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SPACE–TIME–COMPOSITION PATTERNS OF LATE CENOZOIC MAFIC VOLCANISM, SOUTHWESTERN UTAH AND ADJOINING AREAS

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ABSTRACT. Chemical analyses and 68 K-Ar dates for Miocene and younger mafic lava flows define space–time–composition patterns of volcanism along the boundary between the western Colorado Plateaus and the eastern Basin and Range Province in southwestern Utah and southeastern Nevada. Chemically diverse mafic volcanism occurred episodically in various areas. Following locally voluminous intermediate volcanism in the Oligocene (manifested as composite-volcano and ash-flow-erupting-caldera complexes), potassium-rich mafic lavas were erupted 25 to 21 m.y. ago in an area extending from east of Marysvale, Utah in the plateaus due west to beyond Milford, Utah, in the Basin and Range Province. After a hiatus of several million years, basalt was extruded from 14 to 11 and again from 9 to 5 m.y. ago in the same area as well as much farther southwest in the Basin and Range Province. During this mafic activity 25 to 5 m.y. ago, there was an overall progressive decrease in potassium in younger lavas in Utah and Nevada.

In the past 2 m.y., mafic volcanism has yielded diverse saturated and undersaturated basalt, hawaiite, and intermediate lavas of calc-alkalic affinities in essentially two belts. One of these belts, which forms a north-south zone along the easternmost edge of the Basin and Range Province in central Utah, coincides more or less with known geothermal resource areas; the other belt lies along the west-southwest trending southern limit of Oligocene and Miocene intermediate volcanism in southern Utah. Local rhyolitic volcanism accompanied all these mafic episodes.

In the northwest corner of Arizona, where no previous Phanerozoic volcanism had occurred, a variety of basalts and no rhyolite were extruded; this activity began 7 m.y. ago on the west and has apparently advanced east and north into the Colorado Plateaus.

INTRODUCTION

The development in space and time of crustal uplift, fundamentally basaltic volcanism, and extensional-block faulting that characterize the Basin and Range Province and the adjacent west margin of the Colorado Plateaus is poorly understood, although a broad framework for this activity in the western United States has been known for several years (Christiansen and Lipman, 1972).

The Basin and Range Province has been viewed as a continental rift zone not unlike oceanic spreading zones; indeed, they are similar both tectonically and geophysically (Best and Hamblin, 1979). Nevertheless, significant differences between these two environments also exist: the rate of crustal extension is about an order of magnitude less in the Basin and Range Province than that in average oceanic rifts. Extensional faulting and basaltic magmatism of relatively uniform chemical composition are intimately associated and strongly localized along the axis of oceanic rifts in zones only several kilometers wide. In contrast, the Basin and Range Province is several hundred kilometers wide, and contemporaneous basaltic volcanism is sparsely distributed, principally around the margins of the area (Best and Brimhall, 1974, fig. 1). Basaltic lavas associated with extensional faulting since the middle Miocene show exten-

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sive compositional variation, and rhyolite and some intermediate rock types also occur. In many localities, basalt and other mafic lavas are intercalated in the upper part of thick sequences of Oligocene volcanic rocks, chiefly of intermediate composition, which have been referred to variously as arc, subduction-related, or calc-alkaline assemblages. The presence of these early arc assemblages and the difficulty in distinguishing arc-related from extension-related basalt make precise definition of the onset of extension-related volcanism in a particular area generally imposssible.

The chief purpose of this report is to present new K-Ar ages on Miocene and younger mafic lava flows along the boundary between the western Colorado Plateaus and the eastern Basin and Range Province. Relations between age, composition, and geographic distribution of these flows are established in an effort to test old and to formulate new ideas on the late Cenozoic evolution of this region.

PREVIOUS WORK

Basaltic rocks are represented on the Utah geologic map (Hintze, 1963) by two map units: late Tertiary basalt and basaltic andesite flows, (T_2bf), and Quaternary basalt (Qb). The late Tertiary unit includes a variety of mafic flows ranging in age from 37 to 0.1 m.y.; the Quaternary unit is chiefly basalt and ranges in age from 10.8 m.y. to a few thousand years. Other mafic flows occur within areas designated as Sevier River Formation and Tertiary volcanic rocks, undifferentiated.

Chemical analyses and isotopic dates for mafic volcanic rocks of Utah have been published by Callaghan (1939), Smith and others (1963), Embree (1970), Leeman and Rogers (1970), Condie and Barsky (1972), Hogg (1972), Lowder (1973), Best and Brimhall (1974), Hoover (1974), Leedom (1974), Anderson and others (1975), Clark (1977), and Hausel and Nash (1977). Extensive detailed mapping of basaltic fields in southwestern Utah by W. K. Hamblin (oral commun., 1979) is unpublished.

Late Cenozoic mafic volcanic rocks of southeastern Nevada are shown on the state map (Stewart and Carlson, 1974) as Tertiary basalt flows (Tb) and Tertiary and Quaternary basalt flows (QTb). Data on these rocks have been published by Armstrong (1970), Anderson and others (1972), and Anderson (1978).

In northwestern Arizona, detailed mapping by W. K. Hamblin (oral commun., 1979) is unpublished, but generalized maps are presented by Hamblin (1970) and by Best and Brimhall (1974), who also give K-Ar dates and chemical analyses.

The inception of fundamentally basaltic volcanism in the Basin and Range Province is considered by McKee (1971) and Noble (1972) to have coincided closely with the onset of crustal extension. At first recognized in the classic synthesis by Christiansen and Lipman (1972; see also Armstrong and Higgins, 1973), cessation of arc volcanism and inception of basaltic, extension-related volcanism occurred at various times and in various places within the Basin and Range Province and surrounding areas. Christiansen and Lipman (1972), Armstrong and Higgins (1973), Snyder, Dickinson and Silberman (1976), and Cross and Pilger (1978) interpreted this diachronous behavior as a consequence of interaction of the North American and Pacific plates and northward migration of the Mendocino triple junction along the California Coast with cessation of subduction behind it.

The time of inception of extensional-block faulting along the east margin of the Basin and Range Province and the adjoining Colorado Plateaus is poorly known; only locally are geologic data adequate to set any limits on this event. Along lat 38° N. structural differentiation between the two provinces began possibly as early as 26 m.y. ago, but main block faulting did not begin before 22 m.y. ago (Rowley, Anderson and others, 1978). North of Marysvale, Utah, a local faulted basin in which the Sevier River Formation accumulated formed as early as 14 m.y. ago (Steven and others, 1977). Northeast of Delta, Utah, major block faulting in the Thomas Range began after eruption of 21-m.y.-old rhyolite but before that of 6 to 7-m.y.-old rhyolite (Lindsey, 1978). Mafic flows intercalated with coarse clastic deposits north of Cedar City, Utah, are about 9 m.y. old, an age indicating that basin development already was underway by this date (R. E. Anderson, written commun., 1978).

AGE DETERMINATION

Table 1 and figure 1 show 48 new whole-rock K-Ar dates along with 20 published and unpublished dates. For argon analysis most of our samples were crushed to 0.5 to 2 mm; other samples denoted as "treated sample" in table 1 were crushed to 30 to 60 mesh and then washed in 65 percent HF and 14 percent HNO_3 to remove material preferentially holding atmospheric argon. Splits of crushed and treated samples were used for duplicate determination of K_2O by the lithium metaborate fusion technique and flame photometry at the U.S. Geological Survey laboratory in Menlo Park, Calif., by atomic absorption spectrophotometry at the University of Arizona in Tucson, or by the Norrish-Hutton fusion technique and X-ray fluorescence spectrometry at Brigham Young University in Provo, Utah. Argon was measured by isotope dilution-mass spectrometry using ^{38}Ar tracer and conventional extraction techniques at Menlo Park and Tucson (samples 1-7).

