LA-UR -83-2229

Conf-830882--3

LA-UR--83-2229

DE83 015217

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TITLE: GEOCHEMICAL SIMILARITIES BETWEEN VOLCANIC UNITS AT YUCCA MOUNTAIN AND PAHUTE MESA: EVIDENCE FOR A COMMON MAGMATIC ORIGIN FOR VOLCANIC SEQUENCES THAT FLANK THE TIMBER MOUNTAIN CALDERA

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SUBMITTED TO: 2nd Containment Symposium
2-4 August 1983
Kirtland AFB
Albuquerque, NM

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FORM NO 836 R4
ST NO 2629 5/81

GEOCHEMICAL SIMILARITIES BETWEEN VOLCANIC UNITS AT YUCCA MOUNTAIN AND PAHUTE MESA: EVIDENCE FOR A COMMON MAGMATIC ORIGIN FOR VOLCANIC SEQUENCES THAT FLANK THE TIMBER MOUNTAIN CALDERA

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ABSTRACT

Chemical compositions have been determined for sanidine, plagioclase, biotite, and hornblende phenocrysts by electron microprobe for a comprehensive set of samples of Crater Flat Tuff and tuffs of Calico Hills. Most of these samples were obtained from drill holes at Yucca Mountain. Samples of tuffs and lavas of Area 20, obtained from locations at Pahute Mesa, have similarly been subjected to microprobe analysis. Complete modal petrography has been determined for all samples.

Biotite and hornblende in the samples from both Yucca Mountain and Pahute Mesa have Fe-rich compositions that contrast strikingly with Fe-poor compositions in the overlying Paintbrush Tuff and the underlying Lithic Ridge Tuff at Yucca Mountain. Each unit from Yucca Mountain has distinctive compositions for both sanidine and plagioclase that very closely match compositions for a corresponding unit identified within the lower, middle and upper portions of the Area 20 tuffs and lavas from Pahute Mesa. Each of these paired units probably originated from a common parental magma and was erupted contemporaneously or nearly so.

Each pair of units with matching phenocryst chemistries has a similar, but not identical set of petrographic characteristics. The petrographic differences, as well as small differences in phenocryst chemistry, result from a zonal distribution of phenocrysts within the parent magma chamber and eruption through earlier units that differ markedly between Yucca Mountain and Pahute Mesa.

INTRODUCTION

During the past two years, intensive research into the geochemistry of the volcanic rocks of Pahute Mesa has been pursued at Los Alamos. The purpose of this research has been to establish the usefulness of major, minor, and trace element geochemistry (determined mostly by neutron activation analysis, or NAA) and mineral chemistry (determined by electron microprobe) in establishing stratigraphic correlations among units in Pahute Mesa drill holes. This geochemical approach has been highly successful and allows the definition of units based on chemistry and petrography rather than lithology; units so defined are termed "Petrologic Units." A single Petrologic Unit may include several lithologic units, as seen in Table 1. For example, the Pyroxene-bearing Rhyolite of the Scrugham Peak Quadrangle (Petrologic Unit symbol TRPP)

Table 1. Nomenclature and symbols for Petrologic Units discussed in this report. (Units within each area listed in stratigraphic succession, youngest unit at the top. Complete stratigraphic sequence not given.)

Area	Petrologic Unit Symbol	Lithologic Unit Symbol[a]	Subunit	Volcanic Unit	Volcanic Group
	TMRu	Tmr	quartz latite	Rainier Mesa Member	Timber Mountain Tuff
	TMRl	Tmr	rhyolite		
	TPCu	Tpc	quartz latite	Tiva Canyon Member	Paintbrush Tuff
	TRPP	Trpp, Tp(Tb), Tpl		Pyroxene-bearing rhyolite of Scrugham Peak Quadrangle	
Pahute Mesa and vicinity	TRA(ul)	Trau, Trab	mafic-poor	upper	Tuffs and lavas of Area 20
	TRA(u2)	Tral,[b] Trab	mafic-rich	upper	
	TRA(p)	Tral,[c] Trab		plagioclase-rich	
	TRA(m)	Trab		middle	
	TRA(lr)	Trat		lithic-rich	
	TRA(sw)	Tsw		Stockade Wash Tuff	
	TCT	Tp(Tb)		Tram Member	Crater Flat Tuff
Yucca Mountain and vicinity	TH1	Tht, Thl	mafic-poor	tuffs and lavas of Calico Hills	
	TH2	Tht, Thl	mafic-rich		
	TCP	Tcp		Prow Pass Member	Crater Flat Tuff
	[illegible]	Tcb		Bullfrog Member	
	TCT	Tct		Tram Member	
	TLR	Tlr		Lithic Ridge Tuff	
	TTA	Tta		Unit A, USW-G1	
	TTB	Ttb		Unit B, USW-G1	
	TTC	Ttc		Unit C, USW-G1	

[a] Present common usage for NTS volcanic units.
[b] Upper part of lower lavas (Figure 5 in Byers et al., 1976a).
[c] Lower part of lower lavas (Figure 5 in Byers et al., 1976a).

includes the Pyroxene-bearing Lava of the Scrugham Peak Quadrangle (Lithologic Unit symbol Trpp), bedded tuff that underlies the Trpp unit, and the local ash-flow tuff of the Paintbrush Tuff (Tpl Lithologic Unit). All three of these lithologic units have identical mineral compositions and very similar (although not identical) phenocryst contents that contrast strikingly with those of bordering units. Symbols for Petrologic Units (Table 1) are utilized extensively throughout this paper. These symbols are fully capitalized and therefore distinct from symbols for lithologic units, which have only the first letter capitalized (compare symbols in Table 1).

The Petrologic Unit has been particularly successful in the recognition and identification of correlatable horizons within bedded tuffs and lavas beneath Pahute Mesa. Such lithologies generally show poor correlations between drill holes (if correlation is attempted at all), due to intertonguing of lavas with bedded tuffs and to misidentifications which often result due to a lack of distinctive hand-sample characteristics among bedded tuffs and lavas. However, early results indicate that Petrologic Units do not show significant thickness variations where such lithologies interfinger. For example, the TRA(ul) Petrologic Unit in U19aS consists of 229 m of lava and 21 m of bedded tuff but in U19q, only 444 m distant, it consists of 34 m of lava and 213 m of bedded tuff (Warren, in prep.). Although the thicknesses of the individual lithologic components differ strikingly, the TRA(ul) unit is 250 m thick in U19aS and 247 m thick in U19q and the correlation of this Petrologic Unit between these adjacent drill holes is excellent. It is likely that lavas simply represent near-source eruption of magma, and tuffs tend to "fill in" the paleotopography for some distance away from this source.

The purpose of this report is to demonstrate that the Petrologic Unit provides a powerful means to correlate volcanic units by relating units that occur in widely separated areas of the NTS. This correlation could not be achieved using lithologic units, due to striking dissimilarities between lithologies within the volcanic sequences correlated between the two areas. These volcanic sequences are the tuffs and lavas of Area 20 of the Pahute Mesa area and the tuffs and lavas of Calico Hills and the Crater Flat Tuff of Yucca Mountain and vicinity (Byers et al., 1976a; Carr et al., in press; see Figure 1 for locations). In order to establish the correlation of volcanic sequences between these areas, it is necessary to subdivide the tuffs and lavas of Area 20 into members, and to demonstrate the petrographic and chemical equivalence

