part of The Dell showed that the beryllium tuff thins from about 60 m near Spor Mountain to thin, discontinuous lenses on the east side of The Dell.

The beryllium tuff member contains five facies: (1) tuffaceous breccia containing abundant clasts of altered and unaltered dolomite (fig. 10*A*, *B*), (2) thinly stratified tuff containing a few small lithic fragments (fig. 10*C*), (3) bedded, massive ash-flow tuff containing sparse to moderate lithic fragments, (4) bentonite composed mostly of altered pumice (fig. 10*D*), and (5) tuffaceous sandstone and conglomerate (fig. 10*D*). Detailed study of textures in the beryllium tuff member shows that much of facies 1 and 2 are block-flow, ash-flow, and ground-surge deposits (Bikun, 1980). The dominance of a particular facies varies from one section to another. Tuffaceous breccia containing distinctive dolomite clasts that have been hydrothermally altered to fluorite, clay, and silica minerals (Lindsey and others, 1973) grades laterally and vertically into ash-flow tuff and thinly stratified tuff containing sparse dolomite clasts in the vicinity of the beryllium mines. These facies persist eastward into The Dell, where tuffaceous breccia containing carbonate clasts comprises only a minor part of a section dominated by ash-flow tuff, bentonite, and tuffaceous sandstone and conglomerate. In The Dell, tuffaceous breccia containing altered dolomite clasts occurs in thin zones at the top of the tuff, as at the Hogsback prospect and the west side of the Yellow Chief pit; thin ash-flow tuffs are interbedded with bentonite at the Claybank prospect. The Yellow Chief mine section (modified from Bowyer, 1963) illustrates the composition of the beryllium tuff member in The Dell:

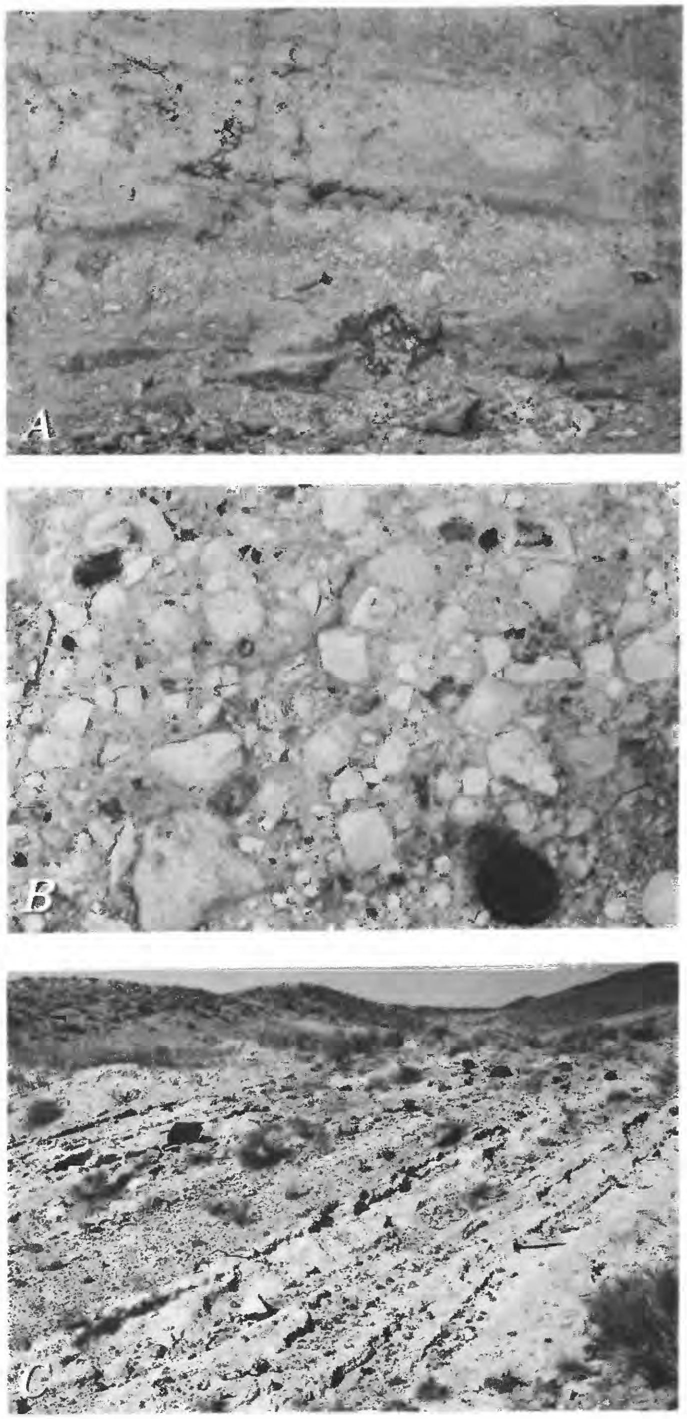
	Thickness in meters
Porphyritic rhyolite (southwest wall of pit only); top of section.	
Tuffaceous breccia with altered dolomite clasts	3
Bentonite	15
Limestone pebble and cobble conglomerate with tuffaceous sandstone matrix	2

	Thickness in meters
Tuffaceous sandstone with abundant quartz and sanidine derived from Dell Tuff	18
Tuffaceous conglomerate and sandstone; cobbles and boulders mostly rhyodacite	18
Stratified tuff containing volcanic-rock fragments (only exposed south of pit in 1977, 8 m reported by Bowyer, 1963, when pit was freshly dug)	8
Dell Tuff; bottom of section.	

A partial section at the Claybank prospect illustrates the marked local variation in thickness of tuffaceous sandstone and conglomerate in the lower part of the beryllium tuff member:

	Thickness in meters
Fault and remnants of mineralized tuffaceous breccia containing altered dolomite clasts; top of section.	
Bentonite	4
Massive ash-flow tuff containing volcanic-rock fragments	0.5
Bentonite	3
Massive ash-flow tuff containing volcanic-rock fragments and compacted pumice	2
Bentonite	7
Massive ash-flow tuff containing volcanic-rock fragments, minor quartzite, and compacted pumice	1.5
Tuffaceous sandstone containing abundant quartz and sanidine derived from Dell Tuff	5
Drum Mountains Rhyodacite; bottom of section.	

Studies of the beryllium tuff member by thin section and X-ray diffraction methods (Lindsey and others, 1973) show that most of the clasts in the tuff are dolomite from formations exposed on Spor Mountain, nodules derived from the alteration of dolomite to calcite, silica minerals, clay and fluorite, and fragments of volcanic rocks and of Ordovician Swan Peak Quartzite. Dolomite fragments dominate in the breccia facies, and volcanic rock fragments dominate in thinly stratified tuff and ash-flow tuff. The matrix of all three facies contains abundant pumice and shards that range from glassy to completely altered; diagenetic alteration formed clinoptilolite and possibly potassium feldspar, and hydrothermal alteration produced smectite, sericite, potassium feldspar, and cristobalite. About 10–20 percent broken crystals of quartz, sanidine, plagioclase, and biotite are scattered through the matrix.



PORPHYRITIC RHYOLITE MEMBER

The porphyritic rhyolite member crops out as flows in The Dell and south and west of Spor Mountain and as domes and small plugs that may have been the source of some of the flows and of the pyroclastic debris in the beryllium tuff member. The largest dome (6 km^2) is both intrusive and extrusive; it intruded the Drum Mountains Rhyodacite west of Wildhorse Spring and reached the surface, as judged from local lenses of beryllium tuff penetrated by drilling beneath the rhyolite nearby. The intrusive contact is well exposed in NE$\frac{1}{4}$ sec. 17, T. 12 S., R. 12 W. A small dome in sec. 10, T. 13 S., R. 12 W., is only 0.25 km^2 in area; it overrode an apron of stratified tuff. Only small remnants of the tuff apron have survived erosion; they are exposed in prospects at the northwest and southwest

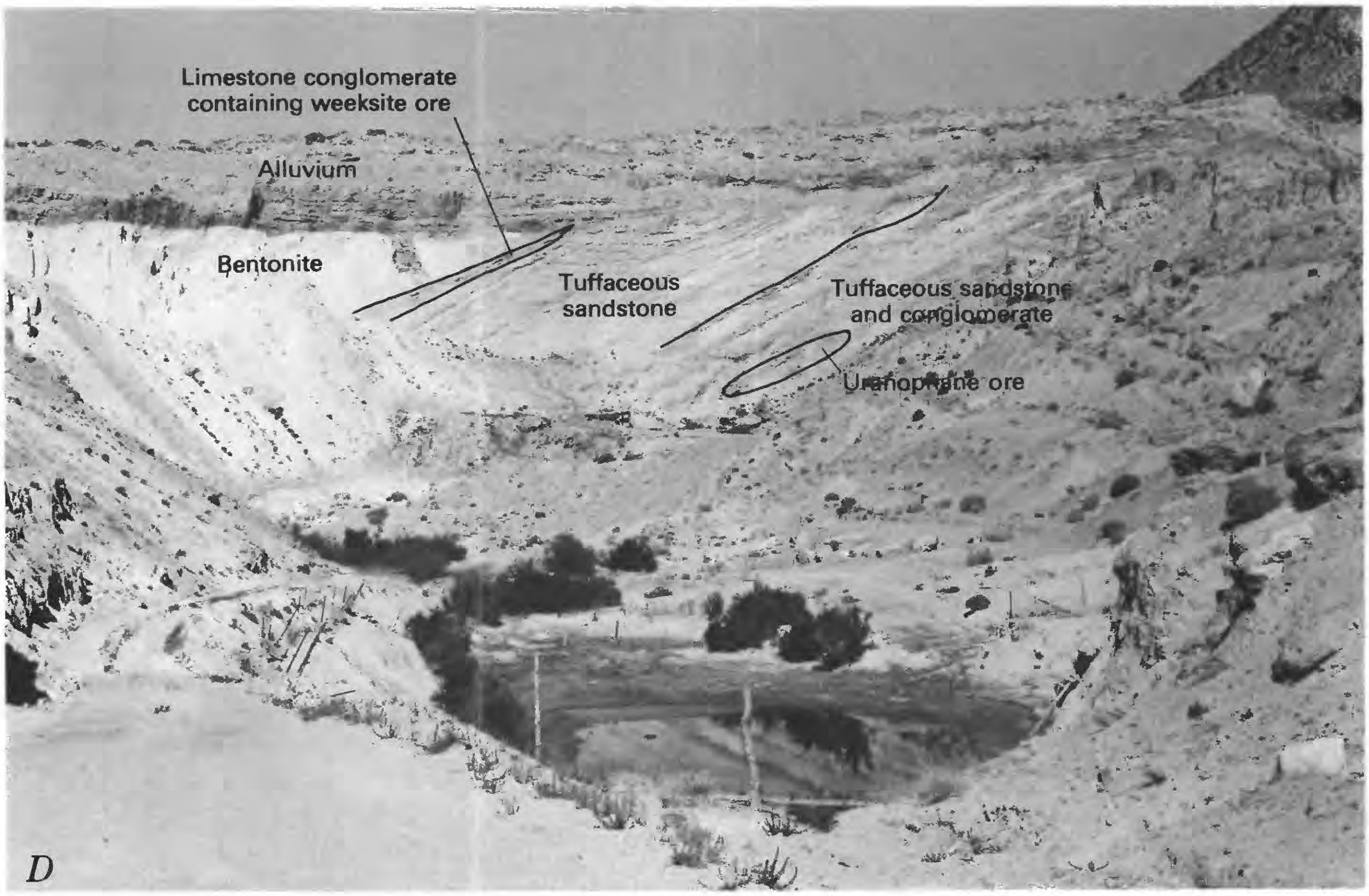


FIGURE 10.—Beryllium tuff member of the Spor Mountain Formation. *A*, Tuffaceous breccia containing abundant clasts of carbonate rock in the Monitor pit (sec. 7, T. 13 S., R. 12 W.). Pick shows scale. *B*, Closeup view of tuffaceous breccia containing clasts of carbonate rock. *C*, Thinly stratified tuff containing sparse clasts of volcanic and sedimentary rock, south of Blue Chalk pit (sec. 9, T. 13 S., R. 12 W.). *D*, Section showing bentonite and epiclastic tuffaceous sandstone and conglomerate at the Yellow Chief mine (secs. 25 and 36, T. 12 S., R. 12 W.).

sides of the dome. Both the tuff and the margin of the rhyolite dome have been incompletely altered to clay and uraniferous fluorite. Several small domes of porphyritic rhyolite occur along faults in The Dell; they are north of the Claybank prospect, south of the Yellow Chief mine, southeast of the Hogsback prospect, and perhaps east of the Oversight prospect (see fig. 15 for prospect locations). A large vent may underlie the Thomas Range east of The Dell, where more than 80 m of porphyritic rhyolite extends east beneath stratified tuff of the Topaz Mountain Rhyolite.

The porphyritic rhyolite contains abundant (average of 40 percent) phenocrysts of euhedral sanidine, quartz, plagioclase (andesine) and biotite; the phenocrysts are conspicuous (3 mm across) and distinguish the rhyolite from most of the Topaz Mountain Rhyolite (table 4). The dome west of Wildhorse Spring contains as much as 60 percent phenocrysts locally and quartz and sanidine phenocrysts as much as 5 mm across (fig. 11*A*). Sanidine phenocrysts are commonly chatoyant. Biotite occurs in the rhyolite as euhedral black phenocrysts containing abundant magnetite inclusions, in contrast to the ragged, red appearance of biotite in the Topaz Mountain Rhyolite. Small pink zircon occurs in trace amounts; the zircon is distinctive from that of older volcanic rocks in that it contains an average of about 10 times as much uranium. Southwest of Spor Mountain, the rhyolite contains numerous dark inclusions; the inclusions contain conspicuous (10–20 mm) large, zoned plagioclase crystals with vermicular intergrowths of plagioclase, potassium feldspar, and glass.

The groundmass of the porphyritic rhyolite, as seen under the microscope, is commonly a coarse-grained (0.1–0.2 mm) mosaic of crystals, although fine-grained and spherulitic textures are common, also. The groundmass consists mostly of potassium feldspar and cristo-

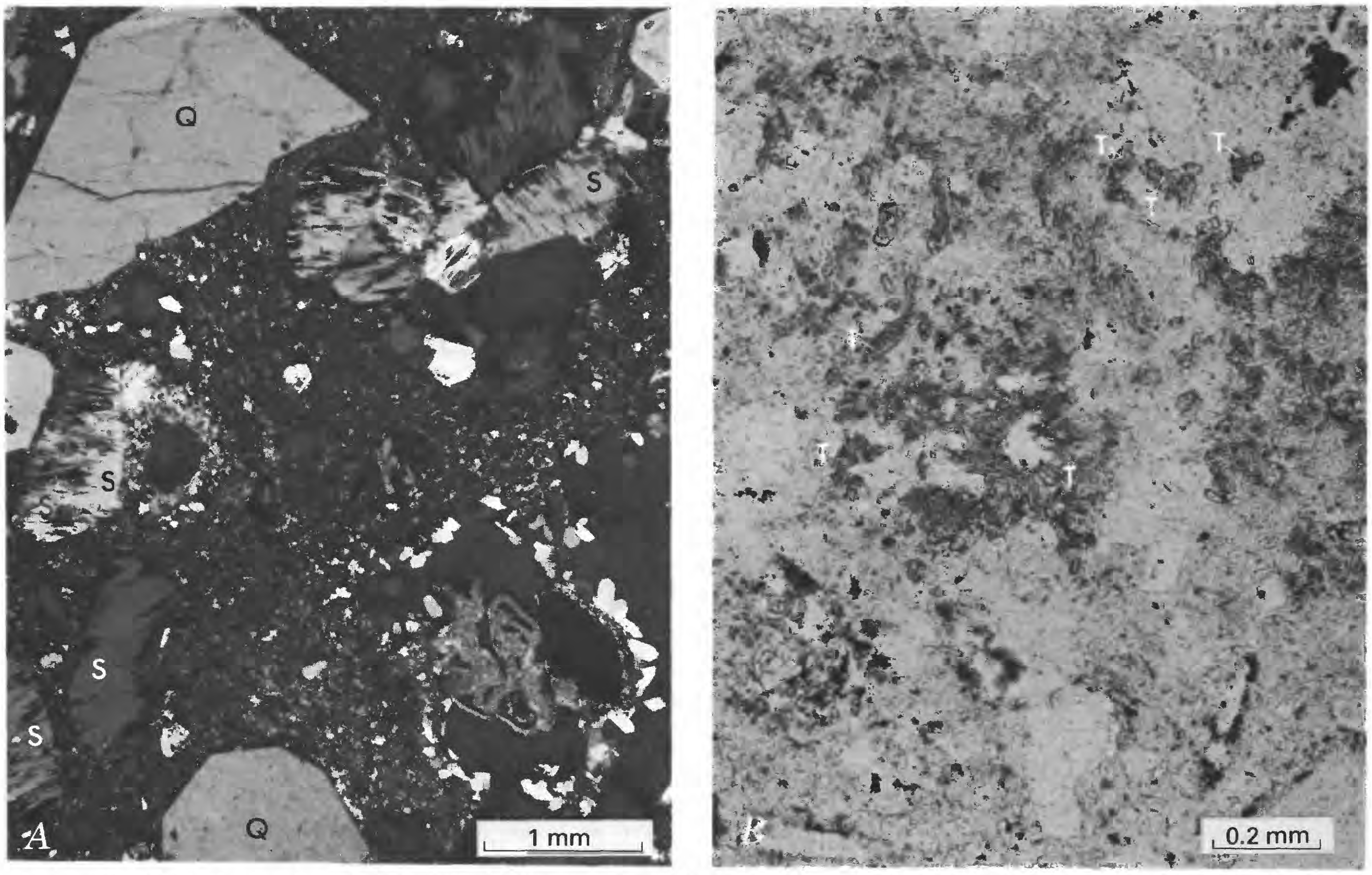


FIGURE 11.—Photomicrographs of porphyritic rhyolite member of the Spor Mountain Formation. *A*, Porphyritic rhyolite at Wildhorse Spring, showing abundant phenocrysts of quartz (Q) and perthitic sanidine (S). Crossed polars. Sample from sec. 9, T. 12 S., R. 12 W. *B*, Groundmass of porphyritic rhyolite, containing abundant acicular and prismatic topaz (high relief, labeled T). Plain light. Sample from Hogsback prospect, sec. 35, T. 12 S., R. 12 W.

balite and lesser disseminated magnetite, fresh gray-brown biotite, and cavity fillings of quartz and topaz (fig. 11*B*). The groundmass biotite is unique because it is completely fresh and free of magnetite; it occurs also as overgrowths on the earlier formed biotite phenocrysts, which are brown and filled with magnetite inclusions. Chemical analyses show that the porphyritic rhyolite is borderline between rhyolite and alkali rhyolite in the classification of Rittmann (1952). The rhyolite is clearly allied to the younger Topaz Mountain Rhyolite; both have high alkali and fluorine contents and anomalous traces of beryllium, lithium, niobium, tin, thorium, uranium, and yttrium.

TOPAZ MOUNTAIN RHYOLITE

The Topaz Mountain Rhyolite is a large complex of alkali rhyolite flows, domes, and interbedded local units of stratified tuff. The entire complex unconformably overlies older volcanic rocks that have been faulted and tilted. Unconformities are also present beneath stratified tuff that separates older from younger flows of the Topaz Mountain Rhyolite. These unconformities do not show visible angular discordance and may be constructional in part, but paleotopography is clearly visible beneath stratified tuff at Topaz Mountain and in the upper reaches of Pismire Wash. Radiometric dates indicate quiescent intervals, of perhaps 100,000 years on Topaz Mountain to perhaps 500,000 years in Pismire Wash, between eruption of major flows and domes.

The Topaz Mountain Rhyolite contains distinctive sequences of lithologies (fig. 12*A*) that are repeated several times in vertical sections; the sequence is stratified tuff, breccia, vitrophyre, and flow-layered rhyolite (Staatz and Carr, 1964, p. 86–90). Flows that extend several kilometers or more are commonly underlain by stratified tuff, whereas some domes and short flows have only breccia or vitrophyre at their bases. Staatz and Carr (1964) divided the Topaz Mountain Rhyolite into five subgroups having implied lateral continuity, but my mapping shows that each subgroup is actually a complex of flows and domes derived from numerous vents. Flows and domes have been mapped separately by me (Lindsey, 1979a) as far as was practical, but the location of the contacts between adjacent flows remains obscure in many places.

FLOWS AND DOMES OF ALKALI RHYOLITE

Flows and extrusive domes of alkali rhyolite have been mapped and their vent areas identified on the basis of lines of viscous flowage and shearing (fig. 12*B*). These flowage lines are visible on aerial photographs and were identified on the ground as lenses of steeply dipping vitrophyre and layered rhyolite. Large flows were erupted from the vent on Topaz Mountain and another vent in the northeastern Drum Mountains; each flow extends west-southwest about 4 km from the vent. A complex of at least four domes and short flows was erupted from separate vents along Antelope Ridge. Other vents are north and south of Colored Pass and north of Pismire Wash. Much of the rhyolite between Topaz Mountain and Pismire Wash issued from a fissure vent that is clearly discernible on aerial photographs as a lineament bounded by subparallel flow lines. Some of the vents were first located by Staatz and Carr (1964), who measured the attitude of flow layering throughout the rhyolite. These attitudes and additional observations by me were used to confirm the orientation of flow lines seen on aerial photographs.