The error limit on dates 8 through 55 reported in table 1 is a weighted value combining the analytical precision at one standard deviation with a subjective estimate of the similarity in analyzed amounts of K_2O and Ar from different splits of the same samples. In general, the ratio of radiogenic ^{40}Ar ($^{40}Ar^*$) to total ^{40}Ar is an index of the limit of error. Samples with 20 percent or more $^{40}Ar^*$ have a possible error of 5 percent or less of the calculated date, those with 10 to 20 percent $^{40}Ar^*$ about 10 percent, those with 5 to 10 percent $^{40}Ar^*$ about 20 percent, and those with less than 5 percent $^{40}Ar^*$ as much as, or more than, 100 percent of the age.

TABLE 1

	Sample	Rock type	Latitude (N.)	Longitude (W.)	K_2O (wt%)	$^{40}Ar^*$ (10^{-12} mol g^{-1})	$^{40}Ar^*$ (% total)	Calculated[1] date (10^6 yr)	Remarks
1.	PED-10-65	Basalt	36°09'	114°46'	2.19, 2.20	43.1	70.2	13.6 ± 0.5	Flow or sill in the Thumb Formation, Nevada
2.	PED-31-66	Basalt	36°55'38"	113°55'44"	1.37, 1.36 1.34, 1.34	5.37 5.56 5.83	20.0 19.2 20.4	2.87 ± 0.20	Old stage I flow, Arizona
3.	PED-34-66	Basalt	36°37'37"	113°53'23"	0.782, 0.779	7.73	56.5	6.87 ± 0.20	Basalt flow in Grand Wash, Arizona
4.	PED-37-66	Basalt	36°06'33"	113°32'32"	1.16, 1.16, 1.16, 1.14	11.46 12.05	14.0 14.6	7.06 ± 0.49	Mount Dellenbaugh, Arizona
5.	PED-39-66	Basalt	36°25'50"	113°33'30"	1.20, 1.19	7.94 8.42	16.0 17.3	4.75 ± 0.26	Old stage I flow, Arizona
6.	PED-42-66	Basalt	36°23'52"	113°09'16"	0.934, 0.936	4.09 4.18 5.74	5.8 5.5 7.7	3.47 ± 0.63	Basal flow on Mount Trumbull, Arizona
	PED-42-66[2]	Basalt	36°23'52"	113°09'16"	0.943, 0.941	4.68 5.06 5.02	42.2 44.5 44.7	3.67 ± 0.09	Basal flow on Mount Trumbull, Arizona
7.	PED-53-66	Basalt	37°10'32"	113°16'49"	1.02, 1.01, 1.00, 1.00	0.55 0.29	11.3 5.3	0.289 ± 0.086	Unit Qb
	PED-53-66[2]	Basalt	37°10'32"	113°16'49"	1.04, 1.06, 1.05, 1.05	0.52 0.50 0.36 0.45	12.7 12.1 9.8 12.6	0.303 ± 0.30	Unit Qb
8.	cal-1	Basalt	37°21'43"	114°32'40"	20.57[4](0.68)	10.44	23.2	12.6 ± 0.08	Basal flow; unit Tb, Nevada
9.	cal-2	Basalt	37°11'36"	114°44'31"	1.75	30.66	39.5	12.1 ± 0.4	Unit Tb, Nevada
10.	cal-3	Basalt	37°11'00"	114°46'05"	2.11	41.42	59.1	13.6 ± 0.2	Unit Unit Nevada
11.	esc-1	Basalt	38°13'02"	112°50'08"	1.70	18.60	33.1	7.6 ± 0.3	Unit T_2bf
12.	esc-5	Andesite	37°31'12"	113°42'39"	2.84	2.117	11.6	0.5 ± 0.1	Unit Qb
13.	esc-6	Basalt	37°33'56"	113°48'03"	1.25	13.97	45.4	7.7 ± 0.2	Old high-level remnant; Unit Qb
14.	esc-7	Basalt	37°45'32"	113°53'34"	1.56	24.27	35.0	10.8 ± 0.6	Old high-level remnant; Unit Qb
15.	esc-9	Andesite	38°05'45"	113°14'42"	3.08	44.84	39.6	10.1 ± 0.2	Unit T_2bf
16.	esc-4	Basalt	38°07'41"	112°44'39"	1.94	18.01	20.0	6.4 ± 0.3	Unit T_2bf
17.	SG-65	Hawaiite	37°18"	113°32'	1.65	2.949	19.4	1.2 ± 0.1	At base of Pine Valley Mountains; Unit Qb
18.	SG-67	Basalt	37°21'45"	113°38'52"	1.50	3.309	9.4	1.5 ± 0.2	Unit Qb
19.	SG-70	Basalt	37°16'48"	113°45'35°	[2]1.48 (1.46)	2.247	20.7	1.1 ± 0.1	Unit Qb
20.	SG-74	Basalt	37°22'42"	113°13'38"	1.48	2.209	13.9	1.0 ± 0.1	Center flow in thick sequence on top of Hurricane Cliffs; Unit Qb
21.	SG-78	Basalt	37°06'54"	113°35'06"	1.67	5.581	26.7	2.3 ± 0.1	Old stage II flow; unit Qb
22.	SG-79	Hawaiite	37°07'09"	113°33'06"	1.29	2.781	28.2	1.5 ± 0.1	Middleton flow; Unit Qb
23.	SG-80	Ankaramite	37°08'55"	113°27'49"	0.74	1.795	32.3	1.7 ± 0.1	Washington flow; Unit Qb
24.	Zion-1A	Basalt	37°23'04"	113°01'37"	[2]0.71(1.68)	1.677	5.3	1.6 ± 0.4	Oldest remnant in Zion Park; Unit Qb
25.	Zion-2	Andesite	37°26'	113°03'	[2]1.82(1.85)	2.959	25.0	1.13 ± 0.05	Unit Qb
26.	Zion-4	Basalt	37°21'20"	113°03'40"	[2]1.04(1.26)	2.103	22.4	1.40 ± 0.08	Unit Qb
27.	Zion-20	Hawaiite	37°15'23"	113°07'54"	[2]2.21(2.41)	0.8381	5.5	0.26 ± 0.09	Unit Qb
28.	Zion-21	Hawaiite	37°23'41"	113°33'34"	1.79	1.437	13.4	0.56 ± 0.06	Unit Qb
29.	Zion-51	Hawaiite	37°26'14"	112°52'49"	1.42	1.557	16.8	0.81 ± 0.05	Unit Qb
30.	Zion-57	Basalt	37°24'00"	112°55'49"	0.96	0.4964	6.6	0.36 ± 0.08	Unit Qb
31.	Zion-58	Basalt	37°26'55"	112°59'24"	1.41	2.436	2.9	1.2 ± 0.6	Unit Qb
32.	Zion-63	Hawaiite	37°34'03"	112°56'14"	1.25	1.570	22.8	0.87 ± 0.04	Unit Qb
33.	Zion-64	Basalt	37°22'	112°19'	1.03	1.583	7.8	1.1 ± 0.1	Unit Qb
34.	Zion-65	Hawaiite	37°12'58"	113°09'01"	1.70	2.458	15.0	1.0 ± 0.1	Unit Qb
35.	Zion-70	K-rich mafic lava	38°15'57"	112°34'52"	[2]3.91 (3.90)	131.56	72.0	23.2 ± 0.2	High-level remnant east of Beaver, Utah Unit Tsr
36.	pan-5	Hawaiite	37°33'09"	112°32'53"	1.96	1.468	12.6	0.52 ± 0.05	Unit Qb
37.	pan-26	K-rich mafic lava	38°15'10"	112°12'39"	3.30	116.19	77.7	21.1 ± 0.2	Northeast of Junction, Utah, Unit T_2bf
38.	pan-27	Basalt	38°09'28"	112°00'00"	1.96	14.03	21.6	5.0 ± 0.3	Antimony flow, Unit T_2bf
39.	pan-28	Andesite	37°44'41"	112°20'00"	2.18	1.768	10.7	0.56 ± 0.07	Red Canyon flow, Unit Qb
40.	hpl-3	K-rich mafic lava	38°30'13"	111°45'51"	4.10	145.2	48.9	24.5 ± 0.5	South of Fish Lake, Utah; Unit T_2bf
41.	hpl-4	Basalt	38°10'00"	111°53'10"	1.57	14.61	26.1	6.5 ± 0.3	Parker Mountain, Unit T_2bf

