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PLEISTOCENE RHYOLITE OF THE MINERAL MOUNTAINS, UTAH—GEOTHERMAL AND ARCHEOLOGICAL SIGNIFICANCE

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Abstract.—Little-eroded rhyolitic tuffs, flows, and domes extend over about 25 km² along the western side of the Mineral Mountains, southwestern Utah, which is along the eastern edge of the Roosevelt KGRA (Known Geothermal Resource Area). Initial eruptions resulted in two low-viscosity lava flows of nonporphyritic rhyolite. These were followed by bedded pumice falls and nonwelded ash flows. The youngest activity produced at least nine viscous domes and small lava flows of rhyolite that contain 1–5 percent phenocrysts of quartz, plagioclase, sodic sanidine, and biotite; distinction between domes and eroded flow segments locally is difficult.

Potassium-argon ages indicate that all the rhyolite of the Mineral Mountains was erupted between 0.8 and 0.5 m.y. ago. The rhyolite rests on dissected granite of the Mineral Mountains pluton, the largest intrusion in Utah, which has yielded published K-Ar ages of 9 and 15 m.y. A small older dissected rhyolite dome, about 8 m.y. old, occurs just west of the range front. Whether the young ages of the pluton represent time of intrusion or of later reheating, they, in conjunction with the Pleistocene rhyolite in the Mineral Mountains, do indicate a major late Cenozoic thermal anomaly, the size and age of which is significant to evaluation of the Roosevelt KGRA. The rhyolite is also the only known source of implement-grade obsidian in the southwest between eastern California and northern New Mexico.

As part of the U.S. Geological Survey's geothermal energy program, age, composition, and distribution data are being obtained for upper Cenozoic volcanoes in the western United States that have erupted significant amounts of silicic rocks. Such silicic rocks, mostly rhyolites, are considered possible indicators of the subsurface presence of shallow magma chambers still sufficiently hot to have potential for geothermal resources. A rationale for this approach is outlined by Smith and Shaw (1975).

Large volumes of rhyolite associated with known geothermal resources have been described from Yellowstone National Park (Allen and Day, 1935; Christiansen and Blank, 1972), in the Jemez Mountains in New Mexico (Smith, Bailey, and Ross, 1970), and in the Long Valley area, California (Bailey, Dalrymple, and Lanphere, 1976). Around the margins of the Colorado Plateau, small volumes of similar silicic rocks that also seem worthy of reconnaissance evaluation in terms of geothermal signifiance occur in the San Francisco Mountains volcanic field, Arizona (Robinson, 1913; Moore, Wolfe, and Ulrich, 1974), in the Mount Taylor and Taos Plateau volcanic fields of New Mexico (Hunt, 1938; Lambert, 1966), and in the Mineral Mountains, Utah.

In the Mineral Mountains, southwestern Utah, young rhyolite masses extend discontinuously for about 15 km along the range crest and cover an area of less than 25 km²; these have been little studied and previously were interpreted as erosional remnants of a single large silicic volcano of late Tertiary age (Earll, 1957; Liese, 1957). This brief report presents new geologic data, including K-Ar ages which demonstrate that many separate lava domes, flows, and tuffs were erupted from vents along the range crest between 0.8 and 0.5 m.y. ago. Along one of the western range-front faults, about 2 km northwest of the nearest rhyolitic volcanic rocks, Roosevelt Hot Springs is located within a KGRA (Known Geothermal Resource Area) that is actively being developed for geothermal power production. The youthful silicic volcanism recorded by the rhyolite of the Mineral Mountains suggests the presence of a still-hot buried magma chamber that may be the heat source for the KGRA.

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GENERAL GEOLOGIC SETTING

The Mineral Mountains, in west-central Utah (fig. 1), are a typical basin-range horst, which rises about 1 km above the adjacent alluviated basins, the Escalante Desert to the west and an unnamed valley to the east. The horst extends nearly 50 km in a northerly direction and is in general about 10 km wide.

On the western and northern sides of the range, metamorphic rocks of the Wildhorse Canyon Series of Condie (1960), of probable Precambrian age, are the dominant rocks, but on the southern, northern, and eastern sides of the range, Paleozoic and Mesozoic sedimentary rocks are exposed widely. These layered rocks are intruded by a distinctive body of granite, the Mineral Mountains pluton, which is the largest single exposed intrusive body in Utah, covering nearly 250 km². This granite and associated pegmatite and aplite may be as young as late Miocene, having yielded two K-Ar ages on feldspars of 15 and 9 m.y. from different sample sites (Park, 1968; Armstrong, 1970). These young apparent ages are supported in a general way by results of a Rb-Sr isotopic study. A Rb-Sr isochron, based on 11 analyses of whole-rock samples ranging in composition from diorite to aplite, shows exceptionally bad scatter but suggests that the age of the main batholith is about 35 m.y., with sizable chemical modification—especially Sr loss—having occurred 7-15 m.y. ago (C. E. Hedge, written commun., 1976).

Prior to the onset of late Cenozoic rhyolitic volcanism in the Mineral Mountains, the Mineral Mountains pluton and its country rocks were deeply dissected to form a rugged erosional topography with towering pinnacles rising above narrow usually dry valleys.

The Mineral Mountains are bounded on the west, and probably on the east side, by north-striking normal faults. The trend of the bounding faults on the west is marked locally in the Roosevelt KGRA by discontinuous elongate mounds of opaline sinter and other hot-spring deposits. Near the northern end of this trend is Roosevelt Hot Springs (Petersen, 1975). Water temperatures as high as 90°C have been recorded from Roosevelt Hot Springs, but sometime prior to 1966 the springs dried up (Mundorff, 1970). Phillips Petroleum Co., the successful bidder on the KGRA in 1974, is continuing exploration on the property. Numerous test wells so far drilled in the KGRA have documented the presence of a low-salinity liquid-dominated geothermal system (Berge, Crosby, and Lenzer, 1976; Greider, 1976). The thermal anomaly covers approximately 32 km², and reservoir temperatures exceed 250°C.

RHYOLITE OF THE MINERAL MOUNTAINS

Rhyolitic rocks in the Mineral Mountains include three stratigraphically distinct sequences. Lowermost are two nearly nonporphyritic obsidian-rich lava flows. These are overlain by a pyroclastic sequence, including both ash-fall and ash-flow tuffs. Stratigraphically highest are porphyritic rhyolite lava domes erupted from at least nine separate vents, most of which are along the range crest.

Flows of Bailey Ridge and Wildhorse Canyon

The oldest rhyolitic rocks in the Mineral Mountains are two lava flows of virtually nonporphyritic flow-layered rhyolite. One flow is exposed for about 3 km along Bailey Ridge and in Negro Mag Wash (fig. 2) northwest of Bearskin Mountain. The other is exposed for about 3.5 km along Wildhorse Canyon, west of Bearskin Mountain. Both flows were originally as much as 100 m thick and followed pre-existing valleys that drained the western side of the Mineral Mountains, with relief much like the present, and that were graded nearly to the present levels at valley fronts. Both flows are only slightly dissected, and much of their primary upper surfaces of frothy pumiceous perlitic rubble is preserved.

