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ABSTRACT

A suite of silicic volcanic rocks is associated with the Roosevelt Hot Springs geothermal area in southwestern Utah. The volcanic sequence includes Tertiary rhyolite 8 m.y. old and obsidian, ash and rhyolite of Quaternary age.

The Quaternary lavas are characterized by high silica content (76.5% SiO₂) and total alkalis in excess of 9 percent. Obsidians commonly contain greater amounts of fluorine than water. Two older flows (0.8 m.y.) can be distinguished from younger dome and pyroclastic material (approximately 0.5 m.y.) by subtle differences in their chemistry. The mineralogy of the rhyolites consists of alkali feldspar, plagioclase, and small amounts of Fe-Ti oxides, biotite, hornblende and rare allanite. Fe-Ti oxide temperatures are 740-785°C for the flows and 635-665°C for the domes; two feldspar temperatures give similar results.

The phase relationships of bulk rock, glass and feldspar compositions demonstrate that the younger Quaternary rhyolites could have been derived from the earlier magma type, represented by the obsidian flows, by a process of crystal fractionation. The major phases which must fractionate are alkali feldspar, plagioclase and quartz with minor amounts of biotite, magnetite and ilmenite participating also. Trace element patterns support this scheme as well. The Tertiary

lavas cannot be related to the Quaternary rhyolites and are thought to represent a separate event.

Introduction

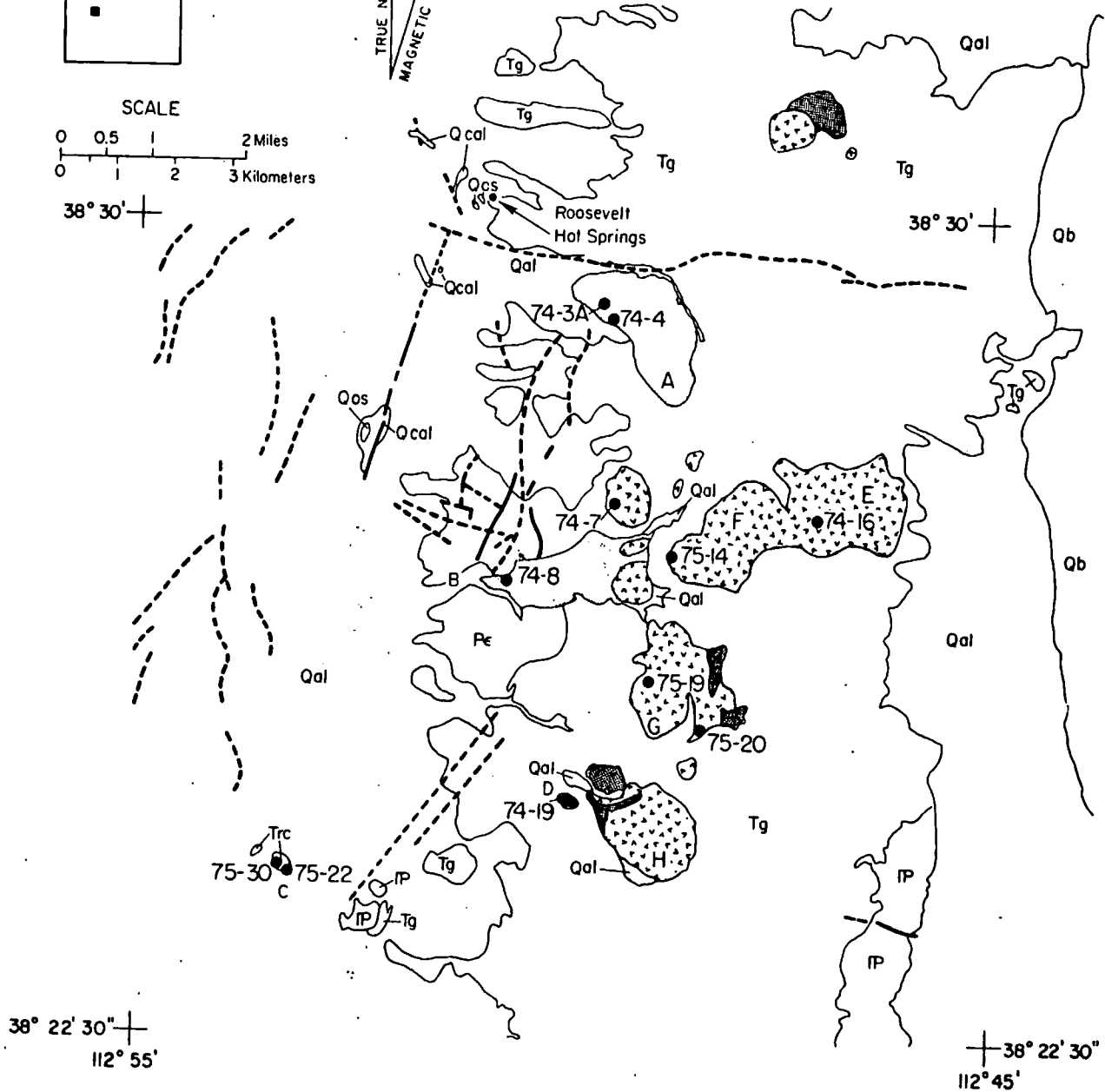
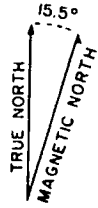
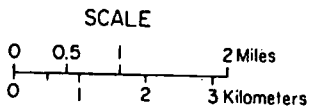
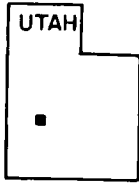
Young silicic volcanics have been considered to be indicators of the presence of shallow magma chambers with sufficient heat remaining to serve as possible geothermal resource centers. In the Mineral Mountains of western Utah obsidian flows and rhyolite domes ranging in age from 0.8 to 0.5 m.y. occur discontinuously for about 15 km. along the range crest. Previous studies of this area (Earl, 1957; Liese, 1957) interpreted all rhyolites as the remnants of a large silicic volcano of Pliocene age. Evidence presented here and in Lipman et al. (1978) demonstrates that many separate lava flows, ashes and domes were erupted along the range crest. Along one of the western range front faults, about 2 km northwest of the nearest rhyolitic volcanics, Roosevelt Hot Springs is located within the Known Geothermal Resource Area (K.G.R.A.), which has been proven to be a commercial area. The silicic volcanism recorded by the rhyolites of the Mineral Mountains perhaps provides the heat source for the K.G.R.A. (Lipman et al., 1978; Evans and Nash, 1975).

General Geology

The Mineral Mountains, located in west-central Utah (Fig. 1), near the eastern margin of the Basin and Range province, rise about 1 km above Escalante Valley to the west and an unnamed valley to the east. The range is nearly 50 km long and averages 10 km in width.

The northern end of the range consists of a domal sedimentary sequence of early Paleozoic and late Mesozoic sediments. The western edge of

Fig. 1. Generalized geologic map of the central Mineral Mountains, Utah. The sample localities are as described in Table 1. Hachured areas are Quaternary rhyolite domes, dark shaded areas are Quaternary ashes, light shaded areas are Quaternary rhyolite flows. Qal-alluvium, Qcal-cemented alluvium, Qos-opal and opaline sinter, Qb-basaltic cinder and flows, Trc-rhyolite domes in Corral Canyon, Tg-granitic basement, P-Permian sediments, pC-Pre-Cambrian basement. A-Bailey Ridge, B-Wild Horse Canyon, C-Corral Canyon, D-Ranch Canyon, E-Bearskin Mountain, F-Little Bearskin Mountain, G-North Twin Flat Mountain, H-South Twin Flat Mountain. The geology is taken from a detailed geologic map published by the University of Utah (Evans, 1977).



the range consists of numerous outcrops of rock, probably Precambrian in age, referred to as the Wildhorse Canyon Series by Condie (1960). The southern end of the range is a rotated fault block containing Paleozoic and Mesozoic sediments overlain by Tertiary intermediate and basic volcanics. Intruding these rocks is the Mineral Mountains pluton nearly 250 km² in extent. This pluton is granitic in composition and contains many pegmatite and aplite dikes as well as mafic dikes of limited dimensions. Two potassium-argon ages of 15 and 9 m.y. (Park, 1968; Armstrong, 1970), indicate that the pluton may be relatively young with respect to the majority of Basin and Range intrusive rocks. However, the possibility exists that partial argon loss occurred during a volcanic episode in the area approximately 8 m.y. ago. Rb-Sr systematics suggest that the maximum age of the pluton is 35 m.y. (Lipman et al., 1978).

Prior to eruption of rhyolitic volcanics of the Mineral Mountains the pluton and its adjacent country rocks were deeply eroded forming a rugged topography much like that of the present. North striking bounding faults mark the western and eastern margins of the Mineral Mountains. In the central portion of the Range the trace of a major fault on the west is marked by elongated mounds of siliceous sinter, opal, and other hydrothermally altered and cemented alluvium. The abandoned Roosevelt Hot Springs resort, where water temperatures of 90°C were recorded (Mundorff, 1970), is located on this major fault. The chemical composition of water from a nearby seep yields a wall rock equilibration temperature of 240°C using the Na-K-Ca thermometer.

of Fournier and Truesdell (1973). In this same area soil temperatures of 95 to 97°C have been measured at depths of 1 to 3 meters.

The region is currently being developed for power production. Exploration drill holes and test wells have produced fluids with temperatures up to approximately 260°C at depths ranging from 300 to 1800 m.

Volcanic Rocks

In the Mineral Mountains three distinct Quaternary volcanic rock types occur. Oldest are obsidian flows with intermediate aged ashes followed by younger rhyolite domes. A complete description of the occurrence and volcanic features is given by Lipman et al. (1978), and only a brief discussion is offered here.

The obsidian flows are unique in their apparent fluidity. The flows, occurring along Bailey Ridge and Wild Horse Canyon (Fig. 1), have lengths of approximately 3 km and are about 80 m thick. An impression is given of unusual fluidity during eruption as flow banding is quite laminar except at the flow margins. Such character implies lower viscosities than many silicic lava flows. Radiometric dating of the Bailey Ridge flow indicates an age of 0.77 ± 0.08 m.y. (Lipman et al., 1978). Paleomagnetic, chemical and morphological similarities between the Bailey Ridge flow and the Wild Horse Canyon flow suggest a similar age. Occasional xenoliths of vesicular basalt are found in pumice from these flows.

Pyroclastic rocks occupy an intermediate position in the stratigraphic sequence of volcanics in the Mineral Mountains. These pyroclastics are of ash-fall and ash-flow origin. The main area of exposure is in Ranch Canyon with other exposures in Wild Horse Canyon and on the ridge between Ranch and Wild Horse Canyons. These ash beds are typically light colored, white to light tan and poorly consolidated. The lowermost beds are typically ash-fall with steep dips resulting from draping over underlying topography. Upper beds are characteristically ash-flow with coarse sorting and are very local in extent. Much of the pyroclastic sequence has been removed by erosion which hinders identification of the source vents.

K-Ar dating on a single obsidian clast from an ash-flow unit in Ranch Canyon yielded an age of 0.68 ± 0.04 m.y. providing an older limit for the age of the pyroclastics (Lipman et al., 1978). The pyroclastics as well as ash in Wild Horse Canyon are of normal magnetic polarity indicating deposition during the Brunhes polarity epoch.

The third volcanic occurrence is that of at least 11 domal rhyolites distributed sporadically over 10 km along or near the crest of the range. The degree of dissection of the domes varies with a basal vitrophyre exposed in some of the domes and very little dissection seen on other domes, such as Bearskin Mountain. Where the interior of the domes are exposed a basal vitrophyre can be seen overlying granitic basement. The vitrophyre has a rubbly base and grades upward into a thoroughly devitrified area. The upper portion of the domes consists of a frothy rhyolite which makes up the blocky carapace.

This rhyolite contains less phenocrysts than the vitrophyre. Due to the lack of dissection of some of the domes, it is difficult to sort out relative ages. Based solely on the degree of dissection it appears that the oldest domes are North and South Twin Flat Mountains and the youngest domes are Bearskin and Little Bearskin Mountains. Stubby flows of rhyolite are also present extending out from the base of Bearskin Mountain. Isolated patches of rhyolite occur, particularly in Ranch Canyon and upper Wild Horse Canyon. These appear to be small, highly eroded remnants of domes. Age determinations on obsidian from Bearskin Mountain and sanidine from Little Bearskin Mountain have yielded K-Ar ages of 0.58 ± 0.12 m.y. and 0.53 ± 0.05 m.y., respectively (Lipman et al., 1978).

Rhyolite also occurs in lower Corral Canyon to the west of the range (Fig. 1). This rhyolite is more highly dissected than the domal material higher in the range and is petrographically distinct as well. Extensive field work indicates that this area may be a remnant of a much older dome or domes. There are two separate rhyolite outcrops, both underlain by a basal vitrophyre. It appears that recent erosion is exhuming the rhyolite from older gravels that are exposed between the two rhyolite patches. A K-Ar date of 7.90 ± 0.3 m.y. on biotite from the basal vitrophyre confirms the older age for this rhyolite.

