Rhyolites in the Gillies Hill–Woodtick Hill area, Beaver County, Utah

STANLEY H. EVANS, JR. *Department of Geology and Geophysics, University of Utah, Salt Lake City, Utah 84112*
THOMAS A. STEVEN *U.S. Geological Survey, Box 25046, M.S. 942, Denver Federal Center, Denver, Colorado 80225*

ABSTRACT

The rhyolite of Gillies Hill forms a cluster of rounded hills between Beaver basin and Cove Fort basin in southwest-central Utah. These rocks were erupted as a series of viscous lava flows, volcanic domes, and minor pyroclastic rocks from centers localized along and near the main fault separating the volcanic rocks in the Marysvale volcanic field to the east from batholithic rocks in the Mineral Mountains to the west. Faulting began in middle Miocene time before eruption of the rhyolite of Gillies Hill and continued episodically into Pleistocene time. Potassium-argon dating indicates that the rhyolite of Gillies Hill formed from a rapid sequence of eruptions about 9.1 m.y. ago.

The rhyolite of Gillies Hill is made up of an older high-silica suite ($SiO_2 > 75\%$) consisting of numerous short stubby flows and of a younger low-silica suite ($SiO_2 = 70\%$) represented by a single

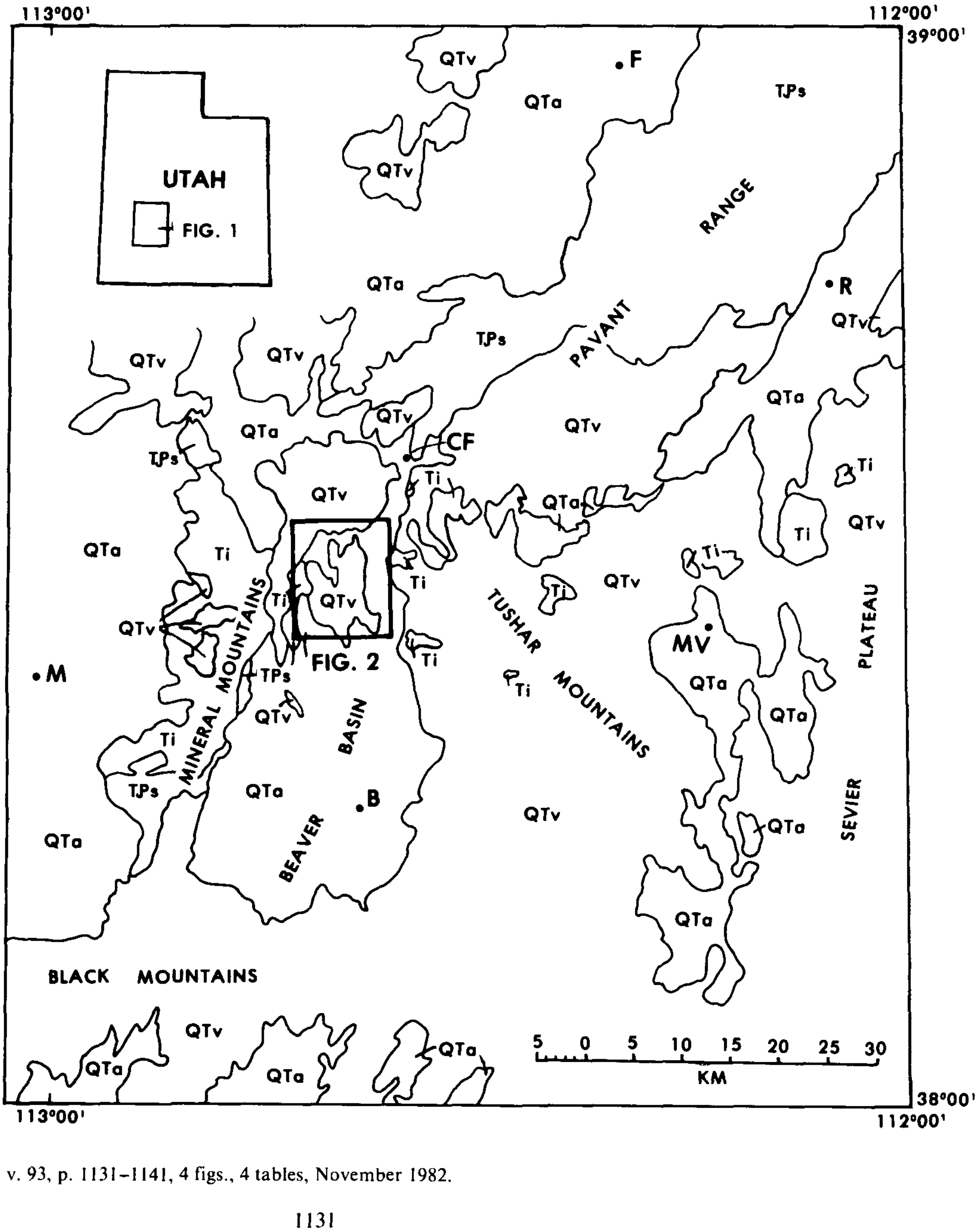
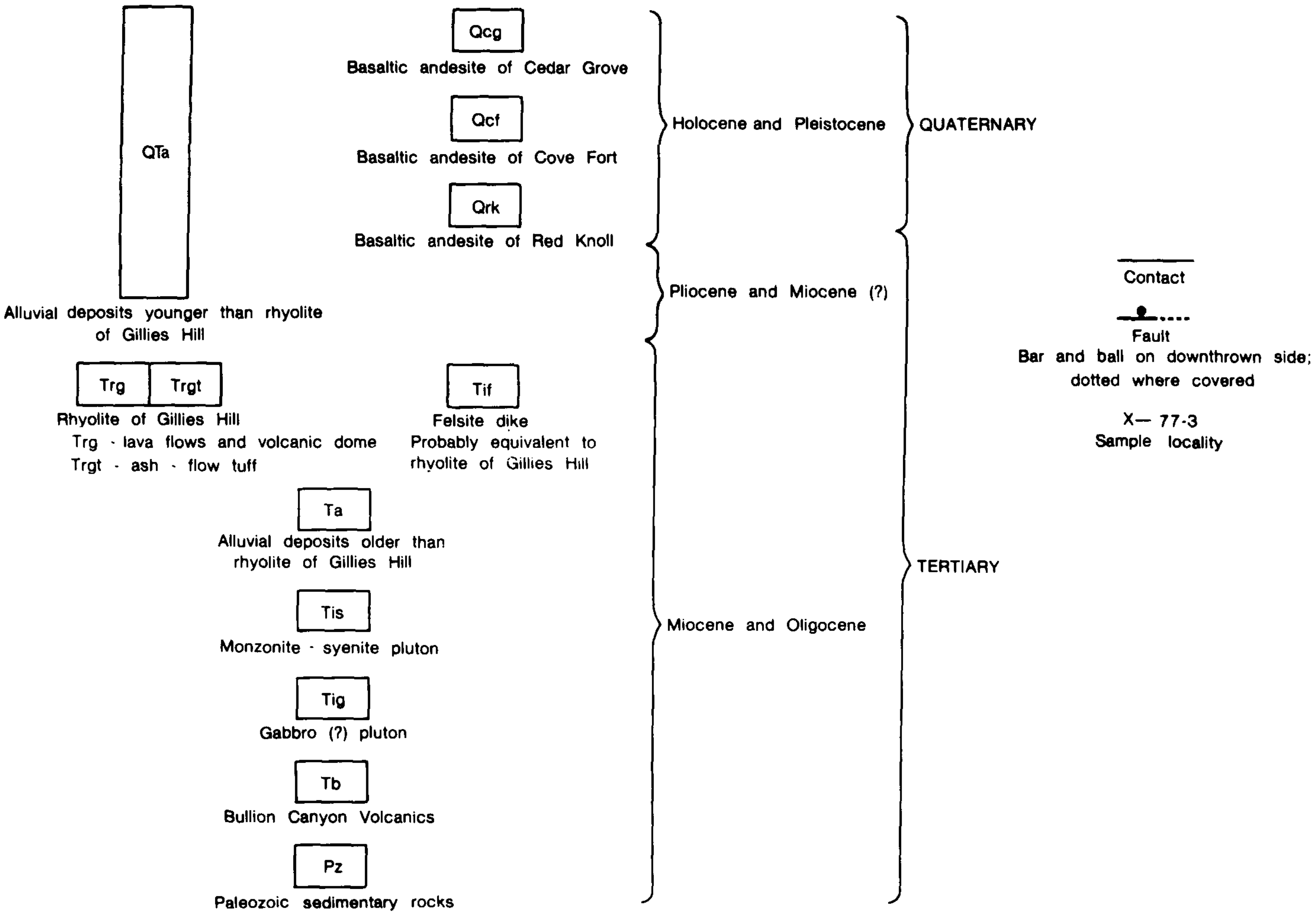