Whole-rock K-Ar ages

	Sample	Rock type	Latitude (N.)	Longitude (W.)	K_2O (wt%)	$^{40}Ar^*$ (10^{-12} mol g^{-1})	$^{40}Ar^*$ (% total)	Calculated[1] date (10^6yr)	Remarks
42.	hpl-5	Basalt	38°08'22"	111°56'29"	1.97	15.37	15.0	5.4 ± 0.4	Unit Tvu
43.	hpl-6	Basalt	38°19'13"	112°09'40"	2.52	46.25	45.9	12.7 ± 0.3	Sample collected near locality of Damon's (1969) sample dated at 12.6 m.y.; Unit T_2bf
44.	hpl-11	Hawaiite	38°32'17°	112°25'34"	2.54	33.62	23.2	9.2 ± 0.4	Younger flow within the Sevier River Formation; slightly altered; Unit Tsr
45.	hpl-12	Hawaiite	38°32'43"	112°25'34"	2.46	26.23	10.3	7.4 ± 0.7	Older flow within the Sevier River Formation; slightly altered; Unit Tsr
46.	cvf-182	Andesite	38°32'25"	112°41'25"	[2]3.01	1.172	3.0	0.3 ± 0.1	Younger flow in Cove Fort field; Unit Qb
47.	cvf-500	Basalt	38°22'18"	112°42'13"	1.72	2.631	4.0	1.1 ± 0.3	Unit Qb
48.	cvf-501	Basalt	38°26'21"	112°44'11"	[2]1.55	2.136	3.6	1.0 ± 0.3	Unit Qb
49.	cvf-503	Basalt	38°37'33"	112°40'18"	2.25	1.549	6.6	0.5 ± 0.1	Shield volcano; Unit Qb
50.	cvf-504	Basalt	38°44'13"	112°39'13"	0.64	2.295	6.8	2.5 ± 0.4	Old flow at south edge of Black Rock Desert; Unit Qb
51.	wah-65	Hawaiite	38°18'53"	113°26'22"	2.83	54.22	49.2	13.3 ± 0.3	East flank Wah Wah Mountains; shown as Tertiary undifferentiated volcanic rocks on stage geologic map.
52.	wah-66	K-rich mafic lava	38°22'25"	113°29'57"	3.32	111.78	23.4	23.2 ± 1.0	Unit Tvu
53.	brd-2	Basalt	39°13'48"	112°44'56"	0.85	0.4902	0.7	0.4 ± 0.4	Deseret flow; Unit Qb
54.	brd-3	Basalt	39°05'51"	112°36'35"	[2]1.08	0.2793	0.8	0.18 ± 0.18	Old Pavant flow[5]; Unit T_2bf
55.	brd-108	Basalt	39°01'46"	112°29'47"	[2]1.00	0.2258	1.0	0.16 ± 0.16	Old Pavant flow[5]; Unit T_2bf
56.	5-1	K-rich mafic lava	39°30'	113°03'	3.20			[7]37.3 ± 0.4	Little Drum Mountains
57.	B-12	Basalt	38°53'	112°37'				[6]0.9 ± 0.1	Old Beaver Ridge flow; Unit T_2bf
58.	B-04	Basalt	38°50'	112°37'				[6]0.5 ± 0.1	Young Beaver Ridge flow; Unit T_2bf
59.	32	Basalt	38°42'57"	112°57'25"				1.0 ± 0.3	C. E. Hedge, personal commun. to Condie and Barsky (1972); Unit T_2bf
60.	2031	Andesite	37°15'50"	114°27'40"	1.44			8.5 ± 0.3	Armstrong (1970); Nevada; Unit Tb
61.	C1445-6	Basalt	37°24'	113°44'				[3]12.3 ± 0.6	Below Ox Valley Tuff in Bull Valley district; Unit Qb
62.	C1445-8	Basalt	37°24'	113°44'	1.79			[3]7.9 ± 0.4[3]	Above Ox Valley Tuff; Unit Qb
63.	D2251-3	Basalt	39°40'11"	112°46'43"	1.24			[3]5.3 ± 0.4[3]	Old Fumarole Butte flow; Unit Qb
64	D2252-4C	Andesite	39°34'32"	112°46'02"	2.28			[3]1.0 ± 0.1[3]	Young Fumarole Butte flow; Unit Qb
65.	C342-5A	Basalt	37°53'	112°59'15"				[3]1.3 ± 0.4[3]	Enoch flow; Unit Qb
66.	CSV-76-14	Basalt	39°14'	112°45'	1.23	11.05	27.6	[4]6.0 ± 0.3[4]	Old Fumarole Butte flow; Unit Qb
67.	Sk-66	Basalt	39°24'	112°52'	0.88	0.384	2.7	[4]0.3 ± 0.1[4]	Young Smelter Knoll flow; shown as young Tertiary rhyolite flow unit on state geologic map
68.	Sk-72	Andesite	39°28'	112°51'	2.40	21.13	14.3	[4]6.1 ± 0.5[4]	Old Smelter Knoll flow; Unit T_2bf

[1] $\lambda_\epsilon + \lambda_\epsilon = 0.581 \times 10^{-10}$ yr^{-1}; $\lambda_\beta = 4.962 \times 10^{-10}$ yr^{-1}; $^{40}K/K = 1.167 \times 10^{-4}$ mol/mol; [2] treated sample; K_2O content of untreated material shown in parentheses; [3] R. E. Anderson (written commun., 1977); [4] W. P. Nash and F. H. Brown (written commun., 1977); [5] J. D. Hoover (1974) gives a statistical maximum age of 0.13 m.y.; [6] J. D. Hoover (1974); [7] S. H. Leedom (1974).