Where deeply dissected, both flows display similar cooling and crystallization zonations. The basal few meters of the flow, resting directly on medium- to coarse-grained Tertiary granite of the Mineral Mountains pluton, consists of dense black obsidian. The obsidian has well-developed flow lamination defined by alined microlites of feldspars and opaque oxides (fig. 3*A*). The basal obsidian zone grades upward within a meter or two into a well-layered zone, in which dark obsidian and light-gray or brown finely crystallized flow-layered lava alternate. The interior of the flow is as much as 10-30 m thick and consists of gray relatively structureless devitrified rhyolite, in places containing concentrations of ovoid gas cavities locally filled with vapor-phase crystallization products.

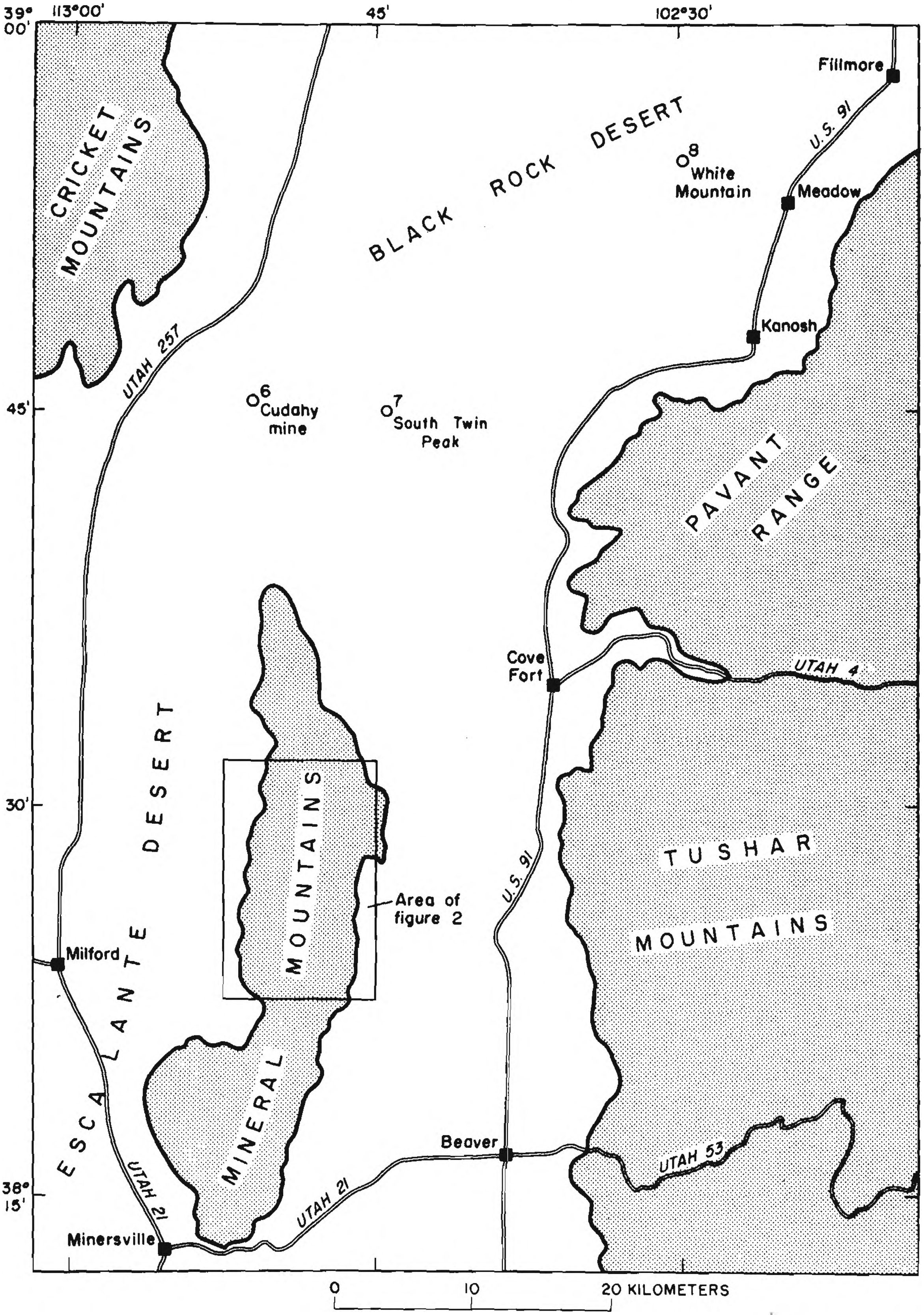


FIGURE 1.—Index map showing location of the Mineral Mountains and nearby areas, Utah. Numbers indicate locations of some dated samples (table 3); the others are shown on figure 2.