Figure 1. Geologic map of southwest-central Utah showing location of Figure 2. TPs, undivided Tertiary to Paleozoic sedimentary rocks; QTv, undivided Quaternary and Tertiary volcanic rocks; QTa, undivided Quaternary and Tertiary rocks; Ti, undivided Tertiary intrusive rocks; F, Fillmore; CF, Cove Fort; B, Beaver; R, Richfield; MV, Marysvale.

Geological Society of America Bulletin, v. 93, p. 1131–1141, 4 figs., 4 tables, November 1982.

EXPLANATION FOR FIGURE 2



large volcanic dome. The high-silica suite is believed to have formed by eruptions from the top of a compositionally zoned magma chamber. The younger low-silica suite came either from a separate magma chamber or from a significantly different level within the same magma chamber. The proximity of sources for both suites suggests eruptions from different levels within a single source chamber, perhaps from different vertically stacked convection cells.

INTRODUCTION

An assemblage of rhyolite lava flows, volcanic domes, and minor pyroclastic rocks, here called the rhyolite of Gillies Hill, forms a cluster of rounded hills adjacent to Interstate Highway 15 at the north end of Beaver basin in southwest-central Utah (Figs. 1 and 2). These rocks belong to the silicic end member of the bimodal basalt-rhyolite suite that was erupted widely in the Basin and Range province during later Cenozoic time (Christiansen and Lipman, 1972). The rhyolite of Gillies Hill has been virtually ignored until quite recently, and, indeed, the Utah State geologic map (Hintze, 1963) shows the area to be underlain largely by Tertiary basin-fill sedimentary rocks. Haugh (1978) published a reconnaissance geologic map and report of the area, in which he identified the rhyolites as remnants of lava flows and domes of Cenozoic age and called attention to their presence. The present authors investigated the area independently; Evans studied the geochemistry and geochronology of the rhyolites as part of a research program at the University of Utah focusing on geothermal energy, and Steven mapped the area geologically as part of a regional study by the U.S. Geological Survey to assess the mineral-resource potential of the Richfield 1° × 2° Quadrangle.

An understanding of the geology, age, and geochemistry of the rhyolite of Gillies Hill is important for several reasons beyond merely filling a local gap in knowledge. The area is only a few kilometres southwest of the Cove Fort–Sulphurdale KGRA (known geothermal resource area) and about 20 km east of the Roosevelt KGRA. If these rhyolites had been sufficiently young, a geothermal potential might have existed. In addition, work in adjacent mountains has shown that multiple episodes of mineralization took place within the surrounding volcanic terrane (Steven and others, 1978a, 1978b, 1979) and that rhyolite centers in particular tend to have uranium and possibly molybdenum deposits associated with them (Cunningham and Steven, 1979a; Steven and others, 1979). Beaver basin to the south is currently the focus of intense exploration interest for possible roll-front or sedimentary-trap uranium deposits that may have been fed from rhyolite sources in the adjacent mountains (Cunningham and Steven, 1979b; Steven and others, 1980). Although the rhyolite of Gillies Hill has proven too old (9.1 m.y.) to have modern geothermal significance, a relationship may exist between the rhyolite and potential mineral deposits in or near the adjacent basins.

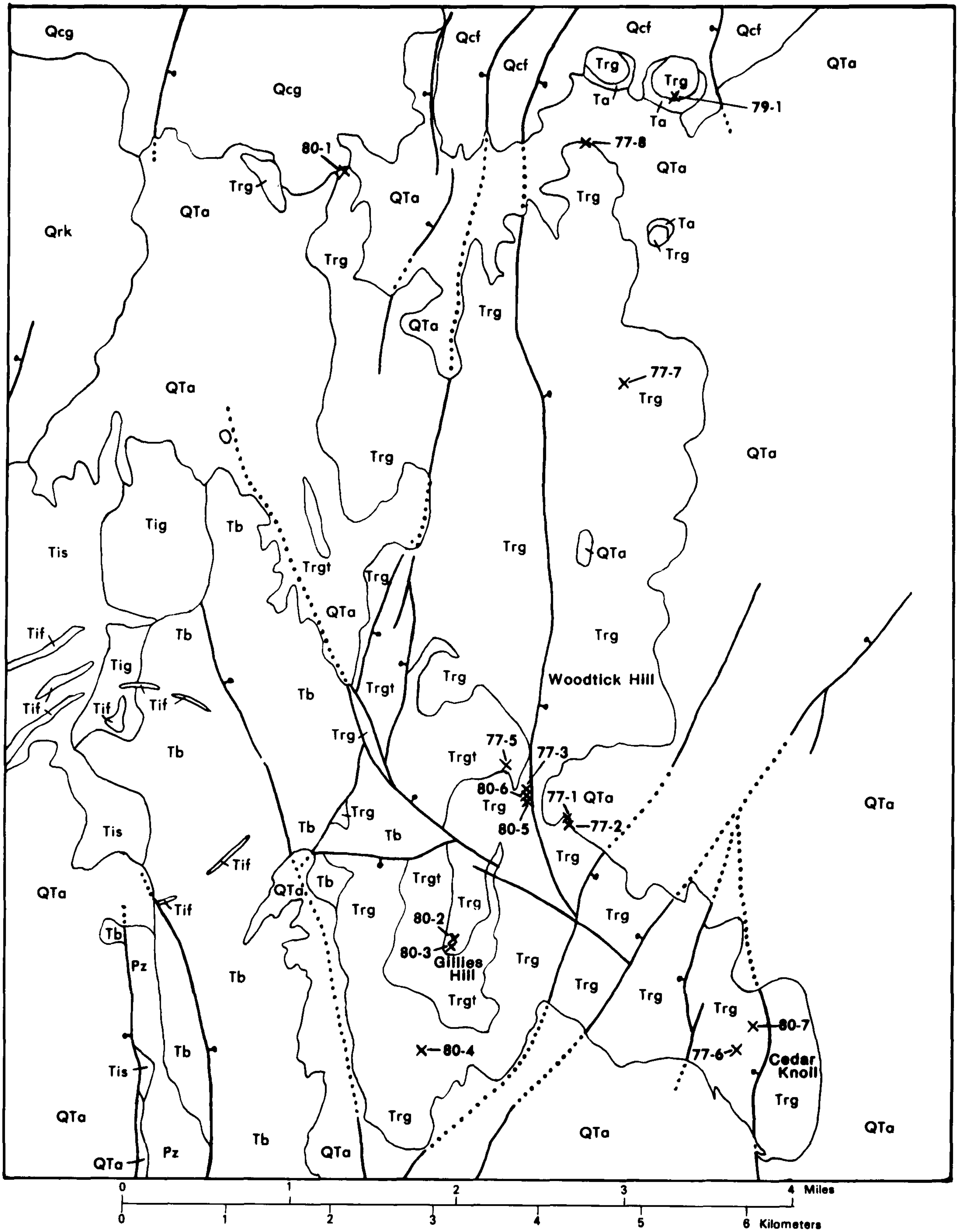


Figure 2. Geologic map of the Gillies Hill–Woodtick Hill area.