Vitrophyre and rhyolite evidently accumulated to considerable heights around vents and then spread laterally under their own weight and by force from injection of new lava within vents, producing concentric flowage lines of sheared vitrophyre and flow-layered rhyolite. Williams (1932, p. 142–145) described a similar origin for the dacite domes of Lassen Peak, Calif. Vitrophyre zones in the Topaz Mountain Rhyo-

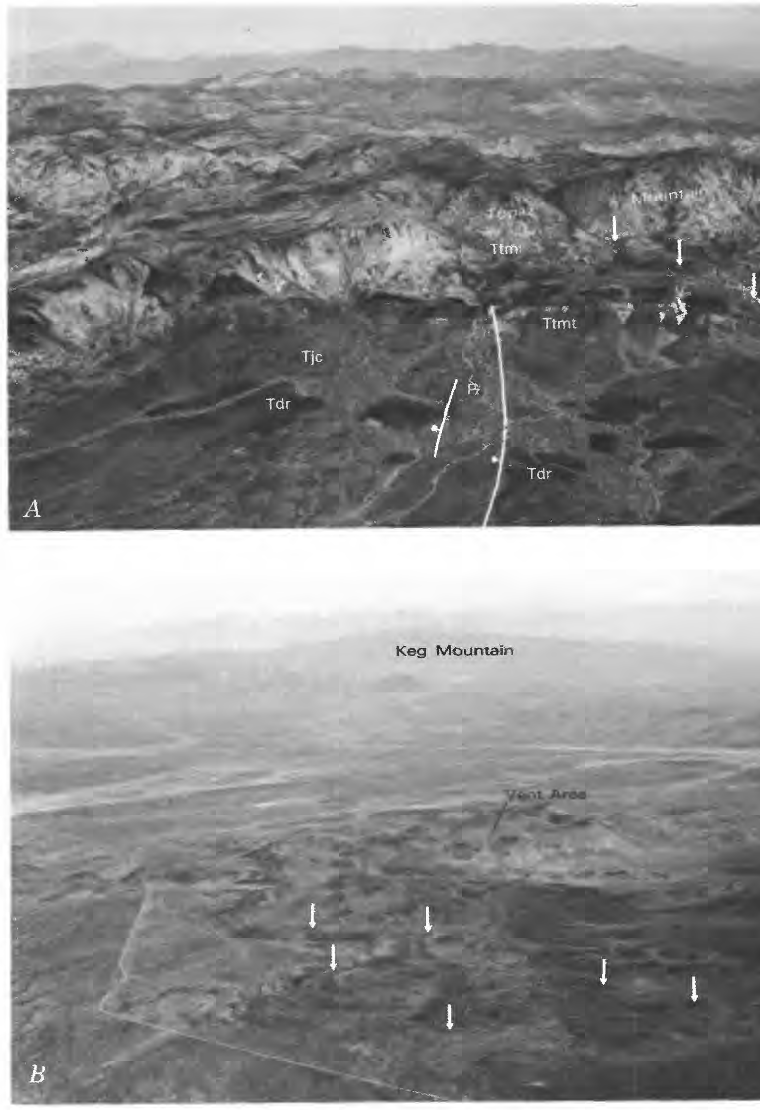


FIGURE 12.—Topaz Mountain Rhyolite. *A*, Aerial view looking north at Topaz Mountain, showing section of stratified tuff (Ttmt), vitrophyre (V), and alkali rhyolite (Ttmr) that issued from vent on top of Topaz Mountain. Crystal tuff member of Joy Tuff (Tjc) and Drum Mountains Rhyodacite (Tdr) downdropped to west along the east side of Joy graben by the Topaz Mountain fault (bars and balls indicate downthrown sides of subsidiary faults), which is covered by Topaz Mountain Rhyolite (Ttmt and Ttmr) on Topaz Mountain, and lineament of buried Topaz Valley fault (arrows); Pz, Paleozoic rocks. *B*, Aerial veiw looking northeast at isolated flow of alkali rhyolite in northeastern Drum Mountains (centered at sec. 7, T.14 S., R. 10 W.), showing alinement of dark lenses of vitrophyre (arrows) that are concentric around the vent area.

lite were formed at the outer chilled margin of each succeeding injection of lava. Lenses of vitrophyre and parallel flow layering in rhyolite dip steeply; in short flows and in domes, the dip is generally toward the vent, but in larger flows and in flows between vents the dip of layering may be either toward or away from the vent. Horizontal lineations, perpendicular to the overall direction of flowage and in the plane of layering, are common in some flows; lineations are defined by rod-shaped vesicles and sets of parallel striations in both vitrophyre and rhyolite. Rhyolite on Antelope Ridge evidently cooled prior to flowage because it contains vesicles with geopetal structures of layered silica which were originally deposited in horizontal position but which now dip steeply toward the vent. The rhyolite also contains many small-scale flowage folds that vary considerably in attitude; these folds probably formed near the vent and became reoriented during outward spreading of the rhyolite.

The Topaz Mountain Rhyolite typically contains about 13 percent phenocrysts that consist mainly of euhedral sanidine, partially resorbed quartz, and lesser amounts of red oxidized biotite and plagioclase (table 4). Small flows and domes in Dugway Valley and at Antelope Ridge contain as much as 37 percent phenocrysts. The groundmass is composed entirely of fine-grained quartz, cristobalite, potassium feldspar, and scattered tiny grains of calcite and specular hematite. Traces of zircon of high uranium content (as much as 11,000 ppm) occur as tiny (0.05–0.10 mm), subround, gray to pink grains. Cavities filled with vapor-phase quartz, opal, and topaz are common, and locally these cavities contain fluorite, pink beryl, garnet, bixbyite, and pseudobrookite (Staatz and Carr, 1964, p. 102–108). Both mosaic and spherulitic groundmass textures are common. Chemical analyses show that most of the flows and domes are alkali rhyolite. The distinctive composition of the rhyolite—anomalous fluorine, beryllium, lithium, niobium, uranium, thorium, and yttrium—has been noted often (Staatz and Griffitts, 1961; Shawe, 1966; Lindsey, 1977).

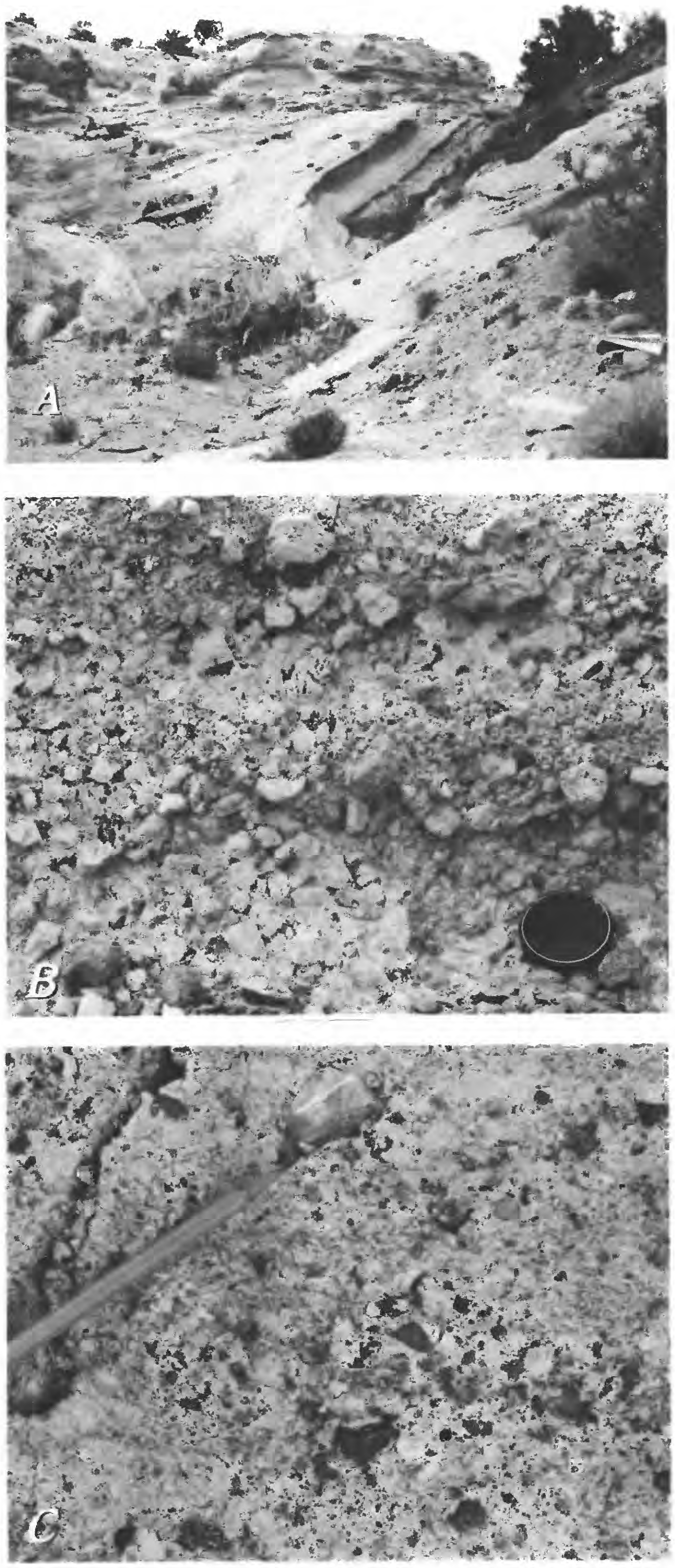


FIGURE 13.—Stratified tuff in the Topaz Mountain Rhyolite. *A*, Stratified tuff filling paleovalley in Joy Tuff east of Topaz Valley (sec. 9, T. 13 S., R. 11 W.). Inclination of strata is believed to result from initial dip and compaction. *B*, Pumice and scattered dark obsidian fragments in air-fall tuff on Antelope Ridge (sec. 13, T. 13 S., R. 11 W.). *C*, Angular fragments of volcanic rock and limestone (at pencil point) in tuff west of Topaz Valley (sec. 16, T. 13 S., R. 11 W.).

STRATIFIED TUFF

Stratified tuff occurs at many places beneath flows of alkali rhyolite in the Thomas Range. At any one section, the tuff is overlain by breccia, vitrophyre, and alkali rhyolite flows. The tuff units are rarely more than 30 m thick and vary greatly in thickness over short distances; the thickest sections occur in paleovalleys over older formations and flows of Topaz Mountain Rhyolite. A paleosurface having more than 30 m of relief (fig. 13*A*) was developed on older alkali rhyolite, the Joy Tuff, and Paleozoic rocks beneath Topaz Mountain.

Detailed study of textures and structures in the tuff indicates deposition by air fall, ash flow, and ground surge (Bikun, 1980). Massive to stratified tuff consisting mostly of pumice is probably of air-fall origin (fig. 13*B*); such air-fall tuffs are abundant in the southern part of The Dell. Massive unsorted beds of pumice and lithic fragments (top of fig. 13*A*, fig. 13*C*) in tuff around Topaz Mountain resemble thin ash-flow tuffs described by Sparks and others (1973). The tuff has been interpreted previously as a water-laid deposit (Shawe, 1972; Lindsey, 1977) because of extensive stratification (fig. 13A), abundant clasts derived from underlying formations (fig. 13*C*), and unconformities at the base of the tuff. Epiclastic tuffaceous sandstone containing abundant quartz and sanidine derived from the Dell Tuff comprises most of the tuff $1\frac{1}{2}$ km north of Wildhorse Spring; such sandstone is probably water laid. Angular fragments of older volcanic rocks as large as 1 m in diameter are locally abundant in the tuff (Lindsey, 1975, fig. 3*B*); these may have been blasted from nearby vents or washed into the tuff from nearby paleohills.

The uppermost few meters of tuff are reddened and fused to welded tuff by overlying flows of alkali rhyolite. This fusing contrasts with the welding of ash-flow tuffs, which generally are most densely welded toward the middle and lower parts of cooling units. Similar fused tuffs beneath rhyolite flows have been described from southern Nevada (Christiansen and Lipman, 1966).

Pumice and shards are the dominant constituents of the tuff (fig. 13*B*); these accompany variable amounts of mostly volcanic rock fragments (fig. 13*C*) and less than 20 percent broken crystals consisting of quartz, sanidine, plagioclase, biotite, and traces of heavy minerals. Some of the tuff is glassy, but large areas have been altered by diagenesis to clinoptilolite, potassium feldspar, and cristobalite. Chemical analyses indicated that the tuff has a rhyolitic composition that, before diagenesis, was probably very close to the composition of the alkali rhyolite. Additional details of the mineral and chemical composition of the tuff have been reported elsewhere (Lindsey, 1975).

STRUCTURAL GEOLOGY

The Thomas Range and northern Drum Mountains are part of a caldera complex that has been extensively modified by basin-and-range block faulting. The Thomas caldera (Shawe, 1972) is the major structural feature of the area (fig. 2); its western outline is delineated by the ring fracture zone of the Joy fault and the Dell fault system, and by faults now buried beneath Topaz Mountain Rhyolite in the Thomas Range. The remainder of the caldera margin has been projected in the western part of Keg Mountain (Shawe, 1972), outside the area of this study. The Thomas caldera contains, nested within it, the younger Dugway Valley cauldron. The Dugway Valley cauldron, whose topographic expression is now obscure, underlies much of Dugway Valley; its western margin is marked by faults and landslide deposits in the northeastern Drum Mountains, but its east side has not been located. The margin of a third cauldron may account for landslide deposits north of Spor Mountain, but other evidence for its existence is lacking. Basin-and-range structures cut across the caldera complex; two of the most prominent are the Joy graben and the horst of the north-central Drum Mountains. Highlands at Spor Mountain and the northwestern and central Drum Mountains compose the rim of the caldera complex; these also have been modified by basin-and-range faulting.

Outlines of the Thomas caldera and the Dugway Valley cauldron are based partly on the distribution of exposed and buried faults and partly on the thickness and distribution of ash-flow tuffs and landslide deposits. In other well-studied caldera complexes, such as those of the San Juan Mountains (Steven and Lipman, 1976) and southern Nevada (Byers and others, 1976), ash-flow tuffs associated with caldera collapse ponded to great thicknesses within the source caldera but are thin or absent outside the margin of the caldera; landslides along the caldera margins left lenses of breccia and megabreccia interbedded with the intracauldron ash flows (Lipman, 1976). All of these features have been identified within the Thomas caldera and Dugway Valley cauldron, and are used here to establish the extent and history of cauldron subsidence.

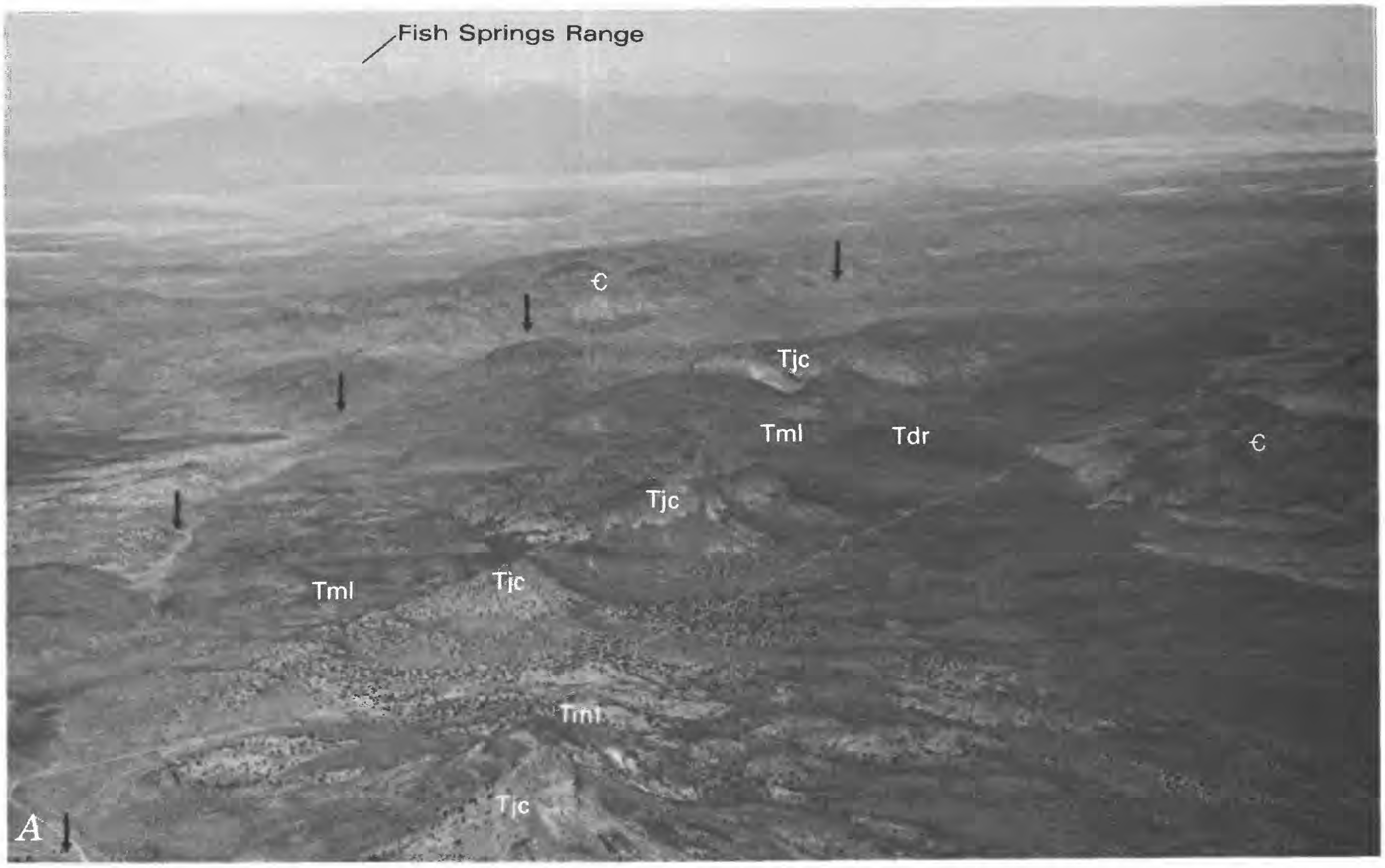
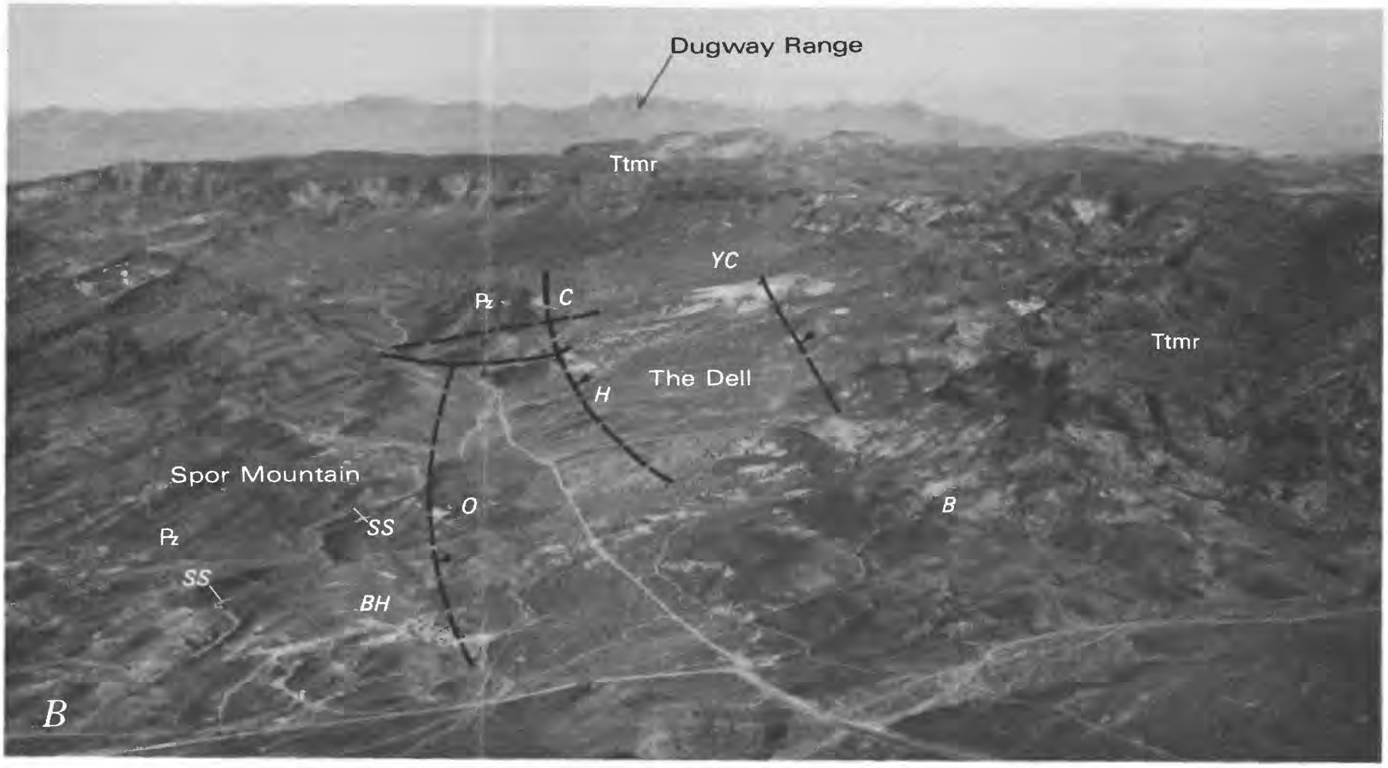


FIGURE 14.—Aerial views of the ring-fracture zone of the Thomas caldera, showing the Joy fault and its northward extension in The Dell. *A*, View looking northwest from above Joy townsite, showing the arcuate trace of the Joy fault (arrows) and the caldera rim of the northwestern Drum Mountains. €, Cambrian sedimentary rocks; Tdr, Drum Mountains Rhyodacite; Tml, Mt. Laird Tuff; Tjc, crystal tuff member of Joy Tuff. *B*, View looking north at The Dell, showing The Dell fault system, remnant of the caldera rim of tilted Paleozoic rocks on Spor Mountain, and the location of mines and prospects, which are the Yellow Chief mine (YC), Bell Hill Mine (BH), Claybank (C), Hogsback (H), Oversight (O), and Buena No. 1 (B). Location of superposed stream (SS) may mark the position of The Dell drainage system during time of unconformity C and deposition of the beryllium tuff member of the Spor Mountain Formation. Pz, undifferentiated Paleozoic rocks; Ttmr, Topaz Mountain Rhyolite.

The faulted structure of the caldera complex, also including postcaldera basin-and-range faults, has been revealed by mapping of numerous lineaments in the alluvium and the Topaz Mountain Rhyolite (fig. 2). These lineaments are interpreted as concealed faults; little or no offset is visible in alluvium and Topaz Mountain Rhyolite along most of the lineaments, but the lineaments are visible on aerial photographs as a result of slight fault movement, compaction, or settling of the covering unit. Many of the lineaments pass into well-exposed faults in rocks older than the Topaz Mountain Rhyolite, thus confirming their identification as concealed faults. Fracturing and small offsets are visible along lineaments in Topaz Mountain Rhyolite at Colored Pass and east of Topaz Mountain, as noted also by Staatz and Carr (1964).

THOMAS CALDERA

The Thomas caldera began to subside about 39 m.y. ago in response to eruption of the Mt. Laird Tuff from vents in the northern Drum Mountains. More than 500 m of Mt. Laird Tuff and interbedded lacustrine sediment accumulated in a depression as much as 15–25 km across. Later eruptions of the Joy Tuff (38 m.y. ago) and the Dell Tuff (32 m.y. ago) largely filled the caldera, and local cauldron collapse in Dugway Valley and perhaps north of Spor Mountain modified the Thomas caldera. In the Thomas Range and Drum Mountains, the western half of the Thomas caldera is well-defined by (1) the ring-fracture zone of the Joy fault and the Dell fault systems, (2) the caldera wall-collapse breccia at Spor Mountain, and (3) the confine-



ment of most of the post-subsidence Joy and Dell Tuffs within the caldera.

Initial subsidence of the Thomas caldera is believed to have accompanied eruption of the Mt. Laird Tuff about 39 m.y. ago. The source of the Mt. Laird Tuff was near Joy townsite, as indicated by tuff breccias associated with probable vents there and by intrusive plugs and dikes resembling Mt. Laird Tuff in the Drum Mountains south of Joy townsite. The intrusive equivalents may represent resurgence of Mt. Laird magma outside the caldera, but none occurs within the caldera or in the ring fractures. Subsidence of the caldera was most pronounced in Dugway Valley, where numerous ash flows of the Mt. Laird Tuff flowed into a lake, leaving more than 500 m of tuff and lacustrine sediments.

The south and west walls of the Thomas caldera are defined by an extensive system of ring fractures, faults, and lineaments that extend nearly the entire length of the mapped area (figs. 14*A*, *B*). The ring fracture of the caldera is exposed as the Joy fault in the Drum Mountains, where it has both a structural and topographic expression. The Joy fault is exposed only in a few prospects in jasperoid and iron-stained Cambrian rocks near Joy townsite. The Joy fault connects with the Dell fault system along the east side of Spor Mountain (figs. 14*B*, 15) and extends northward beneath the Topaz Mountain Rhyolite as a system of lineaments. Lineaments in alluvium near the junction of the beryllium road and the Sand Pass Road and in Topaz Mountain Rhyolite, 2 km northwest of the road junction, may be the surface expression of buried faults in the ring-fracture zone where it extends northward into The Dell. All northerly trending faults mapped in The Dell are downthrown on the east side, indicating that they form part of a complex, steplike boundary on the west side of the Thomas caldera at this locality (fig. 15). The buried northwest corner of the caldera may be quite angular, as indicated by prominent intersecting north- and east-trending buried faults in the northern part of the Thomas Range.