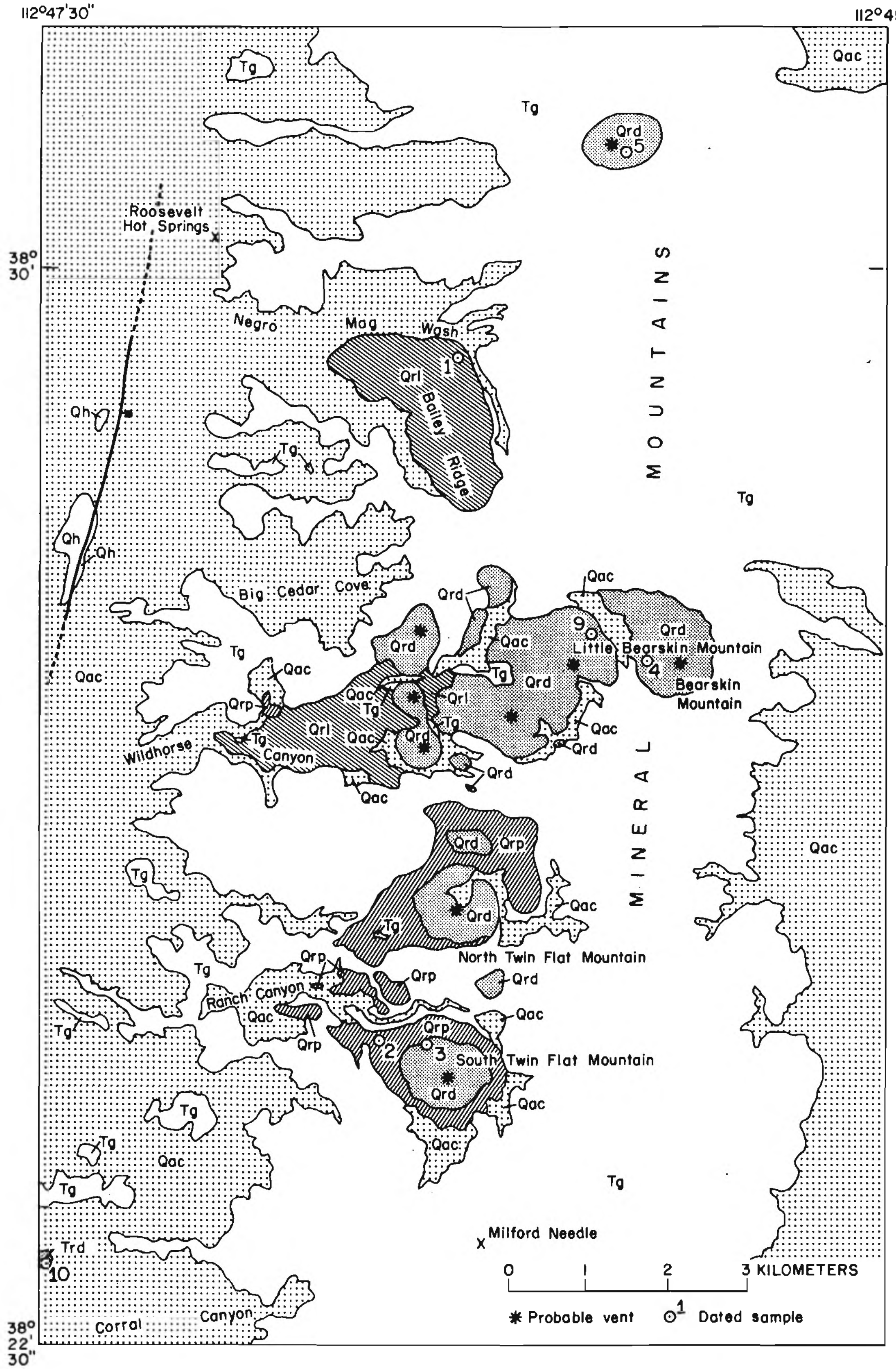
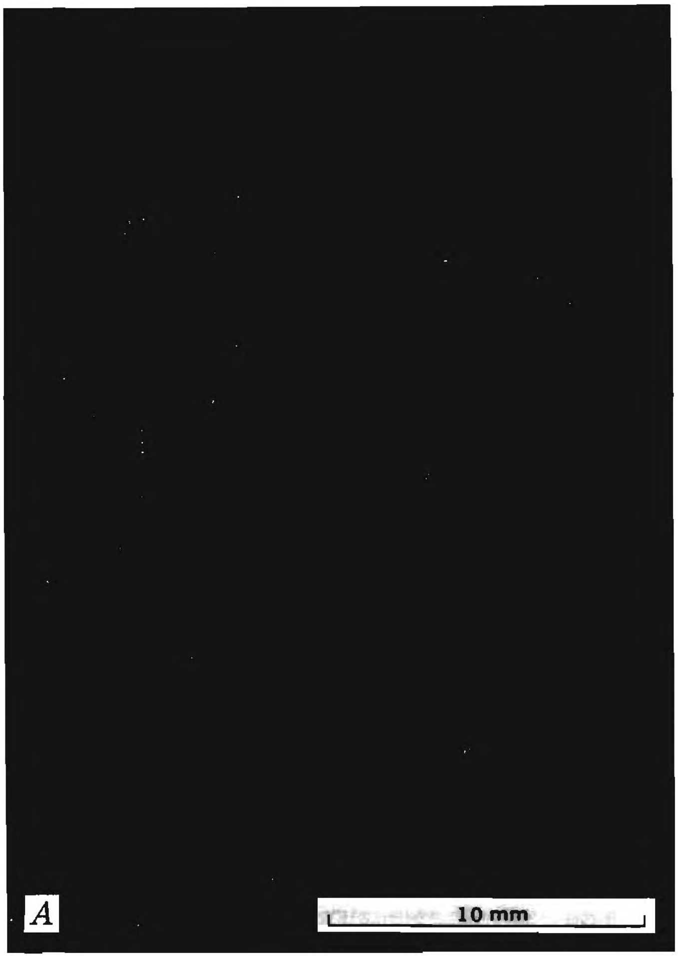


FIGURE 2.—Generalized geologic map of the central Mineral Mountains, Utah, showing distribution of Pleistocene rhyolitic rocks and locations of dated samples (table 3). Rock units, from oldest to youngest: Tg, Tertiary granite of Mineral Mountains; Trd, Tertiary rhyolite dome of Corral Canyon; Qrl, lava flows of Bailey Ridge and Wildhorse Canyon; Qrp, pyroclastic rocks; Qrd, lava domes; Qac, surficial deposits, primarily alluvium and colluvium; Qh, hot-spring deposits. Fault shown (bar and ball on downthrown side), named the Dome fault by Petersen (1975), is only one of many along the western range front.



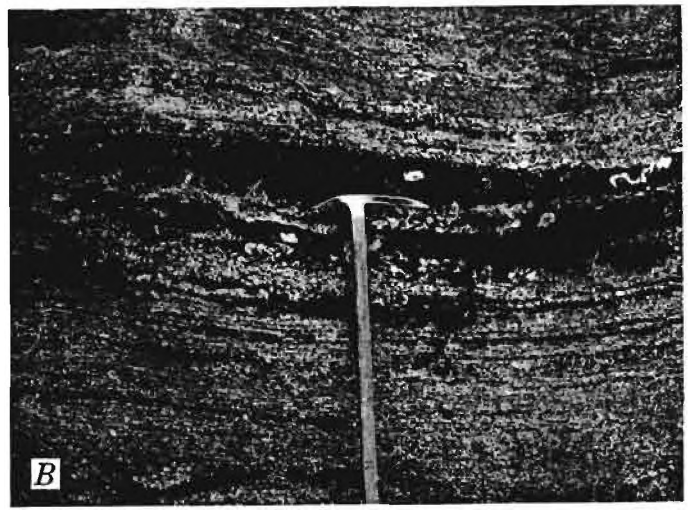


FIGURE 3.—Photographs of the Wildhorse Canyon flow. *A*, Photomicrograph showing recumbently folded flow lamination. Flow structures are defined by alined microlites. *B*, Alternating layers of obsidian and devitrified rhyolite in upper part of flow.

In upper parts of the flow a few meters of flow-layered obsidian are interlayered with devitrified rock (fig. 3*B*), passing upward into a more uniform dark glass zone or grading directly into a frothy rubbly breccia of tan perlitic pumice as much as 10 m thick at the top of the flow.