Small outcrops of basalt are present on the eastern margin of the Mineral Mountains and an extensive field of basalt is located just east of the Mineral Mountains in the Cove Fort area. This basaltic volcanism apparently overlaps with the rhyolitic volcanism of the

Mineral Mountains as the basaltic volcanism is believed to have begun about 10^6 years ago and continued sporadically until perhaps a few thousand years ago (Condie and Barsky, 1972).

Petrography

The silicic volcanics of the Mineral Mountains can be conveniently divided into four petrographic types. These are banded obsidians of the older flows, devitrified rhyolite of Big Cedar Cove and Corral Canyon, ash-falls and ash-flows of Ranch Canyon and glomeroporphyritic vitrophyres and rhyolites of younger domes. Modes of these rock types are given in Table 1.

The flows of Bailey Ridge and Wild Horse Canyon consist of flow banded obsidian near the top and base of the flow with the centers of the flows essentially completely devitrified with lithophysoidal cavities occasionally filled with secondary silica. The tops of the flows are mantled by pumice. In thin section the obsidian is seen to be finely banded with parallel alignment of microlites and micro-phenocrysts. Euhedral sanidine and anorthoclase occur as micro-phenocrysts 0.02 to 0.03 mm in length along with euhedral biotite flakes 0.02 to 0.05 mm in diameter. Quartz is conspicuously absent from the obsidian flows. The mineralogy of the pumiceous mantle is similar to the fresh obsidian of the interiors of the flows (Table 1).

In Big Cedar Cove and Corral Canyon deeply eroded domes of completely devitrified rhyolite occur. These exposures probably represent the interior portions of older domes with their carapaces completely

TABLE 1

Modal Analysis of Mineral Mountains Igneous Rocks (volume percent).

Rock	Quartz	Sanidine	Orthoclase	Plagio- clase	Biotite	Amphibole	Ortho Pyroxene	Glass	Devitri- fied Glass	Void Space	Ground- mass	Other	Opagues
74-3A	-	2.3	-	-	0.1	-	-	96.9	0.7	-	-	-	-
74-4	-	4.0	-	0.1	1.0	-	-	84.9	10.1	-	-	-	-
74-7	3.1	2.8	-	0.9	0.1	-	-	1.5	91.5	-	-	-	0.1
74-8	-	3.6	-	-	0.4	-	-	88.8	6.3	-	-	-	0.9
74-16	-	2.3	-	0.2	-	-	-	97.3	0.3	-	-	-	-
74-19	1.5	0.6	-	0.2	0.2	-	-	92.4	0.2	4.7	-	-	0.1
74-29	25.9	-	66.4	6.3	0.7	-	-	-	-	-	-	0.1	0.6
75-14	2.8	4.7	-	0.6	0.1	-	-	89.5	2.1	-	-	-	0.3
75-19	3.9	0.8	-	1.6	1.1	-	-	2.2	86.0	4.3	-	-	0.1
75-20	1.7	1.2	-	0.5	-	-	-	96.6	-	0.1	-	-	-
75-22	3.8	1.7	-	0.8	0.5	0.1	-	0.3	92.3	-	-	-	0.5
75-30	0.4	0.2	-	8.2	1.6	1.4	0.1	86.0	-	1.1	-	0.5	0.5

Key to Sample Localities

Sample #	Sample Localities	Rock Type	Sample #	Sample Localities	Rock Type
74-3A	Bailey Ridge Flow	Obsidian	74-29	Pass Road	Min. Mtns. Granite
74-4	Bailey Ridge Flow	Pumice	75-14	Little Bearskin Mtn.	Obsidian
74-7	Big Cedar Cove Dome	Rhyolite	75-19	No. Twin Flat Mtn.	Rhyolite
74-8	Wild Horse Canyon Flow	Obsidian	75-20	No. Twin Flat Mtn.	Obsidian
74-16	Bearskin Mtn.	Obsidian	75-22	Corral Canyon Dome	Rhyolite
74-19	Pumice Hole Mine	Pumice	75-30	Corral Canyon Dome	Vitrophyre

eroded. Phenocryst phases consist of rounded sanidine and anorthoclase 0.15 to 0.40 mm across, quartz which is rounded and fractured 0.2 mm in diameter, subhedral oligoclase 0.08 to 0.30 mm long, and biotite scattered throughout the groundmass. The groundmass is completely devitrified and crude flow bands can be seen in thin section as streaks of discolored devitrification. In the rhyolite of Corral Canyon, euhedral hornblende 0.10 mm long is also found, along with rare euhedral allanite. In the Corral Canyon locality isolated remnants of what appear to be a basal vitrophyre occur. This vitrophyre is richer in crystals than other, younger, vitrophyres (Table 1). This vitrophyre contains euhedral phenocrysts of hydrous phases such as biotite and amphibole which are euhedral and show no evidence of disequilibrium due to pressure loss upon eruption. Rare euhedral phenocrysts of hypersthene 0.1 mm long occur in the vitrophyre as well.

The ash flows and ash falls are unconsolidated and show no evidence of welding. The bulk of the ashes are composed of a gradation of sizes from ash up to 2 to 3 cm size pumice lapilli, and lithic fragments of obsidian and granite basement up to 50 cm across. Thin sections of pumice lapilli show glass shards in sub-parallel alignment with no evidence of collapse within the lapilli. Subhedral microphenocrysts of sanidine 0.05 to 0.1 mm long are found along with quartz fragments showing a suggestion of hexagonal outlines ranging around 0.15 mm across, subhedral oligoclase 0.08 to 0.15 mm long and oxides less than 0.01 mm are dusted through the glass; rare euhedral hornblende is

present.

The fourth type of rhyolite in the Mineral Mountains makes up the youngest domes. In thin section the basal vitrophyre has a glomeroporphyritic texture with clasts of feldspar phenocrysts scattered through a glassy groundmass. The phenocryst suite includes subhedral oligoclase 0.1 to 0.15 mm long, subhedral to anhedral sanidine and anorthoclase 0.2 mm long; occasionally oligoclase is mantled by sanidine. Other phases include euhedral and fractured quartz 0.15 mm across and subhedral biotite 0.05 mm across. The mineralogy of the pumiceous capping is identical to the underlying basal vitrophyre. Thin sections of the capping do show remnant flow banding and more advanced devitrification than the basal vitrophyre, however.

Mineralogy

Mineral analyses presented in this paper were done on an ARL-EMX electron microprobe using natural mineral standards and rare earth element glasses. Correction procedures generally included only background when standards were similar in composition to unknowns; Bence-Albee correction procedures were used where standards and samples differed appreciably in composition.

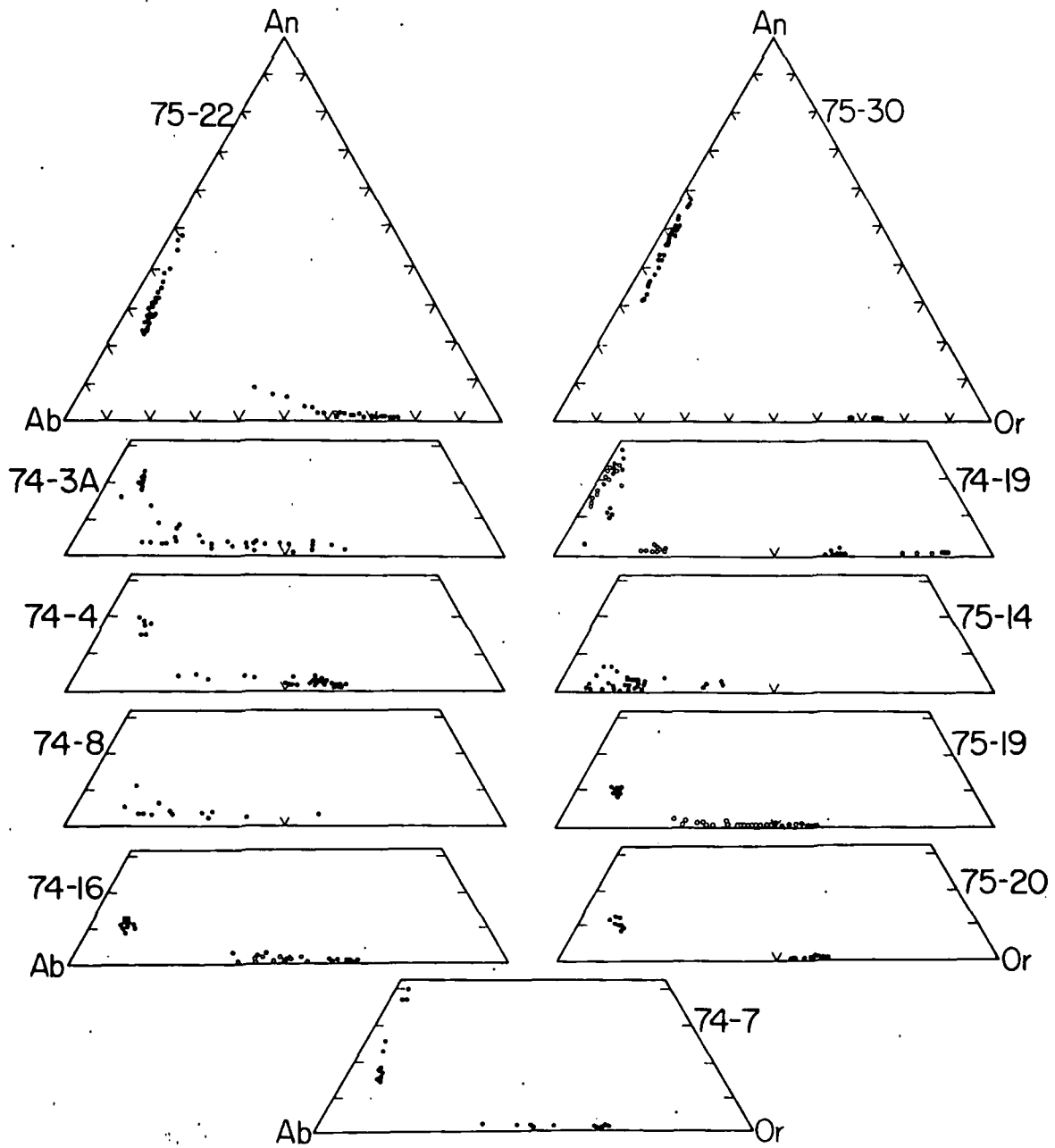
Feldspar. Both alkali feldspar and plagioclase are present in volcanic rocks of the Mineral Mountains. Microlites of feldspar are abundant, particularly in flow banded obsidians but are too small for analysis. Groundmass feldspar consists of small euhedral crystals of

both alkali feldspar and plagioclase. These crystals are rather small but an attempt was made to discern zoning along the length of larger crystals with negative results. Figure 2 presents analytical data on feldspars with points representing individual crystals. It can be seen that plagioclase compositions are restricted to a range of approximately 10 weight percent except in the older rocks of Corral Canyon. On the other hand, alkali feldspar has a wide range of composition varying from 20 to 80 weight percent Or. This wide range of composition apparently reflects a rapid adjustment of alkali feldspar composition to rather small changes in liquid composition.

The rocks of Corral Canyon display marked differences from the younger volcanics. As can be seen in Fig. 2 the groundmass plagioclase shows a much wider compositional range but does not reach as sodic a composition as in the younger volcanics, and alkali feldspar is more restricted in composition.

Phenocrysts of feldspar are not abundant in the volcanic rocks of the Mineral Mountains; however, in the younger domal material phenocrysts of alkali feldspar are present, and range from 40 to 60 percent Or. Zoning in individual alkali feldspar phenocrysts is variable from an extreme of 15% Or to normally around 3-4% from core to rim. In the older domal volcanics of Corral Canyon phenocrysts of both alkali and plagioclase feldspar are present. Zoning is present in both and frequently spans a 15-20% range in variation. Plagioclase is zoned from sodic labradorite to oligoclase and alkali feldspar from cores around Or₇₅ to rims around Or₆₀.

Fig. 2. Microprobe analyses of feldspars from Mineral Mountains rhyolites in terms of weight percent anorthite (An), albite (Ab) and orthoclase (Or). Solid circles represent phenocryst compositions, open circles are groundmass analyses.



Biotite. Biotite is a common accessory mineral in all the lavas of the Mineral Mountains. Microprobe analyses of selected samples are presented in Table 2. These biotites are high in titanium, and most contain substantial fluorine. The biotites are rather low in aluminum, requiring a varying amount of titanium to fill the tetrahedral site in the structural formulas. Biotite from Corral Canyon is distinct with lower SiO_2 and substantially higher BaO . Sample 75-30 from Corral Canyon is low in fluorine compared to other biotites; this sample is from a basal vitrophyre, and it is possible that substantial water-fluorine exchange has taken place.

Amphibole and Pyroxene. In the basal vitrophyre of Corral Canyon euhedral crystals of hornblende and orthopyroxene are imbedded in a glassy groundmass. A single crystal of hornblende was seen in a thin section of ash from Ranch Canyon. Analyses of hornblende and pyroxene are presented in Table 3. The hornblende, like the biotite from this locality, is low in aluminum and high in titanium requiring titanium to enter the tetrahedral site. It has been noted that this condition is common in calc-alkaline rocks containing both biotite and hornblende by Jakes and White (1972) and Wender and Nash (1978). The orthopyroxene on the other hand has sufficient aluminum to fill the tetrahedral site and falls in the hypersthene range observed by Jakes and White (1972) for calc-alkaline rocks.