There is good evidence that the ring fracture and topographic wall of the Thomas caldera existed as early as 38 m.y. ago. The 38-m.y. crystal tuff member of the Joy Tuff is completely confined to the east side of the Joy fault and does not occur on the west side of the Drum Mountains, where the Needles Range(?) Formation lies directly on the Mt. Laird Tuff. The distribution of the Joy Tuff indicates ponding against the scarp of the Joy fault 38 m.y. ago. A small occurrence of Joy Tuff has been found by drilling in the subsurface of Fish Springs Flat west of Spor Mountain, however, indicating that the caldera wall did not block

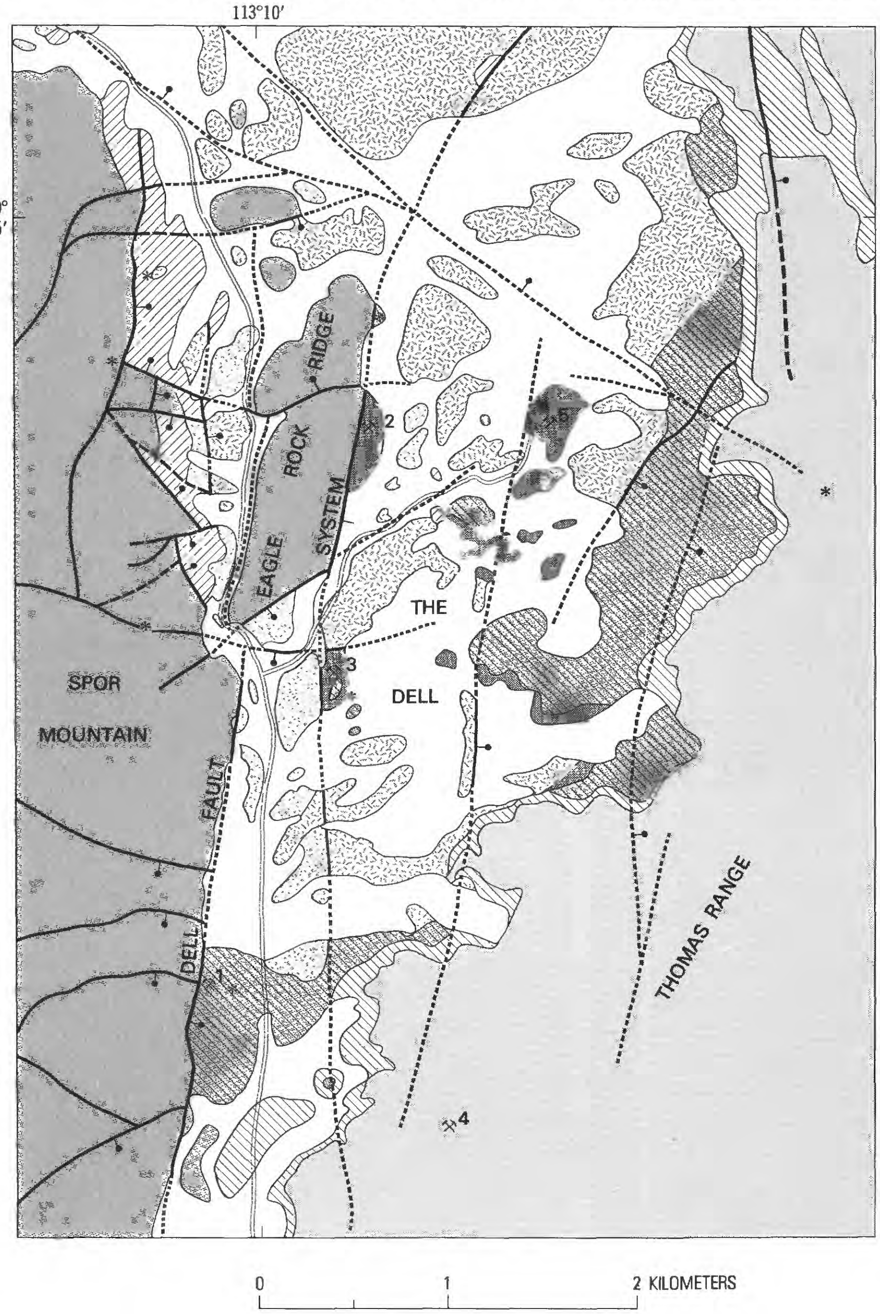


FIGURE 15.—Geologic map of The Dell, showing the setting of uranium mines and prospects (modified from Lindsey, 1978b). Base from U.S. Geological Survey orthophotograph taken in 1976 and enlarged to 1:40,000.

all westward flow of ash north of the Drum Mountains. Some movement of the Joy fault occurred after 38 m.y. ago, as indicated by faulted contacts of the Joy Tuff.

The ring fracture of the Thomas caldera has a long history of movement in The Dell; here, movement can be inferred or documented between 42 and 32 m.y. ago, 32 and 21 m.y. ago, and 21 and 7 m.y. ago (fig. 15). Reinterpretation of the breccia at Spor Mountain as a landslide deposit that may have formed along a fault scarp between 42 and 32 m.y. ago indicates that this part of The Dell fault system was active at that time. Restriction of the Dell Tuff to the east side of Spor

Mountain indicates ponding against the scarps of the Dell fault system 32 m.y. ago. Faults of the Dell system cut the Dell Tuff and older rocks throughout The Dell; they cut the Spor Mountain Formation in the central part of The Dell but are seen as lineaments covered by the Spor Mountain Formation in the southern part of The Dell (fig. 15). These relationships are interpreted to mean that the faults moved prior to 21 m.y. ago, probably during collapse of the Thomas caldera, and were rejuvenated in some sections during basin-and-range faulting after 21 m.y. ago.

DUGWAY VALLEY CAULDRON

The Dugway Valley cauldron is defined by (1) an area of vent breccias in the crystal tuff member of the Joy Tuff north and east of Topaz Mountain, (2) restriction of the black glass tuff member of the Joy to an area south of the vent breccias, and (3) the occurrence of faults and landslide breccias along the cauldron margin in the northeastern Drum Mountains (fig. 2). The Dugway Valley cauldron contains much greater thicknesses of volcanic rocks than the western segment of the Thomas caldera. The center of the Dugway Valley cauldron lies northeast of Antelope Ridge; the west side of the cauldron consists of three fault blocks that are downthrown stepwise into Dugway Valley. The Topaz Valley fault marks the west side of the faulted blocks and extends north beneath Topaz Mountain. The Antelope Ridge west fault is exposed in the northeastern Drum Mountains, where it dropped the black glass tuff member of the Joy Tuff and the overlying landslide megabreccia of the northern Drum Mountains down on the east side. The fault extends north in the subsurface west of Antelope Ridge. The Antelope Ridge east fault extends south from Antelope Ridge into the subsurface. The northwestern extent of the margin of the Dugway Valley cauldron is problematical, but it may extend northward from Topaz Mountain and then eastward, encircling Dugway Valley. Faults in the western part of the Keg Mountain area, mapped by Shawe (1972) as the east side of the Thomas caldera, may also mark the east side of the Dugway Valley cauldron.

The Dugway Valley cauldron collapsed 38 m.y. ago during eruption of the Joy Tuff from vents along the western side of Dugway Valley. Large areas of tuff breccia in Joy Tuff along the west margin of the Dugway Valley cauldron probably formed during simultaneous eruption and collapse. After eruption of the black glass tuff member of the Joy Tuff, which was restricted to the Dugway Valley cauldron, the west wall of the cauldron collapsed and slid over the cauldron fill of Joy Tuff, forming the megabreccia of the northeastern Drum Mountains.

BASIN-AND-RANGE STRUCTURE

Faults that formed during early development of basin-and-range structure in Miocene time are widespread in the Thomas Range and northern Drum Mountains and have modified the caldera structure extensively. Modification was accomplished by rejuvenation of earlier faults that were formed during cauldron subsidence and by initiation of new, north-trending faults. As a result of early basin-and-range faulting, the Joy graben and an adjacent horst in the north-central Drum Mountains probably were formed. Numerous faults of early basin-and-range age cut the rim outside the Thomas caldera.

The Joy graben was formed partly by subsidence of the Thomas caldera and partly by basin-and-range faulting. All of the structures associated with the ring fracture of the Thomas caldera, such as the Joy fault and the Dell fault system, were formed during caldera subsidence. The Dell fault system was rejuvenated after 21 m.y. ago, as shown by large offsets of the Spor Mountain Formation. The east side of the Joy graben and the adjacent horst of the north-central Drum Mountains probably were formed during early basin-and-range faulting. The age of the horst is a problem for the caldera model; the horst had to be absent for caldera-filling ash flows of the Joy Tuff to travel west across the present location of the horst to the caldera wall, but a highland had to exist soon after eruption of the Joy Tuff so that the landslide megabreccia of the northeastern Drum Mountains could slide over the Dugway Valley cauldron. The eastern side of the Joy graben is defined by the Schoenburger Spring fault, which strikes northwest and intersects the north-trending Topaz Mountain fault in the north-central Drum Mountains. The Topaz Mountain fault passes beneath the Topaz Mountain Rhyolite (fig. 12*A*), where it is alined with a system of lineaments and vents in rhyolite that extends north into the Dugway Range, a distance of about 20 km. These structures cut across the caldera and therefore are considered to be of basin-and-range origin.

The rim of the Thomas caldera contains numerous faults of early basin-and-range age. Almost all major faults on Spor Mountain, whatever their trend, extend beyond the Paleozoic rocks and cut the Spor Mountain Formation and volcanic rocks of Oligocene and Eocene ages (figs. 2 and 15). Previous mapping did not show offset of volcanic rocks by many faults, so only a few faults were assigned a Tertiary age (Staatz and Carr, 1964, p. 128–129). Faulting of early basin-and-range age is most evident around the beryllium mines southwest of Spor Mountain, where northeasterly and easterly trending high-angle normal faults displace the Spor Mountain Formation by as much as 200 m or more, throwing the beryllium tuff and porphyritic rhyolite members into large blocks that have been tilted 15°–30° northwest. East of Spor Mountain, easterly and northeasterly trending faults extend into The Dell, where they cut volcanic rocks as young as the Spor Mountain Formation, also. The Drum Mountains are traversed by many westerly, northwesterly, and northerly trending faults, some of which offset rocks of Tertiary age. Faults cut the Drum Mountains Rhyodacite at many places southwest of Joy townsite. South of the Sand Pass Road, faults cut rocks as young as the Needles Range(?) Formation.

Basin-and-range faulting was accompanied by voluminous eruptions of alkali rhyolite. The first eruption, of the Spor Mountain Formation 21 m.y. ago, predated most basin-and-range faulting, although the two may have been closely related. After most early basin-and-range faulting had ceased, the Topaz Mountain Rhyolite was erupted 6–7 m.y. ago. Basin-and-range faults, and earlier faults rejuvenated by basin-and-range faulting, were a major influence on the locus of eruption of the Topaz Mountain Rhyolite. Numerous vents in the Topaz Mountain Rhyolite are at or near fault intersections beneath the rhyolite; these include vents in the north-central Thomas Range, south of Colored Pass, on Topaz Mountain (fig. 12*A*), on Antelope Ridge, and in the northeastern Drum Mountains (fig. 12*B*). Vents north of Colored Pass and in the northeastern part of the Thomas Range occur near faults or along their projections beneath rhyolite. The vent north of the head of Topaz Mountain was a fissure; the extent of the fault is still visible as an east-west lineament between subparallel flow lines in rhyolite. Only minor block-faulting continued after eruption of the Topaz Mountain Rhyolite.

STRUCTURAL EVOLUTION

The structural evolution of the Thomas Range and Drum Mountains during part of Tertiary time can be inferred from the distribution of volcanic rocks and the age of fault movements, as already discussed. The evidence has been integrated in a series of maps depicting the most probable structural evolution of the region (fig. 16), although evidence for the existence and age of some events is lacking or equivocal. It must be emphasized that the degree of confidence in the maps decreases for those showing earlier events; the maps of Eocene and Oligocene time are partly conjectural, and those for Miocene time are mainly factual.

The map of the time of unconformity B (fig. 16*A*), about 38–39 m.y. ago, reflects the eruption of the Mt. Laird Tuff and accompanying subsidence of the Thomas caldera. Both the Mt. Laird Tuff and accompanying lacustrine sediments accumulated in Dugway Valley, whereas the tuff was erupted over a wide area beyond the caldera margin. Eruption of the Mt. Laird Tuff followed eruption of flows, breccias, and tuffs from small central volcanoes in the Black Rock Hills and the Little Drum Mountains, and possibly from fissures in the Thomas Range and Drum Mountains. The Joy Tuff had not been erupted yet.

The Thomas caldera was filled with the mostly intracauldron Joy and Dell Tuffs 38–32 m.y. ago (figs. 16*B* and 16*C*). Eruption of the Joy Tuff 38–37 m.y. ago was accompanied by subsidence of the Dugway Valley cauldron, a subsidiary depression nested within the larger Thomas caldera. This subsidence left a segment of the Thomas caldera as a high rim relative to the Dugway Valley cauldron; the rim collapsed and slid over the west side of the cauldron after 37 m.y. ago (fig. 16*B*). Also, between 42 and 32 m.y. ago the wall of the Thomas caldera at Spor Mountain collapsed; this event may have accompanied initial subsidence of the Thomas caldera or may reflect additional subsidence of the caldera during eruption of the Joy Tuff. Filling of the Thomas caldera was completed 32 m.y. ago by eruption of the Dell Tuff from an unknown source within the Thomas caldera (fig. 16*C*). The Dell Tuff covered some of the landslide breccia at Spor Mountain and ponded against scarps of the Dell fault system.

The interval between deposition of the intracauldron ash-flow tuffs (about 32 m.y. ago) and the Spor Mountain Formation (21 m.y. ago) must have been a period of erosion of the caldera rim, including Spor Mountain, and perhaps of volcanic highlands in the Thomas Range (fig. 16*C*), but the only depositional record of such erosion is in The Dell, where sandstone and conglomerate occur in the beryllium tuff member of the Spor Mountain Formation. There is no evidence for cauldron resurgence (Smith and Bailey, 1968) during this interval; such resurgence should be evident from a moat filling of thick volcaniclastic sediments, intrusive rocks, and lavas along the margin of the caldera. These rocks would have formed soon after ash-flow eruption and cauldron subsidence. None of these features has been observed. The beryllium tuff is a local member that rarely exceeds 60 m in thickness; its conformable relationship with the overlying 21-m.y.-old porphyritic rhyolite member suggests an age close to the latter rather than close to that of the ash-flow tuffs. The oldest postcauldron intrusive rocks and flows belong to the 21-m.y.-old porphyritic rhyolite, indicating a hiatus in local volcanism of nearly 11 m.y.

The tuff, tuffaceous sediments, and rhyolite of the Spor Mountain Formation were deposited on the erosional surface that became unconformity C 21 m.y. ago (fig. 16*D*). Spor Mountain began to rise above a body of alkali rhyolite magma and to shed detritus into the surrounding area; plugs and vents of the porphyritic rhyolite member formed highlands to the north and east of Spor Mountain and erupted volcanic detritus that became incorporated in the beryllium tuff. A small south- and southwest-flowing stream system developed in The Dell and received detritus from Spor Mountain on the west and volcanic highlands on the east. This detritus collected in local tilted fault blocks, such as the one at Yellow Chief mine. The stream in The Dell flowed across the southern end of present-day Spor Mountain, where its probable location is marked by a modern entrenched drainage system that has been superposed across the structural grain of the Spor Mountain block (marked by SS on fig. 14*B*). Fish Springs Flat lay directly downstream from The Dell and received detritus from it and from smaller streams that probably drained southwest from Spor Mountain. At the same time, small air falls and flows of ash and pumice from nearby vents covered the drainage basin and may have been partly reworked by small streams. The tuffs and sediments deposited in this volcanic-sedimentary environment—a mixture of tuffaceous breccia, stratified tuff, and bentonite of ash-flow, ground-surge, and air-fall origin (Bikun, 1980) and epiclastic tuffaceous sandstone and conglomerate—compose the beryllium tuff member of the Spor Mountain Formation.

Unconformity D represents a long period of block faulting and erosion, from 21 m.y. to 7 m.y. ago, that followed the eruption of the porphyritic rhyolite member of the Spor Mountain Formation (fig. 16*E*). The period coincides with the onset of widespread extensional tectonism in the Basin and Range Province (McKee and others, 1970; Noble, 1972). During this time, some faults that formed by cauldron subsidence in the Thomas Range and Drum Mountains were rejuvenated, blocks of Paleozoic rocks were uplifted at Spor Mountain and in the Drum Mountains, and the Spor Mountain Formation was broken into many fault blocks and eroded, so that only part of it remains.

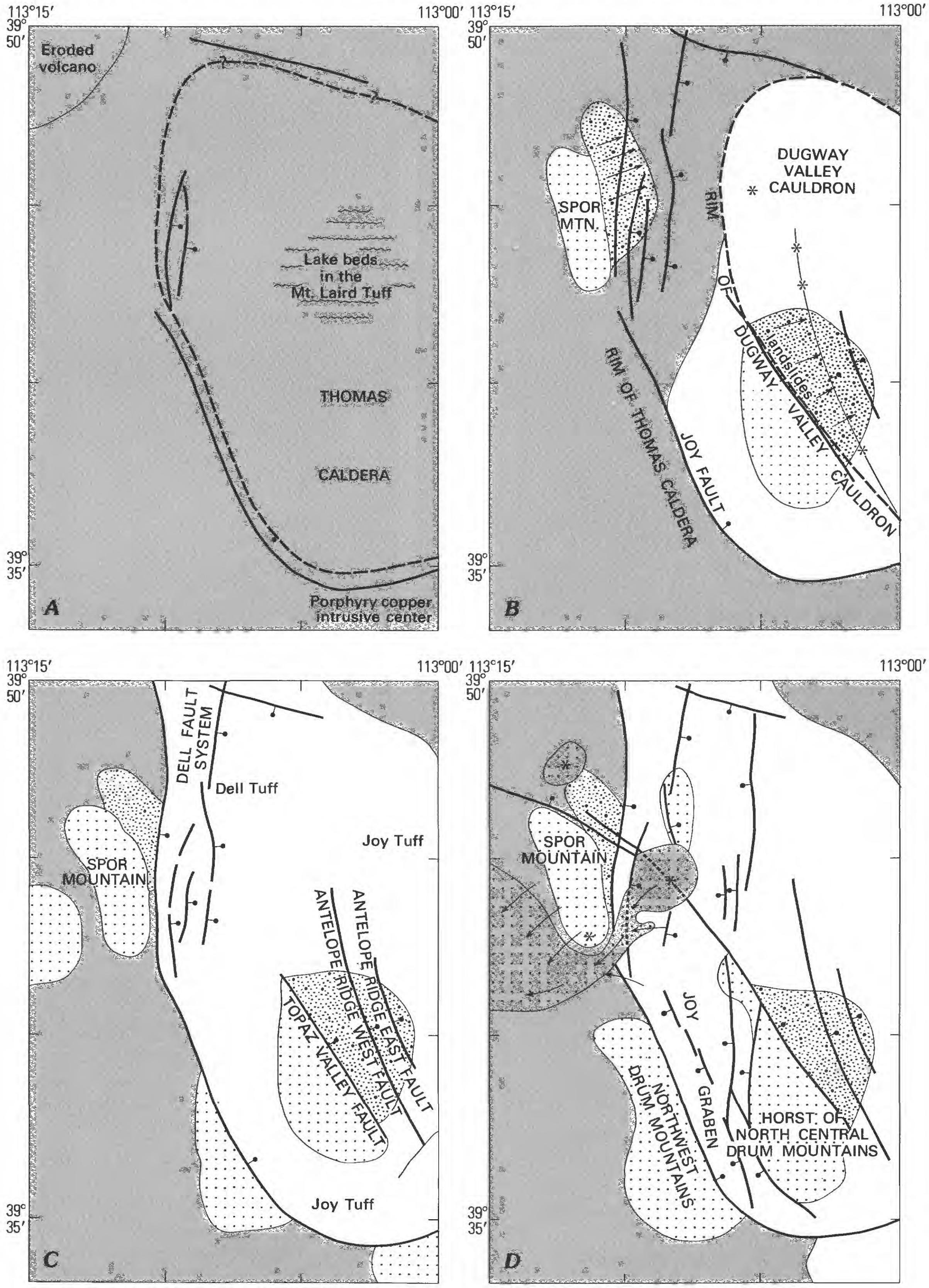
Voluminous flows and domes of the Topaz Mountain Rhyolite began to erupt from vents along old faults about 7 m.y. ago; they covered much of the erosional surface of unconformity D in the Thomas Range (fig. 16*F*). Quiescent periods of as much as 0.5-m.y. duration interrupted intense rhyolitic volcanism. By the end of volcanism at 6 m.y. ago, rhyolite flows and domes had coalesced to form a large plateau; upland areas of the Thomas Range are still flat, attesting to the once great extent of the plateau surface. During the early stages of eruption, the rhyolite vents erupted abundant pumice and rock fragments which, mixed with detritus from nearby hills, filled valleys and low-lying areas with stratified tuff. The depression left by the Dugway Valley cauldron was nearly filled with tuff and rhyolite at this time.

SOME UNSOLVED PROBLEMS

I have sought to integrate the structural development and volcanism of the Thomas Range and northern Drum Mountains into one model which relies on a framework of caldera subsidence and early basin-range faulting. The model may require modification if new information can be obtained concerning some problems. These include (1) the location of the east side of the Thomas caldera, (2) the occurrence of large areas of basement within the Thomas caldera that might date from the time of subsidence, (3) the apparent small volume of ash-flow tuff erupted from the caldera at the time of initial subsidence, and (4) the peculiar absence of individual tuffs from parts of the caldera.

Much work remains to be done to locate and verify the east side of the Thomas caldera and the adjacent Keg caldera proposed by Shawe (1972). The east side of the Thomas caldera was projected through the western part of Keg Mountain by Shawe (1972), but detailed mapping by Staub (1975) in the Picture Rock Hills did not confirm evidence for the ring fracture there. The occurrence of thick sections of Joy Tuff in the Picture Rock Hills and of the Dell Tuff east of Keg Pass suggests that the caldera margin may be farther east than was projected by Shawe. Dikes and plugs of rhyolite to quartz latite in northwestern Keg Mountain have been dated at 32 m.y. (Lindsey and others, 1975); they may be intrusions along a ring-fracture zone, which was interpreted to be that of the Keg caldera by Shawe (1972). The distribution of intracauldron tuffs and of possible ring-fracture-related intrusive rocks and faults should aid in locating the Thomas caldera and smaller calderas nested within it. Additionally, breccias that might indicate tuff vents and collapse of caldera walls should be sought; wall-collapse breccias might be found in the northern part of Keg Mountain, where volcanic and sedimentary rocks predating ash-flow eruption abound.