The flow layering and lamination in these rhyolitic lavas is remarkably planar and uncontorted as compared to the swirly internal structures typical of many rhyolitic lava flows. The "ramp structures" that occur commonly in upper parts of silicic flows (Christiansen and Lipman, 1966), are absent or poorly developed, and subhorizontal layering is typical throughout the Bailey Ridge and Wildhorse Canyon flows. The most common deviations from planar layering are small, typically rootless recumbent folds (fig. 3*A*), most limbs of which are less than 1 m long. These flowage features, as well as the relatively slight thickness of each lava flow as compared to its longitudinal extent, indicate that they were characterized by lower emplacement viscosities than many silicic lava flows.

Vents for these oldest flows of the Mineral Mountains have not been found. The Wildhorse Canyon flow appears to extend up drainage beneath younger lava domes in the upper part of the canyon, although exposures of the critical relations are poor because of cover by rubble. Probably the vent area for this flow is beneath the younger lavas to the east. If the Bailey Ridge flow vented from beneath its uppermost outcrop area, surface structures of this part of the flow give no indication of any concealed vent. This part of the flow is little dissected, however, and the vent area could be completely buried. Alternatively, the Bailey Ridge flow, and also the Wildhorse Canyon flow, might have come from higher on the slope, underneath the area now covered by the Bearskin and Little Bearskin Mountain lava domes. However, this would require that the upper portions of the flows be largely removed by erosion while the lower portions were left relatively undissected.

The Bailey Ridge and Wildhorse Canyon flows are petrographically similar. They contain less than 0.5 percent total phenocrysts, the majority of which are alkali feldspar (table 1). There are trace amounts of oligoclase, biotite, titanomagnetite, and ilmenite. The two flows are virtually identical in chemical composition (table 2). They are typical silicic rhyolites, containing about 76.5 percent SiO_2 and just over 9 percent total alkalis. The fresh obsidians contain more fluorine than water; secondarily hydrated pumice from the Bailey Ridge flow contains 2.4 percent total H_2O. The magmatic temperatures of these flows were about 750°C, as determined from compositions of iron-titanium oxides and coexisting plagioclase and alkali

TABLE 1.—*Modal compositions of radiometrically dated samples*

[Est., estimate; tr., trace; leaders (--), not present; *, microphenocrysts]

Field No.	Unit	Ground-mass	Plagio-clase	K-feldspar	Quartz	Biotite	Horn-blende	Clino-pyroxene	Opaques	Points counted
75L-17	Bailey Ridge flow, obsidian----------------	99.9	--	tr.	tr.	--	--	--	--	Est.
75L-15	Tuff of Ranch Canyon obsidian block---------	98.2	0.6	0.8	0.4	tr.	--	--	tr.	3,615
75L-16	South Twin Flat Mountain dome, obsidian with patchy devitrification-	92.6	1.2	3.9	2.3	tr.	--	--	tr.	3,034
75L-56	Bearskin Mountain, obsidian----------------	97.2	.3	1.2	1.2	0.1	--	--	tr.	4,725
75R-53	Little Bearskin Mountain dome, obsidian---------	96.0	.9	1.9	1.0	--	--	--	0.1	2,000
75L-18A	Northern dome, frothy perlite----------------	97.4	.4	1.3	.7	.1	--	--	.1	2,642
75L-19	Rhyolite of the Cudahy mine, obsidian---------	100	--	--	--	--	--	--	--	Est.
75L-21	Black Rock desert felsite plug-----------	91.2	5.8	1.2	--	tr.	--	1.2	.6	3,188
75L-23	Rhyolite of White Mountain, obsidian-----	94	--	--	--	--	*6	--	--	Est.

TABLE 2.—*Chemical analyses and CIPW norms of rhyolites of the Mineral Mountains*

[Analyses by S. H. Evans, Jr., by standard wet chemical techniques. Key to analyses; 74-3A, Obsidian, Bailey Ridge flow; 74-8, Obsidian, Wildhorse Canyon flow; 75-14, Obsidian, Little Bearskin Mountain dome; 75-20, Basal Obsidian, North Twin Flat Mountain dome. Leaders (---) not present; tr., trace]

Chemical Analyses	74-3A	74-8	75-14	75-20
SiO_2	76.52	76.51	76.42	76.45
TiO_2	.12	.12	.08	.08
Al_2O_3	12.29	12.29	12.79	12.79
Fe_2O_3	.31	.23	.20	.30
FeO	.46	.51	.38	.29
MnO	.05	.05	.09	.10
MgO	.08	.08	.11	.12
CaO	.64	.65	.44	.40
Na_2O	3.80	3.77	4.42	4.39
K_2O	5.24	5.28	4.72	4.73
P_2O_5	.02	.01	tr.	.06
H_2O+	.12	.06	.13	.10
H_2O-	.06	.06	.01	---
F	.16	.15	.42	.44
Sum	99.87	99.77	100.21	100.25
Less F=O	.07	.06	.18	.19
Total	99.80	99.71	100.03	100.06

CIPW Norms	74-3A	74-8	75-14	75-20
Q	33.40	33.28	33.22	32.48
c	---	.26	.41	.45
or	30.96	31.20	27.89	27.95
ab	32.15	31.90	37.40	37.15
an	1.00	1.02	---	---
di-wo	.37	.47	---	---
di-en	.11	.12	---	---
di-fs	.27	.38	---	---
hy-en	.09	.08	.27	.30
hy-fs	.21	.26	.57	.34
mt	.45	.33	.29	.43
il	.23	.23	.15	.15
ap	.05	.02	---	.14
fr	.33	.29	.61	.45
rest	.18	.12	.14	.10
Total	99.80	99.96	99.95	99.94

feldspar. The relatively low emplacement viscosities, indicated by the planar flow structures of these rhyolites, do not therefore seem related to exceptionally high emplacement temperatures.

A single K-Ar radiometric age determination of 0.79±0.08 m.y. (table 3, no. 1), from the toe of the Bailey Ridge flow, is the oldest age obtained from any rhyolite of the Mineral Mountains. The Bailey Ridge flow has a reversed paleomagnetic pole position (table 4) indicating, in conjunction with K-Ar data, that it was erupted toward the end of the Matuyama polarity epoch. The Wildhorse Canyon flow has not yet been dated radiometrically, but it also is characterized by a reversed polarity, which, in conjunction with morphological and chemical resemblance to the Bailey Ridge flow and its position beneath some of the pyroclastic rocks, suggests a similar age.

Pryoclastic rocks

South of Wildhorse Canyon, pyroclastic rocks of ash-fall and ash-flow origin are the lowest exposed rhyolitic rocks. The main area of pyroclastic rocks is in Ranch Canyon, where tuffs bury rugged paleotopography much like the present land surface.