Allanite and Spene. Allanite is an epidote-type mineral containing substantial amounts of rare earth elements. Analyses of three allanites and two spenes are given in Table 4. The presence of

TABLE 2. Average Microprobe Analyses of Biotite.

	74-3A	74-8	74-7	74-16	74-19	75-22	75-30
SiO ₂	37.2	38.6	38.4	38.4	38.9	36.1	36.5
TiO ₂	3.13	2.77	3.26	2.79	3.08	4.57	4.70
Al ₂ O ₃	11.6	12.5	12.4	11.8	11.9	13.1	13.7
FeO*	16.9	16.7	16.2	17.0	17.3	22.1	16.8
MnO	0.73	0.50	0.65	0.94	0.79	0.30	0.17
MgO	15.0	15.4	14.9	14.3	14.2	11.2	14.7
CaO	0.01	0.04	0.04	0.02	0.03	0.04	0.07
Na ₂ O	0.49	0.76	0.46	0.40	0.46	0.44	0.47
K ₂ O	9.15	8.97	9.01	9.10	9.01	8.41	8.97
BaO	0.06	0.23	0.36	0.02	0.04	0.60	0.67
Cl	0.10	0.11	0.09	0.09	0.10	0.06	0.05
F	3.13	3.17	3.21	2.67	2.57	3.51	0.61
Sum	97.5	99.8	99.0	97.5	98.38	100.4	97.4
-O=F,Cl	1.3	1.34	1.35	1.12	1.08	1.48	0.26
TOTAL	96.2	98.4	97.7	96.4	97.3	98.9	97.1

Number of Atoms on the Basis of 22 Oxygens

Si	5.72	8.00	5.76	8.00	5.77	8.00	5.86	8.00	5.86	8.00	5.53	8.00	5.47	8.00
Al	2.10		2.20		2.20		2.12		2.11		2.36		2.42	
Ti	0.18		0.04		0.03		0.02		0.03		0.11		0.11	
Ti	0.18		0.27		0.34		0.30		0.32		0.42		0.42	
Fe	2.17	5.89	2.08	5.84	2.04	5.80	2.17	5.84	2.18	5.79	2.83	5.84	2.10	5.82
Mn	0.10		0.06		0.08		0.12		0.10		0.04		0.02	
Mg	3.44		3.43		3.34		3.25		3.19		2.55		3.28	
Ca	-		0.01		0.01		-		0.01		0.01		0.01	
Na	0.15	1.94	0.22	1.95	0.13	1.89	0.12	1.82	0.13	1.91	0.13	1.82	0.14	1.90
K	1.79		1.71		1.73		1.70		1.77		1.64		1.71	
Ba	-		0.01		0.02		-		-		0.04		0.04	

*All iron reported as FeO.

TABLE 3. Average Microprobe Analyses of Amphibole and Pyroxene

	Amphibole 75-30	Pyroxene 75-30
SiO ₂	45.3	53.7
TiO ₂	2.04	0.13
Al ₂ O ₃	9.30	1.41
FeO*	13.8	19.1
MnO	0.26	0.56
MgO	13.5	24.8
CaO	11.5	1.03
Na ₂ O	1.85	-
K ₂ O	1.02	-
Cl	0.04	-
F	0.33	-
Sum	98.9	-
-O=F,Cl	0.14	-
TOTAL	98.8	100.7

Number of Atoms Based on:

	<u>23 oxygens</u>		<u>6 oxygens</u>	
Si	6.82] 8.00	Si	1.96
Al	1.10		Al	0.04
Ti	0.08			
] 2.00
Ti	0.27] 5.07	Al	0.02
Fe	1.74		Ti	-
Mn	0.03		Fe	0.58
Mg	3.03		Mn	0.02
			Mg	1.35
Ca	1.86		Ca	0.04
Na	0.54] 2.60	-	
K	0.20		-	

*Total iron reported as FeO.

TABLE 4. Average Microprobe Analyses of Allanites and Sphenes

	74-16(Allanite)	74-16(Sphene)	74-19(Allanite)	94-19(Sphene)	75-22(Allanite)
SiO ₂	30.8	30.2	30.7	29.9	31.4
TiO ₂	1.88	34.2	2.04	35.8	1.30
ZrO ₂	0.02	0.14	0.03	0.15	0.02
Al ₂ O ₃	11.5	2.20	11.2	1.53	14.3
FeO	16.4	2.93	16.9	2.78	14.9
MnO	1.80	0.49	1.83	0.23	0.57
MgO	1.17	-	1.13	-	1.29
CaO	9.13	24.5	9.20	24.8	10.5
BaO	-	0.12	-	0.14	-
SrO	-	0.06	-	0.04	-
Na ₂ O	0.07	-	0.06	-	0.04
K ₂ O	0.06	-	0.04	-	0.04
Ce ₂ O ₃	12.5	1.13	12.4	1.59	11.7
La ₂ O ₃	9.53	0.28	9.41	0.44	6.55
Pr ₂ O ₃	1.01	0.24	1.05	0.26	1.32
Nd ₂ O ₃	1.43	0.52	1.52	0.75	3.58
Sm ₂ O ₃	0.71	0.13	0.71	0.27	0.92
Gd ₂ O ₃	0.56	0.01	0.37	0.06	0.45
Y ₂ O ₃	0.06	0.89	0.07	0.75	0.12
Nb ₂ O ₅	0.01	0.53	-	0.32	-
F	0.32	0.65	0.32	0.25	0.15
Sum	99.0	99.21	99.0	100.1	99.2
Less F=O	0.13	0.26	0.13	0.11	0.06
TOTAL	98.9	98.9	98.9	100.0	99.1

allanite is noteworthy, as it is not commonly reported in a volcanic occurrence. It has been found in the Bishop Tuff of California (Hildreth, 1977), Yellowstone National Park (Christiansen, pers. comm.), and the Bandalier Tuff, Jemez Mountains, New Mexico. Total rare earth concentrations in the allanites exceeds 25 percent, with Ce to La ratios ranging from 2:1 to 4:3. This differs slightly from the values given by Frondel (1964) in which values for the ratio of Ce to La were given as 2:1 to 3:1. Frondel's work included only allanites from intrusive igneous bodies and metamorphic rocks.

Two analyses of sphenes from ash in Ranch Canyon and Bearskin Mountain Dome are also presented in Table 4. Rare earth abundances are significant in these sphenes, and comparison with allanites shows that ZrO_2 , Y_2O_3 and Nb_2O_5 are considerably higher in sphenes with the rare earths being less abundant, but their relative abundances seem to follow that of the allanites. Measurable fluorine is present in both allanite and sphene.

Oxide Minerals. Rare crystals of titanomagnetite and ilmenite were recovered from selected samples by heavy liquid separation. Analyses of homogeneous oxide pairs are presented in Table 5, recalculated according to the scheme of Carmichael (1967). The mole percent ulvospinel varies between 14 and 22 in the titanomagnetites with the variation of R_2O_3 in ilmenites being somewhat greater, varying from 6 to 20 mole percent. Many of the ilmenites and titanomagnetites are rather high in MnO, containing up to 6.60 weight percent in ilmenite and 2.75 weight percent in titanomagnetite. When the Buddington and

TABLE 5. Microprobe Analyses of Iron - Titanium Oxides

Sample No.	3A	16	19	22	26	30
Spinel Phase						
SiO ₂	0.03	0.08	0.04	0.28	0.35	0.18
TiO ₂	5.00	4.90	4.73	6.45	5.53	7.51
Al ₂ O ₃	0.93	0.62	0.63	1.52	1.23	1.86
Cr ₂ O ₃	0.03	0.03	0.02	0.07	0.06	0.13
V ₂ O ₃	0.43	0.71	0.72	0.79	0.52	0.55
FeO	86.2	85.8	84.7	83.9	84.9	82.6
MnO	0.90	2.61	2.75	1.25	1.37	0.66
MgO	0.80	0.21	0.20	0.32	0.48	0.79
CaO	0.09	0.01	0.02	0.04	*	0.02
ZnO	0.26	*	0.29	0.25	*	0.22
Sum	94.7	95.0	94.1	94.9	94.4	94.5
Recalculated Iron						
Fe ₂ O ₃	58.6	58.6	58.3	53.6	55.7	51.3
FeO	33.5	33.1	32.2	35.7	34.8	36.4
Total	100.6	100.9	99.9	100.3	100.0	99.6
Rhombohedral Phase						
SiO ₂	0.02	0.08	0.03	0.04	*	0.01
TiO ₂	42.0	46.5	46.7	44.7	40.7	49.8
Al ₂ O ₃	0.13	0.04	*	0.36	0.27	0.03
Cr ₂ O ₃	*	*	*	0.03	0.07	*
V ₂ O ₃	0.23	0.46	0.44	0.49	0.26	0.14
FeO	50.3	44.7	44.8	50.4	53.4	46.6
MnO	3.20	6.40	6.60	2.45	1.73	3.08
MgO	1.50	0.72	0.65	0.32	1.18	0.18
CaO	0.11	0.01	0.02	0.04	*	*
ZnO	0.17	0.44	0.12	0.30	0.02	0.03
Sum	97.7	99.4	99.4	99.1	97.6	99.9
Recalculated Iron						
Fe ₂ O ₃	20.8	12.2	11.9	15.0	23.4	5.87
FeO	31.6	33.7	34.1	36.9	32.4	41.3
Total	99.8	100.6	100.6	100.6	100.0	100.4
Mole % ulvospinel	14.3	14.2	13.7	19.4	17.1	22.0
Mole % R ₂ O ₃	20.2	12.0	11.7	15.3	18.6	5.7
T(°C)	740	650	645	735	780	660
-log f _{O₂}	13.6	16.8	16.9	14.3	12.5	18.2

*Below limit of detection, 0.01%.

Fe₂O₃ recalculated on ilmenite basis and magnetite recalculated on ulvospinel basis of Carmichael (1967). T and -log f_{O₂} are taken from curves of Buddington and Lindsley (1964), with modifications, see text.

Lindsley (1964) oxygen barometer-thermometer is applied to the analyses, pairs with the highest MnO contents give the lowest equilibration temperatures. It is a matter of speculation as to whether low equilibration temperatures give rise to higher MnO contents in Fe-Ti oxide, or that high MnO contents yield lower, erroneous equilibrium temperatures. At the present time this problem cannot be completely resolved due to a lack of comprehensive experimental data. However, temperatures of equilibration and appropriate oxygen fugacities are listed in Table 5 based on methods recommended by D. H. Lindsley (pers. comm.) from his unpublished data on the effects of MnO and MgO. Temperatures range from 650°C to 710°C for domes to 780°C for the obsidian flows and the oxygen fugacity varies from $10^{-18.2}$ to $10^{-12.5}$ b.

All but one of the lavas fall above the FMQ buffer curve in the region of many of the data points of Lipman (1971). The single lava plotting near the FMQ buffer contains orthopyroxene, whereas the others contain biotite phenocrysts. This condition is in complete accord with the observations of Carmichael et al., (1974, Fig. 6-12).

Accessory Minerals. Minor accessory minerals that occur in the lavas of the Mineral Mountains include apatite and topaz, both of which are high in fluorine and are indicative of the high fluorine content of the rhyolite magmas. The topaz occurs in vugs in rhyolite of the domes and is accompanied by pseudobrookite and specular hematite. All of these later minerals presumably crystallized from the vapor phase.

Crystallization of Feldspar

One of the most striking features of these lavas is the large compositional range of feldspars precipitated from liquids of very similar composition. This is best illustrated by Fig. 3 which shows bulk rock and glass compositions together with all of the feldspar determinations. If one deletes the Tertiary rhyolite data (crosses), the feldspar compositional range is not as extensive, but is nevertheless considerable. This behavior is distinct from peralkaline silicic liquids in which alkali feldspar crystallizes almost as if it were a compound with a composition of about Or_{35} (Nicholls and Carmichael, 1969). In the case of the lavas studied here, some of which contain normative corundum, subtle changes in magma composition, and perhaps temperature, can produce substantial compositional changes in feldspar.

As is to be expected, glass compositions are slightly depleted in the feldspar component in comparison to the bulk rock (Fig. 4). Natural conjugation lines may be constructed between feldspar phenocrysts and bulk rock compositions and between groundmass feldspars and glass compositions. These are shown in Fig. 5. The direction of zoning of alkali feldspars toward more sodic compositions is as anticipated from the phase relations and no reversals of zoning were detected.

Many of the lavas have precipitated quartz and the others are clearly very near quartz saturation. In addition, most contain both alkali and plagioclase feldspar. Accordingly, these lavas serve to define

Fig. 3 Bulk rock and glass compositions, in terms of their normative constituents, represented in the granite system (upper portion of diagram). Open squares are glass compositions, filled squares are bulk rock compositions for Quaternary rhyolites; open triangle is glass composition, filled triangles are bulk rock compositions for Tertiary rhyolite. Curved line represents the quartz-feldspar boundary at 500 bars water pressure. Lower portion of diagram presents feldspar data from all rhyolites, filled circles are Quaternary rhyolite phenocrysts, open circles are Quaternary rhyolite groundmass feldspars, and crosses are Tertiary feldspars (values in weight percent).