The presence of basement areas dating from the time of cauldron subsidence may provide insight into the process of subsidence. Such an area of basement is the horst of the north-central Drum Mountains, a large block (about 14 by 4 km) of Paleozoic rocks that probably has existed since about 37 m.y. ago. The horst provided the source from which landslide megabreccias slid over the 37-m.y.-old black glass tuff member of the Joy Tuff after subsidence of the Dugway Valley


113°15′
113°00′
39° 50′
39° 35′
Eroded volcano
Lake beds in the Mt. Laird Tuff
THOMAS
CALDERA
Porphyry copper intrusive center
A
SPOR MTN.
DUGWAY VALLEY CAULDRON
RIM OF DUGWAY VALLEY CAULDRON
landslides
RIM OF THOMAS CALDERA
JOY FAULT
B
DELL FAULT SYSTEM
Dell Tuff
Joy Tuff
SPOR MOUNTAIN
ANTELOPE RIDGE EAST FAULT
ANTELOPE RIDGE WEST FAULT
TOPAZ VALLEY FAULT
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JOY GRABEN
NORTHWEST DRUM MOUNTAINS
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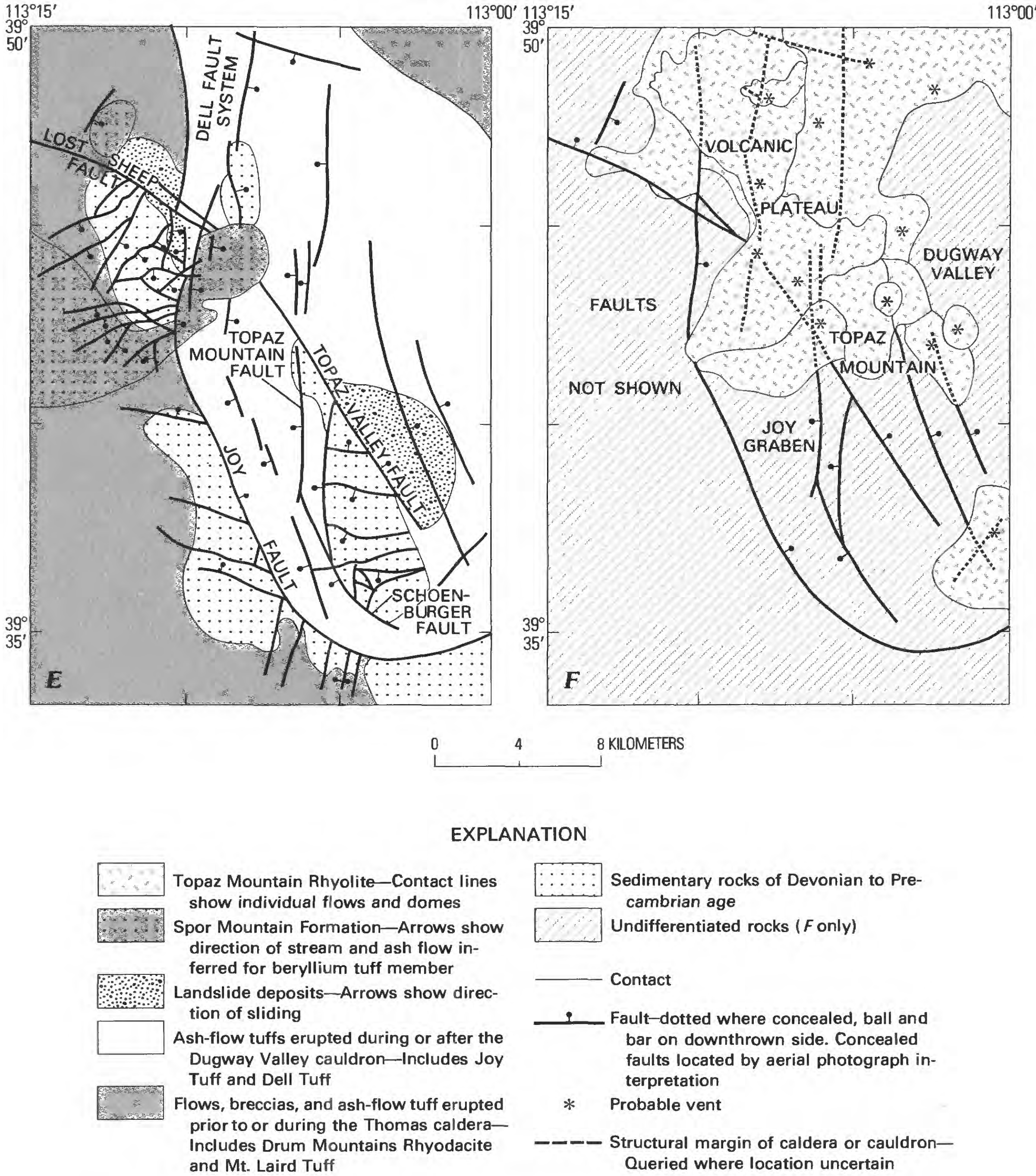


FIGURE 16.—Maps showing structural evolution of the Thomas Range and northern Drum Mountains. *A*, Surface of unconformity B, about 39-38 m.y. ago, after eruption of the Mt. Laird Tuff and subsidence of the Thomas caldera. *B*, Results of eruption of the Joy Tuff 38-37 m.y. ago, accompanying subsidence of the Dugway Valley cauldron, and collapse and sliding of cauldron walls. *C*, Surface of unconformity C, about 30-21 m.y. ago. The Thomas caldera has been filled with intracauldron Joy and Dell Tuffs. The Needles Range(?) Formation has been omitted. *D*, Volcanism and sedimentation at the time of eruption of the Spor Mountain Formation 21 m.y. ago. *E*, Surface of angular unconformity D, resulting from block-faulting and erosion 21-7 m.y. ago. *F*, Results of volcanism 7-6 m.y. ago after eruption of the Topaz Mountain Rhyolite.

cauldron. The horst did not exist 38 m.y. ago, when the crystal tuff member of the Joy Tuff flowed west to the wall of the Thomas caldera. Although the horst probably owes much of its present relief to early basin-range faulting, its early existence seems likely. Two explanations for its origin are (1) uplift over resurgent magma, and (2) differential subsidence within the caldera complex. Uplift by resurgence is considered unlikely because no intrusive rocks or lava flows are associated with the horst. Consideration of differential subsidence leads to the interesting possibility that the entire caldera complex may reflect incomplete or variable degrees of subsidence. Drilling has revealed a high area of Paleozoic rocks beneath Topaz Mountain Rhyolite near Colored Pass, at the head of Pismire Wash in the Thomas Range, that may indicate another horst. If other positive areas are found within the caldera complex, and if these can be shown to be related to fault blocks that predate basin-range structure, then incomplete, differential subsidence will be verified.

The problem of insufficient ash-flow volume for subsidence may reflect inadequate information about the true extent and thickness of ash-flow tuffs. The volume of the Mt. Laird Tuff, believed to be associated with subsidence of the Thomas caldera, is somewhat roughly estimated at 50–100 km^3 (cubic kilometers). This volume seems small for the size of the Thomas caldera, which is at least 15–25 km across. The accuracy of the volume estimate is severely affected by lack of information about the extent of the 500-m-thick section east of Topaz Mountain. Additional drilling or geophysical study is needed to determine the volume of tuff beneath Dugway Valley. The combined volume of the Joy and Dell Tuffs, which filled the Thomas caldera and overflowed it to the east, is estimated at approximately 150–200 km^3 if one assumes a once-continuous distribution of 180 m of tuff from the Joy fault to Desert Mountain. Such a volume of tuff is compatible with the collapse of the Dugway Valley cauldron and perhaps additional undiscovered cauldrons.

Individual formations of ash-flow tuff are absent from parts of the caldera; such distribution would not be expected if a single large area subsided at once. Although the distribution of individual tuffs is incompletely known because of cover and gaps in subsurface information, enough is known to suspect that additional structures related to cauldron subsidence will be found. Such an example is the absence of the Mt. Laird and Joy Tuffs in the caldera throughout the west half of the Thomas Range, and of the Dell Tuff from the complementary part of the caldera. Such a distribution may be caused by a separate time of subsidence for the northwest part of the caldera, perhaps later than the 39–38 m.y. eruptions of the Mt. Laird and Joy Tuffs. Nevertheless, no structure delineating a separate subsidence feature is evident. A second explanation is that of differential subsidence; the northwest part of the caldera may not have subsided as much as the south and east parts; only after these were filled with tuff could the Dell Tuff flow into the northwest part of the caldera. A third explanation is that long periods of erosion removed so much ash-flow tuff that the present distribution beneath rhyolite flows and alluvium is spotty. Long gaps in the record of volcanism, as shown by the ages of volcanic formations, provided time for extensive erosion. If so, the detritus from such erosional epochs must have been carried beyond the volcanic field, because no volcanic sediments in the area are of sufficient volume to account for the expected amount of detritus. Available evidence does not permit a definitive explanation for the absence of individual tuffs from parts of the Thomas caldera.

CHEMICAL COMPOSITION OF VOLCANIC ROCKS

ROCK TYPES

Most of the volcanic rocks of the Thomas Range and northern Drum Mountains are believed to have been derived from local vents. Only the ash-flow tuff of the Needles Range(?) Formation may be from a distant source. Thus, from geographic considerations, magmas beneath the Thomas Range and Drum Mountains could have produced the entire volcanic sequence and the small plutons associated with it, with the possible exception of the Needles Range(?) Formation. Accordingly, the composition of all volcanic units except the Needles Range(?) is compared (fig. 17).

There are three time-dependent rock types among the indigenous rocks of the Thomas Range and northern Drum Mountains. In the classification of Rittmann (1952), the three types are (1) rhyodacite and quartz latite of 42 and 39 m.y. ago (Drum Mountains Rhyodacite and Mt. Laird Tuff), (2) rhyolite of 38 to 32 m.y. ago (Joy and Dell Tuffs), and (3) alkali rhyolite of 21 and 7–6 m.y. ago (Spor Mountain Formation and Topaz Mountain Rhyolite) (fig. 17). Rhyodacite and quartz latite, erupted as both flows and tuffs, are characterized by about 60–67 percent SiO_2, 14–19 percent Al_2O_3, 4–8 percent total iron as Fe_2O_3, 2–4 percent MgO, 4–6 percent CaO, 2–4 percent each of Na_2O and K_2O, and 0.6–1.1 percent TiO_2 (major oxides have been recalculated to total 100 percent and to exclude volatile components). The rhyodacite and quartz latite are about the same age and close in overall composition to the intermediate-composition volcanic rocks in the Lit-

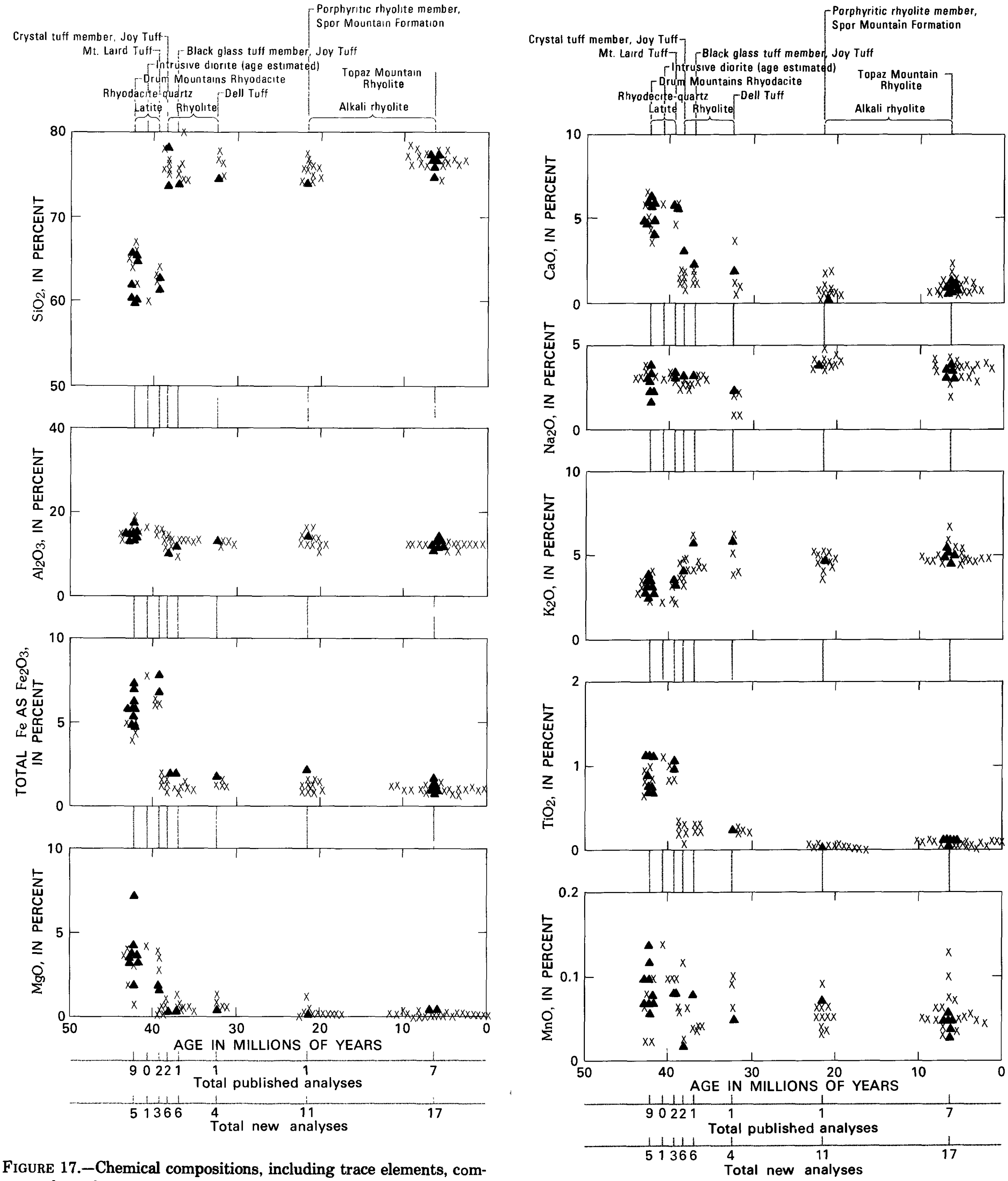


FIGURE 17.—Chemical compositions, including trace elements, compared to the ages of igneous rocks in the Thomas Range and northern Drum Mountains. Major oxides have been recalculated to total 100 percent and to exclude volatile components. Line pattern along the base of some diagrams shows limit of detection when some samples were below the limit. Analyses of major oxides from the literature (shown by triangles) are from Staatz and Carr (1964, p. 110), Newell (1971, p. 38), and Hogg (1972, p. 180). New chemical analyses (shown by x's) are in table 8.

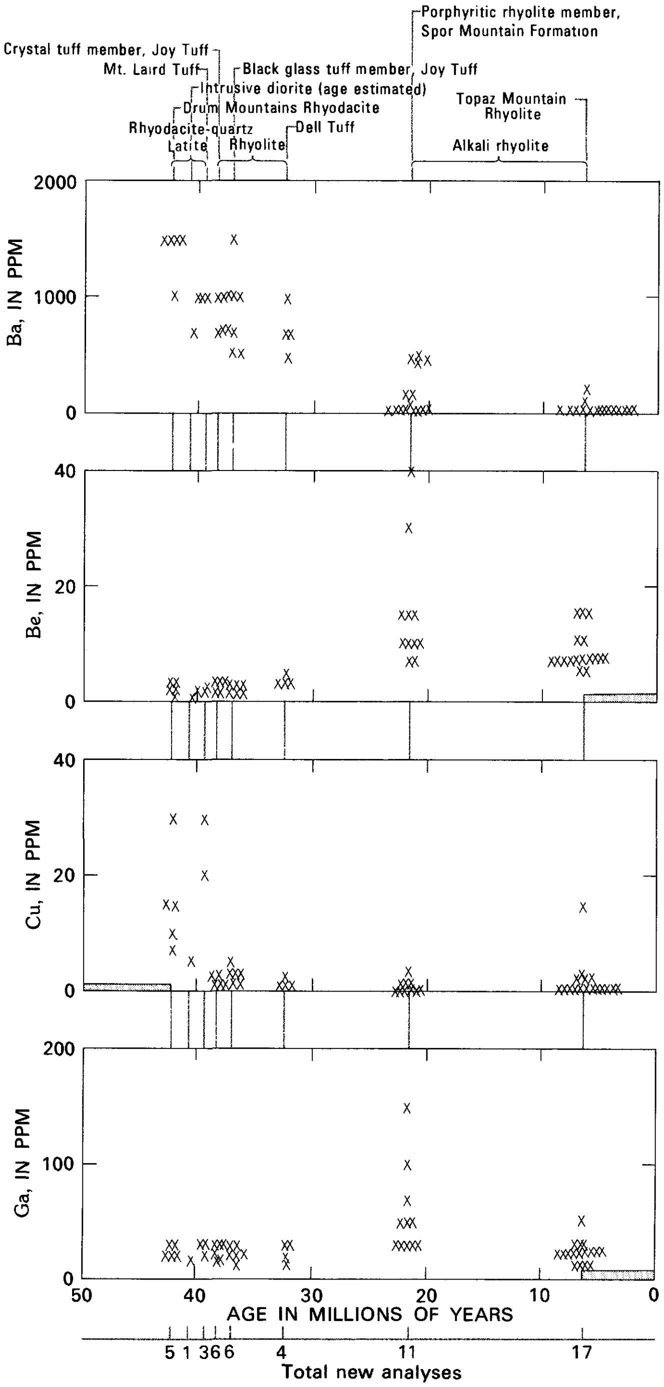


FIGURE 17.--Continued

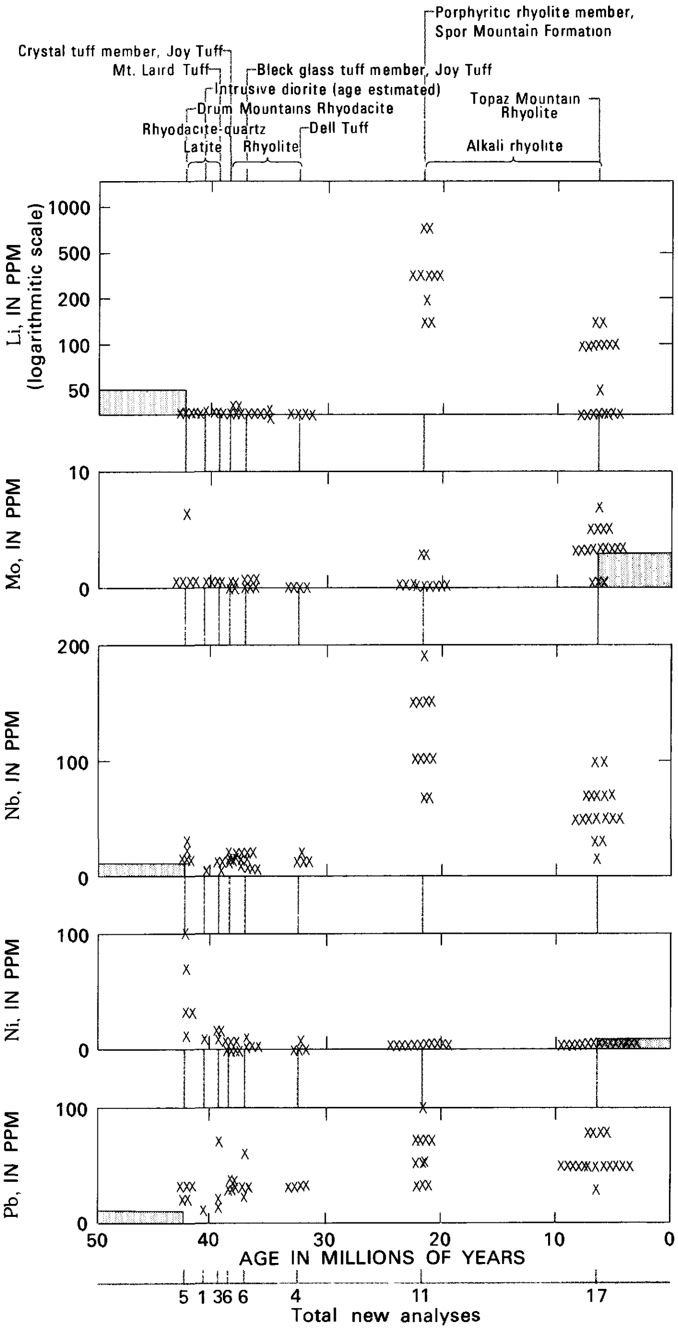
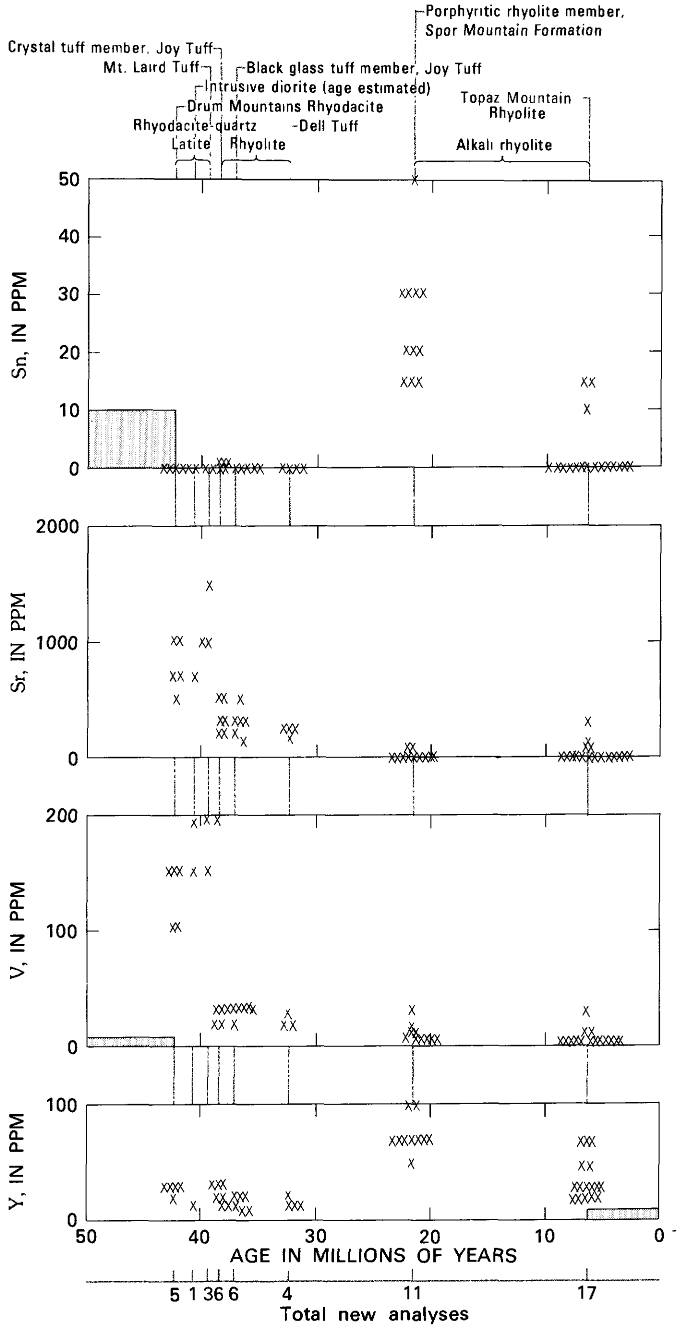


FIGURE 17.—Continued

tle Drum Mountains described as shoshonitic by Leedom (1974) and Pierce (1974). Rhyolite, erupted as ash-flow tuffs, and alkali rhyolite, erupted as flows and tuffs, both contain 74–79 percent SiO_2, 11–14 percent Al_2O_3, 1–2 percent total iron as Fe_2O_3, and less than 1 percent MgO; both are of calc-alkalic affinity, as is shown below. The two rock types differ from each other in that the alkali rhyolite contains slightly less CaO than the rhyolite (commonly less than 1.0 percent but as much as 2 percent, versus 1–2 percent for the rhyolite), more Na_2O (generally 3–4 percent versus 1–3 percent for the rhyolite), slightly more K_2O (generally 4–5.5 percent versus 3–5 percent for the rhyolite), and less TiO_2 (generally 0.05–0.15 percent versus 0.2–0.3



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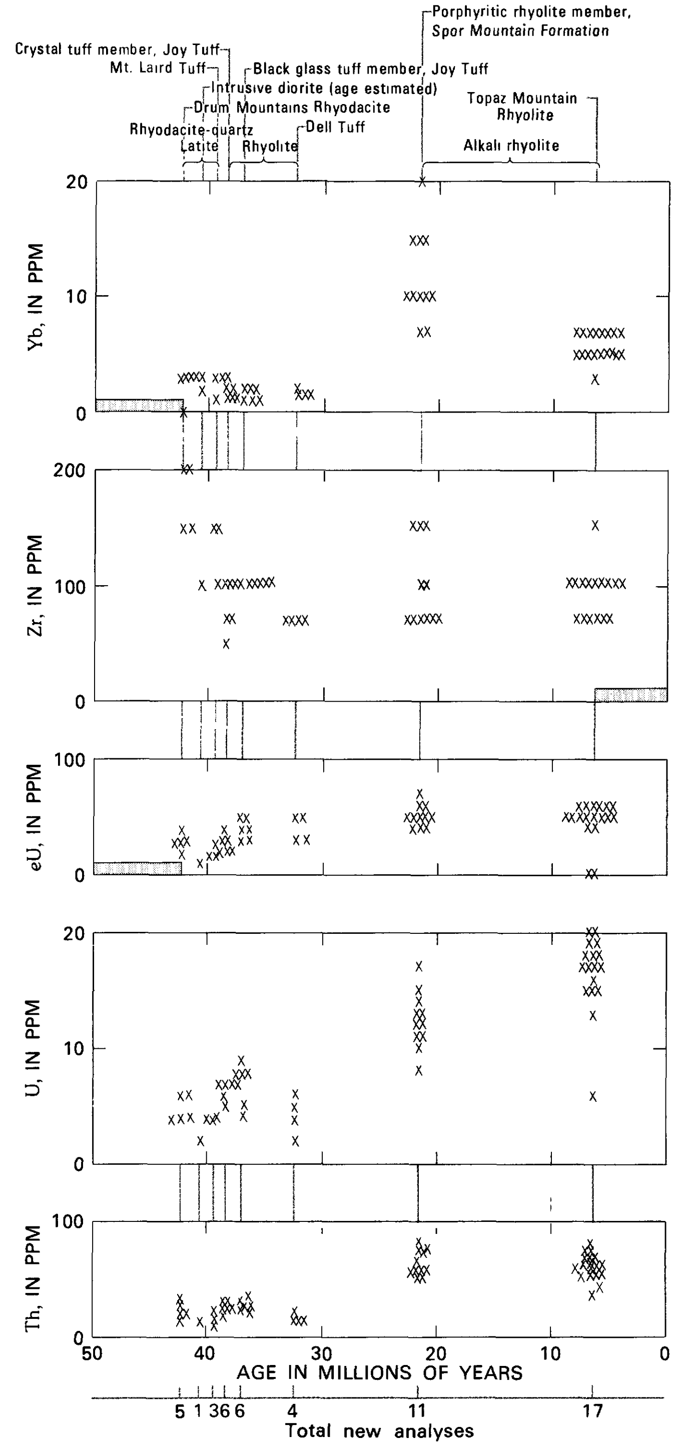

FIGURE 17.—Continued

percent for the rhyolite). Alkali rhyolite also differs from rhyolite in that it contains as much as 0.77 percent fluorine (Staatz and Carr, 1964, p. 110; Shawe, 1966). The high fluorine content of alkali rhyolite is reflected by the widespread occurrence of topaz in that rock.