GEOLOGIC SETTING

The rhyolite of Gillies Hill occupies an area between two highly contrasting igneous terranes: the Marysvale volcanic field in the High Plateaus to the east, and batholithic rocks in the Mineral Mountains to the west (Fig. 1). The two terranes represent different levels of the same middle to late Tertiary igneous episodes and are bounded by upper Cenozoic basin-range faults. Erosion has cut deeply into the highly uplifted Mineral Mountains block, whereas remnants of the youngest volcanic units are still preserved in places on the west slope of the Tushar Mountains. Although many faults are involved, the structure across which the main change in rock types takes place is nowhere exposed; it is buried in part by basin-fill sedimentary deposits and in part by the rhyolite of Gillies Hill, whose main source vents appear to have been localized along and near this major fault.

The Tushar Mountains east of the Gillies Hill–Woodtick Hill area consist of two main volcanic assemblages, the older Bullion Canyon Volcanics and the younger Mount Belknap Volcanics. The Bullion Canyon Volcanics consist largely of intermediate-composition lava flows and volcanic breccia composed of coalescing stratovolcanoes, with interlayered ash-flow tuff units (Steven and others, 1979). These rocks were erupted over a period of time ranging from before 30 m.y. ago (pre-Needles Range Formation) to about 22 m.y. ago. Exposed Bullion Canyon rocks just east of the Gillies Hill–Woodtick Hill area consist largely of the 27-m.y.-old Three Creeks Tuff Member, a very crystal-rich quartz latitic ash-flow tuff, and overlying thick, coarsely porphyritic rhyodacitic lava flows. These rocks are cut by 24- to 23-m.y.-old monzonitic to latitic intrusions that in part pass upward into lava flows in the upper part of the Bullion Canyon assemblage. The intrusions are overlain unconformably by 22-m.y.-old Osiris Tuff.

West of the Gillies Hill–Woodtick Hill area (Fig. 2), Bullion Canyon rocks include intensely propylitized intermediate-composition lava flows and breccia. Although some of the higher flows in this succession are coarsely porphyritic, like those in the upper part of the main volcanic pile in the Tushar Mountains to the east, their base rests unconformably on Paleozoic sedimentary rocks, suggesting that perhaps only the lower part of the Bullion Canyon may be represented here. Presently available data do not permit establishing—or eliminating—any correlations between these different areas of exposure.

In the Tushar Mountains, the Bullion Canyon Volcanics are overlain by highly silicic lava flows and ash-flow tuff of the 21- to 14-m.y.-old Mount Belknap Volcanics. Those Mount Belknap rocks exposed nearest the Gillies Hill–Woodtick Hill area occur in or adjacent to the Mount Belknap caldera, which subsided in response to catastrophic eruption of the Joe Lott Tuff Member about 19 m.y. ago (Cunningham and Steven, 1979c). Intracaldera fill in the Mount Belknap caldera consists in part of densely welded ash-flow tuff closely similar to that in the Joe Lott Tuff Member, and in part of thick, flow-layered rhyolite flows and volcanic domes that accumulated above vents along the southern and western segments of the ring-fracture zone of the caldera (Cunningham and Steven, 1979b). The Joe Lott Tuff Member extended widely over low areas adjacent to the Mount Belknap caldera and may once have covered the Gillies Hill–Woodtick Hill area; if so, it had been removed by erosion before the rhyolite of Gillies Hill was erupted in late Miocene time.

The Bullion Canyon Volcanics west of Gillies and Woodtick Hills (Fig. 2) are cut by some of the oldest intrusive rocks in the Mineral Mountains batholith. The oldest of these intrusive rocks is a strongly porphyritic gabbro(?) that may represent a local border phase of the younger, more equigranular monzonite to syenite body that cuts both the gabbro(?) and the propylitized volcanics. These relatively low-silica rocks may correlate with similar low-silica monzonitic (latitic) intrusions on the west flank of the Tushar Mountains, 8 to 18 km to the east and northeast. A few kilometres west of the area of Figure 2, the monzonite-syenite pluton is cut by a coarsely crystalline quartz-bearing (25% or more) granite or quartz monzonite that is part of a relatively siliceous assemblage that forms most of the Mineral Mountains batholithic complex (Sibbett and Nielson, 1980). If the correlation of the older low-silica gabbro(?)-monzonite-syenite assemblage with the 24- to 23-m.y.-old monzonite intrusions in the Tushar Mountains is valid, it is possible that the younger quartz-rich granite-quartz monzonite batholithic rocks may correlate in a broad sense with the highly siliceous Mount Belknap Volcanics in the Tushar Mountains. Preliminary radiometric-dating results tend to confirm this suggestion (S. H. Evans, unpub. data).

Both the low-silica and high-silica intrusive rocks in the northern Mineral Mountains are cut by late felsite dikes. Some of these dikes extend into the west-central part of the area of Figure 2, where they cut the gabbroic pluton, the monzonite-syenite pluton, and the propylitized Bullion Canyon Volcanics. These late felsite dikes may be related to the rhyolite of Gillies Hill, and preliminary radiometric-dating results tend to confirm this suggestion also (S. H. Evans, unpub. data).

The Gillies Hill–Woodtick Hill area was extensively faulted after deposition of the Bullion Canyon Volcanics, and perhaps after deposition of the Mount Belknap Volcanics. At this time, a rough fault-block topography formed, with the structural basins penecontemporaneously filled by gravelly, sandy, and silty fluviatile sedimentary rocks. The only evidence for the presence of these early basin-fill sediments in the Gillies Hill–Woodtick Hill area is near the northern margin of the area of Figure 2, where tan, gravelly silt is poorly exposed on low slopes beneath the basal vitrophyre of a rhyolite lava flow. Some of the cobbles consist of the gabbro(?) and monzonite-syenite now exposed in the western part of the area of Figure 2, which indicates that erosion had cut down to the levels of these intrusive bodies by middle Miocene time.

Shortly before 9 m.y. ago, the rhyolite of Gillies Hill was erupted, probably along a major basin-range fault zone. The extrusions were chiefly viscous, flow-layered rhyolite domes and flows ranging in size from fairly small domes, such as underlies Cedar Knoll (Fig. 2) near the southeast end of the assemblage, to a large elongate dome that extends from the north flank of Gillies Hill through Woodtick Hill nearly to the north end of the area shown on Figure 2. One coherent unit of soft, zeolitically altered ash-flow tuff accumulated in a valley along the western side of the rhyolite pile (Fig. 2). At least four dome or flow units are recognized, but possibly as many as three or four times that number exist. We do not agree with Haugh (1978) concerning many of the dome (flow) centers he showed in that paper; apparently he was influenced strongly by present topography even though the original volcanic morphology has been greatly modified by late Cenozoic faulting and erosion.