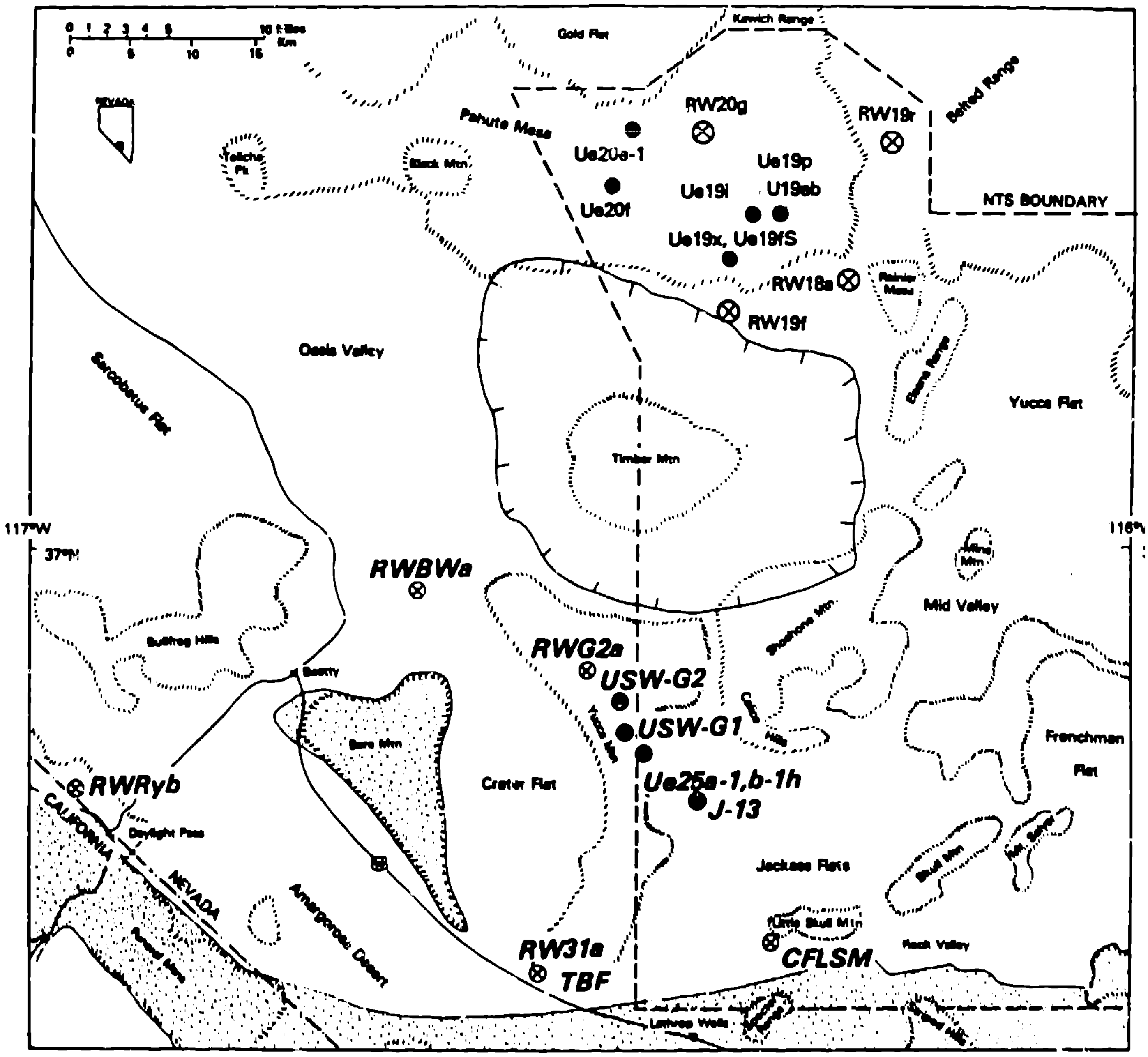

Fig. 1
Location of sample sites. Outcrop locations are open symbols, drill hole locations are closed symbols. Volcanic units of NTS are present throughout region except in stippled areas. Exact locations are given for samples south of Timber Mountain in Warren et al. (in prep.), and for samples of the TRA(u1) unit in Table 2. Locations for samples of other units north of Timber Mountain are Tpb: RW19f; TRA(u2): Ue20f, RW19f; TRA(p): Ue19p, Ue19x; TRA(p)?: Ue20f; TRA(m): Ue19p, U19ab, Ue19fS; TRA(lr): RW19r, Ue19p, U19ab, Ue19i; TRA(sw): RW19r, RW18a; TCT: RW18a. Mineral chemical data are available for all samples from each of these locations (USW-G2 and Ue25b-1h from Broxton et al., 1982), and modal petrographic data are available for all locations (except USW-G2 and Ue25b-1h.)

of tuffs and lavas that comprise a single Petrologic Unit. The following section is devoted to these topics.

DESCRIPTION OF PETROLOGIC UNITS OF THE TUFFS AND LAVAS OF AREA 20

The tuffs and lavas of Area 20 (Byers et al., 1976a) are here divided into four major Petrologic Units, termed the upper, plagioclase-rich, middle, and lower members (Table I). The upper member is further subdivided into an upper, mafic-poor portion [symbol TRA(u1)] and a lower, mafic-rich portion [symbol TRA(u2)]. The lower member includes highly lithic-rich tuff [symbol TRA(lr)] and the Stockade Wash Tuff [TRA(sw)]. An additional Petrologic Unit related to the tuffs and lavas of Area 20 is present beneath the Stockade Wash Tuff at Rattlesnake Ridge (see Fig. 1 for location), southeast of Pahute Mesa. On the basis of a single sample, this unit (symbol TCT) is correlated with the Tram Member of the Crater Flat Tuff (Tct).

Each Petrologic Unit is defined on the basis of well-defined range in certain petrographic and mineral chemical parameters; the most useful and reliable of these is the sanidine composition. Other silicic- to intermediate-composition lavas also occur within the TRA sequence; preliminary study indicates that they are associated with the uppermost portions of the TRA(p) and/or TRA(lr) units. These lavas include the olivine latite of Kawich Valley (Sargent et al., 1966), andesites of U19e and U19g, and a lava misidentified as the pre-Pah lava in U19aj. These lavas are not treated in this report.

Below, summary tables of petrographic and mineral compositional data are given for individual samples of the TRA(u1) unit to illustrate their ranges within a Petrologic Unit (Tables 2-5), but only combined data for all samples of other Petrologic Units are presented. Tables 6-11 include data for each Petrologic Unit of the tuffs and lavas of Area 20, as well as its correlative unit from Yucca Mountain. In each of these tables, data for Petrologic Units appear in groups; the Petrologic Unit at the bottom of each group is found at Yucca Mountain and all those above it are correlative units found at Pahute Mesa and vicinity. Petrologic Units increase in age towards the bottom of each table. For comparison, Table 11 also contains data for units both younger and older than the tuffs and lavas of Area 20.

TRA(ul) Petrologic Unit

The upper, mafic-poor member of the tuffs and lavas of Area 20 consists of ash-flow tuff, bedded tuff, and lava. The TRA(ul) unit is present in most drill holes in Pahute Mesa (where penetrated), and attains a thickness exceeding 1000 m in Ue20h. Petrographic results are given for twelve samples of this unit in Table 2, including (in sequence) three samples of lava, eight samples of bedded tuff, and a single sample of ash-flow tuff. For comparison, results for a single sample of the tuff of Blacktop Buttes (Tpb unit) is also presented at the bottom of Table 2. This unit is positioned stratigraphically within the Paintbrush Tuff by Byers et al. (1976a), but has petrographic and chemical characteristics identical to those of the TRA(ul) unit, and strikingly different from those of other Paintbrush Tuffs. Field work is in progess by Byers and Warren to investigate the possibility that the presently accepted stratigraphic position of the Tpb unit is incorrect.

All samples of the TRA(ul) unit show a consistently low phenocryst content, ranging from 1.4 to 4.5%, and consistently high proportion of quartz phenocrysts. They also have a strikingly low content of mafic minerals, iron-titanium oxides, and accessory minerals. Biotite is the only mafic mineral present in most samples. Ilmenite, sphene, and perrierite (all abundant in most units of the Paintbrush Tuff and many other volcanic units of the NTS) were not found in any of these samples, but allanite is present in many samples. Except for the presence of appreciable hornblende, pyroxene, and apatite in sample RW19r-7, there are no significant differences among the primary mineral contents of the samples of TRA(ul) unit (Table 2).