Rocks intermediate in composition between rhyodacite-quartz latite, rhyolite, and alkali rhyolite are not present (fig. 17). Shifts in composition from one rock type to the next are abrupt, not gradual. For example, the age of the Mt. Laird Tuff is intermediate between the Drum Mountains Rhyodacite and the Joy Tuff, but the composition of the Mt. Laird Tuff closely resembles that of the Drum Mountains Rhyodacite and is distinctly different from the slightly younger rhyolite of the Joy Tuff.

Comparison of total alkali versus silica contents of all three types indicates that they are within the field of subalkalic suites (fig. 18) (Irvine and Baragar, 1971). The rocks also fall within the calc-alkalic field of Irvine and Baragar on an AFM diagram (fig. 19). The three rock types tend to define separate fields in the alkali-silica and AFM diagrams, however, thus supporting the previous observation that volcanic products having compositions intermediate between these rock types are not present. The fields of rhyolite and alkali rhyolite occur close together and might be considered as one, but the rocks of each type plot as a coherent group having only partial overlap. Soda equals or exceeds K_2O in most of the rhyodacites and quartz latites, but K_2O dominates Na_2O in the rhyolites and alkali rhyolites.

TRACE-ELEMENT ASSOCIATIONS

The three rock types are sharply defined by their trace-element association; rhyodacite-quartz latite contains chalcophile and siderophile metals, rhyolite has a scarcity of most trace elements, and alkali rhyolite contains lithophile metals (fig. 17). Rhyodacite and quartz latite contain trace amounts of copper (5-50 ppm), nickel (7-100 ppm), and vanadium (100-200 ppm) that far exceed the amounts of these elements in rhyolite and alkali rhyolite. The most obvious characteristic of the rhyolitic tuffs is their relative scarcity of most trace elements. An exception is barium, which is more abundant (500-1,000 ppm) in rhyolite than in the alkali rhyolite (less than 200 ppm). Rhyodacite and quartz latite contain slightly more barium (1,000-1,500 ppm) than the rhyolite. In contrast to the other rocks, the alkali rhyolites contain traces of lithophile elements such as beryllium (generally 3-15 ppm), lithium (as much as 700 ppm), molybdenum (as much as 7 ppm), niobium (30-200 ppm), tin (as much as 50 ppm), yttrium (20-100 ppm), ytterbium (3-10 ppm), uranium (generally 10-20 ppm), and thorium (50-80 ppm). The abundance of lithophile elements is slightly different in alkali rhyolites of two ages: the older alkali rhyolite of the Spor Mountain Formation contains more gallium, lithium, niobium, tin, yttrium, and ytterbium, and less molybdenum and uranium than the Topaz Mountain Rhyolite.

The consistent associations of trace elements confirm the classification of volcanic rocks in the area into three distinct types. In particular, trace-element abundances reveal significant differences between the character of rhyolite and alkali rhyolite. Whether all three are cogenetic members of a series is not known. Sharp distinctions between the three rock types and a time-

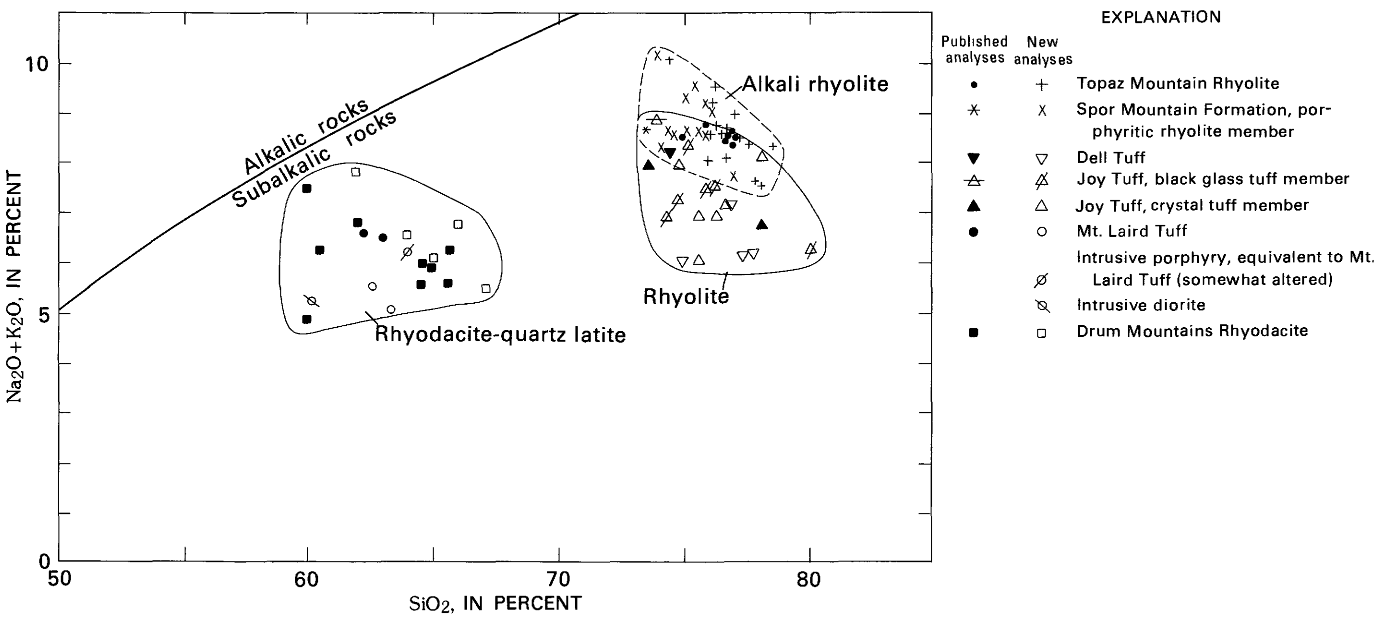

FIGURE 18.—Total alkalis (Na_2O plus K_2O) versus SiO_2 content of igneous rocks of the Thomas Range and northern Drum Mountains. Analyses have been recalculated to total 100 percent and to exclude volatile components. Previously published analyses are from Staatz and Carr (1964, p. 110), Newell (1971, p. 43), and Hogg (1972, p. 180). Line separating alkalic from subalkalic rocks from Irvine and Baragar (1971).

dependent distribution of each are facts which require a unique evolution, if not a unique parentage, for each type.

The trace-element associations in the three rock types are believed to be of magmatic origin. Only fresh rocks were selected for analysis from compact flow rocks and tuffs. Except for the unwelded upper part of the black glass tuff member of the Joy Tuff, which was sampled to aid in stratigraphic assignment of that rock, very porous tuffs were not utilized. Rhyolitic ash-flow tuffs do not show effects of hydrothermal alteration and do not contain anomalous concentrations of trace elements except locally along faults and in The Dell. Geochemical anomalies are widespread in the beryllium tuff member of the Spor Mountain Formation and in stratified tuff of the Topaz Mountain Rhyolite (Lindsey and others, 1973; Lindsey, 1975), but associated flows of alkali rhyolite appear fresh and compact, with only local areas affected by mineralization.

The magmatic origin of uranium in alkali rhyolite was checked by comparing the uranium content of zircon from the three rock types (table 6). Uranium is a highly mobile element, and the uranium measured in whole rocks could possibly have been introduced by hydrothermal fluids or ground water. Zircon, a highly resistant mineral to chemical alteration, contains magmatic concentrations of uranium that would not be expected to change after crystallization. Microphenocrysts of zircon commonly contain zones of high uranium content and do not lose this characteristic in

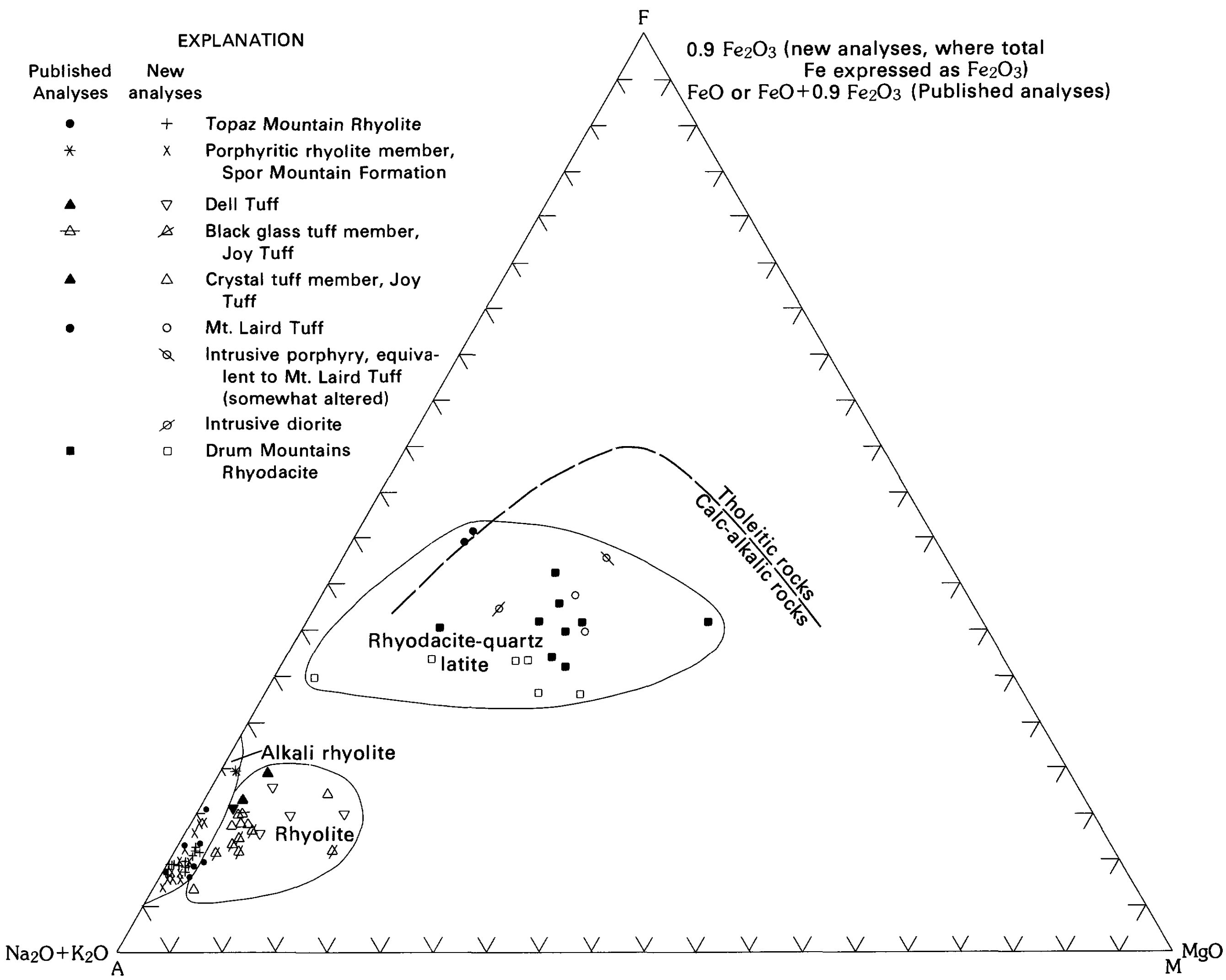

FIGURE 19.—AFM diagram of igneous rocks of the Thomas Range and northern Drum Mountains. Previously published analyses are from Staatz and Carr (1964, p. 110), Newell (1971, p. 43), and Hogg (1972, p. 180). Line separating tholeitic from calc-alkalic rocks from Irvine and Baragar (1971).

TABLE 6.—*Analytical data for uranium content of zircon in volcanic rocks of the Thomas Range*

[Uranium determined by author; neutron dose determined by C. W. Naeser. Estimated ages of volcanic rocks are listed for comparison]

Sample No.	Rock unit	Sample location, T. 12 S., R. 12 W.	Number of grains	Induced tracks in detector		Neutron dose (neutrons/cm^2)	Uranium (ppm)[1]		Estimated age of rock unit (m.y.)
				Number counted	Density (tracks/cm^2)		Average	Range	
				Alkali rhyolite					
U15------	Topaz Mountain Rhyolite-----------	SW1/4 sec. 14	20	597	1.24x10^7	9.06x10^{13}	8,000	5,300-18,000	[2]6.3-6.8
U26------	Porphyritic rhyolite member of Spor Mountain Formation.	NE1/4 sec. 9	20	794	1.65x10^7	9.23x10^{13}	10,000	2,300-16,000	21.3
U7A------	--do------------------------------	SW1/4 sec. 36	20	703	1.47x10^7	9.14x10^{13}	9,500	7,000-13,000	21.3
U12B-1---	Bentonite at Yellow Chief mine----- (beryllium tuff member of Spor	NW1/4 sec. 36	A[3],10	250	9.49x10^6	9.97x10^{14}	570	200-1,300	[5]21.3
	Mountain Formation).	--do---------	B[4],20	494	1.03x10^7	1.05x10^{14}	5,800	3,700-7,500	[5]21.3
				Rhyolite					
T54-A----	Dell Tuff-------------------------	SE1/4 sec. 26	20	717	1.50x10^7	1.00x10^{15}	880	360-2,000	32.0
T42-A----	--do------------------------------	NW1/4 sec. 36	10	493	2.05x10^7	1.24x10^{15}	970	630-1,400	32.0
				Rhyodacite-quartz latite					
U10A-----	Drum Mountains Rhyodacite---------	SW1/4 sec. 35	8	345	2.00x10^6	9.33x10^{14}	130	50-130	42

[1]U (ppm) = induced track density (5.88x10^{10})/neutron dose. Concentrations of U are rounded to two significant digits.
[2]Age estimated by association with dated flows.
[3]Population A is about 10 percent of total zircon and contains low-U zircon dated at 28.3±1.8 m.y. and 40.0±7.0 m.y.
[4]Population B is about 90 percent of total zircon and contains high-U zircon that could not be dated.
[5]Based on geologic relations and correlation of high-U zircon (population B) with volcanism related to porphyritic rhyolite of Spor Mountain Formation.

altered or weathered rocks. Zircon from the volcanic rocks of the Thomas Range shows a high concentration of uranium in alkali rhyolite, with individual crystals containing as much as 1 percent uranium. Uranium in zircon from rhyodacite-quartz latite and rhyolite does not exceed 2,000 ppm. The high concentration of uranium in zircon of alkali rhyolite is strong evidence that this element was concentrated in the alkali rhyolite magma.

The uranium content of all volcanic rocks in the Thomas Range and Drum Mountains is high compared to that of volcanic rocks from orogenic belts. Only two rock samples having less than 4 ppm uranium were analyzed from the Thomas Range-Drum Mountains area, whereas uranium from volcanic rocks in orogenic belts is commonly as little as 1-4 ppm. Volcanic rocks collected from two transects across the central Andes generally did not contain more than about 4 ppm uranium (Zentelli and Dostal, 1977). Volcanic rocks of basaltic to rhyolitic composition in northern New Zealand contain less than 3.4 ppm uranium (Ewart and Stipp, 1968), and rocks of basaltic to intermediate composition in island arcs north of New Zealand generally contain less than 1 ppm uranium (Ewart and others, 1977). The uranium content of the Utah rocks is not unique in the western United States, however, where rhyolitic rocks containing 5-20 ppm uranium and more are common (Zielinski, 1978).

RELATIONSHIP OF VOLCANISM TO MINERALIZATION

The time-dependent rock types are associated with distinctive types of mineralization. Rhyodacite-quartz latite volcanism was associated with chalcophile and siderophile metal mineralization, rhyolite volcanism was probably barren, and alkali rhyolite volcanism was associated with lithophile metal mineralization. The types of mineralization are characterized broadly by the same trace elements that mark the types of igneous rocks.

Early rhyodacite-quartz latite volcanism was associated with sulfur-rich chalcophile mineralization, as illustrated by the occurrence of copper minerals and jarosite in small plutons that may overlie an unexposed mineralized pluton in the Joy area (Newell, 1971). Siderophile mineralization, as illustrated by the manganese, iron, gold-bearing jasperoid, and kaolin deposits of the Drum Mountains (Crittenden and others, 1961; McCarthy and others, 1969; Newell, 1971), probably belongs to the period of chalcophile mineralization when acid, sulfur-rich solutions leached these metals from country rock, concentrated them in fissures and fault zones, and left leached areas of pure clay. Most chalcophile and siderophile mineralization in the Drum Mountains appears to have been confined to rocks older than the Joy Tuff.

Most of the occurrences of the lithophile metals, including beryllium and uranium, are in the beryllium tuff member, which is the oldest representative of alkali rhyolite volcanism. Deposition of fluorite pipes in Paleozoic rocks on Spor Mountain also probably accompanied alkali rhyolite volcanism. Sulfur is believed to have been sparse or absent during lithophile metal mineralization. Some beryllium, fluorite, and uranium were deposited after eruption of the Topaz Mountain Rhyolite 6-7 m.y. ago (Lindsey and others, 1975; Zielinski and others, 1977), but I now believe that late mineralization was relatively minor because of the lack of mineral deposits in the Topaz Mountain Rhyolite and their relative abundance in the older Spor Mountain Formation. The major period of lithophile metal mineralization probably occurred between 7 and 21 m.y. ago, when deposits of low-grade beryllium, uranium, and fluorite were formed in the beryllium tuff member of the Spor Mountain Formation. There is no evidence to associate uranium or other lithophile metal mineralization with the caldera cycle.

ORIGIN OF VOLCANIC ROCKS

The volcanic rocks of the Thomas Range and the northern Drum Mountains were formed in three distinct stages, much as originally proposed by Shawe (1972). (1) Older flow rocks and tuffs of rhyodacite-quartz latite composition were erupted from small central volcanoes and fissures in late Eocene time. Initial subsidence of the Thomas caldera accompanied eruption of the Mt. Laird Tuff. Volcanism was accompanied by emplacement of small plutons and by chalcophile and siderophile metal mineralization. (2) The composition of volcanic products switched abruptly to rhyolitic ash-flow tuff in latest Eocene and Oligocene time. Eruption of tuff was accompanied by collapse of the Dugway Valley cauldron. Rhyolitic ash-flow volcanism in latest Eocene and Oligocene time probably was not followed by cauldron resurgence and probably was not accompanied by mineralization. (3) Alkali rhyolite volcanism accompanied early basin-and-range faulting in Miocene time, producing tuffs, flows, and domes. Block faulting of basin-and-range type rejuvenated earlier faults and was accompanied by local erosion and sedimentation that mixed detritus with the tuffs. Fluorine and lithophile metal mineralization accompanied alkali rhyolite volcanism. Reconnaissance studies by Shawe (1972) and me indicate that, in general, the Tertiary history of Keg Mountain resembles that of the Thomas Range and Drum Mountains.

All of the volcanic rocks could have originated by crustal fusion; alternatively, they may have originated by partial melting of the mantle and contamination with considerable crustal material. These ideas are compatible with strontium isotope evidence for continental felsic rocks in general (Hedge, 1966) and with strontium isotopic compositions of plutonic rocks nearby (Moore and others, 1979). The high content of SiO_2, alkalis, thorium, and uranium in the entire volcanic pile supports a crustal contribution and is in contrast to the low content of these elements in volcanic rocks that are clearly derived from the mantle or from oceanic crust (e.g., Ewart and others, 1977).

Abrupt switches from rhyodacite-quartz latite to rhyolite to alkali rhyolite volcanism through time, accompanied by contemporary changes in magmatic trace-element associations and types of mineralization, suggest that each magma was produced by fusion of a different region of the mantle or crust, or that differentiation proceeded in three steps. If the magmas originated by fusion, it may have been partial or complete; if complete, differentiation may have been necessary to concentrate lithophile elements. Petrographic evidence for an ancestral mafic magma for the Drum Mountains Rhyodacite and Mt. Laird Tuff permits a magmatic history beginning with fusion in the upper mantle followed by upward migration and major contamination with crustal material. The magmas were deep enough, or lacked the necessary vapor pressures, to prevent collapse of the roofs of magma chambers during most rhyodacite-quartz latite volcanism, except during eruption of the Mt. Laird Tuff. The Mt. Laird magma may have migrated to a relatively high level in the crust before explosive eruption and crustal subsidence, as indicated also by plugs and dikes of Mt. Laird composition in the Drum Mountains. The magma chambers of the rhyolitic tuffs were shallow enough and the vapor pressure great enough for subsidence to occur during eruption. Such rhyolitic tuffs have been regarded as differentiates of calc-alkalic magma like the Drum Mountains Rhyodacite (Lipman and others, 1972).