The pyroclastic rocks are only weakly consolidated and are mostly poorly exposed, underlying alluviated slopes. All the pyroclastic deposits, both ash-fall and and ash-flow, are white to light tan. They occur over an altitude range from 1950 m in valley-bottom exposures in Ranch Canyon to as high as 2540 m on the surrounding slopes. They also occur in the Cove Fort area, where they are overlain by basalt lava flows (Nash and Smith, 1977). Much of the pyroclastic sequence has been removed by erosion in Ranch Canyon, and it is not clear to what extent this altitude range reflects an actual total thickness of the original deposit and to what extent the pyroclastic rocks were thinner but blanketed the preexisting topography. In Ranch Canyon these rocks are overlain by the large lava domes on North and South Twin Flat Mountains and by smaller masses of rhyolitic lava on adjacent ridges. Although contacts between these domes and the pyroclastic rocks are nowhere well exposed, this stratigraphic sequence is indicated by structural zones in the rhyolite domes of North and South Twin Flat Mountains. The lowest exposures are of a subhorizontal

TABLE 3.—K-Ar *age determinations on upper Cenozoic rhyolites of the Mineral Mountains, Utah, and adjacent areas*

[Constants: $K^{40}\lambda_{\varepsilon}$ = 0.581 x 10^{-10}/yr, λ_{β} = 4.963 x 10^{-10}/yr; atomic abundance: K^{40}/K = 1.167 x 10^{-4}; *Radiogenic argon; Potassium determinations made with an Instrumentation Laboratories flame photometer with a Li internal standard. Figures 1 and 2 give sample locations. Ages of WM76-3 and MR76-26 determined by S. H. Evans, Jr., and F. H. Brown; other ages determined by H. H. Mehnert]

Sample	Field No.	Unit	Material dated	Location (Lat N Long W)	K_2O (percent)	$*Ar^{40}$ (10^{-10}) (moles/gram)	$*Ar^{40}$ (percent)	Age (m.y.±2σ)
1	75L-17	Bailey Ridge flow-------	Obsidian--------	38°29′, 112°49′	5.10, 5.10	0.058	25.8	0.79±0.08
2	75L-15	Tuff of Ranch Canyon----	Obsidian block--	38°25′, 112°50′	4.63, 4.66	.047	47.1	0.70±0.04
3	75L-16	South Twin Flat Mountain dome---------	Sanidine--------	38°25′, 112°49′	8.14, 8.08	.059	18.1	0.50±0.07
4	75L-56	Bearskin Mountain dome--	Obsidian--------	38°27′, 112°47′	4.48, 4.49	.048	20.2	0.75±0.10
						.039	13.5	0.60±0.12
5	75L-18A	North Dome--------------	Sanidine--------	38°31′, 112°47′	9.36, 9.35	.073	24.5	0.54±0.06
6	75L-19	Cudahy mine-------------	Obsidian--------	38°45′, 112°51′	4.91, 4.93	.168	46.0	2.38±0.15
7	75L-21	South Twin Peak---------	Sanidine--------	38°45′, 112°47′	11.13, 11.12	.373	54.3	2.33±0.12
8	75L-23	White Mountain----------	Obsidian--------	38°55′, 112°30′	4.63, 4.70	.029	15.9	0.43±0.07
	WM76-3		Obsidian--------		5.23, 5.25	.030	21.5	0.39±0.02
9	75R-23	Little Bearskin Mountain dome---------	Sanidine--------	38°27′, 112°48′	9.31, 9.15 [1]9.26	.080	31.8	0.61±0.05
10	MR76-26	Corral Canyon dome------	Biotite---------	38°24′, 112°53′	8.72, 8.75	1.011	61.6	7.90±0.30

[1] Isotope dilution determination

TABLE 4.—*Preliminary data on magnetic polarities of rhyolites of the Mineral Mountains*

Unit	Number of samples	Declination	Inclination	Standard error (percent)
Normal samples:				
Northern dome------------	9	350	62	3
Big Cedar Cove dome------	4	23	67	4
Ranch Canyon dome--------	5	22	44	5
Corral Canyon dome-------	3	332	25	20
Ranch Canyon ash---------	2	356	46	29
Wildhorse Canyon ash-----	6	349	48	5
Reversed samples:				
Bailey Ridge flow--------	6	173	-63	6
Wildhorse Canyon flow----	4	168	-61	2

zone of basal flow breccia below the basal obsidian zone; this is the typical zonation expectable at the base of a lava flow or dome and would be an improbable relation if the pyroclastic rocks had been plastered against older lava domes. Thus, the lava dome of South Twin Flat Mountain overlies pyroclastic rocks that are at least 60 m and probably as much as 180 m thick, and these figures suggest minimum thicknesses of the pyroclastic unit.

The lower pyroclastic rocks are beds of air-fall pumice and ash at least 10 m thick and probably much thicker. Individual beds are a few centimeters to about a meter thick. Variable dips indicate that the ash was deposited on the underlying granite, on a surface as rugged as the present one. The pumice and ash contain several percent of small phenocrysts of quartz, oligoclase, alkali feldspar, biotite, magnetite, ilmenite, sphene, and allanite. This mineral assemblage is generally characteristic of the youngest rhyolite flows as well. Associated with the pumice and ash are a few percent of rhyolitic lithic debris, including devitrified rhyolite, perlite, and sparse obsidian fragments. Phenocrysts in the lithic debris are sparse, generally similar to those in the flows of Bailey Ridge and Wildhorse Canyon.

Ash-flow deposits widely overlie the ash-fall beds in Ranch Canyon. The ash-flow deposits locally are at least 50 m thick; probably the total thickness is much greater, but accurate estimates are difficult because of the poor exposures. The ash-flow deposits are everywhere nonwelded and only weakly consolidated; they tend to weather to small conical hills. On especially steep slopes the ash-flow deposits rest directly against granite, with no intervening ash-fall material (fig. 4). In exceptionally good exposures, several flow units —each a few meters thick—can be recognized in the ash-flow deposits, with partings between the flow units marked by local concentrations of pumice, lithic debris, or better sorted ash.

FIGURE 4.—Ash-flow tuff, resting on a rugged erosion surface cut on granite of the Mineral Mountains pluton. Arrows indicate faint parting between flow units of tuff. From northern side of Ranch Canyon at about 2105-m elevation.

On the northern side of lower Wildhorse Canyon, an isolated patch of pyroclastic material about 150 m across consists of finely laminated white fine-grained ash of lacustrine origin. These beds of water-reworked ash are younger than the Wildhorse Canyon flow and were deposited in a local basin dammed by the flow. The ash has a refractive index similar to that of the pyroclastic rocks in Ranch Canyon, one valley to the south, suggesting to us that it represents a reworked marginal facies of this deposit. In contrast, this patch of lacustrine tuff is interpreted by Glenn Izett (written commun., 1976) as airborne Bishop ash, from the Long Valley caldera in California, on the basis of small compositional differences with other rhyolites of the Mineral Mountains.