Sanidine compositions, represented by their orthoclase (Or, $KAlSi_3O_8$) + celsian (Cn, $BaAl_2Si_2O_8$) molecular percents (mol%) and BaO contents (Table 3) are also very similar for all samples of the TRA(ul) unit. Compared to other units of the NTS, sanidine of the TRA(ul) unit is potassium-rich and barium-poor. There is a slight, but consistent, decrease in the Or+Cn content of sanidine stratigraphically upward at each drill core location, from Or+Cn = 69 in the stratigraphically lowest sample at each location to a value as potassium-poor as Or+Cn = 65 in Ue20e-1. The sanidine compositions near the base of the TRA(ul) unit match those of the underlying TRA(u2) unit, and those near the top match those at the base of the overlying Topopah Spring Member of the Paintbrush Tuff (Warren et al., in prep.; Caporuscio et al., 1982).

Table 2. Summary of petrography for individual samples of TRA(ul) unit and Tpb unit.
(ppmV = parts per million by volume. See below for explanation of symbols.)

Sample no.	Litho-logic unit	Sample type	Rock type	Alter-ation	RESULTS OF POINT COUNT: Thin section area (mm^2)	Points counted	Major components, %: Voids	Pumice	Lithics	Felsic Pheno-crysts	Relative % felsics: Q	K	P
RW20g-3	Trau	o	l	Gl,Sp	724	595	3.4		0.0	1.9	18*	34*	48*
Ue20e-1-1715	Trau	c	l	Gl	617	457	22		0.0	1.5	44*	39*	17*
-3525	Trau	c	l	Sp,Zc	533	528	4.0		0.0	4.5	46	42	12
RW19r-7	Trab	o	b	Gl,mZc	348	435	17		3.4	4.1	42*	42*	16*
RW20g-5	Trab	o	b	Gl	724	595	12	12	3.9	1.4	63*	23*	14*
Ue19p-1600	Trab	c	b	Gl	753	559	5.2	28	11	2.3	52*	37*	11*
-1652	Trab	c	b	Gl	723	535	11	40	7.7	2.1	46*	44*	10*
Ue19x-2301	Trab	c	b	Zc	640	475	2.5		0.4	2.5	51*	43*	6*
-2474	Trab		b	Zc	626	515	2.3		14	2.2	33*	47*	20*
U19ab-1650-60	Trab	da	b	Gl	153	378	2.6	22	13	2.1	39*	33*	28*
-1740-50	Trab	da	b	Zc,Gl	234	580	2.1	23	6.4	3.1	39*	26*	35*
Ue20e-1-3155	Trab	c	nwt	Zc	504	499	2.8		1.2	2.6	28*	29*	43*
RW19f-12	Tpb	o	nwt	Gl	617	508	8.1	25	3.0	2.7	35*	28*	37*

Sample no.	DETERMINED BY SCAN; all values in ppmV — Mafic Phenocrysts: Biot	Hbld	Cpx	Opx	Ol	Ac	Arf	Fe-Ti oxides: Mt/Hm	Ilm	Accessory minerals: Sph	All	Per	Ap	Zr	Ot
RW20g-3	86	0	0	0.6	0	0	0	330	0	0	10	0	9	14	
Ue20e-1-1715	1100	0	0	0	0	0	0	360	0	0	0	0	6	16	
-3525	1400	0	0	0	0	2	0	440	0	0	23	0	0	26	
RW19r-7	440	37	210	29	0	0	0	600	0	0	0	0	33	3	
RW20g-5	280	0	0	0	0	0	0	100	0	0	2	0	0.6	0.3	
Ue19p-1600	82	0	0	0	0	0	0	120	0	0	5	0	2	3	
-1652	170	0	0	0	0	0	0	120	0	0	7	0	2	5	
Ue19x-2301	77	0	0	0	0	0	0	93	0	0	0	0	0	3	
-2474	350	0	0	0	0	0	0	140	12[b]	0	0	0	0	5	
U19ab-1650-60	62	0	0	0	0	0	0	32	0	0	0	0	0	0	
-1740-50	110	0	0	0	0	0	0	180	0	0	8	0	2	5	
Ue20e-1-3155	140	0	0	0	0	0	0	84	0	0	27	0	0	0.2	
RW19f-12	410	71	0	7	0	0	0	280	0	0	92	0	9	7	

[a] Monazite 2 ppmV
[b] Pseudobrookite

Explanation of symbols:

Lithologic unit: Trau = upper rhyolite lava of Area 20; Trab = bedded and ash-flow tuffs of Area 20; Tpb = Tuff of Blacktop Buttes

Sample type: c = drill core; da = cuttings that are representative of lithology; o = outcrop (Nevada State coordinates, in meters: RW20g-3 285195N, 175750E; RW20g-5 286161N, 176010E; RW19r-7 286067N, 189982E; RW19f-12 268818N, 179649E). Numbers for core and cuttings indicate sample depth, in feet.

Rock type: l = lava, b = bedded tuff, nwt = non-welded ash-flow tuff

Alteration: Gl = glassy (vitric), Sp = spherulitic, Zc = zeolitic (clinoptilolite). Modifier "m" indicates "minor."

Minerals: Q = quartz; K = sanidine; P = plagioclase; Biot = biotite; Hbld = hornblende; Cpx = clinopyroxene; Opx = orthopyroxene; Ol = olivine; Ac = acmite; Arf = arfvedsonite; Mt = titanomagnetite; Hm = hematite; Ilm = ilmenite; Sph = sphene; All = allanite; Per = perrierite; Ap = apatite; Zr = zircon.

Asterisks: indicate that relative proportions of felsic phenocrysts were determined from largest phenocrysts only. These phenocrysts comprise 70-100% of the felsic phenocrysts in these samples.

Table 3. Frequency distribution of Or+Cn and BaO contents for sanidine phenocrysts in individual samples of TRA(ul) and single sample of Tpb unit (RW19f-12). (Each value represents the number of analyses that have orthoclase+celsian (Or+Cn) end-member contents, and barium oxide weight contents, within the interval indicated. Symbols for rock type defined in Table 2.)

Sample no.	Rock type	Or+Cn, Mol% 72–70	70–68	68–66	66–64	64–62	62–60	60–58	BaO, wt% 0.0–0.3	0.3–0.6	0.6–0.9	0.9–1.2
RW20g-3	1		1	7	1	3	2		12	2		
-5	b	2	10	1					12	1		
RW19r-7	b	4	5		4	1	1		11	2	2	
Ue19p-1600	b		7	7					13	1		
-1652	b		14	1					13	1		1
Ue19x-2301	b		5	9					12	2		
-2474	b	5	9						11	3		
U19ab-1650-60	b		1	13					12	2		
-1740-50	b		13	1					12	2		
Ue20e-1-1715	1			2	12				13			1
-3155	nwt		9	5					12	1	1	
-3525	1		7	2	3	1	1		3	10	1	
RW19f-12	nwt	8	3					3	13	1		

Plagioclase compositions, represented by their anorthite (An, $CaAl_2Si_2O_8$) molecular percents (mol%) (Table 4) also show a well-defined range for all samples of the TRA(ul) unit. Compared to other units of the NTS, plagioclase of the TRA(ul) unit is moderately calcium-rich (particularly for a mafic-poor unit) and has a relatively narrow compositional range. There is a slight, but consistent, decrease in the An content of plagioclase stratigraphically upward at each location that parallels the change in sanidine compositions (in both cases the chemical change can alternatively be regarded as an increase in sodium content stratigraphically upward). Similarly, plagioclase compositions near the base of the TRA(ul) unit match those of the underlying TRA(u2) unit, and those near the top match those within the rhyolitic portion of the overlying Topopah Spring Tuff (Warren et al., in prep.; Broxton et al., 1982).

Biotite compositions, represented by their molecular Mg/(Mg+Fe) contents ("Mg number," Mg*), show a well-defined range for all samples of the TRA(ul) unit (Table 5). Biotite compositions are very similar among all Petrologic

Table 4. Frequency distribution of An contents for plagioclase phenocrysts in individual samples of TRA(ul) and single sample of Tpb unit (RW19f-12). (Each value represents the number of analyses that have anorthite (An) end-member contents within the interval indicated. Symbols for rock type defined in Table 2.)