The extreme enrichment of lithophile metals in the alkali rhyolite magmas may have resulted from differentiation or from fusion of Precambrian rocks already enriched in these elements. Origin by differentiation would require a large volume of mafic magma; there is no evidence for mafic magmas nearby except the basalt at Fumarole Butte. Origin by crustal fusion would require lithophile-metal-rich rocks nearby. Granitic and clastic metasedimentary terranes of Precambrian age are exposed beneath Paleozoic rocks nearby, as in the Deep Creek Range (Bick, 1966), at Granite Peak (Fowkes, 1964), and in the Simpson and Sheeprock Mountains (Cohenour, 1959). Partial fusion or remobilization of Precambrian terrane having a high content of lithophile metals has been proposed as a source for alkali rhyolite magma and mineralizing solutions that formed beryllium deposits at Spor Mountain (Moore and Sorensen, 1978). Metamorphism of Precambrian terrane during Tertiary time has been documented for the Grouse Creek and Raft River Mountains, about 200 km north of the Thomas Range (Compton and others, 1977). Reheating of Precambrian granitic terrane may have occurred also at Granite Peak, where Precambrian biotite-gneiss and granite are cut by beryl-bearing pegmatite veins of Tertiary age only 20 km north of the Thomas Range (Park, 1968; Moore and Sorensen, 1978).

The volcanic history inferred for the Thomas Range and Drum Mountains supports the broad outlines of volcanism and basin-and-range development as proposed by Lipman and others (1972) and Christiansen and Lipman (1972) and elaborated more recently by Snyder and others (1976). They proposed that calc-alkalic volcanism of early to middle Tertiary age developed in response to subduction of the Farallon plate beneath the American plate, that calc-alkalic volcanism and subduction ended in Miocene time when the Farallon plate was consumed west of the basin-and-range province, and that the basin-and-range structure and fundamentally basaltic volcanism, including bimodal basalt-rhyolite, developed in response to crustal attenuation caused by strike-slip movement between the Pacific and American plates. Two imbricate, easterly dipping subduction zones, one under the present basin and range, and the other under the Rocky Mountains, were proposed to account for calc-alkalic volcanism of the type represented by rhyodacite-quartz latite and rhyolite in the Thomas Range and Drum Mountains.

In their model, Lipman and others (1972, p. 237) noted the Thomas Range as one of two areas of volcanic rocks having high K_2O contents indicative of an anomalously shallow depth to the western Benioff zone, thus possibly reflecting a zone where the descending slab was decoupled from the crust. Correct estimation of the depth to the Benioff zone in western Utah is complicated, however, by the very slight systematic variation of K_2O with SiO_2 in rhyodacite and quartz latite (Hogg, 1972; Leedom, 1974). In any case, the switch from calc-alkalic to fundamentally basaltic volcanism, represented in western Utah by alkali rhyolite, occurred at 21 m.y., somewhat early for the plate-tectonic model as refined by Snyder and others (1976).

Alkali rhyolite volcanism was probably contemporaneous with extensional basin-and-range faulting in the Thomas Range and Drum Mountains, as indicated by widespread faults in all rocks 21 m.y. and older and by only a few faults in rocks 6–7 m.y. old. Extensional tectonism in the Basin and Range Province is generally regarded as having begun about 16–17 m.y. ago (McKee and others, 1970; Noble, 1972). In the Thomas Range, basin-and-range faulting included rejuvenation of caldera ring fractures, as indicated by evidence for recurring movement along the faults of The Dell.

URANIUM OCCURRENCES

Uranium occurs in four diverse settings in the Thomas Range: (1) in fluorspar pipes in Paleozoic rocks of Spor Mountain, (2) associated with beryllium deposits in stratified tuff and tuffaceous breccia of the beryllium tuff member of the Spor Mountain Formation, (3) in tuffaceous sandstone and conglomerate of the beryllium tuff member at the Yellow Chief mine, and (4) in veinlets of opaline SiO_2 in volcanic rocks of all ages.

Production and reserves are limited, but resources may be large. Fluorspar has been produced from the pipes, but no production of uranium has been reported. The uranium deposits in the beryllium tuff member are large but of low grade (0.0X percent); no uranium has been recovered as a byproduct of beryllium mining. The only production of uranium from the area has been from the Yellow Chief mine, which produced more than 90,000 metric tons of ore having a grade of 0.20 percent U_3O_8 (Bowyer, 1963). Veinlets of uraniferous opal, such as those at the Buena No. 1 and Autunite No. 8, have been prospected but none has produced ore. Analyses of samples from several prospects indicate a maximum grade of about 0.2 percent uranium (Staatz and Carr, 1964, p. 152–154).

All of the uranium occurrences were formed as a result of alkali rhyolite volcanism that accompanied early basin-and-range faulting; some were formed by hydrothermal activity and others by ground-water leaching of the products of volcanism. The fluorspar pipes, beryllium deposits, and probably the uraniferous opal veinlets were formed by hydrothermal activity that accompanied volcanism. No primary uranium minerals have been found; uranium in fluorspar pipes and in nodules and veinlets in the beryllium deposits is dispersed in fluorite and opal. Yellow secondary uranium minerals are common. Deposits at the Yellow Chief mine consist entirely of secondary uranium minerals that were precipitated from ground water; the uranium there probably was derived by ground-water leaching of nearby hydrothermal deposits or uranium-rich volcanic rocks.

URANIUM IN FLUORSPAR PIPES

Uraniferous fluorspar pipes are numerous throughout Spor Mountain along faults and fractures in Paleozoic rocks; no new study of the pipes was done, and the information presented in this report is summarized from Staatz and Carr (1964). Analyses of fluorspar show a range of 0.003–0.33 percent uranium (Staatz and Carr, 1964, p. 135). Some of the most uraniferous fluorspar (0.10–0.20 percent range of U_3O_8) occurs near the Bell Hill Mine, at the southeastern end of Spor Mountain. Most of the pipes are small, the largest reported is 47 by 32 m, and they commonly diminish in size at depth (Staatz and Carr, 1964, p. 130).

URANIUM IN THE BERYLLIUM TUFF MEMBER OF THE SPOR MOUNTAIN FORMATION

The beryllium tuff member contains low-grade concentrations of uranium as well as economic deposits of beryllium. Epiclastic tuffaceous sandstone, a facies of the beryllium tuff member at the Yellow Chief mine, contained minable quantities of beta-uranophane; this deposit is discussed separately. Deposits of beryllium in tuff include the North End, Taurus, Sigma Emma, Monitor, Roadside, Fluro, Rainbow, and Blue Chalk claims southwest of Spor Mountain, and the Oversight, Hogsback, and Claybank claims in The Dell (fig. 2). Most of these beryllium deposits contain uranium, also. Previous work has indicated that uranium in the beryllium tuff member is most abundant in and near beryllium ore (Park, 1968; Lindsey and others, 1973), but new data presented here indicate that abundant uranium commonly occurs separate from beryllium ore.

Uranium of hydrothermal origin (as much as 2,000 ppm) occurs with beryllium in the structure of fluorite and opal in zoned nodules in the beryllium tuff member (Lindsey and others, 1973; Lindsey, 1978a). Fission-track maps of fluorite and opal nodules show uniform and zonal distributions of uranium, but no point sources that might indicate the presence of pitchblende or other uranium minerals. Such uranium must have been deposited with fluorite as a result of the breakdown of stable fluoride complex ions of beryllium and uranium (Lindsey and others, 1973), and thus is regarded to have been introduced by hydrothermal fluids. The absence of pyrite, other sulfide minerals, and tetravalent uranium minerals, even in unweathered fluorite-silica nodules, indicates that these minerals were not stable during hydrothermal mineralization.

The conduits for hydrothermal fluids that mineralized the beryllium tuff member are not exposed at the beryllium mines southwest of Spor Mountain but may be revealed by occurrences of fluorite, beryllium, and uranium in prospects on Spor Mountain and in The Dell. Uranium occurs with beryllium and fluorite in plugs and domes of the Spor Mountain Formation and along fault zones that cut the Spor Mountain Formation. Small plugs of porphyritic rhyolite, along faults in Paleozoic rocks near the crest of Spor Mountain (fig. 15), were affected by uraniferous fluorspar mineralization. The fringes of at least two domes of porphyritic rhyolite that overrode aprons of tuff were mineralized. One such dome, in NW$\frac{1}{4}$ sec. 10, T. 13 S., R. 12 W. on the southern part of Spor Mountain (fig. 2), intruded Paleozoic rocks at a prominent fault intersection and overrode an apron of tuff previously erupted from the vent; mineralizing fluids rose from the vent and deposited uraniferous fluorite in brecciated wall rocks of Paleozoic age, in the tuff apron, and in the outer part of the rhyolite dome. A grab sample of fluorite-rich rhyolite from the margin of the dome contained 1,000 ppm uranium and 50 ppm beryllium. Similarly, mineralized tuff underlies the small dome of porphyritic rhyolite south of the Yellow Chief mine in The Dell (fig. 15). Mineralized gouge of tuff and rhyolite occurs in the Dell fault system at the Oversight and Claybank prospects in The Dell (figs. 14*B*, 15). A grab sample of fluorite-rich gouge from the fault at the Oversight prospect contained about 250 ppm uranium and 700 ppm beryllium. Nearby, drillholes have penetrated mineralized beryllium tuff beneath porphyritic rhyolite.

Yellow secondary uranium minerals occur dispersed in the beryllium tuff member, and these form ore deposits at the Yellow Chief mine. Such accumulations are evidently of ground-water origin and may reflect leaching and remobilization of magmatic or hydrothermal uranium in the beryllium tuff member. Little is known about the possible residence of uranium in other minerals, such as smectite, which makes up most of the tuff in altered areas.

The overall abundance of uranium and thorium in part of the beryllium tuff member of the Spor Mountain Formation is indicated by analyses of drill-hole cuttings from southwest of Spor Mountain (secs. 8 and 9, T. 13 S., R. 12 W.; fig. 20). These cuttings, supplied to the U.S. Geological Survey by the Vitro Minerals Corp., are from drill holes that penetrated most of the tuff section and thus should adequately reflect the overall character of the tuff in the area of the drill holes. Histograms (fig. 20) are skewed toward high values of uranium and thorium, indicating that the underlying frequency distributions may have been modified by processes that concentrated uranium and thorium in the tuff. The original (premineralization) content of uranium and thorium in the tuff is probably approximated by the modes of about 20 ppm uranium and about 80 ppm thorium. The resulting thorium: uranium ratio of about 4:1 is a reasonable value for these elements in igneous rocks, and it is close to that of about 5:1 for the overlying porphyritic rhyolite member of the Spor Mountain Formation. The porphyritic rhyolite contains a range of 50–79 ppm thorium (average of 62 ppm) and 8–17 ppm uranium (average of 11 ppm).

The occurrence of uranium and thorium relative to beryllium in tuff is illustrated by analyses of cuttings from drill holes at the Roadside beryllium mine (Grif-

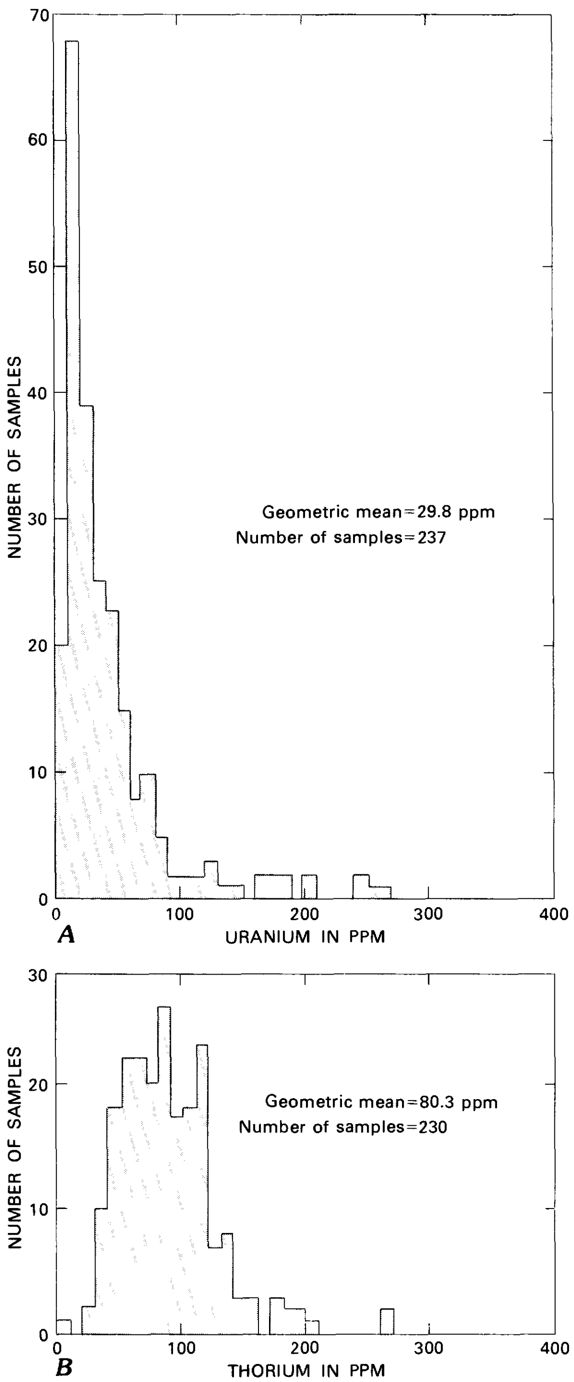

FIGURE 20.—Histograms showing the abundance of *A*, uranium, and *B*, thorium in the beryllium tuff member of the Spor Mountain Formation, as shown by analysis of 237 samples from drill holes southwest of Spor Mountain. Analyses by delayed-neutron method by H. T. Millard, Jr., A. J. Bartel, R. J. Knight, J. P. Hemming, J. T. O'Kelley, and R. J. White.

fitts and Rader, 1963; and Lindsey and others, 1973) (fig. 21). At the Roadside mine, beryllium-fluorite mineralization and attendant hydrothermal alteration were generally concordant to bedding and were most intense in the upper part of the tuff. Feldspathic tuff makes up the uppermost 18 m and lowermost 9 m of a drilled section; incompletely altered argillic tuff lies between the intervals of feldspathic tuff (fig. 21*A*). The upper 6 m of tuff contains beryllium ore (fig. 21*B*) and conspicuous fluorite, the underlying 18 m of tuff contains abundant calcite and lithium (in trioctahedral smectite), and the lower half of the tuff contains abundant dolomite. This alteration sequence reflects increasing intensity of hydrothermal alteration from bottom to top. Thorium (fig. 21*C*) is most abundant in and near the beryllium ore, but uranium (fig. 21*D*) is most abundant below the beryllium ore. Thus, at the Roadside mine, uranium tends to occur separately from beryllium ore.

The relationships among altered zones, beryllium ore, and uranium at the Roadside mine are believed to be typical at Spor Mountain, but they do not hold at all of the mines. For example, beryllium ore occurs at more than one horizon below the top of the beryllium tuff member at the Taurus mine, and the maximum concentration of uranium occurs with that of beryllium in holes drilled through the beryllium tuff by the Anaconda Co. (Park, 1968) and by Bendix Field Engineering Corp. (Morrison, 1980).

The abundance of both uranium and thorium in drill-hole cuttings of tuff supports a magmatic-hydrothermal origin for these elements, but wide variation in the thorium:uranium ratio indicates leaching and reconcentration of uranium with respect to thorium in some of the tuff. If an overall thorium:uranium ratio of about 4:1 is used as a guide, it is evident that tuff having a higher thorium:uranium ratio may have been leached of uranium, whereas tuff having a lower thorium:uranium ratio may have been enriched. A thorium:uranium ratio of about 1 is associated with the highest concentrations of uranium in the drill-hole cuttings (fig. 21*E*), indicating enrichment by either hydrothermal fluids, or more likely, by ground water.

Additional evidence that uranium concentrations occur in the beryllium tuff member separately from those of beryllium is provided by analyses of drill-hole cuttings of selected mineralized zones (Glanzman and Meier, 1979) (fig. 22). These data are from drill cuttings provided to the U.S. Geological Survey by the Anaconda Co. from the east side of Fish Springs Flat (secs. 6, 7, 8, 18, 19, T. 13 S., R. 12 W.; sec. 1, T. 13 S., R. 13 W., and sec. 31, T. 12 S., R. 12 W.). Cuttings of tuff were selected from zones showing visible evidence of alteration and mineralization, such as clay and fluorite. The abundance of BeO, uranium, and thorium in the selected cuttings show the expected effect of mineralization. Histograms of BeO and uranium (figs. 22*A* and 22*B*) are skewed positively toward high concentrations, as would be expected if some beryllium and

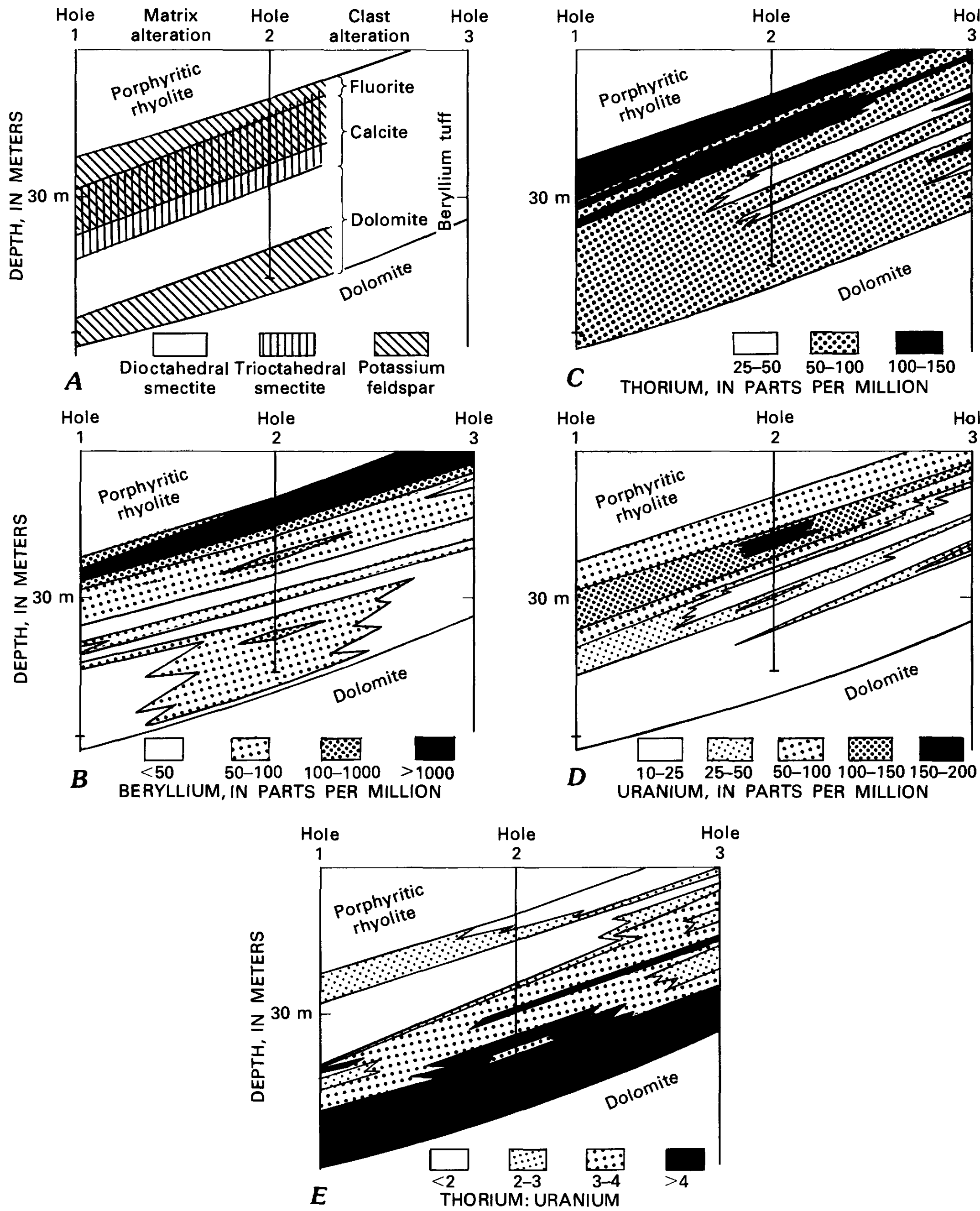

FIGURE 21.—Distribution of (*A*) altered zones (Lindsey and others, 1973), (*B*) beryllium (Griffitts and Rader, 1963), (*C*) thorium, (*D*) uranium, and (*E*) thorium:uranium in the beryllium tuff member of the Spor Mountain Formation at the Roadside mine. Uranium and thorium analyzed by delayed-neutron method by H. T. Millard, A. J. Bartel, R. J. Knight, J. P. Hemming, J. T. O'Kelly, and R. J. White.

uranium had been concentrated by mineralizing fluids. Many samples selected as having been mineralized did not prove to be of beryllium ore grade, however, so that the samples cannot be regarded as representative of beryllium ore. Thorium is generally more abundant (about 100 ppm) in mineralized tuff than in the tuff overall (about 80 ppm), but the frequency distribution of thorium is not skewed positively (fig. 22*C*). The most significant aspect of the data is the separate occurrence of uranium from beryllium, as shown by a scattergram (fig. 22*D*) of 48 samples having 0.1 percent or more BeO or 100 ppm or more uranium. The scattergram defines two distinct groups of samples, one having high beryllium (0.1-1.42 percent BeO) and one having high uranium (100-556 ppm). There is no correlation between beryllium and uranium. This relation

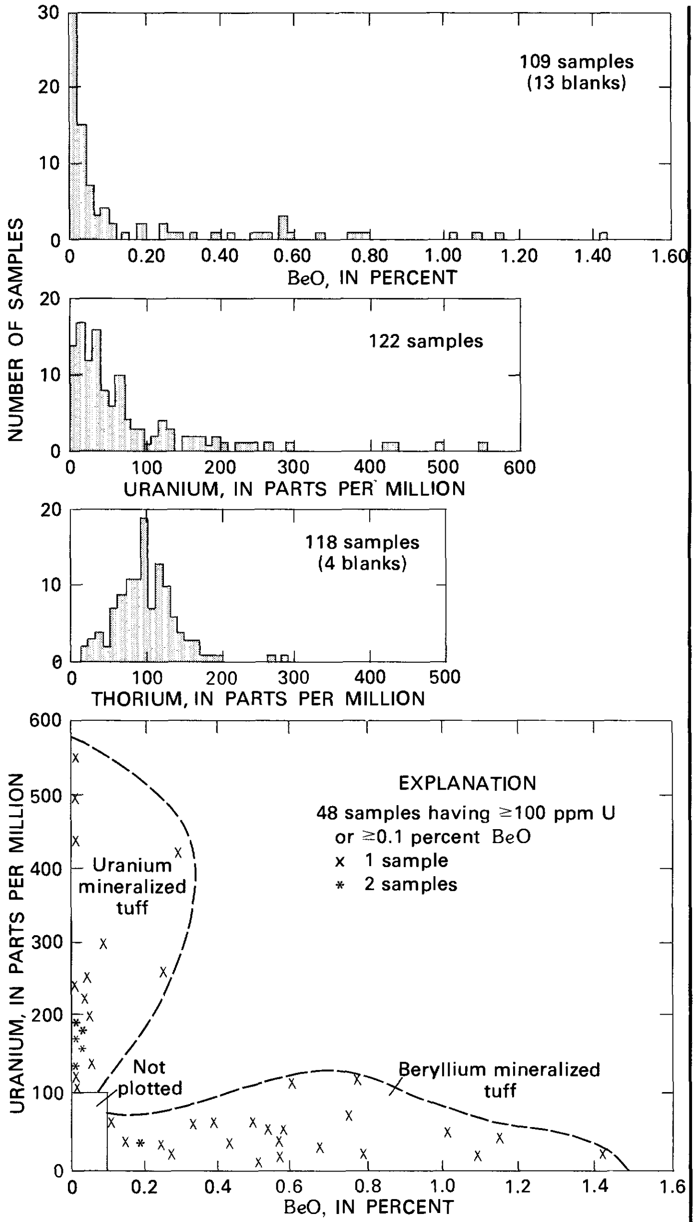

FIGURE 22.—Histograms showing the abundance of BeO, uranium, and thorium, and a scattergram showing segregation of BeO and uranium in drill cuttings of mineralized zones in the beryllium tuff member of the Spor Mountain Formation. Data from Glanzman and Meier (1979).

corroborates that seen in the Roadside drill-hole cuttings (fig. 21), where uranium tends to occur below beryllium ore.