A single whole-rock K-Ar age on an obsidian clast from ash-flow tuff in Ranch Canyon yielded an age of 0.70 ± 0.04 m.y. (table 3, no. 2), providing an older limit for the age of the pyroclastic rocks. The pyroclastic deposits in Ranch Canyon, as well as the local lake beds in Wildhorse Canyon. have normal magnetic polarities in contrast to the reverse polarities of Bailey Ridge and Wildhorse Canyon flows. Thus, the pyroclastic rocks have been deposited during the Brunhes polarity epoch.

Porphyritic lava domes

The stratigraphically highest part of the upper Cenozoic volcanic assemblage in the Mineral Mountains is a group of at least nine separate perlite-mantled lava domes and small flows of porphyritic rhyolite. The domes tend to occur along the crest of the range, discontinuously over a zone about 15 km long. These domes form some of the highest topographic points in the Mineral Mountains, including Bearskin Mountain with an elevation of 2772 m (9095 ft). Individual domes are as much as 1 km across at their bases and stand as much as 250 m high, although dimensions are difficult to determine precisely because of the irregular pre-existing topography and subsequent erosion. Small stubby flows extend out from some of the domes, and some small isolated patches of rhyolite (fig. 2) may represent either eroded flow remnants or small separate domes.

The larger domes, such as Bearskin and Little Bearskin Mountains, are little eroded, and surface exposures consist largely of blocks of tan perlitic glass that are slightly modified remnants of the original brecciated frothy carapaces of the domes. Scattered fragments of dense black obsidian, derived from beneath the perlitic breccia, occur about a third of the way above the base of these domes. Float of well-layered devitrified rhyolite is exposed locally just above the zone of obsidian fragments. Pumiceous material, that in places ravels out from below the level of the obsidian zone. may represent an initial pyroclastic fall that is not well exposed.

Other domes, such as those of North and South Twin Flat Mountains (fig. 5), have been more deeply dissected, in this case by the reexcavation of Ranch Canyon, and their internal structural and crystallization features are better exposed. The internal features of all these late domes are in general similar. A basal black vitrophyric zone is everywhere well developed. in places resting on lighter colored glassy basal flow breccia. The vitrophyre zone, which is as much as 5–10 m thick, grades upward into devitrified rock through a transition zone a few meters thick in which flow-layered obsidian alternates with devitrified rock that is commonly highly spherulitic. The devitrified interiors of the flows tend to be light gray and contain conspicuous spherulites. In places, gas cavities several centimeters across contain lithophysal fillings. The interiors of the flows tend to be crudely flow layered, with the layering subhorizontal just above the basal glass zone, but becoming steeper in upper parts of the lava dome. Near-vertical riblike masses of flow-layered devitrified rock are commonly exposed high on the

FIGURE 5.—Rhyolite domes of North and South Twin Flat Mountains. Rugged terrain in distance, including Milford Needle (elev. 2920 m) on the left side of the picture, is underlain by granite of the Mineral Mountains pluton. Photographed from ridge between Ranch and Wildhorse Canyons.

domes, where erosion has stripped away the surface mantle of frothy perlite. The steeply dipping flow layering and ramp structures of these domes thus are in contrast to structures in the older lava flows of Wildhorse Canyon and Bailey Ridge.

The porphyritic domes typically lack well-developed central craters (for example, the South Twin Flat Mountain dome) although several have slight central depressions that have been breached and accentuated by erosion. Breached depressions are especially evident for the unnamed northern dome, which is on the range crest northeast of Negro Mag Wash (fig. 2), Bearskin Mountain dome, and North Twin Flat Mountain dome (fig. 5).

All the domes contain several percent phenocrysts of quartz, oligoclase, alkali feldspar, biotite, and iron-titanium oxides (table 1). Trace amounts of sphene and allanite occur in some domes. Hornblende, zircon, and allanite are present in the Corral Canyon dome. the southernmost exposure of rhyolitic volcanic rocks. The North and South Twin Flat Mountain domes have 5–8 percent total phenocrysts, distinctly more than any of the others. The obsidian zones of these two domes appear even more phenocryst-rich, because of the presence of small "snowflake" devitrification spots. The flows in upper Wildhorse Canyon and to the north contain only 2–3 percent total phenocrysts.

Two analyzed samples of the porphyritic domes (table 2) are chemically similar silicic alkalic rhyolite. In comparison with the older flows of Bailey Ridge and Wildhorse Canyon, the domes are slightly but significantly higher in Na_2O and F; they are lower in K_2O and CaO.

Lack of continuity, and thus absence of contact relations, between the domes makes relative ages of the domes difficult to determine. On the basis of amount of dissection, North and South Twin Flat Mountains may be among the oldest, and Bearskin Mountain among the youngest of the domes. The K-Ar ages (table 1), petrographic and chemical similarities, and the generally similar degree of erosional dissection indicate that the domes are about the same age. Stratigraphic relations on the northern side of the North Twin Flat Mountain dome suggest that this dome is older than the unnamed ridge-capping flow 0.5 km north of it (fig. 2). Bearskin Mountain and the three domes extending southwest from it appear compositionally homogeneous, consisting of phenocryst-poor rhyolite similar to the rhyolite that overlies the North Twin Flat Mountain dome. The Bearskin Mountain dome has yielded K-Ar ages on obsidian of 0.60 ± 0.12 and 0.75 ± 0.10 m.y. (table 3, no. 4), and the Little Bearskin Mountain dome has an indicated sanidine age of 0.61 ± 0.05 m.y. (table 3, no. 9). Sanidines from obsidian of South Twin Flat Mountain and the unnamed northern dome have yielded K-Ar ages of 0.50 ± 0.07 and 0.54 ± 0.06 m.y. respectively (table 3, nos. 3, 5). Magnetic-polarity determinations for several domes of this group are normal (table 4) indicating, in conjunction with the K-Ar ages, that they were erupted during the Brunhes polarity epoch.

One small dome of mostly devitrified alkalic rhyolite and minor vitrophyre in Corral Canyon, shown as Trd in the lower left corner of figure 2, has been dated at 7.90 ± 0.30 m.y. (table 3, no. 10). These volcanic rocks appear to be unrelated to the young rhyolites higher in the Mineral Mountains; the rhyolite in Corral Canyon is more eroded and contains a different phenocryst assemblage than the other rhyolites. The thermal event about 8 m.y. ago, as represented by these lavas, may have been responsible for producing the anomalously young ages of 14 and 9 m.y. measured on the Mineral Mountains pluton.

DISCUSSION

The stratigraphic relations and K-Ar ages of rhyolites of the Mineral Mountains, newly reported here, indicate that these rocks were emplaced during a relatively brief period in the Pleistocene, between about 0.8 and 0.5 m.y. ago, but an older rhyolitic event occurred about 8 m.y. ago. The Mineral Mountains are flanked on the northern and eastern sides by upper Cenozoic basalt flows (Condie and Barsky, 1972; Hoover, 1974), roughly contemporaneous with and younger than the rhyolite of the Mineral Mountains, and this association of rhyolite and basalt constitutes a bimodal volcanic assemblage of a type that is being recognized widely in the western United States in upper Cenozoic volcanic sequences (Christiansen and Lipman, 1972).