The rhyolite of Gillies Hill was largely covered by upper Cenozoic basin-fill deposits which have been dissected to the present level of exposure. These younger deposits have been studied by Machette and Steven (1980) and Steven and others (1980) and will not be discussed here. The unit QTa on Figure 2 lumps these basin-fill deposits with younger pediment gravels, fanglomerates, stream alluvium, and colluvium.

Pleistocene basalt lava flows cover the north and northwest parts of the mapped area (Fig. 2). These basalts range in age from approximately 1.0 to 0.3 m.y. (Best and others, 1980). Because these basalt flows have no relevance to this report except insofar as they provide evidence for age of faulting, they will not be discussed further.

STRUCTURAL SETTING

The rhyolite of Gillies Hill forms an elongate volcanic pile (Fig. 2) aligned north-south along the trend of a buried fault that juxtaposes plutonic rocks in the Mineral Mountains block with volcanic rocks in the Tushar Mountains block. Geophysical evidence (Cook and others, 1980) supports the presence of this major fault, and geologic evidence points toward middle Miocene as the time of its main displacement. Later faulting along the same general trend has broken the rhyolite of Gillies Hill into elongate blocks. The young faulting apparently took place over an extended period of time from late Miocene to Pleistocene.

Numerous upper Cenozoic faults between the high Mineral Mountains and the Gillies Hill–Woodtick Hill area step irregularly downward to the east. However, batholithic rocks or contact-metamorphosed Paleozoic sedimentary rocks predominate (Fig. 2), and those intermediate-composition volcanic rocks that do occur are adjacent to the plutonic rocks and are intensely propylitized and locally hornfelsed. The whole area west of the rhyolite of Gillies Hill thus shows definite affinities to the Mineral Mountains structural block.

The east flank of the rhyolite of Gillies Hill is covered by younger basin-fill sedimentary rocks and other surficial deposits, but 2.5 km farther east, the lower west flank of the Tushar Mountains consists of thick intermediate-composition lava flows in the middle and upper parts of the Bullion Canyon Volcanics.

A recent gravity study by Cook and others (1980, Fig. 5) shows the covered area between the Mineral Mountains and Tushar Mountains structural blocks to be underlain by a gravity low believed to represent a graben (the Beaver–Cove Fort graben of Cook and others, 1980) filled with low-density basin-fill sediments. The western margin of this graben is marked by a steep gravity gradient that trends almost due north directly under the area covered by the rhyolite of Gillies Hill. Inasmuch as this rhyolite unit consists of thick local flows and volcanic domes that were fed by underlying vents, the accumulation seems to have been localized above a major structural break. This relationship also was recognized by Cook and others (1980, p. 30). The steep gravity gradient is interrupted by a minor gravity high in the vicinity of Gillies Hill and Woodtick Hill, suggesting that the rhyolite had its principal source in this area.

Recurrent fault movement in the Gillies Hill–Woodtick Hill area is indicated by many independent bits of evidence. The map pattern (Fig. 2) suggests that at least one of the westernmost faults may have had early movement, before intrusion of the gabbro(?) and monzonite-syenite plutons. This suggestion may be illusory, however, as exposures are too poor to establish with certainty that the faults do not extend northward into the intrusive bodies.

The rhyolite of Gillies Hill rests directly on older Bullion Canyon Volcanics west of Gillies Hill and Woodtick Hill but overlies basin-fill sedimentary rocks to the north (Fig. 2) and presumably to the east, where the rhyolites extend out over the gravity low marking the Beaver–Cove Fort graben of Cook and others (1980). This dates major fault displacement as younger than the Bullion Canyon Volcanics and older than the upper Miocene rhyolite of Gillies Hill.

Northerly trending faults parallel the underlying gravity gradient along the west side of the Beaver–Cove Fort graben of Cook and others (1980) and probably reflect renewed movement on the buried fault zone. Most displacement apparently was fairly early, as erosion has largely removed or obscured the original fault-block topography. More recent movement is indicated by low scarps cutting Pleistocene basalt flows in the northern part of Figure 2 and by other scarps cutting Pleistocene alluvial deposits elsewhere.

GEOCHRONOLOGY

To determine the age of volcanic activity and to establish the geologic relations with adjacent igneous terranes, five samples from the rhyolite of Gillies Hill were dated radiometrically. In particular, the suggestion by Haugh (1978) that the rhyolites may have been erupted as recently as Quaternary time needed to be checked because of the potential for geothermal resources. Analytical data are given in Table 1; sample locations are shown in Figure 2.

Samples 77-3, 77-7, 77-8, and 79-1 are all from what has turned out to be a single large volcanic dome that extends from the north flank of Gillies Hill northward through Woodtick Hill to the north end of the area shown on Figure 2. This is the youngest major flow unit in the rhyolite of Gillies Hill. Another sample (77-6) was collected from the basal vitrophyre of a small dome called Cedar Knoll (Fig. 2); this dome appears to have resulted from one of the older

TABLE 1. RADIOMETRIC AGES OF THE RHYOLITE OF GILLIES HILL, UTAH

Sample no.	Material dated	Weight (g)	%K	Moles/g Ar^{40}_{Rad} ($\times 10^{11}$)	$\%Ar^{40}_{atm}$	Age (m.y.) ± 1σ
77-3	Biotite	0.93724	6.41	7.747	67	6.96 ± 0.35
77-6	Sanidine	0.70982	8.61	13.672	28	9.13 ± 0.31
77-7	Biotite	0.86234	6.78	10.869	68	9.22 ± 0.46
77-8	Biotite	0.85650	7.01	9.758	57	8.01 ± 0.32
79-1	Biotite	0.81178	7.11	11.266	80	9.11 ± 0.64

Constants used:

$\lambda_\beta = 4.962 \quad 10^{-10}/yr.$

$\lambda_\epsilon = 0.581 \quad 10^{-10}/yr.$

$K^{40}/K_{total} = 1.167 \quad 10^{-4}$ Mole/Mole.

eruptions of the rhyolite of Gillies Hill. Standard techniques for the K-Ar method were used, the details of which are given in Evans and others (1980). It is evident that samples 77-6, 77-7, and 79-1 are concordant, but samples 77-3 and 77-8 are not. Both discordant samples are from the same large volcanic dome as the concordant samples 77-7 and 79-1. The concordant samples are from the youngest major flow unit and one of the oldest units in the rhyolite of Gillies Hill.

Some simple statistical tests were conducted to determine the cause of the variability in the data. Whereas the standard error of the ages is 12.5%, the standard error of potassium values is only 4.6%, suggesting that the major error lies in the argon data. An isochron (Fig. 3) of the potassium and argon data for the concordant samples 77-6, 77-7, and 79-1, with $^{40}Ar/^{36}Ar$ plotted as the ordinate and $^{40}K/^{36}Ar$ as the abscissa, yields an age of 9.13 m.y. An intercept on the ordinate of 297 is very close to the accepted $^{40}Ar/^{36}Ar$ value for atmospheric argon of 295.5. If data from both concordant and discordant samples are included, the isochron (dashed line) shows an apparent age of 9.28 m.y. and an intercept of 277 on the ordinate. This intercept is clearly in error and indicates that samples 77-3 and 77-8 have lost argon. Petrographic examination shows that the biotite in the discordant samples is generally oxidized, in contrast with the fresh biotite in the concordant samples. The loss in argon thus may result from oxidation of biotite.