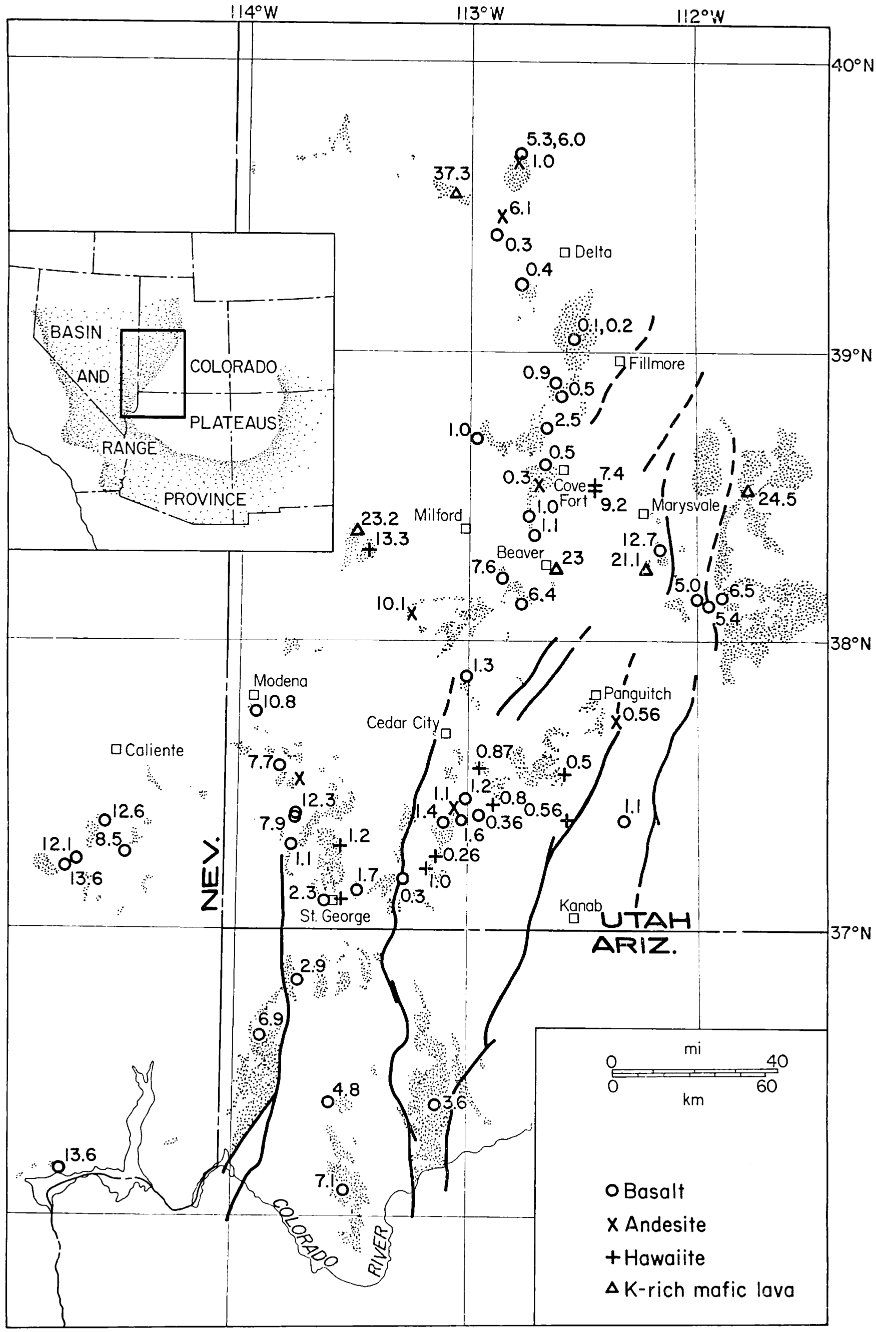

Fig. 1. Mafic lava flows, K-Ar ages, and major high angle block faults along boundary between western Colorado Plateaus and eastern Basin and Range Province. Flows are stippled. Ages are from table 1, rock classification is from figure 2. Flows in Nevada are identified as Tertiary basalt flows on state geologic map (Stewart and Carlson, 1974) and in Utah are mostly mapped as late Tertiary basalt and basaltic andesite flows and Quaternary basalt on the state geologic map (Hintze, 1963). Faults and flows in Arizona are from Hamblin (1970). Several additional ages on basalts in the range 15 to 2 m.y. in the southwest corner of this map area are given in Anderson and others (1972).

COMPOSITION OF LATE CENOZOIC LAVA FLOWS

During 1970 to 1978 more than 300 chemical analyses were performed on late Cenozoic lava flows from the west margin of the Colorado Plateaus and the eastern Basin and Range Province. Most of these analyses have been presented as plots of total alkali versus silica contents (Best and Hamblin, 1979); In this report we use the volcanic rock classification of Irvine and Baragar (1971).

The lava flows comprise a compositional spectrum broad enough to shake the prejudices of those who wish to relate specific rock suites to particular plate-tectonic settings. Figure 2 (see fig. 14-8 of Best and Hamblin, 1978) shows that the mafic flows are transitional in most respects

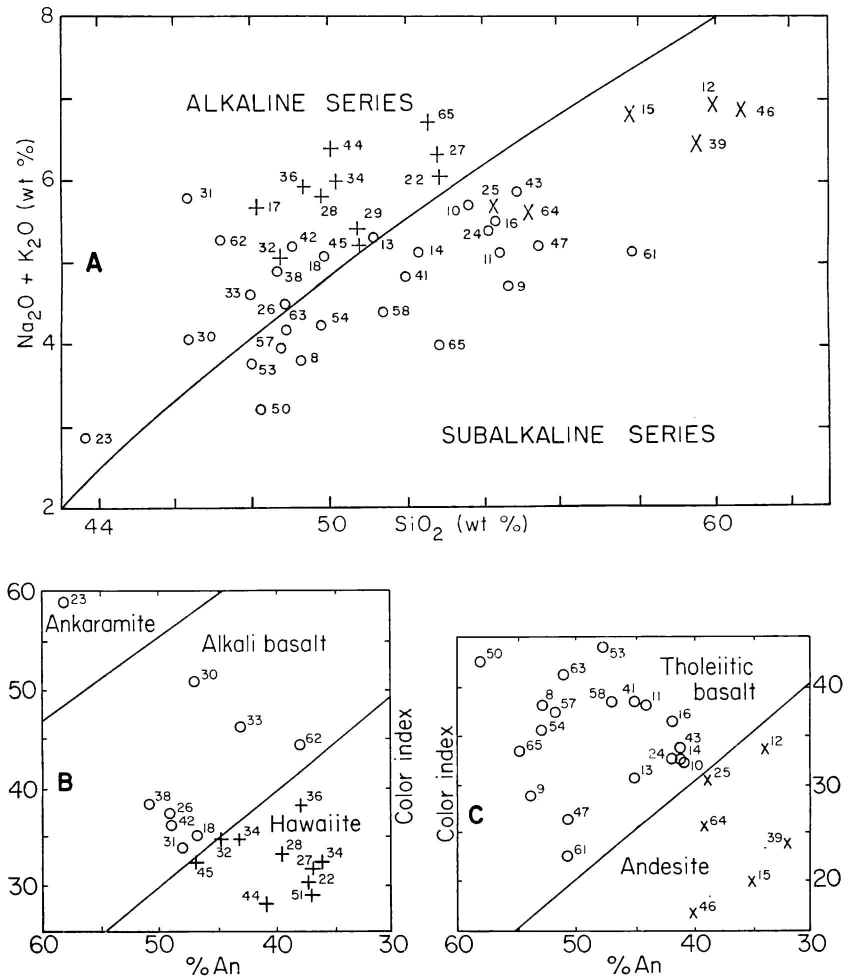

Fig. 2. Normative classification of dated mafic lava flows listed in table 1, according to scheme of Irvine and Baragar (1971). (A) All flows; (B) alkaline series flows; (C) subalkaline series flows.

and straddle the conventional demarcation between alkaline and subalkaline suites, and that most alkaline compositions form a continuum from alkali olivine basalt to hawaiite. Most subalkaline mafic flows, however, consist of tholeiitic basalt; lava flows on the Colorado Plateaus tend to be alkaline or marginally subalkaline, whereas lava flows in the Basin and Range Province are subalkaline or marginally alkaline (Best and Hamblin, 1978).

Surprisingly, most flows less than 1 m.y. old in the Cove Fort, Utah, field (fig. 2), which were clearly extruded during extensional-block faulting, show definite calc-alkaline affinities (Clark, 1977). Similarly, Kasten and others (1976) found calc-alkaline rocks of late Cenozoic age in the Rio Grande rift. These occurrences call for caution in making rigid correlations between plate-tectonic setting and rock suite.