Sample no.	Rock type	An, Mol% 8–10	10–12	12–14	14–16	16–18	18–20	20–22	22–24	24–26	26–28	28–30	30–32	32–34	34–36	36–38	38–40	40–45	45–50	50–55	55–60
RW20g-3	l					1	4	7	1							1					
-5	b				1	1	2	9	1												
RW19r-7	b			1		2	2	7	1					1							
Ue19p-1600	b					3	10														
-1652	b					1	5	7					1								
Ue19x-2301	b					1	7	4													
-2474	b	1				1	5	2	2	1									1		1
U19ab-1650-60	b					1	6	3	3	1											
-1740-50	b					1	4	8			1										
Ue20e-1-1715	l				1	8	4						1								
-3155	nwt					1	4	6	2	1											
-3525	l							4	8	2											
RW19f-12	nwt				1	1	5	3	3			1									

Units of the tuffs and lavas of Area 20, and are strikingly magnesium-poor (Mg*~0.4) compared to most NTS units.

Petrographic results for the TRA(ul) unit are summarized as median values in Table 6. Mineral compositional data discussed above are combined for all samples of the TRA(ul) unit in Table 7 for sanidine, in Table 8 for plagioclase, in Table 9 for biotite, and in Table 10 for hornblende. Dominant values for the compositional parameters represented in Tables 7-10 are given in Table 11; the dominant value is equivalent to the statistical mode.

TRA(u2) Petrologic Unit

The upper, mafic-rich member of the tuffs and lavas of Area 20 consists of ash-flow tuff, bedded tuff, and lava. The TRA(u2) unit is about 230 m thick in Ue20f but is absent in Ue19p. Samples of the TRA(u2) unit contain the same primary minerals as those of the TRA(ul) unit, except that the

Table 5. Frequency distribution of molecular Mg/(Mg+Fe) contents for biotite phenocrysts in individual samples of TRA(ul) and single sample of Tpb unit (RW19f-12). (Each value represents the number of analyses that have molecular Mg/(Mg+Fe) end-member contents within the interval indicated. Symbols for rock type defined in Table 2.)

Sample no.	Rock type	Mg/(Mg+Fe) .30–.32	.32–.34	.34–.36	.36–.38	.38–.40	.40–.42	.42–.44	.44–.46	.46–.48	.48–.50	.50–.52	.52–.54	.54–.56	.56–.58	.58–.60	.60–.62
RW20g-3	1	2	1	1													
-5	b				1												
RW19r-7	b			4	1		1										
Ue19p-1600	b			2	4												
-1652	b			2	1												1
Ue19x-2301	b			1	4												
-[illegible]474	b	1			4		1										
U19ab-1650-60	b			1	3												
-1740-50	h			1	4												
Ue20e-1-1715	1					5											
-3155	nwt		1	1	2			1									
-3525	1					1	8	1									
RW19f-12	nwt		1	5		1											

concentrations of these minerals are much higher (Table 6). The complete absence of all other mafic minerals despite a high concentration of biotite (up to 3.6% in one sample) is particularly distinctive.

Sanidine (Table 7) and plagioclase (Table 8) compositions of the TRA(u2) unit are very similar to those at the base of the TRA(ul) unit, as previously noted. Biotite of the TRA(u2) unit has a slightly, but significantly higher Mg content than biotite of the TRA(ul) unit. Compared to other NTS units (Table 11), sanidine is highly potassium-rich and moderately barium-rich, and plagioclase is calcium-rich.

TRA(p) Petrologic Unit

The plagioclase-rich member of the tuffs and lavas of Area 20 consists of ash-flow tuff, bedded tuff, and lava. The stratigraphic position of the TRA(p) unit is well established in Ue19p between the TRA(ul) and TRA(m) units,

Table 6. Median values for volume contents of lithic fragments and phenocrysts for Petrologic Units of Pahute Mesa (PM), Yucca Mountain (YM), and Rattlesnake Ridge (RR). (ppmV = parts per million by volume. Symbols for minerals are defined in Table 2. Samples of TRA(sw) unit are from both Ammonia Tanks quadrangle and Quartet Dome quadrangle locations discussed in text.)

Petrologic Unit	Location	Number of Samples	Major components, %: Lithics	Felsic pheno-crysts	Relative % felsics: Q	K	P	Mafic phenocrysts (ppmV): Biot	Hbld	Cpx	Opx	Ol	Ac	Arf	Fe-Ti oxides (ppmV): Mt/Hm	Ilm	Accessory Minerals (ppmV): Sph	All	Per	Ap	Zr
TRA(u1)	PM	12	5.2	2.3	44	39	17	155	0	0	0	0	0	0	130	0	0	4	0	1	4
Tpb	PM	1	3.0	2.7	35	28	37	410	71	0	7	0	0	0	280	0	0	92	0	9	7
Th1	YM	5	2.8	2.4	52	22	27	270	0	0	0	0	0	0	[illegible]25		0	0	0	0.2	4
TRA(u2)	PM	3	0.7	12	35	29	26	6500	0	0	0	0	0	0	1300	0	0	260	0	130	33
Th2	YM	1	3.0	25	32	14	54	3000	0	0	0	0	0	0	1100		0	0	0	17	53
TRA(p)	PM	3	3.7	9.8	16	20	64	3800	2400	0	0	0	0	0	820	0	0	510	0	20	49
TRA(p)?	PM	3	0.0	13	15	25	60	6100	4800	0	0	0	0	0	1500	0	0	280	0	170	100
TRA(m)	PM	5	2.0	4.3	5	67	28	190	170	0	0	0	0	0	480	2	0	0	0	0	12
TCP	YM	22	[illegible]	9.6	13	44	43	250	0	0	[a]	0	0	0	880		0	0	0	8	25
TRA(?r)	PM	10	[illegible]	6.9	28	47	25	560	0	0	0	0	6	0	370	0	0	5	0	2	19
TRA(sw)	RR	2	5.8	5.0	22	50	29	1400	900	15	0	0	9	0.5	410	0	0	40	0	16	11
TCB	YM	35	0.5	12	19	36	45	2900	[a]	0	0	0	0	0	1200		0	0	0	28	34
TCT	RR	1	1.4	12	30	38	32	4000	9	0	0	0	0	0	770	0	0	99	4	77	28
TCT	YM	31	6.3	11	33	33	34	3500	0	0	0	0	0	0	1000		0	0	0	52	25

[a] Present as pseudomorphic forms in most samples.

Table 7. Frequency distribution of Or+Cn and BaO contents for sanidine phenocrysts in samples of Petrologic Units from Pahute Mesa, Yucca Mountain, and Rattlesnake Ridge. (Each value represents the number of analyses that have orthoclase+celsian (Or+Cn) end-member contents, and barium oxide weight contents, within the interval indicated. Results combined for all samples of each unit. Data for Yucca Mountain from Warren et al., in prep.)

Petrologic Unit	Location	Number of Samples	Or+Cn, Mol%																										BaO, wt%							
							70					60					50					40					30		0		0.6		1.2		1.8	2.4
TRA(m1)	PM	12				11	21	48	20	5	4																		136	27	4	2				
Tpb	PM	1				9	3					3																	13	1						
TM1	YM	10				6	38	25								3	1	5											67	11						
TRA(m2)	PM	3			1	13	22	2				1						1				1		1	1				6	17	11	6	2	1		
TM2	YM	6	1	3	18	17	22																						36	4	2	9	6	4		
TRA(p)	PM	3							9	9	6	3	7	3	2						1	1	2						20	[illegible]	[illegible]	5		1		
TRA(p)?	PM	3							2	11	10	10	3		2						3	1				1			26	9	[illegible]					
TRA(m)	PM	5					1			1	2		3	14	34	16	7						1	1					70	8			1	1		
TCP	YM	20										1	1	21	74	23	3	3	1	1								1	118	10	1					
TRA(lr)	PM	10						1	5	35	22	13	5	5				1	3		14	11	7	1	3	2			98	25	7	1	1	1	1	
TRA(sw)	RR	2								13	16													1					15	13	2					
TCB	YM	26							2	59	185	37	9	3	2		1	1		1	1			1					45	129	98	26	3	1		
TCT	RR	1					12	4																					7	3	5	1				
TCT	YM	25		1	1	3	38	157	43	8	5	1	1			1													72	69	66	33	14	3		2

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but its position with respect to the TRA(u2) unit is uncertain. A 500-m-thick unit in Ue20f has been identified as the TRA(p)? unit (see Tables 7-11); this unit directly underlies the TRA(u2) unit. Samples of the TRA(p) unit characteristically have consistently high plagioclase contents, and most contain abundant hornblende in addition to biotite (see Table 6).