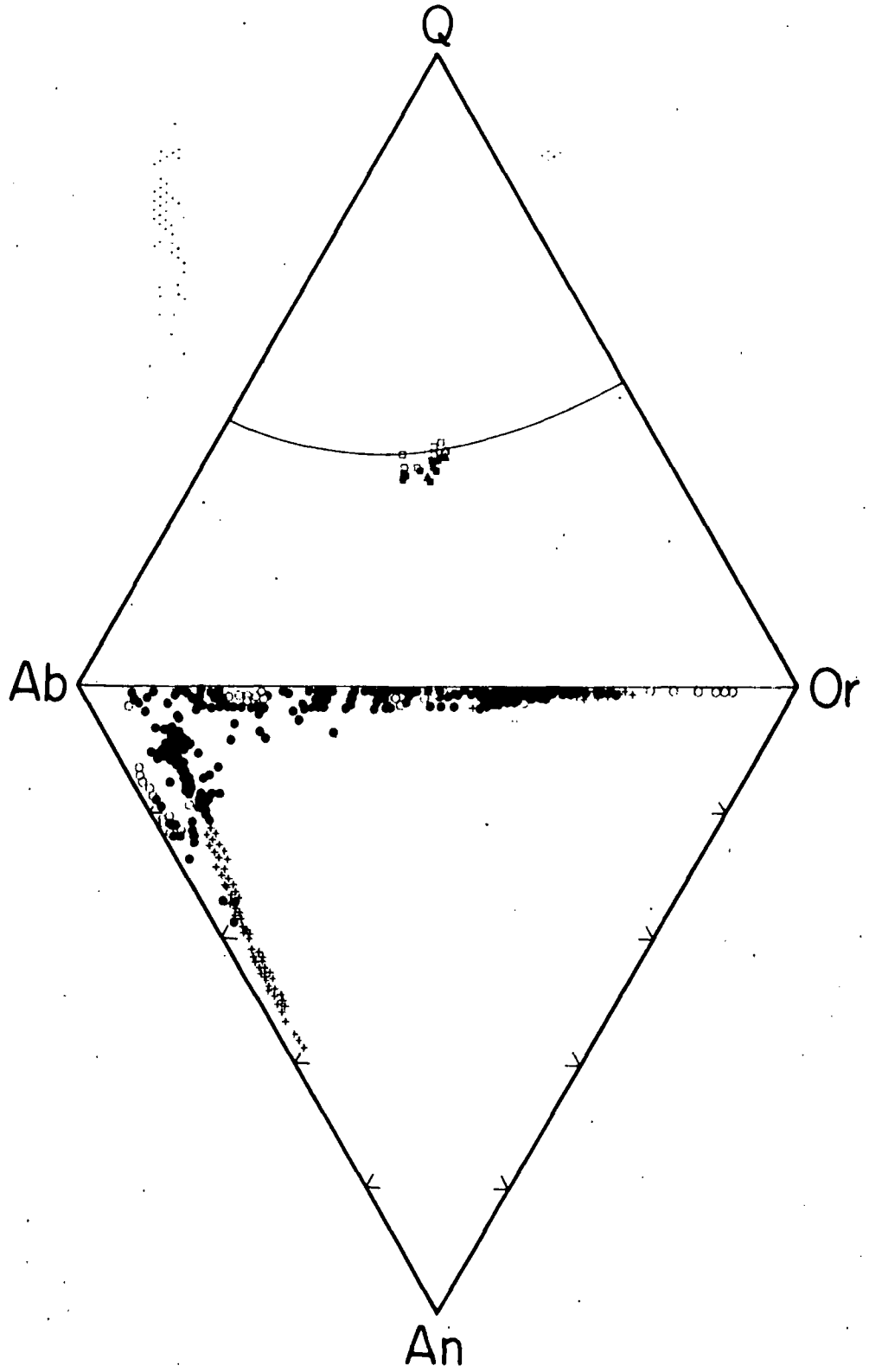


Fig. 4 Normative components of bulk rock (solid circles) and glass (open circles) analyses plotted in terms of quartz (Q), albite (Ab) and orthoclase (Or). Tie lines connect bulk and glass analyses for same sample. Un-numbered data points are rocks whose analyses are not tabulated in this paper.

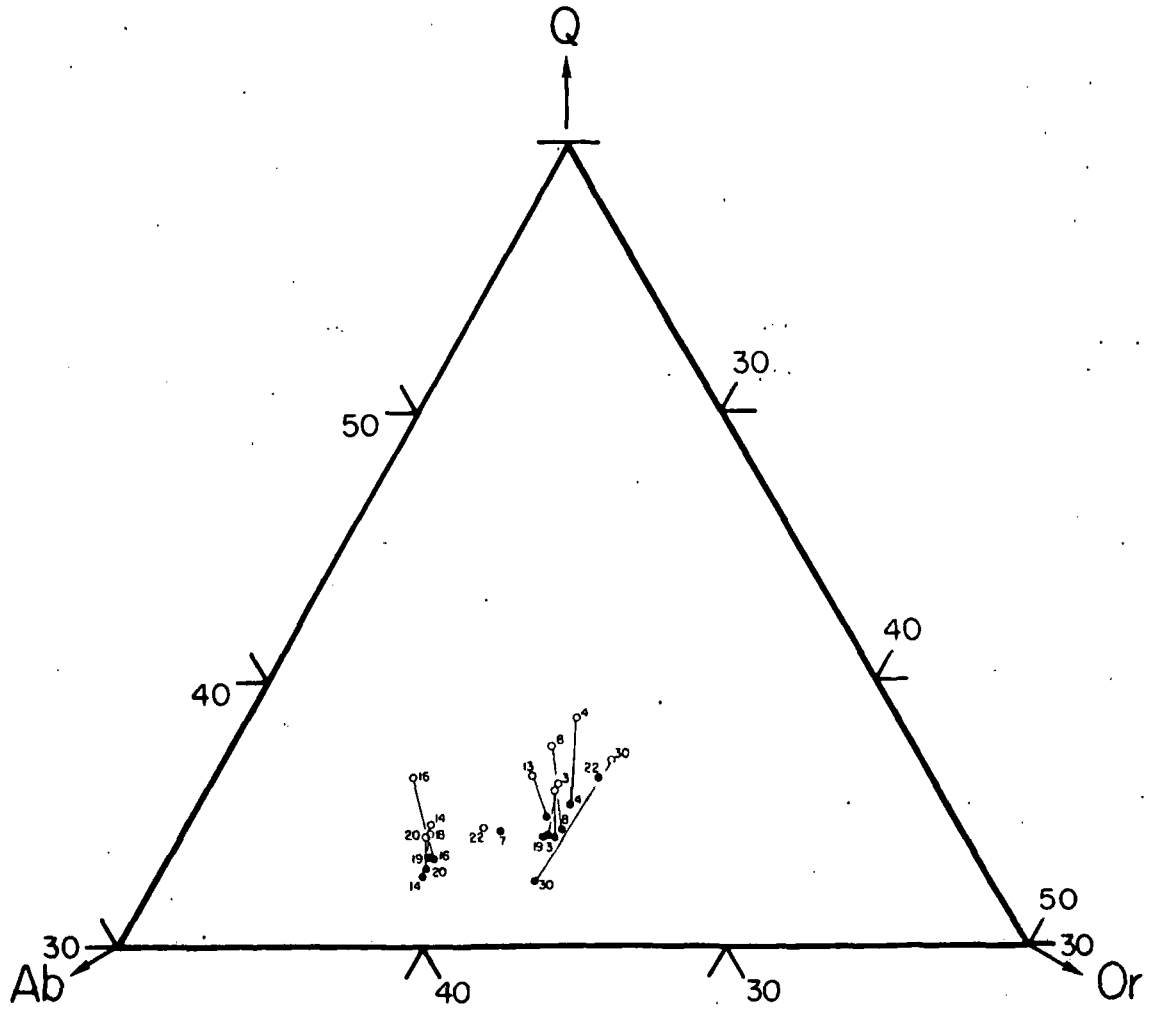
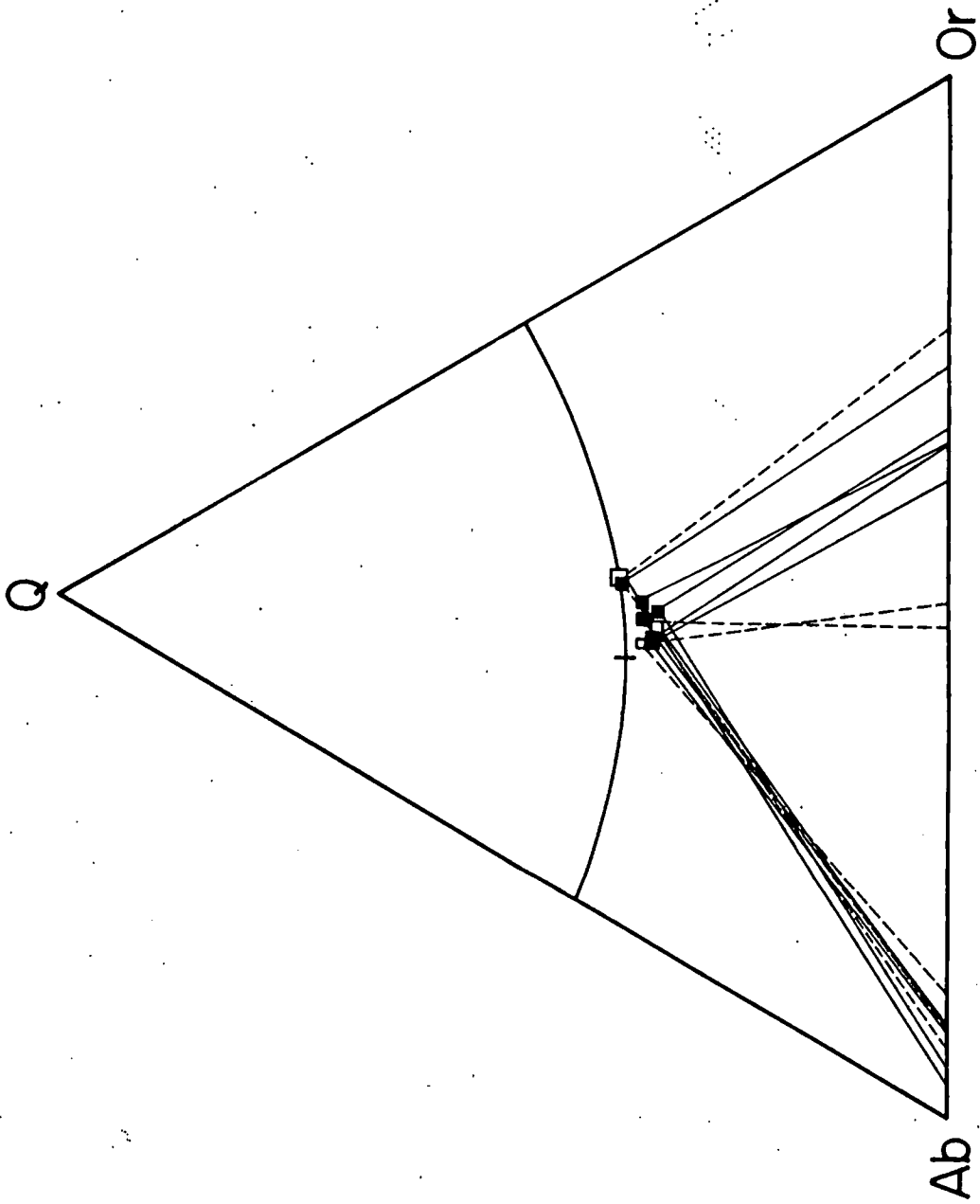


Fig. 5 Rock and glass compositions of selected samples plotted as in Fig. 3. Natural conjugation lines connect phenocryst feldspars with bulk rock compositions (solid lines) and groundmass feldspars with glass compositions (dashed lines).



the locus of the two-feldspar surface at silica saturation in natural lavas. The nature of the two feldspar surface has been postulated for natural systems (Carmichael, 1964; Carmichael et al., 1974) and partially delineated experimentally for synthetic systems (James and Hamilton, 1969). Fig. 6 illustrates those samples for which the compositions of coexisting feldspars could be determined together with their host liquids. Fig. 7 shows the compositions of all liquids, including those that precipitated only one feldspar together with the postulated shape of the two feldspar surface at silica saturation.

Fluorine was deleted from the analyses prior to calculation of the C.I.P.W. normative constituents because fluorine is incorporated in the norm as CaF_2 , thus reducing the normative anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$). Because the rocks are predominantly glass, and fluorite is not present in the mode, it seems proper that calcium be allotted to the anorthite component. Norms including fluorine are given in Table 6 where it can be seen that in some cases normative anorthite becomes zero in two-feldspar rhyolites. Because the two feldspar surface cannot intersect the Ab-Or join, the inclusion of F in the normative calculation leads to a contradictory result for two feldspar rhyolites.