Older black aphanitic lavas with small olivine phenocrysts contain relatively high concentrations of potassium, titanium, and phosphorus (table 2; compare Callaghan, 1939, and Wender and Nash, 1979). In these rocks K_2O generally exceeds 3 wt percent, and K_2O/N_2O is greater than 1. Although superficially resembling basalt, and so designated by some workers, such rocks should not be called basalt because of their significantly different composition. In the compilation by Manson (1967) of 1516 basalt and diabase analyses, not one sample contained more than 2.7 wt percent K_2O, and in the compilation by LeMaitre (1976) of 3594 basalts, samples had a mean of 1.12 ($\pm$0.38, 2 s.d.) wt percent K_2O. We call these Utah rocks "K-rich mafic lavas." Use of alternate names, for example, shoshonite, might connote specific tectonic correlations that do not necessarily apply to southwestern Utah.

TIME–COMPOSITION–SPACE PATTERNS

Although the volumetric distribution of lava flows with respect to age, composition, and locality has not been determined, we believe the age-composition data available (figs. 1, 2, and table 1) are sufficiently representative to draw some tentative conclusions. We thus assume that each dated flow is of equal weight with every other flow. However, the

TABLE 2

Chemical composition of a representative K-rich mafic lava flow 21 km south of Marysvale, 0.5 km east of Highway 89

Constituent	Weight %
SiO_2	51.9
TiO_2	2.43
Al_2O_3	14.8
Fe_2O_3*	10.55
MnO	0.1
CaO	6.89
MgO	4.6
Na_2O	3.0
K_2O	3.82
P_2O_5	1.51
Total	99.60

* total Fe as Fe_2O_3

large volcanic field east of long 112° W. (Williams and Hackman, 1971) is poorly represented, as is the Arizona area in figure 1.

A histogram of dates (fig. 3) reveals apparently episodic mafic volcanism along the boundary between the western Colorado Plateaus and the eastern Basin and Range Province; each episode shows about a 3-m.y. duration, with peak activity falling near 23, 13, 7, and 1 m.y. ago.

Figure 3 shows no obvious correlation between rock type or suite with respect to age, except that the oldest episode of mafic volcanism 25 to 21 m.y. ago apparently produced only K-rich mafic flows. Other potassic mafic flows in this age range have been documented; Anderson and others (1975) defined a sequence of "older basalt flows" in the Marysvale, Utah, area and tentatively correlated them with a sequence of high-K ($K_2O > 3.2$ wt percent) andesite about 60 km east of Marysvale, described by Smith and others (1963) and Williams and Hackman (1971). Isotopic ages on three samples from the "older basalt flows" unit measured by R. J. Fleck (*in* Anderson and others, 1975) are all about 22 m.y., and the K_2O content is given as 2.4 to 2.8 wt percent.

A general correlation exists between the age of a lava flow and its K_2O content (fig. 4) because older flows tend to be more potassic than younger flows. However, in the last 2 m.y., diverse lava flows with a broad range of K_2O contents from 0.5 to 2.8 wt percent were erupted.

Mafic flows of different age and composition are restricted geographically (fig. 5). K-rich mafic lavas occur only in a small area straddling the boundary between the western Colorado Plateaus and the eastern Basin and Range Province; the other potassic mafic flows described above are found in about the same small area. Around Marysvale, voluminous rhyolite is of about the same age and younger — 21 to 17 m.y. old (fig. 6; Steven and others, 1977). To the west, between Milford, Utah, and the

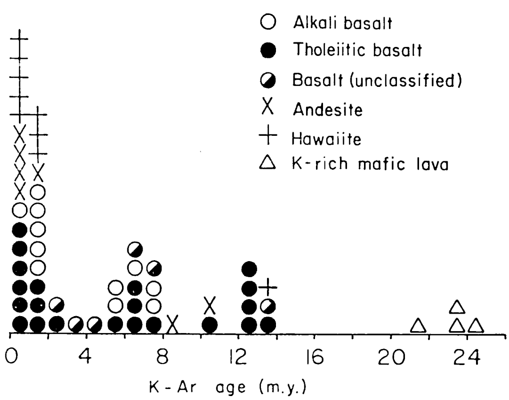

Fig. 3. Dated lava flows plotted according to age and rock type (fig. 2 and table 1). Samples 44 and 45 are not plotted because of alteration and suspected disturbed age. Alkali basalt is denoted by open circles, and tholeiitic basalt by filled circles. Samples 1 to 6 are plotted as half-filled circles, because dated rock has not been chemically analyzed, and type of basalt is uncertain. Samples with age of 1.0 m.y. in table 1 are plotted in 0 to 1.0 m.y. category.

Nevada state line in the southern Wah Wah Mountains and southern Needle Range, 20 to 22 m.y. high-alkali-silica, locally topaz-bearing, rhyolite flows, tuffs and shallow intrusions are widespread, (fig. 6). A 23.2 m.y. age has been obtained on a flow in an extensive sequence of K-rich mafic flows in the southern Wah Wah Mountains.

After a several-million-year hiatus, the next mafic flows were extruded about 14 to 10 m.y. ago in about the same area as the K-rich mafic flows but extending much farther to the southwest into the Basin and Range Province. Rhyolite with ages of 9 to 11 m.y. (fig. 6) occurs southwest of Beaver, Utah near the andesite whose age is 10.1 m.y.

Mafic flows in the 8- to 5-m.y. episode occur all along the boundary zone (fig. 5), where the rhyolite is contemporaneous. A 7.4-m.y.-old ryholite occurs southwest of Beaver, flanked by basalt 7.6 and 6.4 m.y. old. Rhyolite 7 to 5 m.y. old occurs northwest of Delta, Utah, west of 6- to 5-m.y.-old basalt and andesite.

The youngest (0-3 m.y.) episode of mafic volcanism is expressed in three areas (fig. 5): (1) a northern belt along the easternmost margin of the Basin and Range Province, north of lat 38° N.; (2) a belt transverse to the province boundary and more or less coincident with the southern limit of Oligocene and early Miocene arc volcanic rocks; (3) a north-trending belt south of lat 37° N. in the Colorado Plateaus that contains more than 100 youthful cinder cones and many flows less than 1 m.y. old (Hamblin, 1970; Best and Brimhall, 1974). Only the first of these three areas has associated rhyolite of the same age (fig. 6).

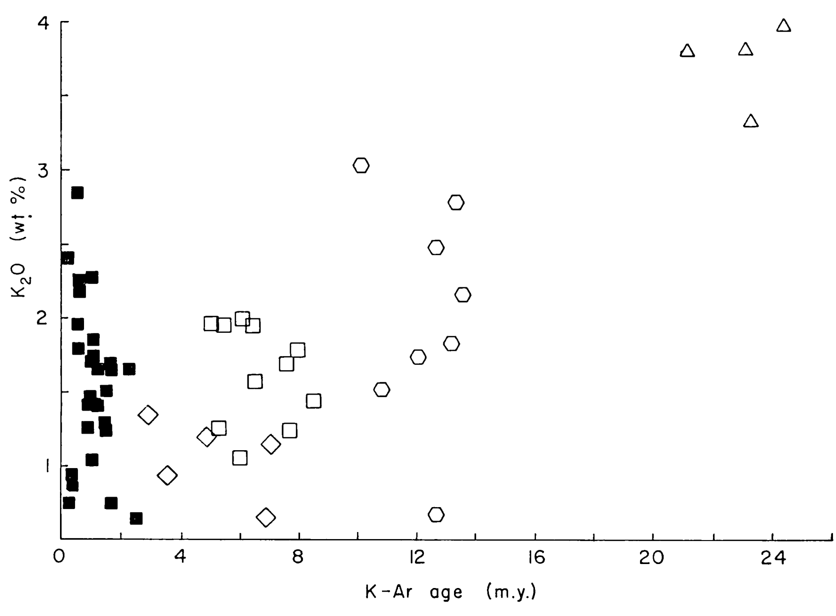

Fig. 4. Plot of K_2O versus age of dated mafic flows from table 1, except for samples 44 and 45. Symbols are coded according to four apparent age episodes; diamonds represent samples from Arizona.