YELLOW CHIEF MINE

The Yellow Chief mine is in a tilted fault block of volcanic rocks in The Dell (fig. 15). Tuffaceous sandstone and conglomerate in the lower part of the beryllium tuff member of the Spor Mountain Formation is the host for uranium ore at the Yellow Chief mine (fig. 10*D*). Westward tilting of the fault block has brought the Spor Mountain Formation down against the Dell Tuff along the footwall of the fault that marks the west side of the block. The fault at the west side of the Yellow Chief has been active for a long time, both before and after 21 m.y. ago; at the pit it downdropped a small erosional remnant of the 21-m.y.-old porphyritic rhyolite and beryllium tuff members. Farther south in The Dell, the fault is exposed in the Dell Tuff but is covered by the Spor Mountain Formation, with no displacement of that unit. Small faults having less than 1-m displacement cut the tuffaceous sandstone and conglomerate in the pit. The stratigraphic section at the Yellow Chief has been described in detail under the discussion of the beryllium tuff member of the Spor Mountain Formation.

The ore at the Yellow Chief is beta-uranophane ($Ca(UO_2)_2(SiO_3)_2(OH)_2 \cdot 5H_2O$), a pale-orange-yellow mineral (Bowyer, 1963). It occurs in lenses as much as 6 m thick and 90 m long that are approximately concordant to the bedding in tuffaceous conglomerate and sandstone (fig. 10*D*). The yellow mineral weeksite ($K(UO_2)_2(Si_2O_5)_3 \cdot 4H_2O$) occurs in lenticular zones less than 1 m thick and 10 m long in the limestone conglomerate that overlies the tuffaceous sandstone (Staatz and Carr, 1964, p. 156). Both of these minerals occupy interstices and fractures and coat sand grains and clasts in the conglomerate. Schroekingerite ($NaCa_3(UO_2)(CO_3)_3(SO_4)F \cdot 10H_2O$) has been reported in veinlets in the tuffaceous sandstone (Staatz and Carr, 1964, p. 157) but has not been found in most of the ore. The host rock is partially altered to smectite, and some limestone clasts in the conglomerates have altered shells, but evidence for intense hydrothermal alteration is lacking. Small bits of earthy yellow jarosite are scattered in the tuffaceous sandstone and conglomerate, and coarsely crystalline calcite cement and veinlets are widespread.

Two lenses of ore exposed on the face of the Yellow Chief pit (fig. 10*D*) were sampled to check for geochemical haloes and possible associations of trace elements that might suggest clues to the origin of the Yellow Chief ores. One ore lens sampled contains weeksite; the other, believed to be more typical of the Yellow Chief ore, contains beta-uranophane. The ore lenses were mapped in the field using a hand-held scintillator, and a series of samples was taken across the middle and ends of each ore lens (fig. 23, table 7). Equivalent uranium (eU), analyzed by a counting technique, and uranium determined by delayed-neutron analysis, are about the same in the ore lenses, indicating that uranium there is approximately in equilibrium. Equivalent uranium exceeds the concen-

TABLE 7.—*Chemical analyses of samples from two ore lenses in the Yellow Chief mine*

[Samples are located in figure 23. Values are in parts per million. eU by beta-gamma scaler by H. G. Neiman; U and Th by delayed-neutron method by H. T. Millard, Jr., A. J. Bartel, R. J. Knight, C. L. Shields, C. M. Ellis, R. L. Nelms, and C. A. Ramsey; F by specific-ion-electrode method by H. G. Neiman and Patricia Guest; Be, Li, Cu, V, Cr, and Pb by six-step semiquantitative spectrographic method by J. C. Hamilton. Ag and Mo not found at detection limits of 0.5 ppm and 3 ppm, respectively, by the spectrographic method. Leaders (--), no data; <, less than]

Sample No.	Sample source	eU	U	Th	F	Be	Li	Cu	V	Cr	Pb
Samples from vicinity of weeksite lens											
1-----	Bentonite-----------	30	15	57	3,600	15	200	5	10	15	70
2-----	--do----------------	90	100	68	6,100	30	1,000	7	30	30	70
3-----	Ore in conglomerate.	910	1,002	--	800	20	150	10	30	70	300
4-----	Barren conglomerate.	50	34	14	1,400	15	100	7	50	100	300
5-----	--do----------------	50	21	14	1,200	30	<50	7	70	100	100
6-----	Sandstone-----------	30	10	14	600	10	<50	3	30	10	50
7-----	Ore in conglomerate.	290	286	--	800	15	<50	7	30	70	70
8-----	Barren conglomerate.	70	49	21	1,300	15	<50	7	30	100	30
Samples of sandstone from vicinity of uranophane lens											
1-----	Outside ore lens.	40	21	28	1,200	50	<50	10	100	70	30
2-----	Ore lens------------	120	76	35	1,400	20	100	10	70	50	30
3-----	--do----------------	80	39	26	1,500	20	<50	10	70	100	30
4-----	Outside ore lens.	40	16	22	1,000	30	<50	7	70	50	70
5-----	Ore lens------------	3,130	3,343	--	1,700	30	100	7	70	30	15
6-----	--do----------------	610	602	--	1,300	30	100	10	70	30	15
7-----	--do----------------	2,200	2,316	--	1,400	30	<50	15	150	70	70
8-----	Outside ore lens.	40	31	33	1,500	5	<50	15	100	70	150

tration of uranium outside the ore lenses because at low concentrations (100 ppm and less) the content of potassium and thorium accounts for a significant part of the eU. Fluorine, beryllium, and lithium, which would be expected to indicate intensity of hydrothermal mineralization associated with beryllium deposits, show no systematic change in abundance across the middle or ends of the ore lenses. Fluorine and lithium are most abundant in the bentonite at the top of the pit wall, indicating that beryllium-related mineralization affected the clay-rich bentonite most. Uranium content of the bentonite is 100 ppm immediately above the weeksite ore, but only 15 ppm 1 m above the ore. Copper, vanadium, chromium, lead, silver, and molybdenum were analyzed by spectrographic methods to determine whether the ores might chemically resemble those of the Colorado Plateau; no enrichment of these elements, except perhaps lead, and no systematic changes were noted for either of the ore lenses.

The uranium deposits at the Yellow Chief mine are of uncertain origin. The paucity of fluorite and beryllium in the uranium ore suggests that the Yellow Chief deposits were not formed by the hydrothermal mineralization that produced the fluorspar and beryllium deposits. Overall, the ores do not resemble those of the Colorado Plateau, inasmuch as they do not contain uranous minerals, organic matter, or pyrite, although jarosite, noted in the host sandstone, might represent oxidized pyrite. Metals that are locally abundant in the beryllium ores (such as manganese, lithium, and zinc) and in the Colorado Plateau ores (such as vanadium, copper, and molybdenum) are not concentrated in the Yellow Chief ore. Uranium at the Yellow Chief may have been introduced by ground waters bearing silica and uranyl carbonate complex ions that dissociated when the calcite cement precipitated.

URANIFEROUS OPAL

Uranium occurs in the structure of opaline silica in fracture fillings in tuff at many places in the Thomas Range. The best known and most uraniferous opal occurs in the crystal tuff member of the Joy Tuff at the Autunite No. 8 prospect on the east side of Topaz Mountain. Fracture fillings of uraniferous opal occur also in the Topaz Mountain Rhyolite above the Autunite No. 8 prospect, at the Buena No. 1 prospect (Staatz and Carr, 1964, p. 152–154), and west of Topaz Valley; in the Dell Tuff in The Dell; with massive uraniferous opal in the beryllium tuff member of the Spor Mountain Formation at many locations; and in the

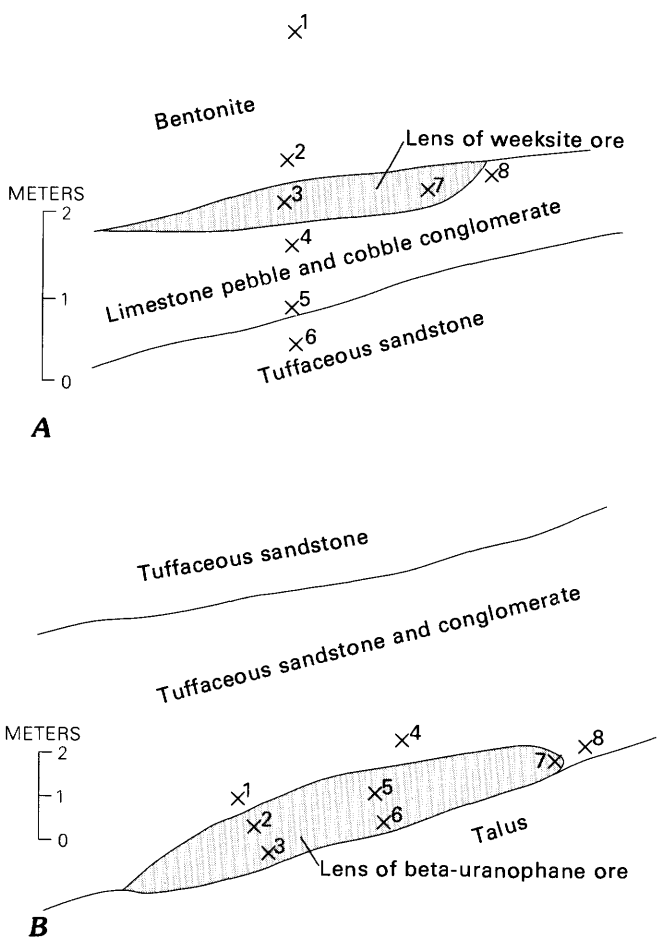

FIGURE 23.—Locations of geochemical samples (table 7) in two ore lenses in the Yellow Chief mine. Location of lenses is shown in figure 10D. *A*, Lens of weeksite ore at the top of limestone pebble and cobble conglomerate. *B*, Lens of beta-uranophane ore in tuffaceous sandstone and conglomerate.

dome of the porphyritic rhyolite member of the Spor Mountain Formation near Wildhorse Spring. Reconnaissance suggests that at least minute quantities of uraniferous opal can be found in any tuff in the Thomas Range. The fracture fillings are generally less than 1-2 cm wide and occur both singly and in zones less than 10 m wide and 30 m long. None has produced ore, and their small size and extent indicate that they are not of economic interest themselves.

The opal in fracture fillings is generally zoned, the zoning being defined by varying sizes of fibrous crystallites oriented perpendicular to the walls of the vein. The opal fluoresces bright yellow green under ultraviolet light, so that it can be readily distinguished from ordinary opal in the Thomas Range, which does not fluoresce. Calcite, quartz, fluorite, weeksite, and perhaps other secondary uranium minerals are commonly associated with the opal. Fission-track maps show that uranium is concentrated in the opal parallel to the zoning, so that there are large variations in uranium content between zones only a fraction of a millimeter thick (Zielinski and others, 1977).

The uraniferous opal is probably of hydrothermal origin; more specifically, such opal may have precipitated in hot springs. Both massive replacement opal and opal in fracture fillings occur in hydrothermal beryllium deposits in the beryllium tuff member of the Spor Mountain Formation. Uranium-lead apparent ages indicate that deposition of opal began 21 m.y. ago, during or soon after eruption of the host Spor Mountain Formation and beryllium-fluorite mineralization, and that deposition of opal continued episodically until 3 m.y. ago (Ludwig and others, 1980). The close temporal relation between the onset of opal formation, beryllium-fluorite mineralization, and igneous activity indicates a genetic relation, also. Many of the fracture fillings show strong zoning of uranium concentration, which suggests wide fluctuation in the supply, rate, or conditions of precipitation of uranium. If silica, calcite, and fluorite were the major phases in equilibrium with the fluids, a likely mechanism for controlling the rate of precipitation was change in temperature or pressure. Fluctuating temperature or pressure and the presence of fluorite support a hydrothermal source. For opal at the Autunite No. 8 locality, temperatures of deposition in the range of 36°C or less were estimated from oxygen-isotope composition (Henry, 1979), but this opal may have been deposited far from its presumed hydrothermal source.

URANIUM IN STRATIFIED TUFF OF THE TOPAZ MOUNTAIN RHYOLITE

A survey of stratified tuff in the Topaz Mountain Rhyolite showed that its original chemical composition was nearly identical to that of the associated alkali rhyolite and that large areas of the once-vitric tuff had been altered to zeolite (Lindsey, 1975). Alteration was accomplished by open-system ground-water leaching of the major alkalis, Na_2O and K_2O, and of minor elements including fluorine, rubidium, manganese, and lead. No analyses of uranium were available for the study reported in 1975, but the eU content, which is dependent on ^{40}K, thorium, and uranium, was found to decline during zeolitization. The tuff was weakly affected by beryllium-fluorite mineralization, also.

A random selection of 20 samples used in the 1975 survey was analyzed for uranium and thorium by the delayed-neutron method by H. T. Millard, Jr., Cynthia McFee, and C. A. Bliss of the U.S. Geological Survey. These analyses show that the stratified tuff contains 7-23 ppm uranium (average of 16 ppm) and 44-71 ppm thorium (average of 55 ppm). Zeolitic tuff does not contain appreciably less uranium and thorium than vitric tuff, but the small number of samples may be insufficient to detect differences. The analyses do show that the overall uranium and thorium content of the tuff is very close to that of alkali rhyolite. Seventeen samples of alkali rhyolite showed 6–20 ppm (average of 16 ppm) and 36–76 ppm thorium (average of 62 ppm). Although the wide range of uranium content in some of the tuff and rhyolite suggests that uranium has been mobile, study of similar tuffs at Keg Mountain (Zielinski and others, 1980) indicates that most of the uranium has not been flushed from the tuff to be concentrated in ore deposits. No concentrations in excess of trace amounts of uranium, except in uraniferous opal, are known in the Topaz Mountain Rhyolite.

A MODEL FOR URANIUM DEPOSITS AND SOME SUGGESTIONS FOR EXPLORATION

The uranium (and other lithophile metal) mineralization of the Thomas Range was associated with extensional block faulting (early basin-and-range faulting) and fluorine-rich alkali rhyolite volcanism beginning 21 m.y. ago. Uranium and other lithophile metals did not accompany the caldera cycle, which was complete by 32 m.y. ago. A hiatus of 11 m.y. separates uranium mineralization at Spor Mountain from the caldera cycle; thus uranium clearly is not associated with the caldera cycle or with earlier magmas that contained abundant sulfur and chalcophile metals.

Uranium in the Thomas Range has been concentrated by (1) magmatic fluids, (2) hydrothermal fluids, and (3) ground water. These methods of concentration correspond respectively to the (1) initial magmatic, (2) pneumatogenic, and (3) hydroallogenic classes of volcanogenic uranium deposits proposed by Pilcher (1978). All of these fluids circulated in an environment of extensional faulting and alkali rhyolite volcanism, however, and their only relation to the caldera cycle was their introduction through fractures that were formed during cauldron subsidence and later reactivated during basin-and-range faulting. Uranium was concentrated by magmatic fluids in the beryllium tuff member (about 20 ppm) and in alkali rhyolite (10–20 ppm) of both the Spor Mountain Formation and the Topaz Mountain Rhyolite. Particularly large amounts of uranium, beryllium, and fluorine were present in the magma of the Spor Mountain Formation, which underlay the vicinity of Spor Mountain and which was erupted as the beryllium tuff and porphyritic rhyolite members. Uranium was further concentrated in hydrothermal fluids rising through conduits that were opened by early basin-and-range faulting. Such faulting tapped fluorine and lithophile-metal-rich fluids in the top of alkali rhyolite magma that underlay the vicinity of Spor Mountain. The fluids deposited uraniferous fluorite in pipes along faults and fault intersections on Spor Mountain (Staatz and Carr, 1964, p. 130–148) and spread laterally into the beryllium tuff member, where they deposited disseminated fluorite, beryllium, lithium, and uranium (Lindsey, 1977). Uranium of hydrothermal origin was deposited in the structure of fluorite and opal; no tetravalent uranium minerals have been found. Uranium in the structure of fluorite at Spor Mountain may be tetravalent, but this possibility remains unproven.

The oxidizing chemical environment of hydrothermal uranium mineralization at Spor Mountain contrasts with the reducing chemical environments at McDermitt, Nevada-Oregon (Rytuba and Glanzman, 1978), and Marysvale, Utah (Cunningham and Steven, 1978). Pitchblende, pyrite, and fluorite are common in uranium ores at both McDermitt and Marysvale, but pitchblende and pyrite have not been found at Spor Mountain. At McDermitt, hydrothermal fluids containing sulfur, fluorine, mercury and uranium mineralized volcanic domes and moat sediments of the McDermitt caldera complex. At Marysvale, uranium-bearing hydrothermal fluids contained abundant fluorine, which complexed with uranium, and minor concentrations of sulfur, which was in the reduced state; uranium probably traveled as a tetravalent fluoride complex and was precipitated as the fluids cooled and the pH rose by reaction with wall rocks (Cunningham and Steven, 1978). At Spor Mountain, uranium probably traveled in hydrothermal fluids as hexavalent fluoride and SiO_2 complexes; precipitation of uranium occurred in response to precipitation of fluorite and SiO_2 and accompanying breakdown of complex ions. Fluorite and SiO_2 were probably precipitated by cooling of fluids; reaction of the fluids with carbonate rock and porous tuff caused the pH to rise and resulted in widespread smectite and potassium-feldspar alteration (Lindsey and others, 1973). Ground water has redistributed hydrothermal uranium at Spor Mountain and concentrated it locally in deposits of secondary minerals.

The potential for finding magmatic or hydrothermal deposits of pitchblende in the Thomas Range is uncertain. No pitchblende or other tetravalent uranium mineral has been found in the near-surface environment exposed at Spor Mountain, indicating that no reducing agent or environment was present to precipitate large amounts of uranium. No reducing agent, such as pyrite or carbonaceous matter, has been observed in the fluorspar pipes or in the beryllium tuff member by me, but such reductants might occur in deep environments. Some Paleozoic carbonate rocks on

Spor Mountain are fetid and might serve as a local reducing environment along the walls of fluorspar pipes and rhyolite vents. The discovery of carbonaceous and pyritic lakebeds in the Mt. Laird Tuff of the subsurface northeast of Topaz Mountain indicates yet another reducing environment. The most favorable areas are near vents for alkali rhyolite lava, where the lava has passed through carbonate rocks, or Tertiary lakebeds that contain carbonaceous matter. A mineralized plug of porphyritic rhyolite, in the southern part of Spor Mountain, and vents of alkali rhyolite at Topaz Mountain, Antelope Ridge, and the northeastern Drum Mountains fit this criterion.

A deep hydrothermal environment at Spor Mountain may be present near a hypothetical pluton of alkali rhyolite that was the source of the beryllium tuff and porphyritic rhyolite of the Spor Mountain Formation, and of the beryllium-fluorite-uranium mineralization that followed. The vicinity of intrusion of the hypothesized pluton can be predicted from the distribution of the Spor Mountain Formation around Spor Mountain and the intensity of mineralization associated with that area. Also, Spor Mountain may have been lifted trap-door fashion by the pluton after eruption of the Spor Mountain Formation 21 m.y. ago. The hinge of the trap door would have been west of the mountain, and the region of greatest uplift would be along the Dell fault system where it displaces Spor Mountain Formation against Paleozoic rocks. Maximum upward projection of the pluton might be expected about 1 km west of Eagle Rock Ridge. The depth to the pluton is probably unpredictable without geophysical data, and the nature of the ores, if any, that might be associated with it seems equally difficult to predict. If sufficiently reducing environments are present at depth, there is a possibility of finding large concentrations of uranium and perhaps other metals. Anomalous traces of molybdenum, tin, and tungsten near the surface, concentrated in manganese oxide minerals near beryllium ore, may be generally indicative of other metals that would be expected below (Lindsey, 1977).

The Spor Mountain Formation and the Topaz Mountain Rhyolite are the most favorable source rocks for uranium deposited by ground waters. In general, the alkali rhyolites contain 10–20 ppm uranium, which is approximately two to four times as much as other volcanic rocks in the area. The beryllium tuff member probably contained 20 ppm uranium at the time of deposition and local concentrations of 2,000 ppm or more were added in hydrothermal fluorite and silica. The stratified tuffs of the Topaz Mountain Rhyolite also contained 10–20 ppm uranium. The tuffs of both formations are porous and were initially glassy, and they are between relatively impermeable (though not totally impermeable) rhyolite and other rocks, so that they provided a good conduit for fluids to leach and transport uranium. Thus, it is not surprising that many occurrences of secondary uranium minerals, including the Yellow Chief deposits, are in the beryllium tuff member of the Spor Mountain Formation. Much secondary uranium, probably deposited by ground water, occurs in the beryllium tuff member, as shown by the separate occurrence of uranium and beryllium in the tuff. The Yellow Chief deposit, which consists entirely of secondary uranium minerals, probably was formed by ground water also.

The potential for finding oxidized uranium deposits formed by ground water in the beryllium tuff member of the Spor Mountain Formation is moderate. The scarcity of reductants to precipitate uranium in tuff indicates that deposits of reduced uranium minerals such as uraninite and coffinite, which usually occur in deposits of the Colorado Plateau and Wyoming types, will not be found unless a hydrologic basin favorable to entrapment and precipitation of uranium can be located; none is exposed. The beryllium tuff member southwest of Spor Mountain has been drilled extensively in the search for both beryllium and uranium, so it is not likely that large high-grade deposits could have been overlooked. There may be much potential, however, for uranium-bearing tuff of low grade (0.0X percent). The best possibility for discovery of additional uranium deposits formed by ground water may be concentrations of secondary uranium minerals like those at the Yellow Chief. Favorable host rocks in The Dell may extend beneath the Thomas Range, where they may be expected in down-faulted blocks covered by Topaz Mountain Rhyolite.

Finally, another area of possible but very uncertain uranium potential, as yet mostly unexplored, is in the subsurface of Dugway Valley north and east of Antelope Ridge. The potential hosts there are stratified tuff of the Topaz Mountain Rhyolite and lakebeds of the Mt. Laird Tuff. Drilling and testing of Dugway Valley to 500–1,000 m will be necessary to evaluate its uranium potential. The cauldron environment there is a passive factor favoring occurrence of uranium; subsidence of both the Thomas caldera and the Dugway Valley cauldron created a depression filled with lakebeds, tuffaceous sediments, and ash-flow tuffs that could act as a reducing trap for uranium leached by ground water from adjacent highlands of alkali rhyolite and tuff in the Thomas Range and Keg Mountain.