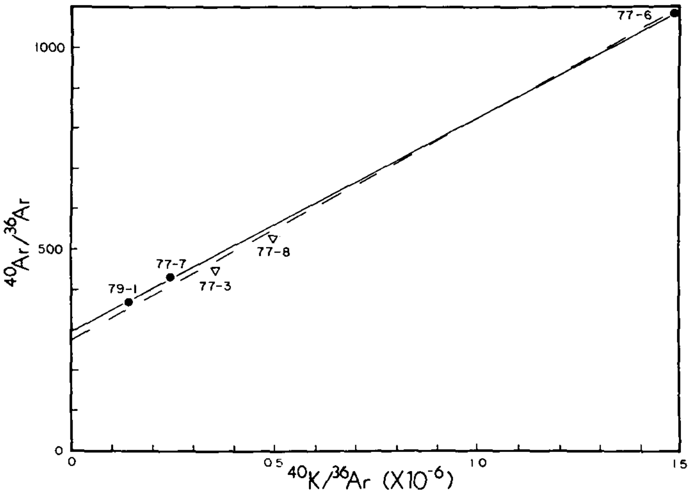


Figure 3. Potassium/argon isochrons of the rhyolite of Gillies Hill. Filled circles lie on the isochron; open triangles are discordant points. Solid isochron has an age of 9.13 m.y. and an intercept of 297; dashed isochron has an age of 9.28 m.y. and an intercept of 277.

Inasmuch as the concordant samples came from both old and young flow units within the rhyolite of Gillies Hill, it is concluded that the volcanic activity took place within a short period of time about 9.1 m.y. ago.

PETROGRAPHY

In addition to the samples collected for radiometric dating, others were taken to determine the petrographic and chemical character of the rhyolite of Gillies Hill. Sample locations are shown on Figure 2, and modal analyses are shown in Table 2. Modes were not determined on samples 80-5 and 80-6, which were collected from the same locality as 77-3. Sample 77-5, a zeolitized tuff consisting largely of quartz and clinoptilolite, also was not counted.

Chemical analyses (see following section) show that the rhyolite of Gillies Hill clearly forms both a high-silica suite (SiO_2 >75%), represented by all but the youngest flows and domes in the unit, and a low-silica suite (SiO_2 = 70%), represented by the single large dome at the top of the unit.

Stubby flows and domes of the high-silica suite are exposed in three lobate areas that extend outward from the topographically high source near Gillies Hill and Woodtick Hill. Seven samples (samples 77-1, 77-2, 77-6, 80-1, 80-3, 80-4, and 80-7) exhibit a range in phenocryst content from 12% to 25% and show variations in relative abundances of the different minerals (Table 1). The phenocrysts consist of euhedral quartz crystals (2% to 10%) 0.5 to 2 mm across; euhedral to subhedral sanidine crystals (3% to 7%) 0.25–0.75 mm long; subhedral plagioclase laths (oligoclase) 0.5–2 mm long; euhedral biotite flakes and books ranging from very small to 0.75 mm across (samples 77-1, 77-2, 77-6, and 80-7 only); and traces of hornblende (sample 80-1), sphene, and iron oxides. The groundmass of samples 80-1 and 80-4 is completely devitrified, but the groundmass of the other high-silica samples remains glassy.

The low-silica suite is represented by a single large volcanic dome that extends northward from Gillies Hill, through Woodtick

TABLE 2. MODAL ANALYSES OF THE RHYOLITE OF GILLIES HILL

	Low-silica suite				High-silica suite						
										Cedar Knoll	
Sample number	77-3	77-7	77-8	79-1	77-1	77-2	80-1	80-3	80-4	77-6	80-7
Quartz	..	..	..	..	2.4	2.7	5.0	9.9	4.8	9.4	5.8
Sanidine	..	..	..	..	5.9	5.3	6.6	2.7	3.8	4.5	4.3
Plagioclase	16.1	15.3	11.1	14.4	6.6	4.7	12.3	5.3	3.0	4.4	1.2
Biotite	3.9	2.9	2.7	4.1	1.8	2.5	1.1	0.4	0.6	0.3	0.3
Hornblende	..	1.0	0.7	0.3	0.2	0.1	0.1	..	..	..	..
Sphene	..	..	..	..	0.1	..	..	0.1	..	0.1	..
Oxides	..	0.2	0.4	0.2	..	..	0.6	0.3	0.1	0.1	0.4
Glass	..	..	..	..	83.0	84.7	..	81.3	..	81.2	88.0
Groundmass	80.0	80.6	85.1	81.0	..	..	74.3	..	87.7	..	..
Sum	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

Modes based on 1,000 points counted per thin section.

TABLE 3. CHEMICAL ANALYSES AND CIPW NORMS OF THE RHYOLITE OF GILLIES HILL

	Low-silica suite						High-silica suite								Zeolitic tuff
													Cedar Knoll		
	77-3	77-7	77-8	79-1	80-5	80-6	77-1	77-2	80-1	80-2	80-3	80-4	77-6	80-7	77-5
SiO_2	70.5	70.0	70.7	70.0	70.7	70.8	76.1	76.8	75.1	77.2	75.9	75.2	76.9	77.7	79.6
TiO_2	0.36	0.40	0.39	0.36	0.36	0.36	0.19	0.15	0.27	0.07	0.15	0.27	0.06	0.10	0.16
Al_2O_3	15.4	15.3	15.1	15.2	15.4	15.2	12.9	12.7	13.1	12.5	14.0	13.6	12.7	12.7	11.9
Fe_2O_3	2.09	1.49	2.16	1.87	2.08	2.02	0.75	0.75	1.24	0.16	0.56	1.18	0.36	0.35	0.97
FeO*	0.53	1.34	0.55	0.64	0.53	0.53	0.53	0.31	0.34	0.39	0.36	0.37	0.55	0.33	0.11
MnO	0.06	0.06	0.05	0.04	0.04	0.04	0.06	0.06	0.05	0.05	0.06	0.06	0.06	0.06	0.05
MgO	0.56	0.59	0.57	0.73	0.54	0.52	0.28	0.17	0.50	0.30	0.38	0.30	0.10	0.17	0.75
CaO	2.27	2.79	2.26	3.18	2.23	2.39	0.80	0.66	0.87	0.94	0.92	0.64	0.44	0.51	2.93
Na_2O†	3.61	3.43	3.38	3.43	3.49	3.50	3.52	3.53	3.55	3.01	2.64	3.77	4.11	3.29	1.26
K_2O†	4.46	4.48	4.70	4.44	4.45	4.47	4.83	4.87	4.91	5.31	5.11	4.56	4.73	4.78	2.25
P_2O_5	0.13	0.15	0.14	0.11	0.15	0.15	0.03	0.01	0.06	0.01	n.d.	0.05	n.d.	n.d.	0.03
CIPW Norms, weight percent §															
Q	27.1	26.2	27.8	25.9	28.5	27.9	35.0	36.0	33.2	36.8	38.4	34.1	33.5	38.8	56.3
C	0.82	0.10	0.68	..	1.19	0.61	0.50	0.45	0.55	0.09	2.41	1.45	0.02	1.16	2.14
or	26.4	26.5	27.8	26.2	26.3	26.4	28.5	28.9	29.0	31.4	30.2	27.0	28.0	28.3	13.3
ab	30.6	29.0	28.6	29.0	29.2	29.6	29.8	29.9	30.0	25.5	22.3	31.9	34.8	27.8	10.7
an	10.4	12.9	10.3	13.0	10.1	10.9	3.77	3.21	3.92	4.60	4.56	2.85	2.18	2.53	14.3
hy	1.39	2.15	1.42	1.06	1.34	1.30	0.85	0.42	1.25	1.31	1.01	0.75	0.97	0.69	1.87
di	..	..	..	1.63	..	..	..	..	..	..	..	..	..	..	..
mt	0.86	2.16	0.81	1.15	0.80	0.80	1.09	0.76	0.48	0.23	0.81	0.61	0.52	0.51	0.05
il	0.68	0.76	0.74	0.68	0.68	0.68	0.36	0.28	0.51	0.13	0.28	0.51	0.11	0.19	0.30
hm	1.50	..	1.60	1.08	1.53	1.47	..	..	0.91	..	..	0.76	..	..	0.93
ap	0.31	0.36	0.33	0.26	0.36	0.36	0.07	0.02	0.14	0.02	..	0.12	..	..	0.07

*Determined by ammonium meta vanadate titration, S. H. Evans, analyst (Carmichael and others, 1968).