Five of the lavas precipitated alkali feldspar initially, while plagioclase precipitated first in the Tertiary rhyolite (Fig. 6). Carmichael (1963) presents three data points, two of which fit our postulated surface (Fig. 7); the other falls above our preferred intersection of the two feldspar surface with the silica volume. The

Fig. 6 Compositions of coexisting alkali and plagioclase feldspars plotted together with the normative feldspar components of their host rocks. The upper solid triangle is the bulk rock normative feldspar for sample 75-30, the Tertiary rhyolite of Corral Canyon, which contains only plagioclase phenocrysts. Its residual glass (open triangle) coexists with groundmass plagioclase and alkali feldspar. The second solid triangle is the crystalline rhyolite of Corral Canyon (sample 75-22). The remaining data points are for the Quaternary lavas.

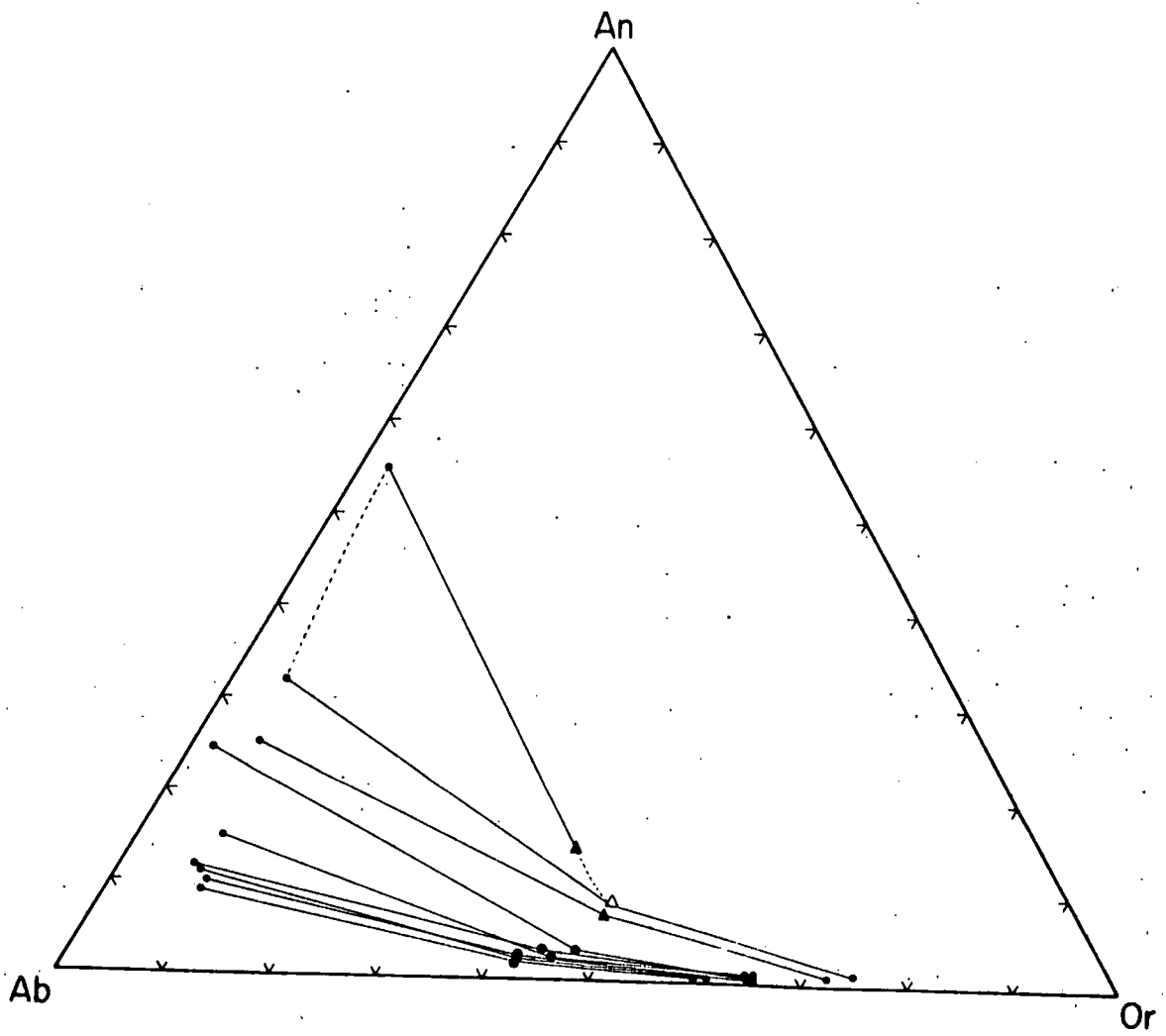
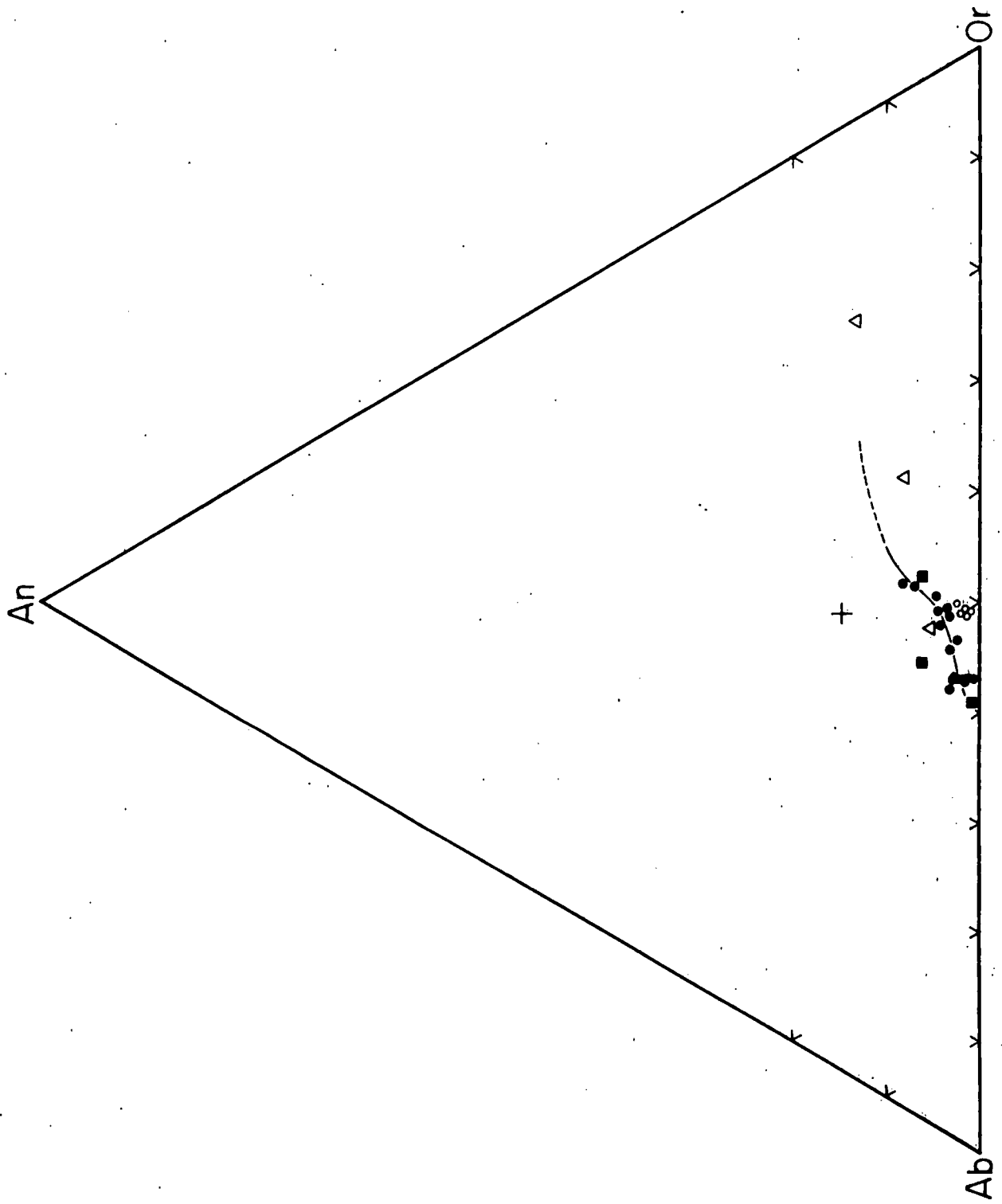


Fig. 7 Normative feldspar constituents of natural silicic liquids at or near quartz saturation. Solid circles are lavas with two feldspars. Rocks represented by open circles precipitated alkali feldspar initially, whereas the rock represented by the cross precipitated plagioclase first. Solid squares are two feldspar liquids from Carmichael (1963), and open triangles are piercing points for the two feldspar surface delineated experimentally by James and Hamilton (1969). The postulated location of the intersection of the two-feldspar surface at quartz saturation for natural liquids is shown as a solid line.



piercing points of James and Hamilton (1969) are consistent with the natural data. The albite-rich liquids which lie very near the base of the diagram contain euhedral plagioclase and alkali feldspar; they show no evidence of the resorption of plagioclase which should occur at the termination of the two-feldspar surface.

The evolution of the Quaternary lavas may be interpreted in terms of this projection. The first Quaternary lavas initially precipitated alkali feldspar producing residual liquids which reached the two feldspar surface. Younger lavas were erupted from magma that had evolved along the two-feldspar surface approaching its termination near the base. The earliest of the Quaternary lavas cannot be related to the Tertiary magma type by any simple feldspar fractionation scheme because, in contrast, the Tertiary lavas initially precipitated plagioclase feldspar followed by alkali feldspar. Thereafter any evolving residual liquids would be constrained to the two-feldspar surface.

Chemistry

Major Elements. Chemical analyses of representative samples of the Mineral Mountains volcanic rocks, along with their norms are presented in Table 6. The method of analysis is that of Carmichael et al., (1968). The first analysis, 74-3A, is the average of three analyses of obsidian from the Bailey Ridge flow. The standard deviations give an idea of the homogeneity of the flows. There appear to be two distinct groups of younger rhyolites, one containing about 5.2 percent

TABLE 6. Chemical Analyses and Norms of Volcanic Rocks and Residual Glasses from the Mineral Mountains, Utah. For Key to Samples, See Table 1.

	74-3A	*S	74-3AG	74-4	74-4G	74-8	74-8G	74-7	74-16	74-16G	74-19	74-29	75-14	75-14G	75-19	75-20	75-20G	75-22	75-30	75-30G
SiO ₂	76.52	0.06	76.6	74.51	74.1	76.51	77.1	76.82	76.00	76.0	72.87	77.55	76.42	76.5	76.46	76.45	76.5	75.97	70.13	74.8
TiO ₂	0.12	0.00	0.12	0.12	0.12	0.12	0.12	0.10	0.06	0.06	0.08	0.10	0.08	0.07	0.06	0.08	0.07	0.20	0.32	0.14
Al ₂ O ₃	12.29	0.02	12.4	11.98	12.0	12.29	12.4	12.64	12.58	13.0	12.46	12.22	12.79	12.6	12.57	12.79	12.8	12.89	14.14	12.9
Fe ₂ O ₃	0.31	0.02	-	0.33	-	0.23	-	0.61	0.24	-	0.19	0.17	0.20	-	0.41	0.30	-	0.26	0.68	-
FeO	0.46	0.02	0.73	0.43	0.65	0.51	0.74	0.15	0.39	0.56	0.42	0.48	0.38	0.53	0.18	0.29	0.58	0.46	1.25	0.82
MnO	0.05	0.01	0.06	0.04	0.05	0.05	0.06	0.05	0.07	0.09	0.07	0.02	0.09	0.11	0.10	0.10	0.11	0.04	0.02	0.05
MgO	0.08	0.02	0.09	0.10	0.06	0.10	0.09	0.10	0.37	0.05	0.17	0.10	0.11	0.04	0.08	0.12	0.04	0.17	0.58	0.12
CaO	0.64	0.03	0.55	0.62	0.56	0.65	0.55	0.50	0.45	0.42	0.40	0.44	0.44	0.38	0.44	0.40	0.40	0.91	2.02	1.06
Na ₂ O	3.80	0.03	3.68	3.56	3.29	3.77	3.58	4.03	4.27	4.14	3.64	3.40	4.42	4.23	4.35	4.39	4.29	3.40	3.44	3.26
K ₂ O	5.24	0.06	5.10	5.10	4.78	5.28	4.95	5.00	4.64	4.26	4.99	4.87	4.72	4.58	4.69	4.73	4.53	5.19	4.58	5.06
P ₂ O ₅	0.02	0.00	-	0.01	-	0.01	-	0.01	0.01	-	tr	tr	tr	-	0.04	0.06	-	tr	0.12	-
H ₂ O+	0.12	0.03	-	2.27	-	0.06	-	0.02	0.26	-	3.11	0.05	0.13	-	0.18	0.10	-	0.23	2.07	-
H ₂ O-	0.06	0.02	-	0.23	-	0.06	-	0.04	0.06	-	0.89	0.04	0.01	-	0.04	-	-	0.06	0.24	-
F	0.16	0.01	0.16	0.13	0.08	0.14	0.15	0.12	0.38	0.25	0.26	0.07	0.42	0.34	0.35	0.44	0.33	0.10	0.09	0.03
Sum	99.87	-	99.5	99.43	95.7	99.76	98.7	100.14	99.62	98.7	99.55	99.51	100.21	99.4	99.95	100.25	99.7	99.88	99.68	98.2
Less O=F	0.07	-	0.1	0.05	0.03	0.06	0.1	0.05	0.16	0.1	0.11	0.03	0.18	0.1	0.15	0.19	0.1	0.04	0.04	-
Total	99.80	-	99.4	99.38	95.7	99.70	99.6	100.14	99.62	98.7	99.44	99.48	100.03	99.3	99.80	100.06	99.6	99.84	99.64	98.2