Sanidine (Table 7) and plagioclase (Table 8) compositions of the TRA(p) unit are significantly more sodium-rich than those of the TRA(u2) unit, and sanidine is considerably more potassium-rich than sanidine of the underlying TRA(m) unit. However, a sample of the TRA(p) unit cannot be confidently distinguished from one of the TRA(lr) unit on the basis of mineral chemistry (compare units in Tables 7-10). Furthermore, some individual samples of the TRA(lr) unit that have relatively high plagioclase contents and relatively low contents of lithic fragments are petrographically similar to samples of the TRA(p) unit, and so a distinction between these units based on petrography is also uncertain. The TRA(lr) and TRA(p) units can be confidently distinguished only if the' stratigraphic relation to the distinctive TRA(m) unit is known.

TRA(m) Petrologic Unit

The middle member of the tuffs and lavas of Area 20 consists of ash-flow tuff and bedded tuff. Lavas have not presently been recognized for the TRA(m) unit, which consists mostly of very fine (ash fall) tuff where characterized. The unit is 65 m thick in Ue19p. The TRA(m) unit is distinct due to a consistently and distinctly low content of quartz and high content of sanidine (Table 6). In addition, samples of the TRA(m) unit exhibit extremely low biotite contents, but contain hornblende contents that approximately equal that of biotite.

Sanidine (Table 7) and plagioclase (Table 8) compositions of the TRA(m) unit are relatively sodium-rich. Sanidine compositions are particularly distinct from those of any other TRA unit (Table 7). In addition, one sample of the TRA(m) unit contains an appreciable content of Fe-rich orthopyroxene (Mg* ~0.3). Such orthopyroxene is rarely found in NTS rocks and has been presently identified only in single samples of the TRA(p), Tpb, and TCP units.

TRA(lr) Petrologic Unit

The lithic-rich member of the tuffs and lavas of Area 20 consists of non- to partially welded ash-flow tuff. The TRA(lr) unit is widely distributed

Table 8. Frequency distribution of An contents for plagioclase phenocrysts in samples of Petrologic Units of Pahute Mesa, Yucca Mountain, and Rattlesnake Ridge. (Each value represents the number of analyses that have anorthite (An) end-member contents within the interval indicated. Results combined for all samples of each unit. Data for Yucca Mountain from Warren et al., in prep.).

															An, mol%																			
Unit	Number of Samples	Location		10					20					30					40					50					60					70
TRA(ul)	12	PM	1		1	2	21	63	57	18	5	1		2	1		1					1					1							
Tpb	1	PM				1	1	5	3	3			1																					
TH1	8	YM	1	1		6	11	25	19	3	1	1																						
TRA(u2)	3	PM							3	8	15	5	2	3		2		2	1	1	1													
TH2	3	YM					5	11	7	13	9	6	4	1	1	2	5	3	3	2	1	3	3	1										
TRA(p)	3	PM		6	1	5	7	7		7	1		2	1	2	1	2	1	1	1	2					1			1					
TRA(p)?	3	PM	1	3	13	1[illegible]			2	1			1			1	3	1		1	1				1									
TRA(m)	5	PM	1	19	23	14	4		1	2	1			1		2	1		1		1		1	1										
TCP	16	YM	19	59	17	1		1		1	4	2	3	3	3	2	4	2	1	1	1	3	1	1	2				1					
TRA(lr)	10	PM		2	26	45	13	8	3	3	2		2	2	1	5	4	3	1	8	3	1	1	1	1									
TRA(sw)	2	RR		1	4	15	6	1								1		1	1			1												
TCB	29	YM		3	35	127	79	16	15	3	4	6	6	6	6	6	4	6	6	1	5	5	1			1								
TCT	1	RR						2	4	4			1	2						1	[illegible]	1		1										
TCT	26	YM				2	5	32	58	28	17	15	18	10	14	14	13	13	9	4	4	1	5	3	3	3	1	1	2	2	1	1		

Table 9. Frequency distribution of molecular Mg/(Mg+Fe) contents for biotite phenocrysts in samples of Petrologic units of Pahute Mesa, Yucca Mountain, and Rattlesnake Ridge. (Each value represents the number of analyses that have molecular Mg/(Mg+Fe) end-member contents within the interval indicated. Results combined for all samples of each unit. Data for Yucca Mountain from Warren et al., in prep.).

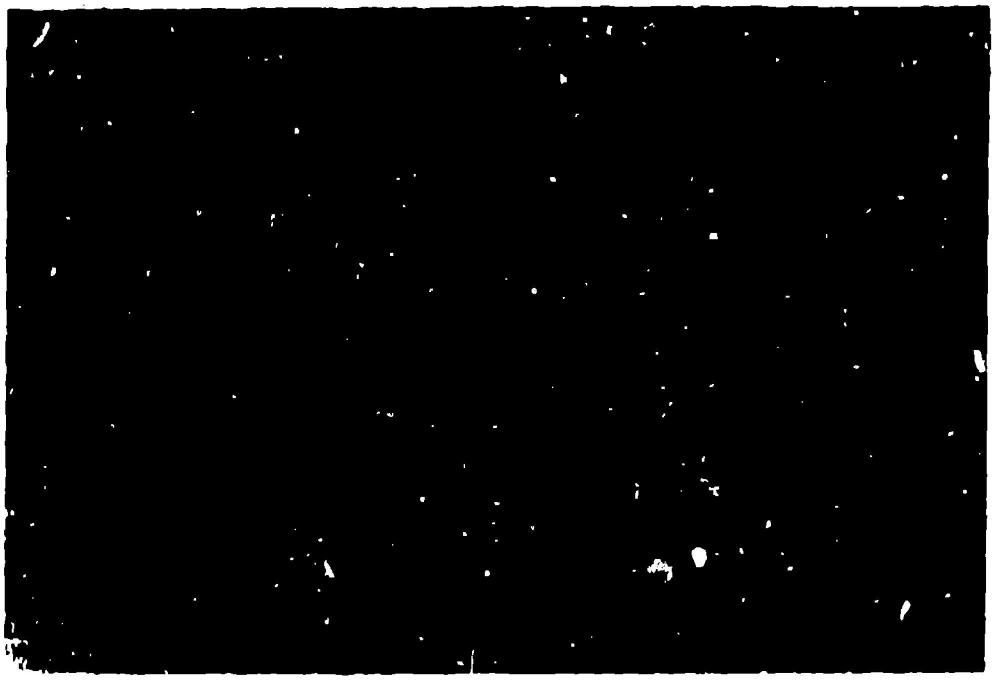
									molecular Mg/(Mg+Fe)													
Unit	Number of Samples	Location	.30					.40					.50					.60					.70
TRA(ul)	12	PM	3	2	13	24	6	10	2									1					
Tpb	1	PM		1	5		1																
TH1	7	YM			6	13	13		2	1		1											
TRA(u2)	6	PM						7	8	1[illegible]	4												
TH2	6	YM				1	11	4	7	9	9	1											
TRA(p)	3	PM			2	3	2	3	1	7	8												
TRA(p)?	3	PM					3	11	7		1						1				1		
TRA(m)	4	PM		2	1	3	3	1				2	1	2	1								
TCP	6	YM			1		2	6	3	5			2	2				1					
TRA(lr)	10	PM	1	1	7	27	12	4	4	1	3	4	1	3	5								
TRA(sw)	2	RR				1	4	5	3														
TCB	20	YM	1		3	5	[illegible]	34	4	1				1		1	6	2	1	1			
TCT	1	RR						2	1	1													
TCT	18	YM		1	4	5	8	22	27	13	4	6	1			2	3		2	1		1	

throughout Pahute Mesa. It is >400 m thick in Ue19p and about 500 m thick in Ue20f. Except near the uppermost portion of the unit, samples of the TRA(lr) unit consistently contain exceptionally high contents of lithic fragments (Table 6) derived almost exclusively from the underlying peralkaline units of the Silent Canyon area. These lithic fragments are unusually poorly sorted; their sizes range down to microscopic, as illustrated in Figure 2, and up to meters. Their presence provides a highly distinct petrographic characteristic of the TRA(lr) unit. Samples of the TRA(lr) unit characteristically contain a low to moderate content of felsic phenocrysts with plagioclase subordinate to sanidine and quartz (Table 6). The biotite content is low, and hornblende is absent. However, near both the top and bottom of the unit, samples have phenocryst contents as high as 26%, plagioclase is dominant, and both biotite and hornblende are abundant.