†Determined by flame photometry, J. Mason, analyst.

n.d. = not detected.

All other oxides determined by X-ray fluorescence spectrometry, F. H. Brown and J. Mason, analysts.

Analyses matrix corrected using procedures of Norrish and Hutton (1969).

§Norms calculated on a volatile-free basis.

Hill, and on to the two erosional remnants at the north end of the mapped area (Fig. 2). Six samples were collected from this unit: 77-3, 77-7, 77-8, 79-1, 80-5, and 80-6. Thin sections of all of these samples are virtually indistinguishable from each other except for minor variations in abundance of phenocryst minerals and in oxidation of biotite. All samples are flow layered, with a linear fabric shown by parallel alignment of plagioclase laths. The dome contains abundant euhedral phenocrysts of andesine (11% to 16%) that range from 0.25 to 1 mm long. Euhedral grains of biotite (3% to 4%) are as large as 0.75 mm across, and sparse hornblende (0% to 1%) also is present. In samples 77-3 and 77-8, the biotite is oxidized and mantled by iron oxides, whereas in samples 77-7 and 79-1, the biotite is fresh. The groundmass of this unit is completely devitrified and consists of a felted mass of feldspar microlites.

The large volcanic dome constituting the low-silica suite appears to have had a source somewhere east or northeast of Gillies Hill. This is suggested by an outcrop a few metres east of sample location 77-3, where steeply dipping (85° W), north-striking, flow-layered rhyolite containing a 20-cm glassy selvage cuts sharply up and across a ridge crest. The material intruded by the steeply dipping rhyolite is not exposed; it may be autoclastic debris marginal to the same low-silica flow, or it may be older material in the rhyolite of Gillies Hill. In either case, the steep glassy selvage probably is some manifestation of the vent that fed the young low-silica volcanic dome. Although this dome is everywhere younger than rocks of the high-silica suite, the nearly identical K-Ar ages indicate that the time span of eruptions of all rocks in the rhyolite of Gillies Hill was small.

The petrography of the rhyolite of Gillies Hill shows some similarities to other nearby upper Miocene rhyolites, especially the 7.5-m.y.-old rhyolite of Corral Canyon on the west side of the Mineral Mountains (Lipman and others, 1978; S. H. Evans, unpub. data) and another 7.5-m.y.-old rhyolite from a local center near the southwest corner of Beaver basin (S. H. Evans, unpub. data). These occurrences may be remnants of what was once a much more extensive area of rhyolitic volcanism in late Miocene time.

CHEMISTRY

Major Elements

Chemical analyses and CIPW norms of selected samples from the rhyolite of Gillies Hill are given in Table 3, along with the analytical techniques used. These analyses have been recalculated on an anhydrous basis to 100% in order to remove the effect of variable water content and to allow for a more meaningful comparison of major-element chemistry. With the exception of sample 79-1, all of the samples are corundum normative and are readily divisible into a high-silica suite ($SiO_2 > 75\%$) and a low-silica suite ($SiO_2 = 70\%$). Sample 77-5 is of a highly silicified and zeolitized ash-flow tuff and will not be discussed further.

The low-silica suite is represented by six samples from a single volcanic dome that is the youngest eruptive unit in the rhyolite of Gillies Hill. These samples (77-3, 77-7, 77-8, 79-1, 80-5, and 80-6) are virtually indistinguishable from one another by their major-element chemistry (Table 3). Of particular interest are the silica content between 70% and 71% and the alumina content greater than 15%. Minor variations are present in Na_2O and CaO, as shown by normative compositions, but these are not reflected by modal variations in plagioclase (see Table 2). The low-silica suite of the rhyolite of Gillies Hill is unique among nearby upper Cenozoic rhyolite centers in that no other center contains lavas that combine the relatively low silica values with such high alumina values. In the Twin Peaks area, 30–35 km to the north, rhyolite domes and flows contain silica contents as low as 72% (Mehnert and others, 1978; Lipman and others, 1978; Crecraft and others, 1981), but alumina contents do not exceed 13.5%. These lavas were erupted significantly later (2.5–2.3 m.y. ago) than the rhyolite of Gillies Hill. In an area of silicic volcanism in the central Mineral Mountains, only high-silica rhyolites were erupted (Mehnert and others, 1978; Lipman and others, 1978). Again, these lavas are significantly younger (0.8–0.5 m.y.) than those of Gillies Hill.

The high-silica suite consists of stubby flows and domes probably erupted from several vents. This group is composed of rocks with chemistries similar to those of other rhyolites of the bimodal suite of the Basin and Range province. Silica content ranges from 75% to 77%, and alumina, from 12.5% to 14%. Magnesia content is low and variable, although in general it is higher than in other, more evolved rhyolites from nearby centers (Lipman and others, 1978; Crecraft and others, 1981). Soda values range from 3.5% to 4.1% and potash values range from 4.7% to 5.3%; these values are also typical for younger, nearby rhyolites from the Mineral Mountains and Twin Peaks areas (Lipman and others, 1978; Crecraft and others, 1981).

Trace Elements

Table 4 shows contents of selected trace elements determined using X-ray fluorescence techniques. In order to ascertain if any systematic variations in trace elements are present, values were plotted against rubidium, an incompatible element used here as a monitor of magmatic evolution (Fig. 4).

As is evident from Figure 4, some striking patterns emerge. For the low-silica suite samples (filled boxes) from a single volcanic dome, unexpected variations are noted in samples whose petrography and major-element chemistry are very uniform. Lead varies from 0 to 75 ppm. Zirconium shows a positive correlation with Rb, as do Sr, Y, Th, and Nb. More fieldwork will be required to determine the precise location and configuration of the source vent and the relative time-space positions of the samples within the volcanic dome. Only if such data can be determined will it be possible to relate the trace-element variations in this low-silica suite to the chemical geometry of the source magma chamber.

Trace-element variations among the samples from the high-silica suite (Fig. 4, filled circles), show variations similar to those of other rhyolite centers in the Basin and Range province. With the exception of Zr, the high-silica suite shows systematic linear variations with degree of enrichment of rubidium, that is, degree of evolution. For Zr, there seems to be a linear negative correlation of all but the most evolved sample (77-6), for which the trend reverses. This sample also differs from the others by having marked relative enrichment in Rb.