TABLE 6. Continued

q	33.40	-	34.67	33.16	35.47	33.28	36.18	33.45	32.60	35.18	32.03	37.98	32.22	34.03	33.05	32.48	33.78	34.27	27.44	33.83
c	-	-	0.26	0.25	0.61	-	0.56	0.06	0.53	1.49	1.04	0.74	0.41	0.68	0.34	0.45	0.79	0.29	0.37	0.21
or	30.96	-	30.14	30.14	28.25	31.20	29.25	29.55	27.42	25.17	29.49	28.78	27.89	27.06	27.71	27.95	27.06	30.67	27.06	29.90
ab	32.15	-	31.14	30.12	27.84	31.90	30.29	34.10	36.13	35.03	30.80	28.77	37.40	35.79	36.81	37.15	36.30	28.77	29.11	27.59
an	1.00	-	1.56	1.65	2.19	1.02	1.63	1.48	-	0.25	0.08	1.67	-	-	-	-	-	3.78	8.62	5.04
di-wo	0.37	-	-	0.17	-	0.47	-	-	-	-	-	-	-	-	-	-	-	-	-	-
di-en	0.11	-	-	0.07	-	0.12	-	-	-	-	-	-	-	-	-	-	-	-	-	-
di-fs	0.27	-	-	0.11	-	0.38	-	-	-	-	-	-	-	-	-	-	-	-	-	-
hy-en	0.09	-	0.22	0.19	0.15	0.08	0.22	0.25	0.92	0.12	0.42	0.25	0.27	0.10	0.20	0.30	0.10	0.42	1.44	0.30
hy-fs	0.21	-	0.43	0.30	0.34	0.26	0.67	0.00	0.55	0.55	0.61	0.61	0.57	0.59	0.08	0.34	0.38	0.37	1.24	0.62
mt	0.45	-	0.48	0.48	0.43	0.33	0.35	0.36	0.35	0.32	0.28	0.25	0.29	0.28	0.59	0.43	0.45	0.38	0.99	0.43
il	0.23	-	0.23	0.23	0.23	0.23	0.23	0.19	0.11	0.11	0.15	0.19	0.15	0.13	0.11	0.15	0.13	0.38	0.61	0.27
hm	-	-	-	-	-	-	-	0.36	-	-	-	-	-	-	-	-	-	-	-	-
ap	0.05	-	-	0.05	-	0.02	-	0.02	0.02	-	-	-	-	-	0.09	0.14	-	-	0.28	-
fr	0.33	-	0.33	0.27	0.16	0.29	0.31	0.25	0.61	0.51	0.53	0.14	0.61	0.53	0.54	0.45	0.56	0.21	0.17	0.06
rest	0.18	-	-	2.50	-	0.12	-	0.06	0.32	-	4.00	0.09	0.14	-	0.22	0.10	-	0.29	2.31	-
Total	99.80	-	99.46	99.64	95.67	99.70	99.69	100.14	99.56	98.73	99.43	99.47	99.95	99.19	99.74	99.94	99.55	99.83	99.64	98.25

*Standard deviation of three analyses of samples from Bailey Ridge Flow
 G = glass analysed by microprobe; total Fe reported as FeO

K_2O and the other 4.8 percent K_2O . The more potassic varieties are from the older obsidian flows, except sample 74-7 which is a dissected rhyolite dome from Big Cedar Cove. The younger domes and ashes are less potassic and slightly less sodic than the flows. Rhyolite from Corral Canyon is quite different from the younger material. These rocks are more calcic and contain more iron and magnesium than other lavas. Their alkali content is similar to the Quaternary lavas, however. When the bulk rock analysis of the basal vitrophyre (sample 75-30) is compared to the crystalline rhyolite (sample 75-22) there appears to be a substantial difference in the content of aluminum, sodium and calcium in the two rocks. When the glass analysis (sample 75-30G) from the vitrophyre is compared to the rhyolite the analyses are quite comparable. The difference in bulk rock analyses is directly attributable to the high modal percentage (8%) of plagioclase in the basal vitrophyre (see Table 1).

Many samples contain normative corundum; a direct result of including fluorine in the norm calculation in which calcium is allotted to CaF_2 before the calculation of normative anorthite. When the norms are calculated without fluorine, none of these Quaternary rhyolites, with the exception of hydrated pumice, contain normative corundum.

Normative analyses of glasses are included in Table 6, and were calculated using the same ferrous/ferric ratio as the whole rock. In comparing whole rock and glass analyses, normative quartz is greater in the glasses, as would be expected. Other systematics are less clear. Normative alkali feldspar decreases and normative anorthite

increases in rocks with CaO in excess of that required for fluorite. The sample from Corral Canyon however shows an increase in normative orthoclase and reduced normative albite and anorthite. The presence of normative diopside in the two flows can be explained by greater CaO and lower fluorine in these rocks.

Fluorine contents of Mineral Mountains rhyolites are significant and equal or exceed values given for the Shoshone Province of Coats et al., (1963). Most specimens from the Mineral Mountains are low in water and have suffered little hydration. It may be assumed that these fluorine contents are representative of pristine liquid values (Noble et al., 1967). In the only obsidian - perlite pair analysed from the Mineral Mountains (74-3A and 74-4) the fluorine content is slightly lower in the perlite. This reduction in fluorine possibly occurred during hydration although it has been observed that some perlites have greater amounts of fluorine than their coexisting obsidian (Zielinski et al., 1977). An interesting pattern of fluorine distribution between whole-rock and glass pairs can be seen in Table 6. In the two flows, fluorine contents of glasses and whole-rocks are essentially identical, which would be expected due to their low phenocryst content. Rhyolites of the younger domes show a consistently lower value of fluorine in the glasses compared to the whole rock. This is attributed to the higher phenocryst content of these rocks, and particularly to biotite that is present. Sample 74-4 and its glass are exceptional for the flow material in that the glass is lower in fluorine than the whole-rock. This is most likely due to

fluorine loss on hydration of the glass which has not so extensively affected the biotite.

In general the Quaternary rhyolites of the Mineral Mountains have characteristics which set them apart from rhyolites of calc-alkaline affinities. The Mineral Mountain rhyolites are high in silica, and the ratio of Fe to Mg is high. Al, Ca, and Mg are low and the ratio of Ca to Mg is high. These characteristics are shared by the rhyolites of Yellowstone and may represent a set of characteristics unique to rhyolites of bimodal basalt - rhyolite provinces (Christiansen, pers comm., 1977). The Tertiary rhyolite of Corral Canyon does not fit the above characteristics and probably does not share a common parentage with the Quaternary rhyolites. As an evaluation of the possible common parentage for the Quaternary rhyolites, a mathematical test of phases required to be added to or subtracted from the flow rhyolites which would result in compositions matching the younger dome rhyolites was calculated. The method is similar to that of Bryan et al. (1969). The results indicate that the removal of approximately 40 units of alkali feldspar, 5 units of plagioclase, 25 units of quartz, 0.6 units of biotite, 0.3 units of magnetite and 0.3 units of ilmenite from 100 units of initial magma, leaving a residual magma of approximately 29% of the original parent, is required to produce a magma matching the dome rhyolites.

Trace Elements. Preliminary X-ray fluorescence analyses for selected elements are presented in Table 7. A comprehensive program of trace element analyses is underway, the results of which will be published

TABLE 7. Mineral Mountain Trace Elements in PPM (Values rounded to nearest 5 ppm)

	74-3A	74-8	74-7	74-16	74-19	74-29	75-14	75-19	75-20	75-22	75-30
Ba	200	180	130	-	-	15	-	-	-	645	1115
Ce	85	90	80	50	40	65	65	55	55	85	100
La	45	40	40	30	30	30	35	35	35	40	45
Nb	25	25	30	40	35	30	45	45	35	25	-
Nd	20	20	15	5	5	10	10	10	10	30	35
Pb	35	35	40	45	35	25	30	30	35	20	20
Pr	10	5	5	5	-	5	5	5	5	10	10
Rb	195	200	195	320	245	155	340	330	340	160	120
Sr	35	35	30	-	5	15	-	-	-	105	270
Th	25	25	25	40	35	20	35	35	35	10	15
Y	15	15	15	20	15	20	15	15	20	10	15
Zn	40	35	45	40	40	20	45	50	45	30	60
Zr	100	100	80	85	60	80	85	80	90	85	110
K/Rb	225	215	210	120	170	260	115	115	115	275	310

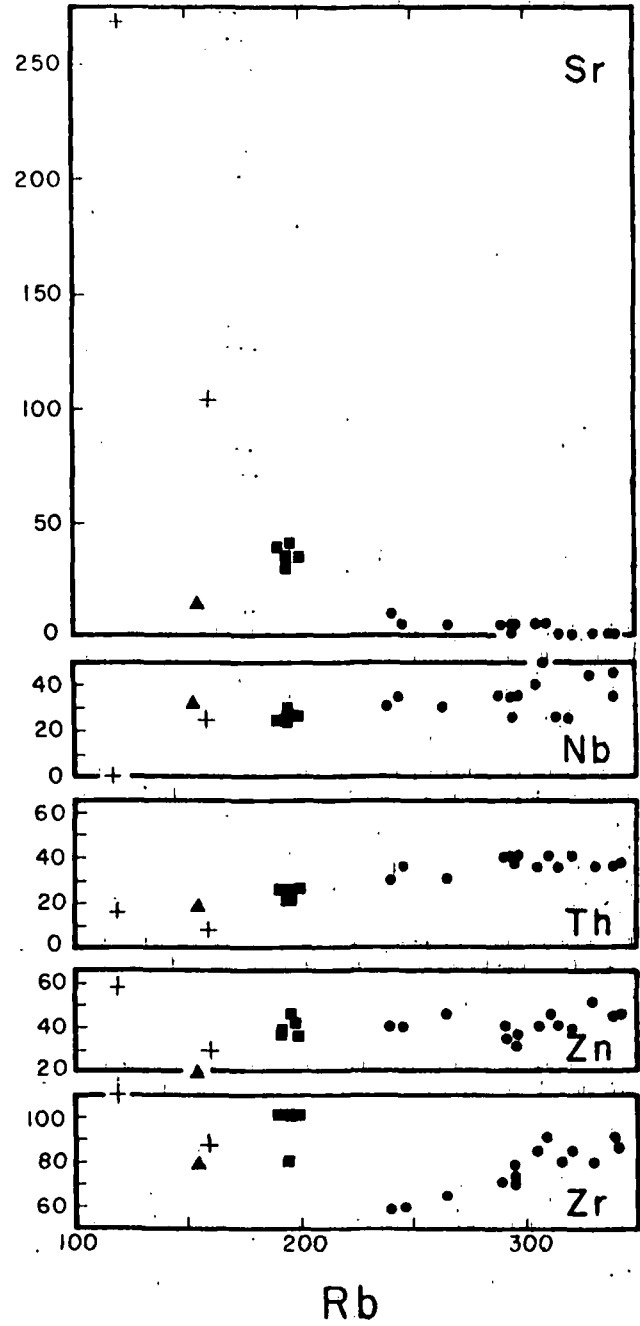
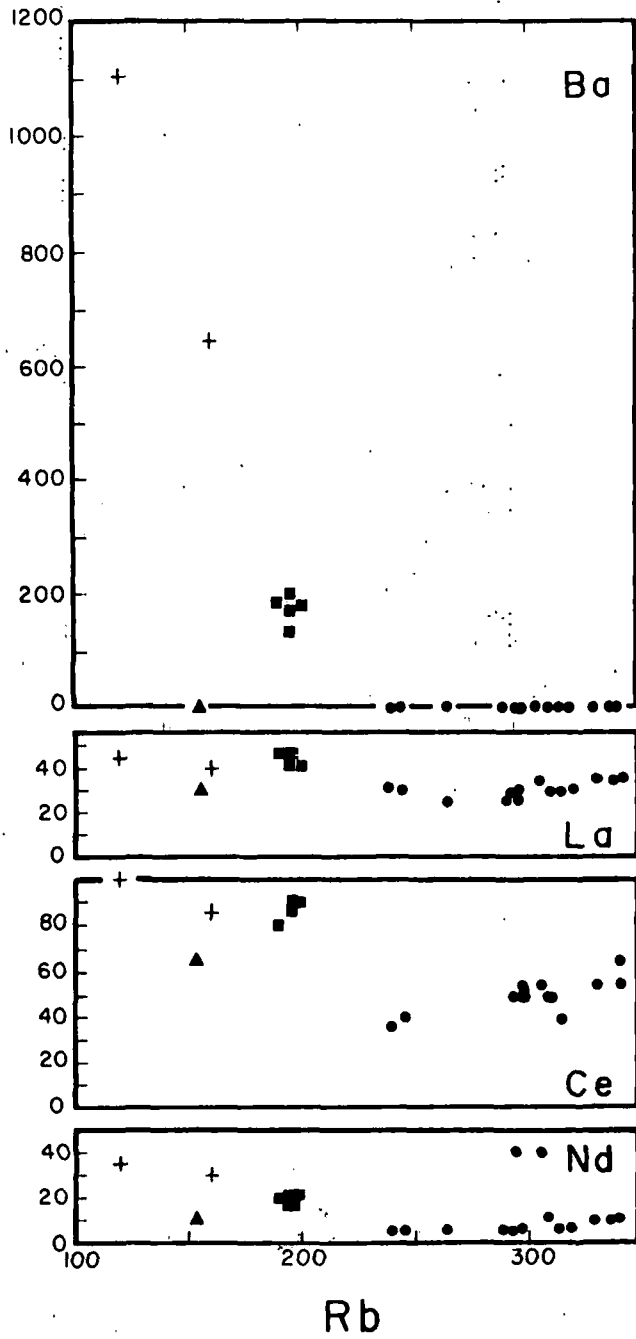
- not detected