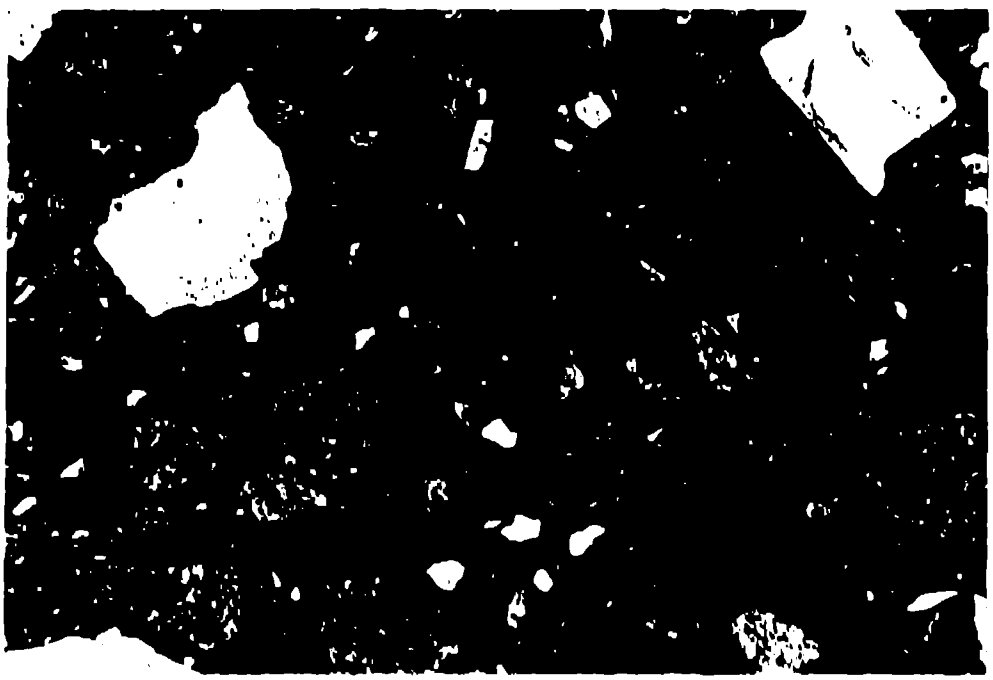
Two very distinct compositions occur for sanidine in samples of the TRA(lr) unit; one with a dominant Or+Cn value of 62 mol% and the other with an Or+Cn value of 40 mol% (see Table 7). The former composition is similar to dominant compositions for other TRA units (see Tables 7,11), and represents the true phenocryst chemistry. The latter composition matches those for sanidine in samples of the underlying peralkaline rocks and for sanidine phenocrysts within the lithic fragments of the TRA(lr) unit; sanidine grains with these compositions are clearly xenocrysts. No other unit of the NTS is known to contain sanidine xenocrysts in such abundance. Plagioclase compositions (Table 8) are not unusual compared to other NTS units (Table 11), and both biotite (Table 9) and hornblende (Table 10) compositions are magnesium-poor (Table 11), typical of the tuffs and rhyolites of Area 20.

TRA(sw) Petrologic Unit

The TRA(sw) Petrologic Unit is equivalent to the Stockade Wash Tuff(?) of Byers et al. (1976a) and may additionally include bedded tuff stratigraphically bounding the ash-flow cooling unit. Two samples of the Stockade Wash Tuff were examined; these were collected from locations (RW19r and RW18a, Fig. 1) that Byers et al. (1976a) consider probably not stratigraphically equivalent. The stratigraphic position of the TRA(sw) unit in the Quartet Dome quadrangle (Sargent et al., 1966) has been confidently established at location RW19r, where it directly underlies the TRA(lr) Petrologic Unit ("conglomerate" of Sargent et al., 1966). The petrography and mineral



a.



b.

Fig. 2
Photomicrographs of sample Ue19p-2204, TRA(1r) unit. Note the abundant lithic fragments (mottled appearance), particularly those with very small sizes. Field of view 1.9 x 2.8 mm. (a) reflected light, (b) transmitted light.

Table 10. Frequency distribution of molecular Mg/(Mg+Fe) contents for hornblende phenocrysts in samples of Petrologic units of Pahute Mesa, Yucca Mountain, and Rattlesnake Ridge. (Each value represents the number of analyses that have molecular Mg/(Mg+Fe) end-member contents within the interval indicated. Results combined for all samples of each unit. Data for Yucca Mountain from Warren et al., in prep.).

Unit	Number of Samples	Location	molecular Mg/(Mg+Fe) <.30	.30					.40					.50					.60					.70
TRA(ul)	1	PM									1	1												
Tpb	1	PM		1			2		2															
TRA(p)	3	PM	1				3	4			3	5	5	1	2				1					
TRA(p)?	2	PM						2		10	7	1	2				1	1		1	1			
TRA(m)	4	PM		1	1	3	8	4	1	1														
TCP	2	YM			1		1							1					1					
TRA(lr)	4	PM				2	1	2	1	4	2	2					1							
TRA(sw)	2	RR		1		1				3	5	1												
TCB	4	YM					1			7	5													
TCT	1	RR														1								

chemistry of the sample at location RW18a from the Ammonia Tanks quadrangle (Hinrichs et al., 1967) identically matches the sample of this unit from the Quartet Dome quadrangle. Nonetheless, the correlation of the unit between these areas is considered uncertain due to a possible confusion with the TRA(p) unit.

TCT Petrologic Unit (Rattlesnake Ridge Location)

A single sample of bedded tuff from Rattlesnake Ridge (location in Figure 1) is tentatively correlated with the TCT unit of Yucca Mountain. This thin (18 m thick) bedded tuff is bounded stratigraphically below by the Grouse Canyon Member of the Belted Range Tuff and above by the TRA(sw) unit. It is conceivable that the TRA(sw) unit at this location correlates with the TRA(p) rather than the TRA(lr) unit [see discussion of TRA(sw) unit]; in this case the sample of bedded tuff might represent the base of the TRA(p) unit. Such is considered unlikely because the petrography and mineral chemistry of this sample of TCT unit differs distinctly from all known or tentatively assigned samples of TRA(p) unit (see Tables 6-11).

Table 11. Dominant values for compositional parameters of phenocrysts for Petrologic Units of Pahute Mesa, Yucca Mountain, and Rattlesnake Ridge. (The dominant value is equivalent to the statistical mode for the frequency distribution of analyses represented in Tables 7-10. Symbols for all Petrologic Units defined in Table 1.)

Petrologic Unit		Location	Number of Samples	Sanidine Mol% Or+Cn	Sanidine wt% BaO	Plagioclase Mol% An	Mafic Minerals Molecular Mg/(Mg+Fe) Biot	Mafic Minerals Molecular Mg/(Mg+Fe) Hbld
TMRu		a	6	60	0.00, 1.13[b]	19, 24[b]	0.62	0.64
TMRl	upper	PM	1	53	0.00	13		
	lower	b	7	62	0.00	13	0.60	0.72
TPCu	upper	PM	1	49	0.05	13[c]	0.68	0.65
	lower	PM	3	36	0.05	6[c]	0.66	0.70
TKPP		PM	9	49	0.75	13	0.65	
TRA(u1)		PM	12	69	0.12	20	0.37	0.46
Tpb		PM	1	71	0.09	20	0.35	0.39
TH1		YM	10	68	0.10	20	0.38	
TRA(u2)		PM	3	69	0.58	25	0.44	
TH2		YM	7	71	0.21	24	0.43	
TRA(p)		PM	3	63	0.36	17	0.43	0.47
TRA(p)?		PM	3	61	0.25	13	0.42	0.44
TRA(m)		PM	5	53	0.05	12	0.37	0.37
TCP		YM	22	53	0.14	11	0.42	
TRA(lr)		PM	10	62, 40[b]	0.13, 0.00[b]	15	0.37	0.43
TRA(sw)		RR	2	62	0.29	15	0.40	0.44
TCB		YM	35	61	0.56	15	0.40	0.44
TCT		RR	1	69	0.27	22	0.42	
TCT		YM	31	67	0.55	21	0.42	
TLR		YM	16	65	0.67	18	0.59	
TTA		YM	8	64	0.55	18	0.55	
TTB		YM	2	66	0.96	26	0.59	
TTC		YM	6	72	3.4	31	0.62	

[a] Locations throughout NTS
[b] Bimodal population
[c] K-rich anorthoclase. Ca-rich plagioclase (mantled by K-rich feldspar) also present.