DISCUSSION

The field, geochronologic, and chemical data presented herein indicate that the rhyolite of Gillies Hill shows both similarities and differences to trends shown in other rhyolite centers in the western United States. The high-silica suite shows evolutionary patterns characteristic of silicic lavas erupted from compositionally zoned magma chambers, but field evidence is at present insufficient to establish firmly whether trace-element patterns evolved with time or

TABLE 4. TRACE-ELEMENT ANALYSES OF THE RHYOLITE OF GILLIES HILL

	Low-silica suite						High-silica suite								Zeolitic tuff
													Cedar Knoll		
	77-3	77-7	77-8	79-1	80-5	80-6	77-1	77-2	80-1	80-2	80-3	80-4	77-6	80-7	77-5
Ba	1 030	1105	1035	1020	1045	1030	230	160	490	5	190	205	n.d.	90	175
Nb	15	n.d.	40	35	15	10	30	30	25	30	30	35	105	25	25
Pb	20	n.d.	75	75	20	20	30	35	25	35	30	30	50	25	35
Rb	145	55	305	300	135	135	190	215	155	290	255	180	495	220	100
Sr	440	405	515	515	425	435	120	95	170	75	220	125	n.d.	75	645
Th	20	20	40	35	15	15	30	35	20	30	30	20	50	25	30
U	< 2	< 2	5	< 2	< 2	< 2	10	5	< 2	5	< 2	< 2	35	5	< 2
Y	15	5	30	30	15	15	15	15	15	15	15	15	120	15	10
Zr	165	105	230	220	160	165	100	95	145	65	95	115	110	75	85
Th/U	..	..	8	..	..	..	3	7	..	6	..	..	1.4	5	..

n.d. = not detected.
F. H. Brown, J. Mason, analysts.

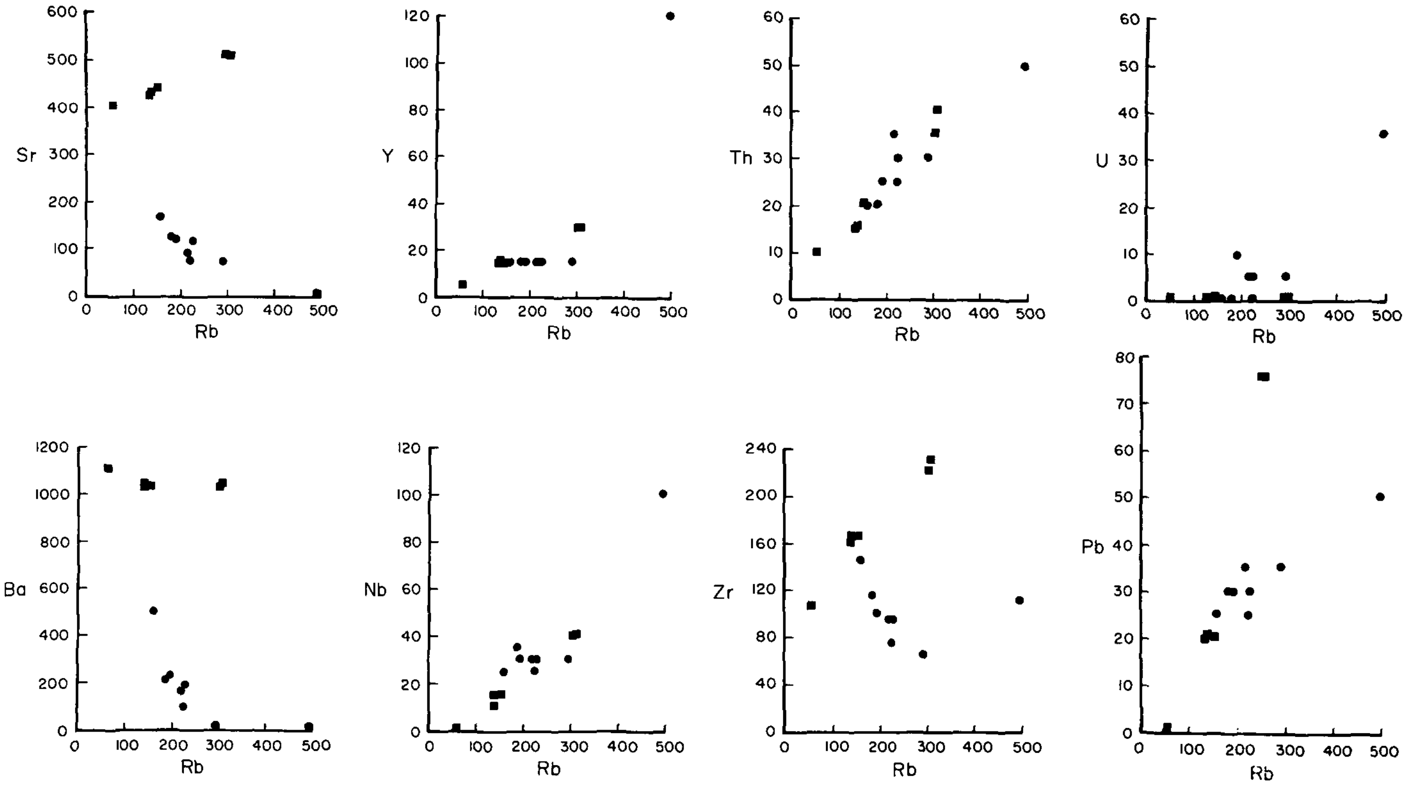


Figure 4. Plots of trace-element variations versus rubidium concentration. Filled boxes are samples from the low-silica suite; filled circles are samples from the high-silica suite.

whether they reflect geologically instantaneous magma. Several different lava flows are represented by the data, so evolution with time is permissible; the flows, however, could have been erupted in very rapid succession, which would have minimized the influence of time.

In the trace-element patterns developed in the Bishop Tuff from eastern California, Hildreth (1979) shows enrichments and depletions similar to those in the rhyolite of Gillies Hill, but the Bishop Tuff formed from a geologically instantaneous eruption and thus reflects chemical variations within the source magma chamber at one point in time. In the Bandolier Tuff in New Mexico (Smith, 1979), on the other hand, the Nb data indicate cyclic regeneration of a zoned magma chamber that was tapped periodically as the magma evolved.

The younger low-silica suite is quite distinct chemically from the earlier flows in the rhyolite of Gillies Hill. This chemical discontinuity suggests either a different magma chamber or eruption from significantly different levels within the same magma chamber. Trace-element variations within the low-silica suite also suggest that subtle chemical gradients existed within its source magma.

It is tempting to visualize the high-silica suite as representing eruptions from the top of a compositionally zoned magma chamber. Sample 77-6 from the Cedar Knoll dome near the base of the rhyolite of Gillies Hill is strongly enriched in incompatible elements, notably uranium and rubidium; from its stratigraphic position, it should have been erupted from the highly evolved top of the magma chamber. As the silicic portion of the chamber was drawn down, less-evolved material was erupted, with the least evolved being represented by samples 80-1 or 80-4.

Recent studies by McBirney and Noyes (1979), McBirney (1980), Chen and Turner (1980), Irvine (1980), and Rice (1981) have suggested that stacked convection cells containing contrasting chemical compositions may exist within single magma chambers. Modeling experiments, particularly those of Chen and Turner (1980), have simulated magma chambers in which a vertically stacked cellular structure is developed when vertical gradients in temperature and composition exist simultaneously in a liquid. The distinctive low-silica suite overlying the high-silica suite thus may have come from the lower of two compositionally zoned cells, the uppermost one of which was exhausted by eruption of the earlier high-silica suite. Whereas the upper cell was strongly zoned in composition and may have been dynamically stable, the lower cell was much more uniform, except for subtle gradients in trace-element contents, and it may have been mixed by convection (McBirney, 1980, p. 366–368). The rate of convective overturn would have had to have been slow enough not to erase the gradients in trace elements but still be rapid enough to homogenize the major elements. The rhyolite of Gillies Hill could have attained the compositional variations noted by rapid eruption from such a cellularly zoned magma chamber by episodic eruption from different levels within either a singly or a multiply zoned magma chamber, or by some combination.