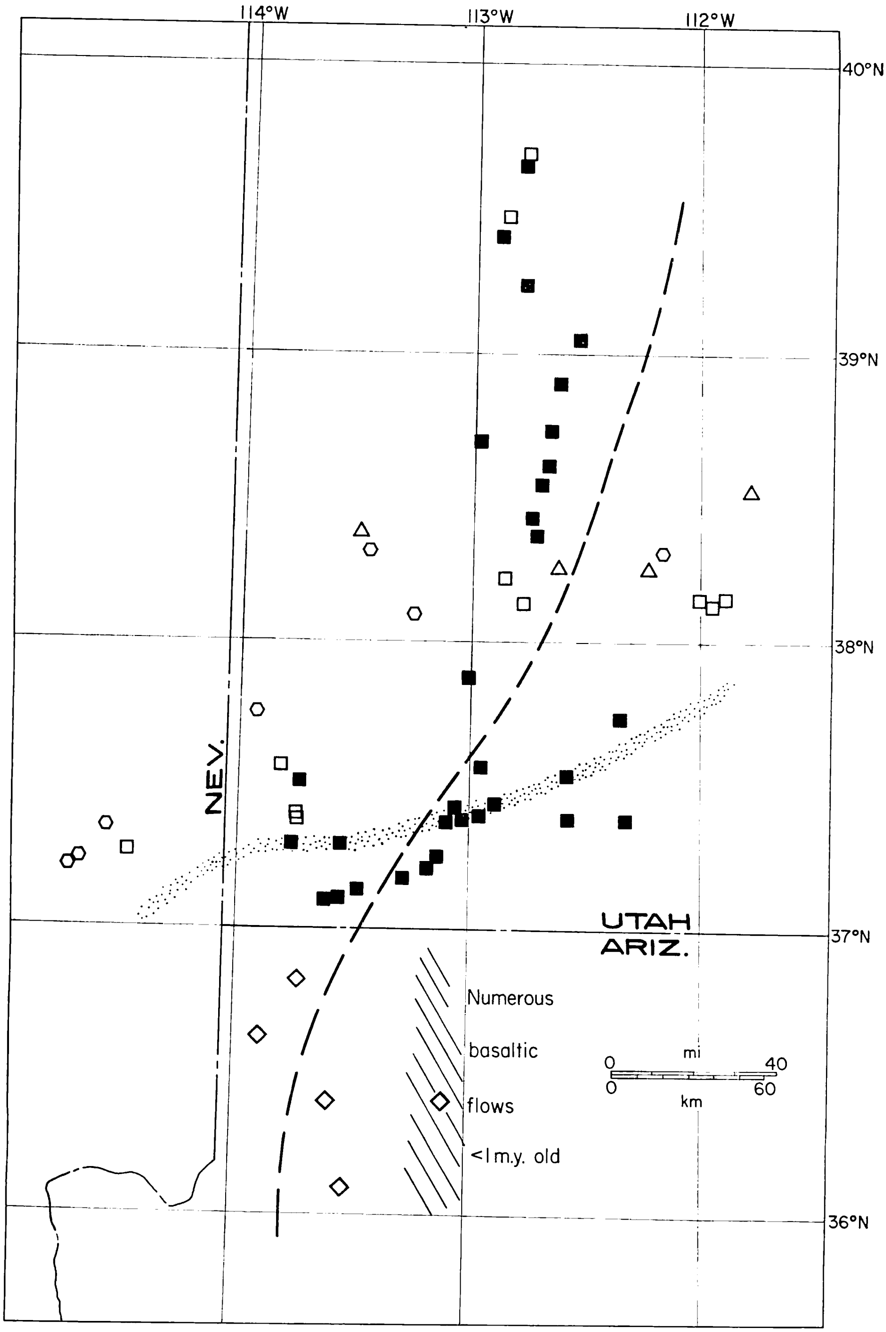

Fig. 5. Geographic distribution of K_2O versus age groups from figure 4. Shaded band indicates southern limit of Oligocene arc volcanic rocks. Dashed line shows approximate boundary between western Colorado Plateaus and Basin Range Province. See figure 1 for additional details.

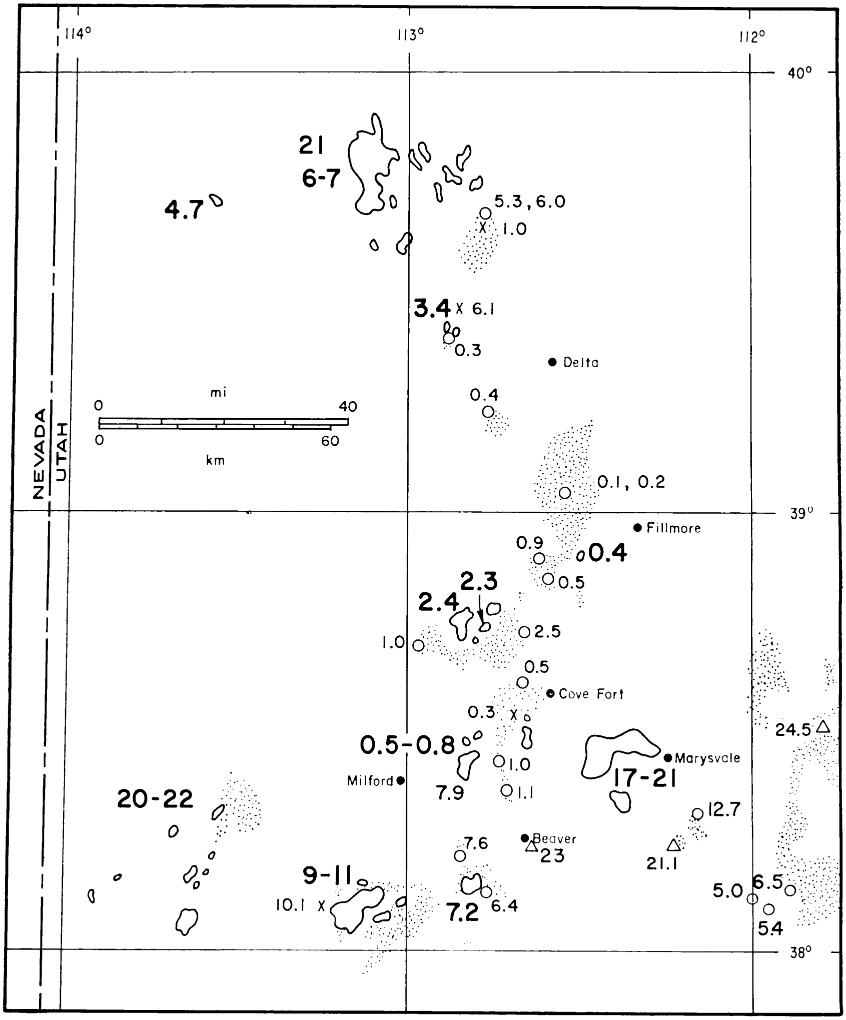

Fig. 6. Distribution and ages of Miocene and younger bimodal rhyolite-basalt (or K-rich mafic flows) associations. Rhyolite areas outlined but unpatterned; ages (m.y.) are in bold-face numbers. Mafic flow fields stippled and ages in smaller numbers (fig. 1). Ages on rhyolite are from Armstrong (1970), Lemmon, Silberman, and Kistler (1973), W. P. Nash and F. H. Brown (written communi., 1977), Steven and others (1977), Lindsey (1978), Lipman and others (1978), Mehnert, Rowley, and Lipman (1978), Rowley, Lipman, and others (1978), and M. G. Best (unpub.). Stippled areas with symbols represent mafic flows and respective ages from figure 1.