A significant question is whether the thermal anomaly of the Roosevelt KGRA is due to proximity to the late Cenozoic volcanic centers in the Mineral Mountains. Roosevelt Hot Springs and other inactive hot springs are located along the mountain-front fault on the western side of the Mineral Mountains, about 2 km west of the nearest exposed rhyolite (fig. 2). The size and shape of the Pleistocene magmatic system underlying the Mineral Mountains cannot be determined with any precision from the surface distribution of rhyolite vents, yet the extent of the vents for 15 km along the crest of the range suggests the possibility of a sizable magmatic system at depth. The elongate trend of rhyolite vents might even mark a segment of a large evolving circular igneous structure, such as interpreted for the Coso rhyolite domes in California (Duffield, 1975). The rhyolites of the Mineral Mountains were extruded along the eroded core of the large Mineral Mountains pluton, itself a late Cenozoic intrusion of remarkably large size for so young an age. Proximity in space and time suggests that the rhyolite of the Mineral Mountains represents a late stage in the evolution of a complex magmatic system that earlier gave rise to the granite of the Mineral Mountains. Alternatively, the rhyolite volcanism might have evolved independently of the granite, but has been partly localized where the crust was still hot from an earlier plutonic event. It seems likely, though not provable, that this large complex magmatic system has also been the heat source for the Roosevelt KGRA, with the shallow thermal anomaly enhanced along the range front by deep fault-controlled convective circulation of hot water.

This interpretation of a complex shallow magmatic system is supported by limited available rare-earth element data (table 5), which indicate that the rhyolite of the Mineral Mountains had a magmatic residence time in a shallow environment for a sufficiently long time to undergo major low-pressure fractional

TABLE 5.—*Rare-earth element analyses of rhyolites of the Mineral Mountains*

[Analyses by J. S. Pallister and H. T. Millard by neutron activation, using a chemical concentration technique. (See Zielinski and Lipman, 1976.)]

	Bailey Ridge flow	Wildhorse Canyon flow	South Twin Flat Mountain dome	Bearskin Mountain dome
	(75L-17)	(75L-60A)	(75L-16)	(75L-56)
La------	43.5	44.3	24.9	25.0
Ce------	95.6	94.3	51.5	44.2
Nd------	27.0	25.5	9.6	7.5
Sm------	3.6	3.5	1.3	.90
Eu------	.42	.40	.037	.035
Gd------	2.8	2.5	1.3	.88
Tb------	.52	.49	.30	.20
Tm------	.38	.35	.47	.31
Yb------	2.9	2.9	4.2	3.0
Lu------	.52	.49	.79	.57

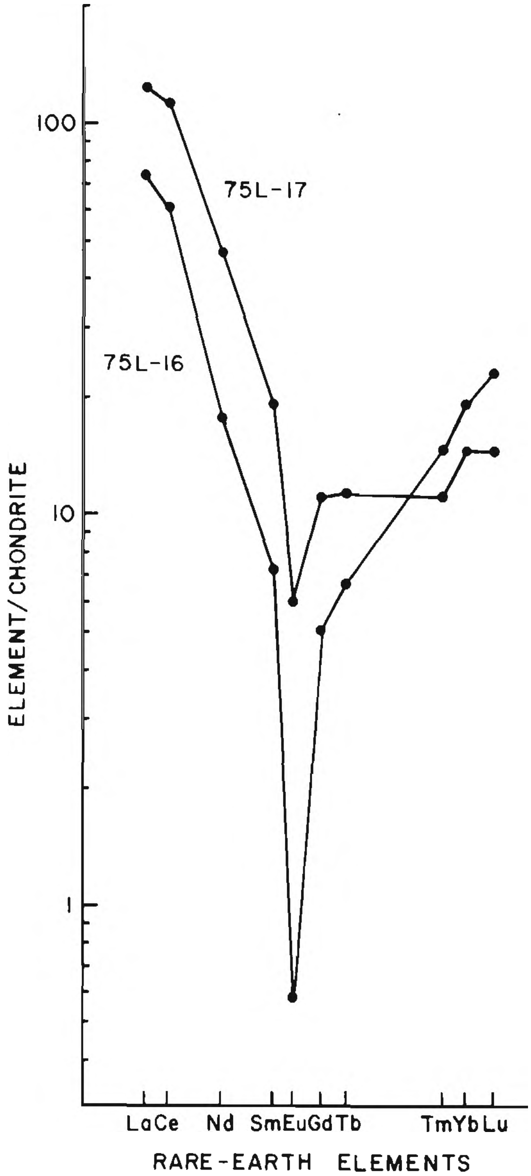


FIGURE 6.—Chrondite-normalized rare-earth-element plot for two rhyolites of the Mineral Mountains (75L–16 and 75L–17), showing negative Eu anomalies.

crystallization involving removal of feldspar. Chondrite-normalized analyses of two whole-rock samples show large negative Eu anomalies (fig. 6), indicative of major feldspar removal (Arth, 1976). This pattern contrasts with that of some other voluminous Cenozoic silicic rocks in the western United States (Zielinski and Lipman, 1976; P. W. Lipman, unpub. data, 1976) which show small or no Eu anomalies and appear to have developed their silicic compositions by processes not involving major feldspar fractionation, probably because the environment of differentiation was at pressures too high for feldspar to be stable.

Occurrences of upper Cenozoic alkalic rhyolite of possible geothermal significance in southwestern Utah are not restricted to the Mineral Mountains. We dated obsidian "Apache tears" from an eroded rhyolite flow at the Cudahy mine about 25 km north of the Mineral Mountains (fig. 1), as 2.38±0.15 m.y. (table 3, no. 6). A large rhyolite plug (South Twin Peak) in the Black Rock desert about 10 km east of the Cudahy mine yielded a similar K-Ar age of 2.33±0.12 m.y. (table 3, no. 7). Marginal obsidian from a small body of rhyolite at White Mountain, about 50 km northeast of the Mineral Mountains (fig. 1), yielded ages of 0.43±0.07 and 0.39±0.02 m.y. (table 3, no. 8), the youngest of any of our ages. The rhyolite at White Mountain contains inclusions of a distinctive dated basalt, indicating a maximum age for the dome of about 1 m.y. (Hoover, 1974). This rhyolite occurs less than 1 km from the nearest exposure of upper Pleistocene basalt of the Tabernacle volcanic field estimated to be 10 000–20 000 yr old (Hoover, 1974). Basalts of the Ice Springs volcanic field, 3 km north of White Mountain, are post-Lake Bonneville in age, that is, less than 12 000 yr old. These basaltic and rhyolitic rocks together offer another example of a bimodal basalt-rhyolite association in Utah. Thus, the potential for volcanic-related thermal anomalies in southwestern Utah is not confined to the Mineral Mountains. In fact, White Mountain is about 7 km north of Meadow and Hatton hot springs (Mundorff, 1970).