in a subsequent paper. Three distinct groups of data can be discerned. The flows of Bailey Ridge and Wild Horse Canyon are essentially identical. The rhyolite from Big Cedar Cove dome is chemically similar to, and possibly contemporaneous with the flows. The second chemical group is the domal rhyolites. Tentatively included in this group is the sample of ash from Ranch Canyon (74-19). The ash is hydrated more extensively than the dome rhyolites and may have suffered alkali loss. The final group consists of the Tertiary rhyolites of Corral Canyon. These rocks are considerably higher in Ba and Sr and lower in Rb than the younger flows and domes. Other subtle differences may be seen in lower Pb, Th and Y. The trace element concentrations in rhyolites of the Mineral Mountains exhibit systematic variations when plotted against Rb content (Fig. 8). Rb content is taken as a measure of degree of evolution, and on this basis Ba and Sr decline rapidly as the magmas evolved.

Barium contents of phenocryst feldspar exceed or equal those of their host rocks, and the trace element data, when considered alone, show that by fractionation of feldspar, both types of Quaternary rhyolite magma could be derived from a parent represented by the composition of the Corral Canyon rhyolite. However, derivation of the Quaternary magmas from the Tertiary lava of Corral Canyon is inconsistent with the systematics of feldspar crystallization, as shown previously. Thus, we conclude that the Tertiary rhyolites are not related to the Quaternary lavas by any common liquid line of descent.

Chemical differences between flow and dome rhyolites are illustrated

Fig. 8 Trace element concentrations in parts-per-million for rhyolite lavas from the Mineral Mountains, plotted against Rb content. Solid triangle is the Mineral Mountains granite pluton, crosses are Tertiary rhyolites, filled squares are the early rhyolite flows and filled circles are later domes and ash deposits.

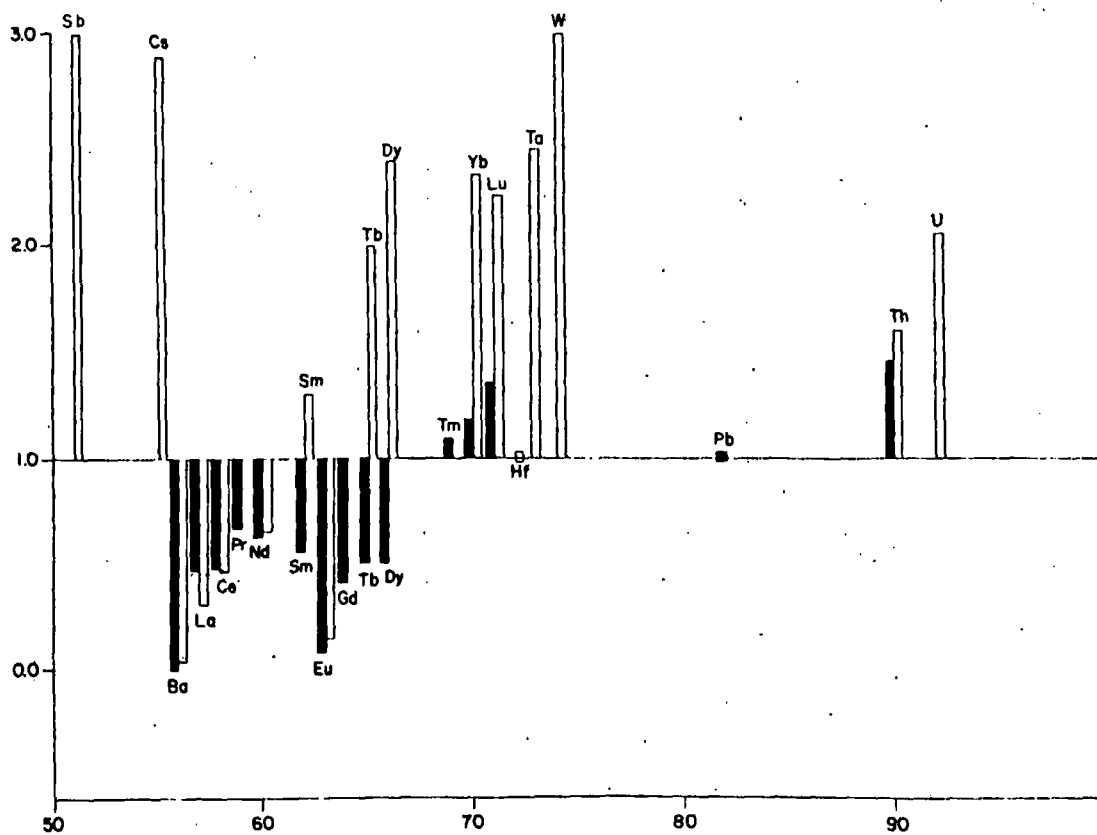
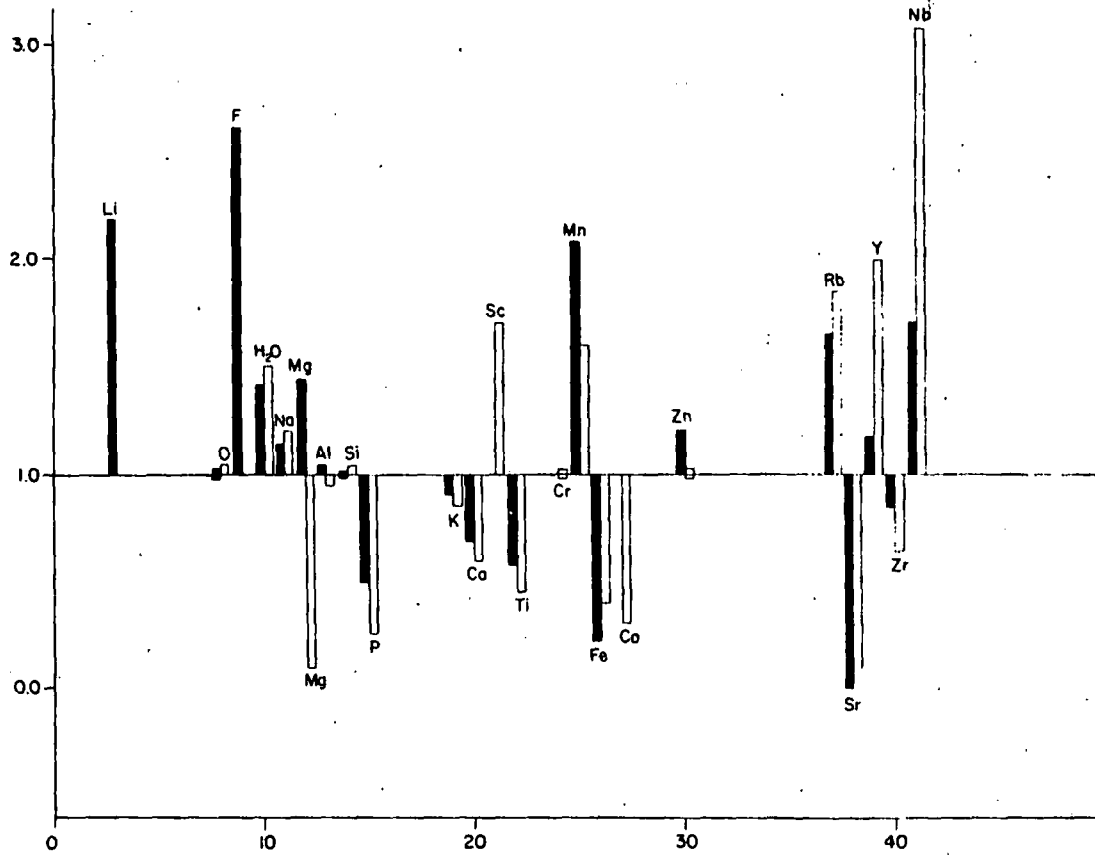


in Fig. 9 where elemental concentrations in an average dome rhyolite have been divided by those in the earlier flow rhyolite. These enrichment factors for the Mineral Mountains rhyolites exhibit remarkable similarity to those in the upper portion of the zoned magma chamber of Long Valley, California, which gave rise to the Bishop Tuff (Hildreth, 1977). This similarity lends support to our hypothesis that the two batches of rhyolite magma in the Mineral Mountains are genetically related, and that the more primitive magma which produced the flows differentiated over a period of 300,000 years to produce the more highly evolved dome-forming magma.

Geothermometry

Various geothermometers have been proposed for estimating equilibration temperature for coexisting mineral phases. Temperatures obtained from co-existing Fe-Ti oxides (Buddington and Lindsley, 1964) are given in Table 5. In addition, temperatures for some rhyolites have been calculated from co-existing plagioclase and alkali feldspar (after Stormer, 1975). Table 8 presents the temperature data obtained. There is reasonable agreement between feldspar microphenocryst and phenocryst rim temperatures and the oxide temperatures. The obsidian flows were apparently erupted at higher temperatures than the younger domes (approximately 760°C for the flows and 650°C for the domes). Temperatures obtained from feldspar phenocrysts indicate that cores of the phenocrysts began crystallizing at nearly 800°C; final quenching took place in the domes at 650°C, indicating a crystallization interval of perhaps 150°.

Fig. 9 Elemental enrichment factors from Mineral Mountains rhyolites (solid bars) and the erupted portion of the Bishop Tuff magma chamber (open bars). For the Mineral Mountains the factors are concentrations in young dome rhyolites divided by concentrations in the earlier rhyolite flows. For the Bishop Tuff (Hildreth, 1977), factors are concentrations in the roof zone samples divided by concentrations in sample derived from deeper in the magma chamber. Rare earth element data are from F. Asaro (pers. comm., 1977) and Lipman et al. (1978).



ATOMIC NUMBER

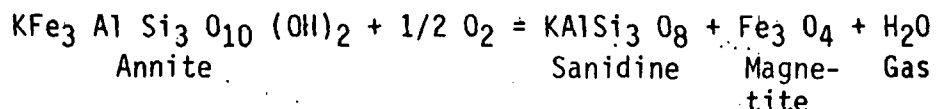
TABLE 8. Temperature data for Feldspar and Iron-Titanium Oxide geothermometers

<u>Rock</u>	<u>Stromer Feldspar Geothermometer</u>		<u>Iron-Titanium Oxides</u>		
	<u>Micropheno- crysts</u>	<u>Phenocrysts</u> <u>Rim Temp</u>	<u>Core Temp</u>	<u>Temp</u>	<u>Log f_{O2}</u>
74-3A(Flow)	690°C (1bar)	_____	_____	740°C	-13.6
74-8 (Flow)	690°C (1bar)	_____	_____	780°C	-12.5
74-19(Ash)	710°C (1bar)	710°C (1bar)	700°C (1kbar) 800°C (5kbar)	645°C	-16.9
74-16(Dome)	_____	620°C (1bar)	630°C (1kbar) 690°C (5kbar)	650°C	-16.8
75-19(Dome)	_____	710°C (1bar)	690°C (1kbar) 740°C (5kbar)	_____	_____
75-22(Dome)	_____	770°C (1bar)	750°C (1kbar) 800°C (5kbar)	750°C	-14.3
75-30(Dome)	_____	_____	_____	660°C	-18.2

Microphenocrysts of feldspar in the flows give anomalously low temperatures when compared with the oxide temperatures. This probably results from plagioclase having nearly equal molar contents of orthoclase and anorthite, in which case the thermometer will have a greater uncertainty (Stormer 1975).