DISCUSSION AND CONCLUSIONS

Interpretation of the tectonic significance of late Cenozoic volcanic rocks along the boundary between the western Colorado Plateaus and the eastern Basin and Range Province is relatively clear in northwestern Arizona but hazardous in Utah. All three of the extension-related volcanic fields defined by Christiansen and Lipman (1972) — namely, basalt fields, bimodal basalt-rhyolite fields, and differentiated basaltic and alkalic fields — appear to occur along the boundary.

In the northwest corner of Arizona and perhaps extending to St. George, Utah, are basalt fields composed of hundreds of flows and more than 100 cinder-spatter cones (Best and Brimhall, 1974), all less than 7 m.y. old. Earlier arc volcanic rocks are absent, and the flows rest upon erosional surfaces cut into Paleozoic and Mesozoic strata. In this area the inception of extension-related basaltic volcanism is clear and shows an eastward migration with time that extends more recently into the Colorado Plateaus (Best and Hamblin, 1978).

All three types of extension-related volcanism are found in Utah, but their inception does not seem to have followed any pattern as simple as in Arizona, although the time of inception in any particular area is difficult to define.

One could argue that the K-rich mafic lava flows and associated rhyolites extruded about 22 m.y. ago constitute an extension-related, bimodal basalt-rhyolite partnership. Although we are adamant that the K-rich mafic flows should not be labeled "basalt", this contention in no way invalidates the concept of a bimodal mafic flow-rhyolite association with possible broader geologic implications. Indeed, as the result of 1:24,000 scale mapping by the senior author in the southern Wah Wah Mountains between Milford and the Nevada state line it is clear that this magmatic association is intimately related to widespread northeast-trending horst and graben block-faulting. Some faults show evidence of horizontal (left-lateral?) slip and many influenced local hydrothermal activity. In the southern Needle Range to the west of the Wah Wah Mountains, unpublished mapping by S. K. Grant (oral commun., 1979) reveals northeast-trending faults and rhyolite dikes but little mafic flows. Significantly, this northeast trending activity is oblique to the east-west 20 to 2 m.y. old Blue Ribbon Lineament of Rowley, Lipman, and others (1978) passing through the same area and to the essentially north-south aligned fault blocks characterizing the Basin and Range Province.

The mafic flows extruded during the 14 to 10 m.y. episode are still quite potassic but are here classed as basalt. Rhyolite is locally associated with these flows, so this association may constitute an extension-related, bimodal basalt-rhyolite assemblage in the sense of Christiansen and Lipman (1972).

The last two episodes of mafic volcanism, beginning about 8 m.y. ago, produced diverse compositions, but most basaltic flows contain less than 2 wt precent K_2O. Rhyolite is widespread within the eastern Basin and Range Province. Clearly, bimodal basalt-rhyolite volcanism was well underway by 8 m.y. ago.

Certain age-composition groups of flows seem to be distributed independently of the apparent tectonic boundary between the Colorado Plateaus and the Basin and Range Province. During earlier episodes this boundary may not have been active. However, a large field of flows less than 2 m.y. old trends northeast oblique to the boundary, which must have been active then; the location of this field corresponds more closely to distribution of the earlier arc-volcanic assemblage than to current tectonic provinces. Stewart, Moore, and Zietz (1977) and Rowley, Lipman, and others (1978) have hypothesized that east-trending Cenozoic features in the Basin and Range Province are related to similarly trending warps in the subducting lithospheric plate and to an intracontinental transform fault. Magma-generating processes in the upper mantle somehow activated by this transform about 22 m.y. ago could have tapped regions of metasomatized periodotite enriched in K and other incompatible elements (Best, 1975) which had been developing for some time near the top of the asthenosphere. As large volumes of the resulting K-rich mafic magmas rose into the crust rhyolitic partial melts may have been produced to yield the 22 ± m.y. bimodal association. Long term residence in the crust may also account for the high K-content of the mafic lavas. In the upper crust, the transform activity during this time was presumably manifest as a series of en echelon northeast-trending subvertical faults with lateral (?) and vertical components of displacement.

Mafic lavas extruded 14 to 2 m.y. ago conceivably became less potassic, because mantle-generated magmas were tapping progressively reduced concentrations and volumes of incompatible-element enriched source rock. During this same time east-west extensional tectonism became dominant, producing the present-day Basin and Range Province.

Speculations regarding an intracontinental transform and related magma-generating activity must be rigorously tested by further field investigations coupled to isotopic and trace-element analyses of the igneous rocks. Fundamental problems far beyond the scope of this reconnaissance paper are involved.

Still another fundamental enigma is the reason for the apparent episodic nature of the volcanism along the boundary of the Colorado Plateaus and Basin and Range Province. These episodes are only evident over the entire boundary region and so are not likely to be associated with recurrent phenomena in local magma chambers in the crust or source regions of the upper mantle. A large-scale control is implied. The real scale of episodic magmatic activity is better appreciated by making a comparison with a recent compilation of age-dates by Kennett, McBirney, and Tunnell (1977) for late Cenozoic circum-Pacific volcanism (including the Snake River Plain and Columbia Plateau basalt provinces). The last two episodes, peaking at about 6 and at less than 2 m.y. ago, agree closely with those of the last two episodes along the western boundary of the Colorado Plateaus. However, the 12- to 14-m.y. episode along this boundary clearly postdated the 14- to 17-m.y. period of main basaltic activity in the Columbia Plateau.

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REFERENCES

Anderson, J. J., Rowley, P. D., Fleck, R. J., and Nairn, A. E. M., 1975, Cenozoic geology of southwestern high plateaus of Utah: Geol. Soc. America Spec. Paper 160, 88 p.

Anderson, R. E., 1978, Chemistry of Tertiary volcanic rocks in the Eldorado Mountains, Clark County, Nevada, and comparisons with rocks from some nearby areas: U.S. Geol. Survey Jour. Research, v. 6, p. 409-424.

Anderson, R. E., Longwell, C. R., Armstrong, R. L., and Marvin, R. F., 1972, Significance of K-Ar ages of Tertiary rocks from the Lake Mead region, Nevada-Arizona: Geol. Soc. America Bull., v. 83, p. 273-288.

Armstrong, R. L., 1970, Geochronology of Tertiary igneous rocks, eastern Basin and Range province, western Utah, eastern Nevada, and vicinity, U.S.A.: Geochim. et Cosmochim. Acta, v. 34, p. 203-232.

Armstrong, R. L., and Higgins, R. E., 1973, K-Ar dating of the beginning of Tertiary volcanism in the Mohave Desert, California: Geol. Soc. America Bull., v. 84, p. 1095-1100.

Best, M. G., 1975, Migration of hydrous fluids in the upper mantle and potassium variation in calc-alkalic rocks: Geology, v. 3, p. 429-432.

Best, M. G., and Brimhall, W. H., 1974, Late Cenozoic alkalic basaltic magmas in the western Colorado Plateaus and the Basin and Range transition zone, U.S.A., and their bearing on mantle dynamics: Geol. Soc. America Bull., v. 85, p. 1677-1690.