Another intriguing aspect of the rhyolites in the Mineral Mountains is their significance as a source of artifact obsidian. Implement-grade obsidian is relatively scarce in the southwestern United States, yet obsidian artifacts occur widely in archeological sites. Well-known sources of archeological obsidian include the Jemez Mountains in New Mexico, Coso Mountains and Long Valley areas in east-central California, Medicine Lake Highlands and associated rhyolitic centers in northeastern California, Newberry volcano and numerous small areas of rhyolite in eastern Oregon, and Yellowstone rhyolite plateau in Wyoming (fig. 7). The little known Mineral Mountains locality is in a region where high-quality obsidian is scarce, nearly equidistant from better known sources, yet it contains abundant obsidian suitable for implement manufacture. Individual blocks of nonporphyritic obsidian from the Bailey Ridge and Wildhorse Canyon flows are as much as 0.5 m across. Obsidian from the Mineral Mountains has recently been recognized in several archeological sites in southwestern Utah and adjacent parts of Nevada (Umshler, 1975), but how widely it has been distributed has yet to be established.

FIGURE 7.—Well-known sources for archeological obsidian in the western United States.

Available compositional data indicate that obsidian artifacts derived from the Mineral Mountains should be distinguishable, especially by minor-element compositions, from those of most of the better known obsidian sites.

Fission-track age dating, by G. A. Izett and C. W. Naeser, and obsidian-hydration age dating, by Irving Friedman, were conducted—independently of our study—on selected samples of rhyolite from the Mineral Mountains. The ages determined by these two other techniques provide a cross-check on the ages presented above that were determined by the K-Ar isotope method. Comparisons of the results of the three techniques are presented separately, in the sections that follow.

FISSION-TRACK DATING

By G. A. Izett and C. W. Naeser

Fission-track age determinations were made on samples of obsidian from the Bailey Ridge flow and the Bearskin Mountain dome. The fission-track age of the Bailey Ridge obsidian is in fair agreement with the K-Ar age of the obsidian, but the fission-track age of the Bearskin Mountain obsidian is anomalously younger than the K-Ar age. Th sample we dated of the Bearskin Mountain obsidian contains no fossil fission tracks; however, the age can be estimated by assuming the presence of one fossil track as shown in the table below. The anomalously young fission-track age of the Bearskin Mountain obsidian probably is due to the annealing of fossil tracks from a recent thermal event. The fission-track analytical data follow:

Fission-track analytical data

[Fission tracks etched for about 10 seconds in 48 percent hydrofluoric acid; ± 1 sigma about the mean. $\lambda f = 6.85 \times 10^{-17} yr^{-1}$]

Locality	ϕ (neutrons cm^{-2})	ρ_s (tracks cm^{-2})	ρ_i (tracks cm^{-2})	Fission track glass age x 10^6 years	K-Ar glass age x 10^6 years[1]
Bearskin Mountain dome	8.72×10^{14}	$<3.37 \times 10^{1}$(1)	1.25×10^{5}(309)	<0.02	0.75 ± 0.1 0.60 ± 0.12
Bailey Ridge flow	0.5×10^{15}	7.89×10^{2}(3)	4.40×10^{4}(213)	0.55 ± 0.30	0.79 ± 0.08

[1]See table 3.

OBSIDIAN-HYDRATION DATING

By Irving Friedman

Four rhyolite lava flows or domes from the Mineral Mountains, Utah, were dated by the obsidian-hydration technique. Most of the results agree with K-Ar and fission-track dates of the same flows.

Obsidian-hydration dating depends upon the fact that a newly formed surface on obsidian, such as a cooling crack, adsorbs water from the atmosphere. This adsorbed water slowly diffuses into the obsidian, and the depth of penetration of the water can be measured under the microscope in a thin section cut normal to the surface (Friedman and Smith, 1960). The rate at which the water diffuses into the obsidian is dependent upon temperature and glass composition (Friedman and Long, 1976).

The thickness of the hydrated layer (in micrometers) for the rhyolite units is tabulated below. Also listed is the expected rate of hydration (in $\mu m^2/10^3$ yr) for each flow, calculated for an estimated effective hydration temperature of 8°C and from the chemical composition of the obsidian. (See Friedman and Long, 1976.) The calculated obsidian-hydration age is also given, as is the K-Ar age.

Although the effective hydration temperature is assumed to be the same for all the flows sampled, the differing whole-rock chemistry of the obsidian gives different calculated hydration rates. Compositions of two of the obsidians are from table 2 in this paper; the analysis of the Bearskin Mountain dome is from S. H. Evans (written commun., 1976). No analysis is available for the South Twin Flat Mountain dome. An analysis for the North Twin Flat Mountains (table 2) was used instead; the hydration rate and calculated age are accordingly uncertain.

The calculated hydration rates vary by a factor of 2.5, owing mainly to differences in the amount of CaO+MgO. The chemical analyses were on whole-rock samples, but the hydration-rate calculation should be based on glass compositions. The Wildhorse Canyon and the Bailey Ridge glasses are almost free of phenocrysts, but the Bearskin Mountain and particularly the

Rhyolite	Thickness of hydration µm (± 1 µm)	Chemical index	Calculated hydration rate $\mu m^2/10^3$ yrs	Calculated age 10^6 yrs	Corrected age	K/Ar age
Wildhorse Canyon flow------------	41	42.5	2	0.85	0.85	([1])
Bailey Ridge flow------------	40	41.7	2	.80	.80	0.79
Bearskin Mountain dome------------	31	47.4	4	.24	.48	.75 .60
South Twin Flat Mountain dome---	22	51.1(?)	5(?)	.10(?)	.25	.50

[1]No determination

South Twin Flat Mountain glasses are porphyritic. Obsidian from Wildhorse Canyon, Bailey Ridge, and South Twin Flat Mountain all have refractive indices of 1.4847±0.0005, whereas Bearskin Mountain dome has a slightly higher index, 1.4856±0.0005. The similarity in index of all four glasses makes any assumption of greatly differing hydration rates for these samples unrealistic. If we assume that the chemical compositions of the glass phase of all four samples are similar, then the hydration rates also will be similar and the dates shown in the column "Corrected age" should apply.

The corrected ages agree with the K-Ar dates, except for the date for the South Twin Flat Mountain dome, where the hydration date is about half that derived by K-Ar dating. The reasons for this discrepancy are not known, but we may not have sampled sufficiently to find an original surface on the samples from this site. Alternatively, the discrepancy may be due to some inherited argon in the sanidine used for K-Ar dating.

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