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TABLE 8

[Silica, Al_2O_3, total iron as Fe_2O_3, CaO, K_2O, TiO_2, and some MnO by X-ray fluorescence by J. S. Wahlberg: MgO and Na_2O by atomic absorption by C. A. Gent, V. M. Merritt, and H. G. Neiman. Equivalent uranium (eU) by beta-gamma scaler by H. G. Neiman, V. M. Merritt, and C. A. Gent. Manganese and boron through zirconium by six-step semiquantitative spectrographic method by R. G. Havens and F. E. Lichte. For samples Sp-0, Sp-1, and Sp-2, lithium by atomic absorption by V. M. Merritt. Uranium and thorium by delayed neutron method by H. T. Millard, Jr., Cynthia McFee, C. A. Bliss, C. M. Ellis, and V. C. Smith. N, not detected; L, detected but below the limit of detection; $<$, less than. Leaders (—), not determined. Analyses do not total 100 percent because H_2O and volatile constituents were not determined; also, SiO_2 by X-ray fluorescence is subject to considerable but unmeasured error]

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*

	Lower limit of detection	U3	U10A	U33	U37	U65
		Composition in percent				
SiO_2---	--	59	62	63	62	61
Al_2O_3--	--	18	14	14	13	15
Fe_2O_3--	--	3.7	4.2	3.8	4.6	4.2
MgO----	--	.51	1.65	3.69	2.82	3.49
CaO----	--	5.7	4.5	3.4	6.2	4.1
Na_2O---	--	3.6	3.11	2.98	2.93	3.43
K_2O----	--	3.8	3.3	2.2	2.9	2.8
TiO_2---	--	.92	.77	.60	.81	.90
MnO----	[1] 0.05;.0001	<.05	<.05	.090	.077	.0065
		Composition in parts per million				
B------	20	N	N	L	N	L
Ba-----	1.5	1,500	1,000	1,500	1,500	1,500
Be-----	1	3	2	3	2	1.5
Ce-----	150	200	L	N	L	300
Co-----	3	10	10	30	15	20
Cr-----	1	20	150	200	150	150
Cu-----	1	10	15	15	7	30
Ga-----	5	20	20	30	20	30
La-----	30	150	70	70	70	150
Li-----	50	N	N	N	N	N
Mo-----	3	N	N	7	N	N
Nb-----	10	30	20	15	15	15
Nd-----	70	100	70	N	70	150
Ni-----	5	10	30	70	30	100
Pb-----	10	30	20	30	30	20
Sc-----	5	7	15	15	15	30
Sn-----	10	N	N	N	N	N
Sr-----	5	1,000	500	700	700	1,000
V------	7	100	100	150	150	200
Y------	10	30	30	20	30	30
Yb-----	1	3	3	3	3	3
Zr-----	10	200	150	200	150	300
eU-----	10	20	30	30	29	40
U------	--	6	4	4	4	6
Th-----	--	26	19	19	17	30

Footnotes at end of table.

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	U233	U57	U62	[2]U222
Composition in percent				
SiO_2---	53	60	59	55
Al_2O_3--	14	15	15	13
Fe_2O_3--	6.8	5.7	5.5	5.2
MgO----	3.6	3.24	3.49	2.20
CaO----	5.1	5.3	5.1	3.9
Na_2O---	2.68	2.81	2.90	2.85
K_2O----	1.9	2.1	2.3	2.7
TiO_2---	1.0	.80	.80	.90
MnO----	.12	.090	.090	.09
Composition in parts per million				
B------	N	L	L	N
Ba-----	700	1,000	1,000	1,000
Be-----	N	1.5	1.5	L
Ce-----	N	N	N	N
Co-----	15	20	20	15
Cr-----	30	70	70	10
Cu-----	5	30	50	20
Ga-----	15	30	30	20
La-----	L	70	70	50
Li-----	N	N	N	N
Mo-----	L	N	N	L
Nb-----	N	10	10	N
Nd-----	N	70	70	N
Ni-----	7	15	15	10
Pb-----	10	20	70	15
Sc-----	30	30	30	15
Sn-----	N	N	N	N
Sr-----	700	1,000	1,500	1,000
V------	150	200	200	150
Y------	15	30	30	15
Yb-----	2	3	3	1.5
Zr-----	100	150	150	100
eU-----	10	20	30	20
U------	2	4	4	4
Th-----	11	12	13	16

Footnotes at end of table.

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	U32	U34	U43	U49	U56	T51-A
Composition in percent						
SiO_2---	74	70	76	73	75	73
Al_2O_3--	11	12	13	13	14	12
Fe_2O_3--	.70	1.4	1.3	1.6	1.3	1.4
MgO----	.33	.39	.46	.96	.46	.31
CaO----	.77	1.6	1.4	1.7	1.3	1.4
Na_2O---	3.1	3.18	3.30	2.90	3.30	2.93
K_2O----	4.5	4.3	3.6	3.1	3.6	3.9
TiO_2---	.067	.29	.30	.30	.20	.21
MnO----	.11	.057	.065	.065	.065	.022
Composition in parts per million						
B------	L	20	20	L	30	20
Ba-----	700	1,000	1,000	700	1,000	700
Be-----	1.5	2	3	3	3	1.5
Ce-----	L	N	N	N	N	L
Co-----	N	L	L	L	L	L
Cr-----	1	1.5	7	3	7	1
Cu-----	1.5	1.5	3	3	1.5	1.5
Ga-----	15	30	20	30	30	15
La-----	70	70	L	50	L	L
Li-----	N	N	N	N	N	N
Mo-----	N	N	N	N	N	L
Nb-----	15	15	15	15	15	15
Nd-----	N	N	N	N	N	L
Ni-----	N	N	N	L	L	L
Pb-----	30	30	30	30	30	30
Sc-----	L	L	5	7	5	L
Sn-----	N	N	N	N	N	N
Sr-----	200	300	500	500	300	300
V------	20	30	30	30	30	20
Y------	20	30	15	20	15	15
Yb-----	2	3	1.5	2	1.5	1.5
Zr-----	70	70	100	100	100	50
eU-----	20	20	40	20	30	30
U------	7	6	7	5	7	7
Th-----	21	19	25	22	25	22

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	Sp-0	U141B	U141A	U155	[3]Sp-1	[3]Sp-2
			Composition in percent			
SiO_2---	70	74	71	76	76	66
Al_2O_3--	12	13	13	13	9.9	12
Fe_2O_3--	1.1	1.2	1.3	1.2	.9	1.0
MgO----	.37	.47	.51	.49	.42	1.23
CaO----	1.46	1.2	1.7	1.1	1.44	2.10
Na_2O---	3.03	3.18	2.73	3.06	1.00	1.99
K_2O----	4.80	4.0	4.2	4.4	4.82	4.13
TiO_2---	.20	.20	.30	.30	.20	.20
MnO----	.039	.039	.039	.039	.026	.013
			Composition in parts per million			
B------	20	30	30	30	L	L
Ba-----	700	1,000	1,000	1,500	500	500
Be-----	1	2	2	2	1	1
Ce-----	150	200	L	L	150	150
Co-----	N	L	L	L	N	5
Cr-----	5	10	15	15	7	10
Cu-----	3	3	5	3	2	2
Ga-----	20	30	30	20	15	20
La-----	70	100	70	70	50	70
Li-----	<10	N	N	N	<10	20
Mo-----	L	L	N	N	N	N
Nb-----	L	15	20	20	L	L
Nd-----	N	70	70	70	N	N
Ni-----	5	L	L	L	L	5
Pb-----	20	50	30	30	15	30
Sc-----	5	5	7	7	N	5
Sn-----	N	N	N	N	N	N
Sr-----	200	300	300	300	150	500
V------	20	30	30	30	15	20
Y------	20	20	15	20	10	10
Yb-----	1	2	2	2	1	1
Zr-----	100	100	100	100	100	100
eU-----	50	50	40	30	40	30
U------	8	9	8	8	5	4
Th-----	27	23	23	24	21	27

Footnotes at end of table.

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	U78	U84	T42-A	T54-A
	Composition in percent			
SiO_2---	77	76	70	71
Al_2O_3--	13	12	12	12
Fe_2O_3--	1.3	1.3	1.3	1.3
MgO----	.61	.73	1.16	.8
CaO----	.50	1.1	1.1	3.5
Na_2O---	.80	2.10	2.13	.79
K_2O----	6.4	4.0	3.6	4.9
TiO_2---	.20	.20	.25	.23
MnO----	.065	.09	--	.096
	Composition in parts per million			
B------	L	L	30	L
Ba-----	1,000	500	700	700
Be-----	3	5	3	3
Ce-----	N	N	N	L
Co-----	L	N	3	L
Cr-----	10	3	2	2
Cu-----	1.5	1.5	2	1.5
Ga-----	30	30	20	15
La-----	50	50	30	50
Li-----	N	N	N	L
Mo-----	N	N	N	N
Nb-----	15	15	20	15
Nd-----	N	N	N	L
Ni-----	N	N	N	L
Pb-----	30	30	30	30
Sc-----	5	L	7	L
Sn-----	N	N	N	N
Sr-----	200	200	200	150
V------	30	20	20	20
Y------	15	15	20	15
Yb-----	1.5	1.5	2	1.5
Zr-----	70	70	70	70
eU-----	50	50	30	30
U------	4	5	2	6
Th-----	23	21	24	21

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	U2A	U7A	U11A	U20A	U97	U122
			Composition in percent			
SiO_2---	68	64	72	73	72	73
Al_2O_3--	11	12	13	12	15	15
Fe_2O_3--	1.1	.83	.89	1.1	.8	.9
MgO----	.16	.11	.11	.10	.20	.14
CaO----	.98	.52	.64	.65	.80	.20
Na_2O---	3.8	4.2	3.9	3.8	3.5	4.1
K_2O----	4.7	4.5	4.9	4.8	4.5	4.3
TiO_2---	.072	<.05	.050	.079	<.05	<.05
MnO----	<.05	.053	.053	.063	.039	.065
			Composition in parts per million			
B------	50	30	30	30	20	L
Ba-----	100	30	30	150	70	30
Be-----	10	15	10	15	7	10
Ce-----	L	L	L	L	L	L
Co-----	N	N	N	N	N	N
Cr-----	N	N	N	N	3	N
Cu-----	2	1	N	N	3	1
Ga-----	30	50	30	50	100	150
La-----	70	70	70	70	50	50
Li-----	150	300	300	300	150	700
Mo-----	N	N	N	N	N	N
Nb-----	100	70	100	150	150	200
Nd-----	70	70	N	100	N	N
Ni-----	N	N	N	N	N	N
Pb-----	100	70	30	50	70	70
Sc-----	N	N	N	N	N	L
Sn-----	15	30	50	15	20	30
Sr-----	30	15	15	20	15	15
V------	15	10	N	7	N	30
Y------	100	70	70	200	50	70
Yb-----	15	10	10	20	7	10
Zr-----	70	70	70	150	100	70
eU-----	50	40	60	50	70	50
U------	12	11	10	14	8	13
Th-----	79	54	55	75	56	50

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	T53-TR-A	T53-TR-B	U21C	U26	U100
Composition in percent					
SiO_2---	76	74	73	72	74
Al_2O_3--	14	13	12	11	12
Fe_2O_3--	1.5	1.5	1.2	1.4	.6
MgO----	.13	.08	.10	.08	.11
CaO----	.54	.47	.72	1.7	1.7
Na_2O---	3.60	3.73	3.8	4.1	3.98
K_2O----	4.9	4.7	5.0	4.0	3.5
TiO_2---	.053	.055	.072	.25	<.05
MnO----	.034	.036	.050	<.050	.090
Composition in parts per million					
B------	70	30	30	20	L
Ba-----	15	20	150	50	50
Be-----	15	7	10	50	30
Ce-----	L	L	L	N	N
Co-----	N	N	N	N	N
Cr-----	L	L	N	N	3
Cu-----	L	L	1	N	N
Ga-----	30	30	50	30	70
La-----	70	70	70	L	L
Li-----	300	300	700	300	200
Mo-----	3	3	N	N	N
Nb-----	150	150	100	100	70
Nd-----	100	150	70	N	N
Ni-----	L	L	N	N	N
Pb-----	30	30	50	50	70
Sc-----	L	L	N	N	L
Sn-----	30	30	20	20	15
Sr-----	15	15	70	15	70
V------	L	L	10	N	7
Y------	70	100	70	70	70
Yb-----	15	15	10	10	7
Zr-----	150	150	70	70	100
eU-----	60	50	50	40	40
U------	17	11	12	13	15
Th-----	71	72	64	51	53

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	U15	U16	U72	T50-TR-A	T50-TR-B
Composition in percent					
SiO_2---	74	72	78	75	76
Al_2O_3--	12	12	11	12	12
Fe_2O_3--	1.1	1.2	.80	.90	.84
MgO----	.23	.18	.09	.20	.07
CaO----	.52	.67	.80	1.4	.66
Na_2O---	3.5	3.5	2.68	1.95	3.51
K_2O----	4.6	4.8	4.8	6.6	4.6
TiO_2---	.071	.056	.090	.069	.073
MnO----	.053	.055	.065	.100	.036
Composition in parts per million					
B------	20	20	L	L	L
Ba-----	30	30	50	15	7
Be-----	15	15	10	7	7
Ce-----	N	N	L	L	L
Co-----	N	N	N	N	N
Cr-----	N	N	30	L	L
Cu-----	1.5	1	1	L	L
Ga-----	30	30	50	15	20
La-----	N	L	70	50	50
Li-----	150	150	L	L	L
Mo-----	N	N	3	L	3
Nb-----	100	100	70	50	50
Nd-----	N	N	N	L	N
Ni-----	N	N	N	L	L
Pb-----	50	50	70	30	50
Sc-----	N	N	L	L	L
Sn-----	10	15	15	N	N
Sr-----	30	30	70	300	20
V------	10	10	L	L	L
Y------	70	70	30	20	20
Yb-----	7	7	5	5	5
Zr-----	100	100	150	70	70
eU-----	60	50	60	60	50
U------	15	17	18	19	17
Th-----	56	53	68	59	61

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	T52-TR-A	T52-TR-B	T13-TR-A	T13-TR-B	T21-TR-A	T21-TR-B
			Composition in percent			
SiO_2---	75	75	75	77	73	62
Al_2O_3--	12	12	12	12	12	10
Fe_2O_3--	.97	1.0	.98	1.00	1.0	.93
MgO----	.16	.11	.06	.06	.15	.19
CaO----	1.4	2.5	1.0	.86	1.3	1.6
Na_2O---	3.25	3.14	3.71	3.58	3.51	3.49
K_2O----	4.7	4.7	4.7	4.8	4.7	4.9
TiO_2---	.092	.110	.079	.095	.087	.087
MnO----	.048	.047	.071	.053	.061	.053
			Composition in parts per million			
B------	L	L	L	L	L	L
Ba-----	20	70	10	15	10	20
Be-----	7	7	15	10	7	7
Ce-----	L	L	L	L	L	L
Co-----	N	N	N	N	N	N
Cr-----	L	L	L	L	L	L
Cu-----	L	L	L	L	L	L
Ga-----	15	15	20	20	20	20
La-----	70	70	50	70	70	70
Li-----	100	100	100	100	100	100
Mo-----	3	3	5	5	7	3
Nb-----	50	30	70	70	70	70
Nd-----	L	70	L	L	L	L
Ni-----	L	L	L	L	L	L
Pb-----	50	50	50	50	50	50
Sc-----	L	L	L	L	L	L
Sn-----	N	N	N	N	N	N
Sr-----	50	100	15	15	30	70
V------	L	L	N	L	L	7
Y------	20	20	30	30	30	20
Yb-----	5	3	7	7	7	5
Zr-----	100	70	100	70	100	100
eU-----	50	50	60	60	50	50
U------	18	17	20	17	19	18
Th-----	61	65	64	74	73	76

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

	T40-TR-A	T40-TR-B	SP-13	U74	T03-TR-A	T03-TR-B
Composition in percent						
SiO_2---	64	62	74	75	71	74
Al_2O_3--	10	11	11	11	12	12
Fe_2O_3--	.92	1.0	.68	1.0	.91	.96
MgO----	.12	.18	.02	.19	.04	.05
CaO----	.66	.66	.55	1.3	.46	1.1
Na_2O---	3.39	3.34	3.45	2.76	4.07	3.58
K_2O----	4.6	4.9	4.2	4.4	4.5	4.7
TiO_2---	.090	.100	.087	.10	.050	.070
MnO----	.043	.050	.032	.039	.12	.050
Composition in parts per million						
B------	L	L	L	L	20	L
Ba-----	5	7	15	200	5	10
Be-----	7	7	5	5	7	7
Ce-----	L	L	150	L	N	N
Co-----	N	N	N	N	N	N
Cr-----	L	L	L	L	L	L
Cu-----	L	L	1	15	L	L
Ga-----	20	15	20	30	20	20
La-----	70	70	70	70	L	L
Li-----	L	L	50	L	100	L
Mo-----	5	3	5	3	3	3
Nb-----	50	50	15	30	50	50
Nd-----	L	L	N	N	L	L
Ni-----	L	L	N	N	L	L
Pb-----	50	50	50	70	70	70
Sc-----	L	L	L	N	N	L
Sn-----	N	N	N	N	N	N
Sr-----	50	50	10	70	7	15
V------	L	L	L	20	N	L
Y------	30	30	50	50	70	50
Yb-----	7	5	5	5	7	7
Zr-----	100	100	100	100	70	70
eU-----	50	50	60	40	50	40
U------	15	15	13	6	20	16
Th-----	67	68	63	36	51	59

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

No.	Rock type	Location
U3-----	Drum Mountains Rhyodacite, flow	SE1/4SW1/4, sec. 2, T. 13 S., R. 12 W.
U10A---	--do---------------------------	SE1/4SW1/4, sec. 35, T. 12 S., R. 12 W.
U33----	--do---------------------------	NW1/4NW1/4, sec. 21, T. 13 S., R. 11 W.
U37----	--do---------------------------	SW1/4NW1/4, sec. 30, T. 13 S., R. 12 W.
U65----	--do---------------------------	NW1/4NW1/4, sec. 16, T. 14 S., R. 11 W.
U233---	Intrusive diorite--------------	SW1/4SE1/4, sec. 36, T. 14 S., R. 11 W.
U57----	Mt. Laird Tuff-----------------	SE1/4NE1/4, sec. 21, T. 14 S., R. 11 W.
U62----	--do---------------------------	NE1/4SW1/4, sec. 16, T. 14 S., R. 11 W.
U222---	Intrusive porphyry, slightly altered, equivalent to Mt. Laird Tuff.	SW1/4SW1/4, sec. 35, T. 14 S., R. 11 W.
U32----	Joy Tuff, crystal-tuff member--	NW1/4NW1/4, sec. 22, T. 13 S., R. 11 W.
U34----	--do---------------------------	SE1/4NE1/4, sec. 20, T. 13 S., R. 11 W.
U43----	--do---------------------------	SE1/4SW1/4, sec. 17, T. 13 S., R. 11 W.
U49----	--do---------------------------	SW1/4SW1/4, sec. 5, T. 13 S., R. 11 W.
U56----	--do---------------------------	SE1/4NE1/4, sec. 21, T. 14 S., R. 11 W.
T51-A--	--do---------------------------	NE1/4NW1/4, sec. 10, T. 13 S., R. 11 W.
Sp-0---	Joy Tuff, black glass tuff member, basal black welded zone.	SW1/4SE1/4, sec. 25, T. 13 S., R. 11 W.
U141B--	--do---------------------------	NW1/4NE1/4, sec. 36, T. 13 S., R. 11 W.
U141A--	Joy Tuff, black glass tuff member, middle gray welded zone.	NW1/4NE1/4, sec. 36, T. 13 S., R. 11 W.
U155---	--do---------------------------	NW1/4SW1/4, sec. 6, T. 14 S., R. 11 W.
Sp-1---	Joy Tuff, black glass tuff member, upper unwelded zone.	SW1/4SE1/4, sec. 25, T. 13 S., R. 11 W.
Sp-2---	--do---------------------------	SW1/4SE1/4, sec. 25, T. 13 S., R. 11 W.
U78----	Dell Tuff----------------------	NE1/4NW1/4, sec. 26, T. 11 S., R. 11 W.
U84----	--do---------------------------	SE1/4NE1/4, sec. 2, T. 13 S., R. 12 W.
T42-A--	--do---------------------------	NW1/4NW1/4, sec. 36, T. 12 S., R. 12 W.
T54-A--	--do---------------------------	NE1/4SE1/4, sec. 26, T. 12 S., R. 12 W.
U2A----	Spor Mountain Formation, porphyritic rhyolite member, flow.	NW1/4NW1/4, sec. 11, T. 13 S., R. 12 W.
U7A----	--do---------------------------	SE1/4SW1/4, sec. 36, T. 12 S., R. 12 W.
U11A---	--do---------------------------	SE1/4SW1/4, sec. 35, T. 12 S., R. 12 W.
U20A---	--do---------------------------	NW1/4SE1/4, sec. 9, T. 13 S., R. 12 W.

TABLE 8.—*Chemical analyses of igneous rocks from the Thomas Range and northern Drum Mountains*—Continued

No.	Rock type	Location
U97----	--do---------------------------	NW1/4NE1/4, sec. 25, T. 12 S., R. 12 W.
U122---	--do---------------------------	SW1/4SE1/4, sec. 25, T. 12 S., R. 12 W.
T53-TR-A	--do---------------------------	SW1/4NE1/4, sec. 8, T. 13 S., R. 12 W.
T53-TR-B	--do---------------------------	SW1/4NE1/4, sec. 8, T. 13 S., R. 12 W.
U21C----	Spor Mountain Formation, porphyritic rhyolite member, plug.	NE1/4NW1/4, sec. 10, T. 13 S., R. 12 W.
U26-----	Spor Mountain Formation, porphyritic rhyolite member, extrusive dome.	NW1/4SE1/4, sec. 9, T. 12 S., R. 12 W.
U100----	--do--------------------------	NE1/4SE1/4, sec. 8, T. 12 S., R. 12 W.
U15-----	Topaz Mountain Rhyolite, older flow.	SW1/4SW1/4, sec. 14, T. 12 S., R. 12 W.
U16-----	--do--------------------------	NW1/4SE1/4, sec. 22, T. 12 S., R. 12 W.
U72-----	--do--------------------------	NE1/4NE1/4, sec. 19, T. 12 S., R. 12 W.
T50-TR-A	--do--------------------------	NE1/4NE1/4, sec. 28, T. 12 S., R. 11 W.
T50-TR-B	--do--------------------------	NE1/4NE1/4, sec. 28, T. 12 S., R. 11 W.
T52-TR-A	Topaz Mountain Rhyolite, younger flow.	NW1/4SW1/4, sec. 15, T. 13 S., R. 11 W.
T52-TR-B	--do--------------------------	NW1/4SW1/4, sec. 15, T. 13 S., R. 11 W.
T13-TR-A	--do--------------------------	SW1/4NE1/4, sec. 1, T. 13 S., R. 12 W.
T13-TR-B	--do--------------------------	SW1/4NE1/4, sec. 1, T. 13 S., R. 12 W.
T21-TR-A	--do--------------------------	NE1/4SE1/4, sec. 28, T. 13 S., R. 11 W.
T21-TR-B	--do--------------------------	NE1/4SE1/4, sec. 28, T. 13 S., R. 11 W.
T40-TR-A	Topaz Mountain Rhyolite, younger flow.	NW1/4NE1/4, sec. 16, T. 13 S., R. 11 W.
T40-TR-B	--do--------------------------	NW1/4NE1/4, sec. 16, T. 13 S., R. 11 W.
Sp-13---	--do--------------------------	NW1/4NW1/4, sec. 16, T. 13 S., R. 11 W.
U74-----	Topaz Mountain Rhyolite, dome.	NE1/4NW1/4, sec. 26, T. 12 S., R. 11 W.
T03-TR-A	--do--------------------------	SW1/4SW1/4, sec. 14, T. 13 S., R. 11 W.
T03-TR-B	--do--------------------------	SW1/4SW1/4, sec. 14, T. 13 S., R. 11 W.

[1]Limits of detection for MnO are 0.05 percent by X-ray fluorescence; 0.0001 by six-step spectrographic method.

[2]Rock has been partly altered by hydrothermal fluids.

[3]Alkali metals may have been leached by ground water.

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