Best, M. G., and Hamblin, W. K., 1978, Origin of the northern Basin and Range province: Implications from the geology of its eastern boundary: Geol. Soc. America Mem. 152, p. 313-340.

Callaghan, E., 1939, Volcanic sequence in the Marysvale region in southwest-central Utah: Am. Geophys. Union Trans., v. 20, pt. 3, p. 438-452.

Christiansen, R. L., and Lipman, P. W., 1972, Cenozoic volcanism and plate tectonic evolution of the western United States. II. Late Cenozoic: Royal Soc. London Philos. Trans., ser. A, v. 271, p. 249-284.

Clark, E. E., 1977, Late Cenozoic volcanic and tectonic activity along the eastern margin of the Great Basin, in the proximity of Cove Fort, Utah: Brigham Young Univ. Geology Studies, v. 24, pt. 1, p. 87-114.

Condie, K. C., and Barsky, C. K., 1972, Origin of Quaternary basalts from the Black Rock desert region, Utah: Geol. Soc. America Bull., v. 83, p. 333-352.

Cross, T. A., and Pilger, R. A., 1978, Constraints on absolute motion and plate interaction inferred from Cenozoic igneous activity in the western United States: Am. Jour. Sci., v. 278, p. 865-902.

Damon, P. E., 1966, Correlation and chronology of ore deposits and volcanic rocks: U.S. Atomic Energy Comm. Contract At (11-1)-689, Ann. Prog. Rept. C00-689-60: Tucson, Arizona Univ. Geochronology Labs, 159 p.

Embree, G. F., 1970, Lateral and vertical variations in a Quaternary basalt flow: Petrography and chemistry of the Gunlock flow, southwestern Utah: Brigham Young Univ. Geology Studies, v. 17, pt. 1, p. 67-115.

Hamblin, W. K., 1970, Late Cenozoic basalt flows of the western Grand Canyon, *in* Hamblin, W. K. and Best, M. G., eds., Guidebook to the Geology of Utah, No. 23: Salt Lake City, Utah, Utah Geol. Soc., p. 21-38.

Hausel, W. D., and Nash, W. P., 1977, Petrology of Tertiary and Quaternary volcanic rocks, Washington County, southwestern Utah: Geol. Soc. America Bull., v. 88, p. 1831-1842.

Hintze, L. F. (compiler), 1963, Geologic map of southwestern Utah: Salt Lake City, Utah Geol. Min. Survey, scale 1:250,000.

Hogg, N. C., 1972, Shoshonitic lavas in west-central Utah: Brigham Young Univ. Geology Studies, v. 19, pt. 2, p. 133-184.

Hoover, J. D., 1974, Periodic Quaternary volcanism in the Black Rock desert, Utah: Brigham Young Univ. Geology Studies, v. 21, pt. 1, p. 3-72.
Irvine, T. N., and Baragar, W. R. A., 1971, A guide to the chemical classification of the common volcanic rocks: Canadian Jour. Earth Sci., v. 8, p. 523-548.
Kasten, J. A., Bolivar, S. L., Kudo, A. M., and Brookins, D. G., 1976, Calcalkaline andesites within the Rio Grande rift [abs.]: EOS, Am. Geophys. Union Trans., v. 57, p. 1023.
Kennett, J. P., McBirney, A. R., and Thunell, R. C., 1977, Episodes of Cenozoic volcanism in the circum-Pacific region: Jour. Volcan. Geotherm. Research, v. 2, p. 145-163.
Leedom, S. H., 1974, Little Drum mountains, an early Tertiary shoshonitic volcanic center in Millard County, Utah: Brigham Young Univ. Geology Studies, v. 21, pt. 1, p. 73-108.
Leeman, W. P., and Rogers, J. J. W., 1970, Late Cenozoic alkali-olivine basalts of the Basin-Range province, U.S.A.: Contr. Mineralogy Petrology, v. 25, p. 1-24.
Le Maitre, R. W., 1976, The chemical variability of some common igneous rocks: Jour. Petrology, v. 17, p. 589-597.
Lemmon, D. M., Silberman, M. L., and Kistler, R. W., 1973, Some K-Ar ages of extrusive and intrusive rocks of the San Francisco and Wah Wah Mountains, Utah: Utah Geol. Assoc. Pub. 3, p. 23-26.
Lindsey, D. A., 1978, Geology of volcanic rocks and mineral deposits in the southern Thomas Range, Utah: a brief summary: Brigham Young Univ. Geology Studies, v. 25, pt. 1, p. 25-32.
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, with sections by G. A. Izatt and C. W. Naeser and by I. Friedman: U.S. Geol. Survey Jour. Research, v. 6, p. 133-147.
Lowder, G. G., 1973, Late Cenozoic transitional alkali olivine tholeiitic basalt and andesite from the margin of the Great Basin, southwest Utah: Geol. Soc. America Bull., v. 84, p. 2993-3012.
Manson, V., 1967, Geochemistry of basaltic rocks: Major elements, *in* Hess, H. H., and Poldervaart, A., eds., Basalts, the Poldervaart treatise on rocks of basaltic composition: New York, Intersci., p. 215-270.
McKee, E. H., 1971, Tertiary igneous chronology of the Great Basin of western United States—implications for tectonic models: Geol. Soc. America Bull., v. 82, p. 3497-3502.
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. 3-8.
Noble, D. C., 1972, Some observations on the Cenozoic volcano-tectonic evolution of the Great Basin, western United States: Earth Planetary Sci. Letters, v. 17, p. 142-150.
Rowley, P. D., Anderson, J. J., Williams, P. L., and Fleck, R. J., 1978, Age of structural differentiation between the Colorado Plateaus and Basin and Range provinces in southwestern Utah: Geology, v. 6, p. 51-55.
Rowley, P. D., Lipman, P. W., Mehnert, H. H., Lindsey, D. A., and Anderson, J. J., 1978, Blue Ribbon lineament, an east-trending structural zone within the Pioche mineral belt of southwestern Utah and eastern Nevada: U.S. Geol. Survey Jour. Research, v. 6, p. 175-192.
Smith, J. F., Huff, L. C., Hinrichs, E. N., and Luedke, R. G., 1963, Geology of the Capital Reef area, Wayne and Garfield Counties, Utah: U.S. Geol. Survey Prof. Paper 363, 102 p.
Snyder, W. S., Dickinson, W. R., and Silberman, M. L., 1976, Tectonic implications of space-time patterns of Cenozoic magmatism in the western United States: Earth Planetary Sci. Letters, v. 32, p. 91-106.
Steven, T. A., Cunningham, C. G., Naeser, C. W., and Mehnert, H. H., 1977, Revised stratigraphy and radiometric ages of volcanic rocks and mineral deposits in the Marysvale area, west-central Utah: U.S. Geol. Survey Open-File Rep. 77-569, 77 p.
Stewart, J. H., and Carlson, J. E., compilers, 1974, Preliminary geologic map of Nevada: U.S. Geol. Survey Misc. Field Studies Map MF-609, scale 1:1,000,000.
Stewart, J. H., Moore, W. J. and Zietz, I., 1977, East-west patterns of Cenozoic igneous rocks, aeromagnetic anomalies, and mineral deposits, Nevada and Utah: Geol. Soc. America Bull., v. 88, p. 67-77.
Wender, L. E., and Nash, W. P., 1979, Petrology of Oligocene and early Miocene calc-alkalic volcanism in the Marysvale area, Utah: Geol. Soc. America Bull., v. 90, p. 2-3.
Williams, P. L., and Hackman, R. J., 1971, Geology, structure and uranium deposits of the Salina quadrangle, Utah: U.S. Geol. Survey Misc. Geol. Invest. Map I-591, scale 1:250,000.