A more detailed study of the eruptive sequence and petrochemistry of the rhyolite of Gillies Hill is in order to see whether any of these alternatives can be substantiated. Relative ages of eruption are particularly critical, but present geochronologic data probably cannot be refined sufficiently to be definitive. Establishing an accurate detailed sequence of eruptive units within the older, high-silica suite will be difficult because of poor exposures. Abundant chemical data, particularly of trace elements, would be especially helpful.

ACKNOWLEDGMENTS

Research conducted at the University of Utah was funded by the Division of Geothermal Energy of the Department of Energy under Contract no. DE-AC07-80ID12079. We also acknowledge the assistance of F. H. Brown, James Mason, M. B. Sienkewicz, and Beatrice Griffey of the University of Utah, and Lori Glassgold of the U.S. Geological Survey.

REFERENCES CITED

Best, M. G., McKee, E. H., and Damon, P. E., 1980, Space-time-composition patterns of late Cenozoic mafic volcanism, southwestern Utah and adjoining areas: American Journal of Science, v. 280, p. 1035–1050.

Carmichael, I.S.E., Hampel, J., and Jack, R. N., 1968, Analytical data on the USGS standard rocks: Chemical Geology, v. 3, p. 59–64.

Chen, C. F., and Turner, J. S., 1980, Crystallization in a double-diffusive system: Journal of Geophysical Research, v. 85, no. B5, p. 2573–2593.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States—[Pt.] II, Late Cenozoic: Royal Society of London Philosophical Transactions, ser. A, v. 271, p. 249–284.

Cook, K. L., Serpa, L. F., and Pe, Win, 1980, Detailed gravity and aeromagnetic surveys of the Cove Fort–Sulphurdale KGRA and vicinity, Millard and Beaver Counties, Utah: Utah University Department of Geology and Geophysics Topical Report 78-1701.a.5.2 (available from U.S. Department of Energy as Report No. DOE/ET/28392-30).

Crecraft, H. R., Nash, W. P., and Evans, S. H., Jr., 1981, Late Cenozoic volcanism at Twin Peaks, Utah, Part 1—Geology and petrology: Journal of Geophysical Research, v. 86, no. B11, p. 10303–10320.

Cunningham, C. G., and Steven, T. A., 1979a, Uranium in the Central Mining Area, Marysvale district, west-central Utah: U.S. Geological Survey Miscellaneous Investigations Map I-1177.

——1979b, Environments favorable for the occurrence of uranium within the Mount Belknap caldera, Beaver Valley, and Sevier River Valley, west-central Utah: U.S. Geological Survey Open-File Report 79-434, 15 p.

——1979c, Mount Belknap and Red Hills calderas and associated rocks, Marysvale volcanic field, west-central Utah: U.S. Geological Survey Bulletin 1468, 34 p.

Evans, S. H., Jr., Crecraft, H. R., and Nash, W. P., 1980, K/Ar ages of silicic volcanism in the Twin Peaks/Cove Creek dome area, southwestern Utah: Isochron/West, no. 28, p. 21–24.

Haugh, G., 1978, A preliminary geologic map of the Wildcat Creek area, eastern Beaver County, Utah: Utah Geology, v. 5, p. 33–36.

Hildreth, W., 1979, The Bishop Tuff—Evidence for the origin of compositional zonation in silicic magma chambers, *in* Chapin, C. E., and Elston, W. E., eds., Ash-flow tuffs: Geological Society of America Special Paper 180, p. 43–76.

Hintze, L. F., 1963, Geologic map of southwestern Utah: Provo, Utah, Brigham Young University, Department of Geology, scale 1:250,000.

Irvine, T. N., 1980, Experimental modeling of convection in interlayered intrusions, *in* Annual report of the Director, Geophysical Laboratory: Carnegie Institution of Washington Year Book 79, p. 247–256.

Lipman, P. W., Rowley, P. D., Mehnert, H. H., Evans, S. H., Jr., Nash, W. P., and Brown, F. H., 1978, Pleistocene rhyolite of the Mineral Mountains, Utah—Geothermal and archeological significance: U.S. Geological Survey Journal of Research, v. 6, p. 133–147.

Machette, M. N., and Steven, T. A., 1980, Preliminary geologic map of the northwest quarter of the Beaver quadrangle, Beaver County, Utah:

U.S. Geological Survey Open-File Report 80-1269.

McBirney, A. R., 1980, Mixing and unmixing of magmas: Journal of Volcanology and Geothermal Research, v. 7, p. 357–371.

McBirney, A. R., and Noyes, R. M., 1979, Crystallization and layering of the Skaergaard intrusion: Journal of Petrology, v. 20, p. 487–554.

Mehnert, H. H., Rowley, P. D., and Lipman, P. W., 1978, K-Ar ages and geothermal implications of young rhyolites in west-central Utah: Isochron/West, no. 21, p. 3–7.

Norrish, K., and Hutton, J. T., 1969, An accurate X-ray spectrographic method for the analysis of a wide range of geological samples: Geochimica et Cosmochimica Acta, v. 33, p. 431–453.

Rice, Alan, 1981, Convective fractionation: A mechanism to provide cryptic zoning (macrosegregation), layering, crescumulates, banded tuffs and explosive volcanism in igneous processes: Journal of Geophysical Research, v. 87, no. B1, p. 405–417.

Sibbett, B. S., and Nielson, D. L., 1980, Geology of the central Mineral Mountains, Beaver County, Utah: Salt Lake City, Utah, University of Utah Research Institute Earth Science Laboratory, 42 p.

Smith, R. L., 1979, Ash-flow magmatism, *in* Chapin, C. E., and Elston, W. E., eds., Ash-flow tuffs: Geological Society of America Special Paper 180, p. 5–27.

Steven, T. A., Cunningham, C. G., Naeser, C. W., Mehnert, H. H., and Ludwig, K. R., 1978a, Multiple ages of mineralization in the Marysvale area, west-central Utah [abs.]: International Association on the Genesis of Ore Deposits, Symposium, 1978, Programs and Abstracts, p. 185.

Steven, T. A., Cunningham, C. G., and Rowley, P. D., 1978b, Geology and mineralization in the Marysvale mining area, west-central Utah, *in* Shawe, D. R., and Rowley, P. D., eds., International Association on the Genesis of Ore Deposits, Guidebook to mineral deposits of southwestern Utah: Utah Geological Association Publication 7, p. 67–70.

Steven, T. A., Cunningham, C. G., Naeser, C. W., and Mehnert, H. H., 1979, Revised stratigraphy and radiometric ages of volcanic rocks and mineral deposits in the Marysvale area, west-central Utah: U.S. Geological Survey Bulletin 1469, 40 p.

Steven, T. A., Cunningham, C. G., and Machette, M. N., 1980, Integrated uranium systems in the Marysvale volcanic field, west-central Utah: U.S. Geological Survey Open-File Report 80-524, 39 p.

MANUSCRIPT RECEIVED BY THE SOCIETY SEPTEMBER 15, 1981
REVISED MANUSCRIPT RECEIVED NOVEMBER 16, 1981
MANUSCRIPT ACCEPTED DECEMBER 2, 1981

Printed in U.S.A.