Other Petrologic Units

Most other Petrologic Units discussed in this report (Table 1) consist of well-described ash-flow cooling units, mostly from Yucca Mountain (location shown in Figure 1). Each such Petrologic Unit also includes stratigraphically bounding bedded tuff that can be petrographically and chemically related to the ash flow, but this added tuff is so volumetrically insignificant that the distinction between Petrologic and Lithologic Units is unimportant. Descriptions of units younger than the TRA units are found in Byers et al. (1976a), and descriptions for Petrologic Units of Yucca Mountain are contained in Warren et al. (in prep.).

COMPARISON OF TRA PETROLOGIC UNITS OF PAHUTE MESA WITH UNITS OF YUCCA MOUNTAIN

The occurrence of substantial petrographic variations within single lithologic units of the NTS are well documented. Many NTS ash-flow cooling units have mafic-rich caprocks (e.g., Lipman et al. 1966; Byers et al., 1976a). Substantial petrographic variations are now well documented for ash-flow cooling units that do not have mafic-rich caprocks; for example, the upper portion of the TCB unit of USW-G1 is quartz-rich, but the lower portion is quartz-poor (Carr et al., in press; Warren et al., in prep.). The TPCu unit is a single cooling unit only 22 m thick in Ue19p, but the phenocryst content differs by a factor of 3.5 between top and bottom of the unit and mafic mineral and trace mineral contents differ by an order of magnitude or more (Warren, in prep.). It is clear that primary minerals (phenocrysts) are not homogeneously distributed within most magmas. Furthermore, it might be expected that the upper portion of a magma might concentrate volatiles. Explosive release of these volatiles would result in eruption of the upper portion of the magma as tuff, whereas the lower, more volatile-depleted portion of the magma would tend to erupt more quietly, as a lava flow. Such an eruption would result in both tuff and lava from the same magma. Historical eruptions in such a manner are known (Hildreth and Drake, 1983). Additionally, large-volume eruptions of tuff will occur near-source as massive and poorly sorted ash flows, but as well sorted (bedded) tuffs farther from the source (see, for example, Figure 8 in Sheridan, 1979). Overprinted on these primary features due to emplacement mechanics are the zonal cooling features of compaction and crystallization described by Smith (1960). Thus, although eruption of a given magma might provide a time-stratigraphic marker, the recognition of this "pulse" might be very difficult due to vertical and lateral variations both in the lithology and in the primary mineral content in the erupted material.

Fortunately, the mineral chemistry of most eruptive sequences of the NTS has been found to be unaffected by petrographic and lithologic variations. For example, substantial petrographic variations occur both vertically and horizontally within the TCB unit (Warren et al., in prep.). Although samples from this unit were obtained from numerous locations, separated by as much as 55 km, compositions for sanidine are identical at all locations within the small analytical uncertainty of about 1 mol% Or+Cn. Similar results have been obtained for other minerals, particularly biotite and plagioclase. In general, each unit has a unique set of mineral compositions that differs from those of all other NTS units and serves as an invaluable aid in its recognition. The similarity in mineral chemistries between the TRA(p) and TRA(sw) units noted in their descriptions is an unusual, and highly significant exception. It should be noted, however, that not all units show as remarkable a vertical and lateral consistency in mineral compositions as does the TCB unit. There are significant systematic variations in sanidine composition within the Topopah Spring (Broxton et al., 1982) and Rainier Mesa rhyolites that could be employed to define stratigraphic levels within these units.

Comparison of Mineral Chemistry

Although there are small (but significant) differences among individual units, all TRA units have distinctively Mg-poor mafic minerals. In contrast, mafic minerals in units of the overlying Paintbrush Tuff and allied lavas of Pahute Mesa have characteristically Mg-rich compositions (see Table 11). The peralkaline rocks that underlie the TRA sequence are extremely biotite-poor (most samples lack biotite) and instead contain olivine and clinopyroxene phenocrysts that in many cases are nearly pure Fe end members.

At Yucca Mountain, mafic minerals in the Crater Flat Tuff and overlying tuffs and lavas of Calico Hills have Mg-poor compositions that are identical to those of the TRA units of Pahute Mesa (see Tables 9-11). The overlying Paintbrush Tuffs, except for the Topopah Spring rhyolite, have characteristically Mg-rich mafic minerals identical to those in the Paintbrush Tuffs and allied lavas of Pahute Mesa. The Crater Flat Tuff of Yucca Mountain, however, overlies the Lithic Ridge Tuff and associated lavas rather than the peralkaline rocks that underlie the TRA units of Pahute Mesa. The Lithic Ridge and older units are generally plagioclase-rich units (Warren et al., in prep.) that bear Mg-rich mafic minerals (Table 11). It is clear that the TRA units of Pahute Mesa and the Crater Flat and Calico Hills tuffs of Yucca Mountain have compositions for mafic minerals that are indistinguishable from each other but are highly different from those of bounding volcanic groups.

In contrast to mafic mineral compositions, sanidine and plagioclase compositions differ distinctly among units, and can be compared unit-by-unit throughout the stratigraphic columns of Pahute Mesa and Yucca Mountain (Figure). Sanidine compositions (Table 7) are identical within the small analytical uncertainties for each pair of units in the stratigraphic sequence at both locations. All compositions of individual phenocrysts that differ substantially from those of the dominant composition (Table 11) are due to xenocrysts

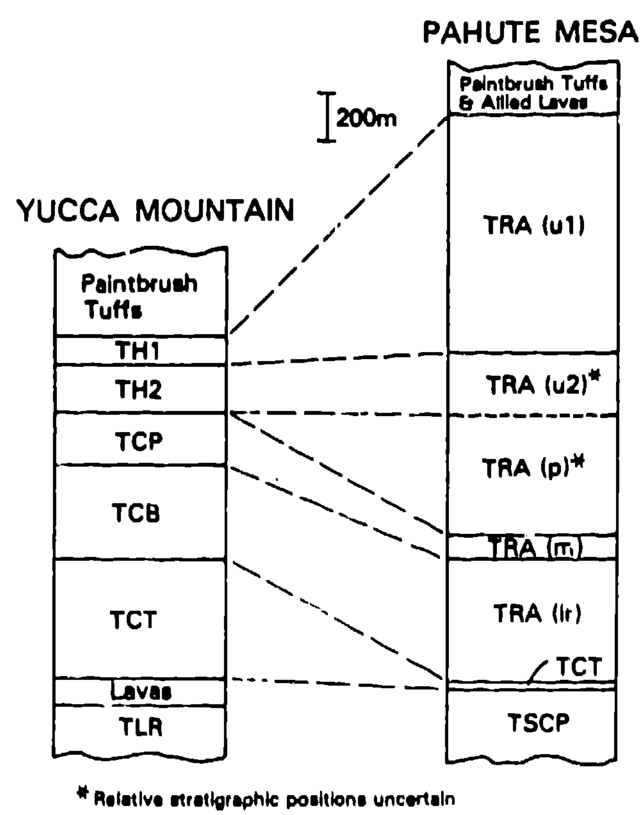


Fig. 3
Correlation diagram between Petrologic Units of Yucca Mountain and Pahute Mesa. (Symbols for units defined in Table 1. TSCP = peralkaline rock of the Silent Canyon area. Greatest known or inferred thickness for each unit illustrated.)

or to the occurrence of narrow sodium-rich rims (see Figure 4) produced from late-stage deuteric alteration (Warren et al., in prep.). Matching units, stratigraphically downward (unit present at Pahute Mesa listed first), are TRA(u1) and TH1; TRA(u2) and TH2; TRA(m) and TCP; TRA(lr) and TCB; and TCT and TCT. A unit equivalent to the TRA(p) unit of Pahute Mesa is not known for Yucca Mountain. Plagioclase compositions (Table 8) match in similar fashion.