Water Fugacity

The fugacity of water in a magma may be estimated from the assemblage biotite-sanidine-magnetite, if the fugacity of oxygen and the quench temperature can be established. For rhyolites of the Mineral Mountains this has been done where it is felt these phases represent equilibrium assemblages based on petrographic interpretation. For the reaction (Wones, 1972),



the expression:

$$\begin{aligned} \log f_{\text{H}_2\text{O}} = & \frac{7409}{T} + 4.25 + 1/2 \log f_{\text{O}_2} + 3 \log x_{\text{Fe}^{+2}}^{\text{bio}} \\ & + 2 \log x_{\text{OH}}^{\text{bio}} - \log a_{\text{san}} - \log a_{\text{mt}} \end{aligned}$$

permits $f_{\text{H}_2\text{O}}$ to be calculated. Here the term $2 \log x_{\text{OH}}^{\text{bio}}$ takes into account the assumed ideal mixing of F in the OH site. Values for T and f_{O_2} were taken from Table 5, and the activities of sanidine were obtained from the relationship of Waldbaum and Thompson (1969).

Hildreth (1977) has proposed a new free energy value for the previous reaction, based upon a reevaluation of the experimental data along the Ni-NiO buffer over the temperature range of 600 to 800°C.

Substantially lower water fugacities are obtained in this manner.

Table 9 lists calculated values for f_{H_2O} as well as the equivalent P_{H_2O} calculated from the data of Burnham et al. (1969). The calculated water pressures for the flows (74-3A and 74-8) are higher than for the domes. The Tertiary rhyolite in Corral Canyon has a f_{H_2O} roughly equivalent to the Quaternary flow rhyolite.

Petrogenesis

In this paper we have presented three lines of evidence which suggest a possible genetic relationship between the Quaternary lavas.

Feldspar-liquid equilibria, trace element distributions, and crystal fractionation calculations all indicate that it is possible to derive the younger dome rhyolites from a magma whose composition is that of the older rhyolite flows. These tests are merely permissive and do not preclude other modes of origin, including the formation of separate unrelated magmas, or chemical differentiation in a stagnant magma chamber as proposed by Hildreth (1977).

Any general model for the formation of these rhyolites must depend in part on the regional tectonic setting. Rhyolitic volcanism can be divided conveniently into three broad types each of which is characterized by a distinct tectonic regime.

Rhyolite occurs in oceanic environments such as Iceland (Carmichael,

Table 9. Water Fugacities and Pressures for Mineral Mountain Rhyolites. Free energies used are (1) Wones (1972) and (2) Hildreth (1977).

<u>Sample N.</u>	<u>$f_{\text{H}_2\text{O}}$ (bars)</u>		<u>$P_{\text{H}_2\text{O}}$ (bars)</u>	
	(1)	(2)	(1)	(2)
74-3A	2708	774	3657	962
74-8	2988	807	3765	966
74-19	424	177	520	192
74-16	409	153	495	166
75-22	2523	762	3475	944

1964). In this setting rhyolite is not a major rock unit and is accompanied by significant amounts of basalt, basaltic andesite and andesite (icelandite). The rhyolite characteristically contains one feldspar only (plagioclase) and is chemically distinct from Mineral Mountain rhyolites, containing less silica and alkalis. The alkali content of Icelandic rhyolite is also distinct from Mineral Mountain rhyolite in that they contain more Na_2O than K_2O . Rhyolite in this setting has been derived from a basaltic parent by crystal fractionation (Carmichael, 1964, 1967).

A second major rhyolite occurrence is in the calc-alkalic association developed in island arcs or along continental margins where subduction of oceanic crust is a dominant tectonic feature. Well described examples include the Talasea Peninsula, New Britain (Lowder, 1970, Lowder and Carmichael, 1970) and Mount Lassen, California (Smith and Carmichael, 1968). Rhyolites from this setting typically contain only plagioclase feldspar and are lower in silica and alkalis when compared to rhyolites of the Mineral Mountains. Crystal fractionation models and isotopic evidence indicate that calc-alkalic rhyolites are derived by fractionation from a more mafic parental magma (Lowder and Carmichael, 1970; Peterman et al., 1970).

The third major environment of rhyolitic volcanism is the basalt - rhyolite bimodal association of continental regions. Intermediate rock types such as andesite and dacite are rare, and rhyolites are characterized by higher silica and alkali contents than those from other tectonic settings. It is significant that these rhyolites

contain two feldspars as opposed to typical oceanic and calc-alkalic rhyolites. Examples of this third type of rhyolite occur in Yellowstone National Park, Inyo Craters, California (Carmichael, 1967) and the Coso volcanic field, California (Duffield and Bacon, 1977). The latter is remarkably similar to the Mineral Mountains setting. At Coso rhyolitic domes have been erupted onto granitic basement, and to the east is a large area of older basaltic volcanics with perhaps the youngest volcanism of the area represented by basaltic outpourings to the south of the rhyolite dome field. The rhyolite domes are aligned in nearly a north-south orientation, similar to the Mineral Mountains, and neither at Coso nor in the Mineral Mountains is there any clear evidence for the formation of a caldera system.

It seems clear that the large outpouring of basalts, to the north and southeast of the Mineral Mountains, must bear some relationship to the generation of the rhyolitic magmas described here. High regional heat flow (80mW/M^2 , Sass et al., 1976) and a thin crust (25 km) in the vicinity of the Mineral Mountains must also be considered as important factors in magma generation. It is proposed here that the general regional high heat flow combined with the injection of basaltic magma into the crust has caused crustal melting to produce rhyolitic magmas which have subsequently been erupted in the Mineral Mountains.

Shallow level differentiation of this magma could have produced the magma which was subsequently erupted up a number of conduits to form the many domes of the Mineral Mountains. Periodic injections of basalt into the crust may have served to re-supply heat to the

rhyolitic magma system allowing them to remain fluid enough to differentiate. A less preferred alternative is the possibility that the chemically distinct rhyolites represent independent magma batches generated by separate influxes of basalt into the crust. Here chemical differences would reflect source rock differences not affected by differentiation. Which of these two processes is correct is a matter of current investigation.

Acknowledgements

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REFERENCES

- Armstrong, R. L.: Geochronology of Tertiary igneous rocks, eastern Basin and Range Province, western Utah, eastern Nevada, and vicinity, U.S.A. *Geochim. Cosmochim. Acta* 34, 202-232 (1970)
- Bryan, W. B., Finger, L. W. and Chayes, F.: Estimating proportions in petrographic mixing equations by least-squares approximation. *Science* 163, 925-927 (1969)
- Buddington, A. F., Lindsley, D. H.: Iron-titanium oxide minerals and synthetic equivalents. *J. Petrol.* 5, 310-357 (1964)
- Burnham, C. W., Holloway, J. R., Davis, N. F.: Thermodynamic properties of water to 1,000°C and 10,000 Bars. *Geol. Soc. Amer. Sp. Paper* 132, 96 p. (1969)
- Carmichael, I. S. E.: The crystallization of feldspar in volcanic acid liquids. *Quart. J. Geol. Soc. Lond.* 119, 95-131 (1963)
- Carmichael, I. S. E.: The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *J. Petrol.* 5, 435-460 (1964)
- Carmichael, I. S. E.: The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contrib. Mineral. Petrol.* 14, 36-64 (1967)
- Carmichael, I. S. E., Hample, J., and Jack, R. N.: Analytical data on the U.S.G.S. standard rocks. *Chem. Geol.*, 3, 59-64 (1968)
- Carmichael, I. S. E., Turner, F. J., Verhogen, J.: *Igneous Petrology*. McGraw-Hill, New York, 739 p. (1974)
- Coats, R. R., Goss, W. D., Rader, L. F.: Distribution of fluorine in unaltered silicic volcanic rocks of the western conterminous United States. *Econ. Geol.* 58, 941-951 (1963)
- Condie, K. C.: Petrogenesis of the Mineral Range pluton, southwestern Utah. M. S. Thesis, Univ. of Utah, 94 p. (1960)
- Condie, K. C., Barsky, C. K.: Origin of Quaternary basalts from the Black Rock Desert Region, Utah. *Geol. Soc. Amer. Bull.* 83, 333-352 (1972)

- Duffield, W. A., Bacon, C. R.: Preliminary geologic map of the Coso volcanic field and adjacent areas, Inyo County, Calif., U.S. Geol. Survey open file map 77-311 (1977)
- Earll, F. N.: Geology of the central Mineral Range, Beaver County, Utah. Ph.D. Thesis, Univ. of Utah, 112 p. (1957)
- Evans, S. H., Jr., Nash, W. P.: Low-temperature rhyolites from the Roosevelt geothermal area, Utah. Geol. Soc. Amer. Abs. with Programs, v. 7, no. 7, 1070 (1975)
- Evans, S. H., Jr.: Geologic map of the central and northern Mineral Mountains, Utah. Dept. of Geol. and Geophys. Report 77-7, Univ. of Utah (1977)
- Ewart, A., Hildreth, W., Carmichael, I. S. E.: Quaternary acid magma in New Zealand. Contrib. Mineral. Petrol. 51, 1-27 (1975)
- Fournier, R. O., Truesdell, A. H.: An empirical Na-K-Ca geothermometer for natural waters. Geochim. Cosmochim. Acta 37, 1255-1275 (1973)
- Fronde! , J. W.: Variation of some rare earths in allanite, Amer. Mineral. 49, 1159-1177 (1964)
- Hildreth, E. W.: The magma chamber of the Bishop Tuff: Gradients in temperature, pressure, and composition. Ph.D. Thesis, Univ. of Calif., Berkeley, 328 p. (1977)
- Jakes, P., White, A. J. R.: Hornblendes from calc-alkaline volcanic rocks of island arcs and continental margins. Amer. Mineral. 57, 887-902 (1972)
- James, R. S., Hamilton, D. L.: Phase relations in the system $\text{NaAlSi}_3\text{O}_8$ - KAlSi_3O_8 - $\text{CaAl}_2\text{Si}_2\text{O}_8$ - SiO_2 at 1 kilobar water vapour pressure. Contrib. Mineral. Petrol. 21, 111-141 (1969)
- Liese, H. C.: Geology of the Northern Mineral Range, Millard and Beaver Counties, Utah. M. S. Thesis, Univ. of Utah, 88 p. (1957)
- Lipman, P. W.: Iron-titanium oxide phenocrysts in compositionally zoned ash-flow sheets from southern Nevada. Jour. Geol. 79, 438-456 (1971)
- Lipman, P. W., Rowley, P. D., Mehnert, H., Evans, S. H., Nash, W. P., Brown, F. H.: Pleistocene rhyolite of the Mineral Mountains Utah: geothermal and archeological significance. Jour. Res. U. S. Geol. Survey 6, 133-147 (1978)

- Lowder, G. G.: The volcanoes and caldera of Talesea, New Britain: Mineralogy. Contrib. Mineral. and Petrol. 26, 324-340 (1970)
- Lowder, G. G., Carmichael, I. S. E.: The volcanoes and caldera of Taesea, New Britain: Geology and petrology. Geol. Soc. Amer. Bull. 81, 17-38 (1970)
- Mundorff, J. C.: Major thermal springs of Utah. Utah Geol. Mineral. Survey, Water Resources Bull. 13 (1970)
- Nicholls, J., Carmichael, I. S. E.: Peralkaline acid liquids: A petrological study. Contrib. Mineral. Petrol. 20, 268-294 (1969)
- Noble, D. C., Smith, V. C., Peck, L. C.: Loss of halogens from crystallized and glassy silicic volcanic rocks. Geochim. Cosmochim. Acta 31, 215-223 (1967)
- Park, G. M.: Some geochemical and geochronologic studies of the beryllium deposits in western Utah. M. S. Thesis, Univ. of Utah, 195 p. (1968)
- Peterman, Z. E., Lowder, G. G., Carmichael, I. S. E.: Sr^{87}/Sr^{86} Ratios of the Talesea Series, New Britain, Territory of New Guinea. Bull. Geol. Soc. Amer. 81, 39-40 (1970)
- Sass, J. H., Diment, W. H., Lachenbruch, A. H., Marshall, B. V., Munroe, R. J., Moses, T. H., Jr., Urban, T. C.: A new heat flow contour map of the conterminous United States. U. S. Geol. Survey Open file report 76-756, p. 24 (1976)
- Smith, A. L., Carmichael, I. S. E.: Quaternary lavas from the southern Cascades, Western U. S. A. Contrib. Mineral. Petrol. 19, 212-238 (1968)
- Stormer, J. C., Jr.: A practical two-feldspar geothermometer. Amer. Mineral. 60, 667-674 (1975)
- Waldbaum, D. R., and Thompson, J. B., Jr.: Mixing properties of sanidine crystalline solutions: pt: IV, Phase diagrams from equations of state. Amer. Mineral. 54, 1274-1298 (1969)
- Wender, L. E., Nash, W. P.: Chemical and mineralogical evolution of the Cenozoic volcanic rocks of the Marysvale area, Utah. in press (1978)

Wones, D. R.: Stability of biotite: a reply. Amer. Mineral. 57,
316-317 (1972)

Zielinski, R. A., Lipman, P. W., Millard, H. T., Jr.: Minor element
abundances in obsidian, perlite, and felsite of calc-alkalic
rhyolites. Amer. Mineral. 62, 426-437 (1977)