Although the TRA(lr) unit of Pahute Mesa contains sanidine whose composition (dominant Or+Cn value = 62, Tables 7 and 11) matches the TCB unit of Yucca Mountain, it also contains a population of sodium-rich sanidine xenocrysts that do not occur in the TCB unit. Additionally, there are significant differences in the barium contents of sanidine for many paired units, most notably between the TRA(lr) and TCB units (see Table 11). Discussion of these differences is deferred to a following section.

Comparison of Lithology and Petrography

The primary mineral contents of the TRA units of Pahute Mesa are quite similar to their paired unit of Yucca Mountain (Table 6). At both locations,

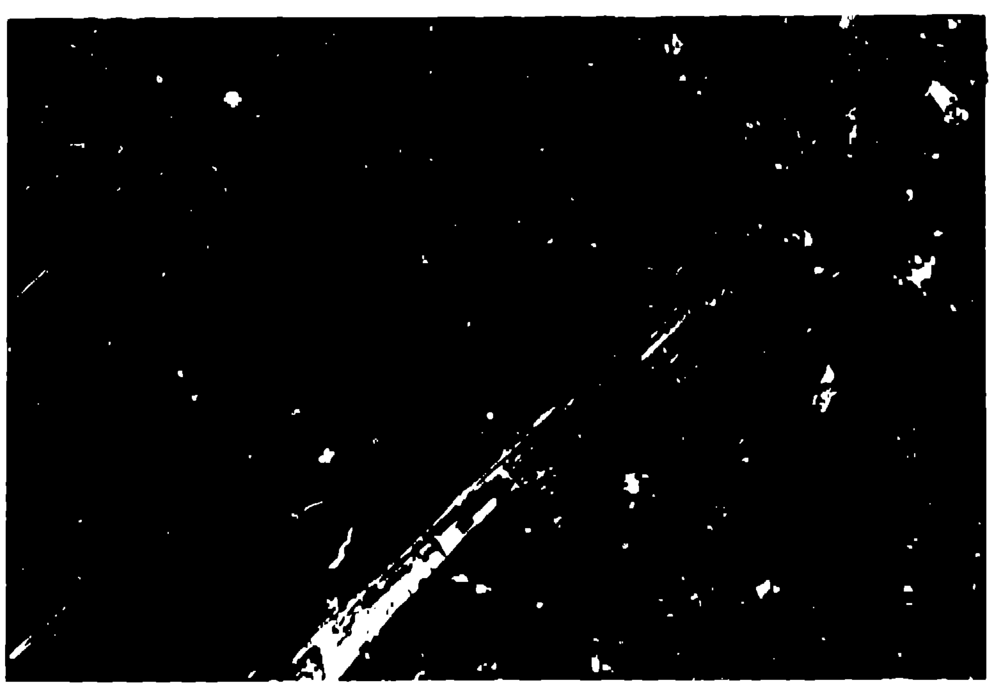


Fig. 4
Transmitted light photomicrograph (crossed nicols), of sodium-enriched rim of sanidine in sample CFLSM-5, TCB unit. Field of view 0.24 x 0.35 mm.

these units contain abundant quartz, and variable amounts of biotite, hornblende, and allanite. Pyroxene, sphene, and perrierite rarely occur in samples of these units. These petrographic characteristics contrast strikingly with those of stratigraphically bounding units of both areas (Byers et al., 1976a; Warren et al., in prep.; Warren, in prep.). The match in primary mineral contents is excellent for several of the paired units of Figure 3, particularly for the TRA(ul) and THl units.

The most substantial lithologic and petrographic differences between paired units occur between the TRA(lr) and TCB units. Samples of these units are grossly dissimilar in hand sample; the TRA(lr) unit is exceptionally lithic-rich and generally non-welded whereas the TCB unit is quite lithic-poor and always occurs as a well-defined cooling unit. Portions of the TCB cooling unit may be densely welded or even vitrophyric. Differences in the primary mineral contents of these units are not as great, but nonetheless they are appreciable. Most conspicuous is the much higher median biotite content of the TCB unit (0.20%) compared to that of the TRA(lr) unit (0.06%). However, highly phenocryst- and mafic-rich zones occur within the TRA(lr) but not within the TCB unit. Thus, the average phenocryst and mafic contents of the TRA(lr) unit are considerably higher than median values, and averages probably match much better for the two units than the medians. The TRA(m) unit of Pahute Mesa also differs appreciably in lithology and primary mineral content from the TCP unit of Yucca Mountain. The TRA(m) unit generally has a low to moderate content of phenocrysts, mostly sanidine (Table 6), and occurs as a well-sorted (bedded) tuff where presently characterized. It is distinctly quartz-poor. The TCP unit contains a considerably higher phenocryst content, and occurs as a well-defined ash-flow cooling unit. Both units, however, contain a highly distinctive, magnesium-poor orthopyroxene that provides a striking correlation of primary mineral contents.

DISCUSSION OF RESULTS: EVIDENCE FOR A COMMON MAGMATIC ORIGIN OF VOLCANIC SEQUENCES THAT FLANK THE TIMBER MOUNTAIN CALDERA

Each TRA unit of Pahute Mesa and correlative unit of Yucca Mountain (Figure 3) contains Mg-poor mafic minerals, consisting primarily of biotite and/or hornblende. The chemistry of these minerals differs distinctly from those of bounding volcanic groups, and suggests that the sequences at each location were derived from closely similar magmas or from the same magma. By contrast, the chemistry of sanidine and plagioclase differs markedly between successive Petrologic Units. These large chemical differences within each stratigraphic succession are parallel at each location. It is considered highly unlikely that separate magmas could evolve in such a manner to produce the observed correspondence in feldspar chemistry. The mineral chemical data thus strongly indicates that each of the paired units of Yucca Mountain and Pahute Mesa was derived from the same magma.

It is unlikely that Petrologic Units that include lavas have been emplaced very far from their source; such units include the TRA(u1), TRA(u2), and TRA(p) units of Pahute Mesa and the TH1 and TH2 units of Yucca Mountain. Thick exposures of the TH units occur north of Yucca Mountain and at Calico Hills (Byers et al., 1976b). If these lavas ascended directly upward from a magma chamber, a very large magma chamber must have been present during eruption of the TH and TRA(u) units if indeed these units represent magma from the same chamber. The distribution of TRA and TH lavas (shown in Figure 5) may then represent the approximate limits of this magma chamber. The Timber Mountain Caldera, a much younger feature, is located near its center. Lavas intermediate in age between the tuffs and lavas of Area 20 and the Timber Mountain Tuff have also been correlated across the Timber Mountain Caldera (see Figure 19 in Byers et al., 1976a). This suggests that the Timber Mountain area has been the center of a sequence of chemically different magma systems throughout an extensive period of time. It is probable that these magma systems, which produced a thick sequence of NTS volcanic rocks including the tuffs and lavas of Calico Hills, tuffs and lavas of Area 20, Paintbrush Tuff and Timber Mountain Tuff are related as a single, large evolving magma system centered beneath Timber Mountain. A model that might describe such a magma system is described by Hildreth (1981). Each pair of units found on opposite sides of Timber Mountain might have been erupted from a central source, the present location of Timber Mountain, or from separate sources. If the former is true, Pahute Mesa and Yucca Mountain are marginal to a major structure (e.g., caldera) associated with eruption of these units. The latter possibility, eruption from separate sources, is consistent with presently accepted views. In this case, the Crater Flat Tuffs and tuffs and lavas of Area 20 were erupted from structures that flank Timber Mountain (Carr, 1982; Orkild et al., 1968). It is likely that the magma chamber was not fully emptied during the final stages of eruption and the remaining liquid has

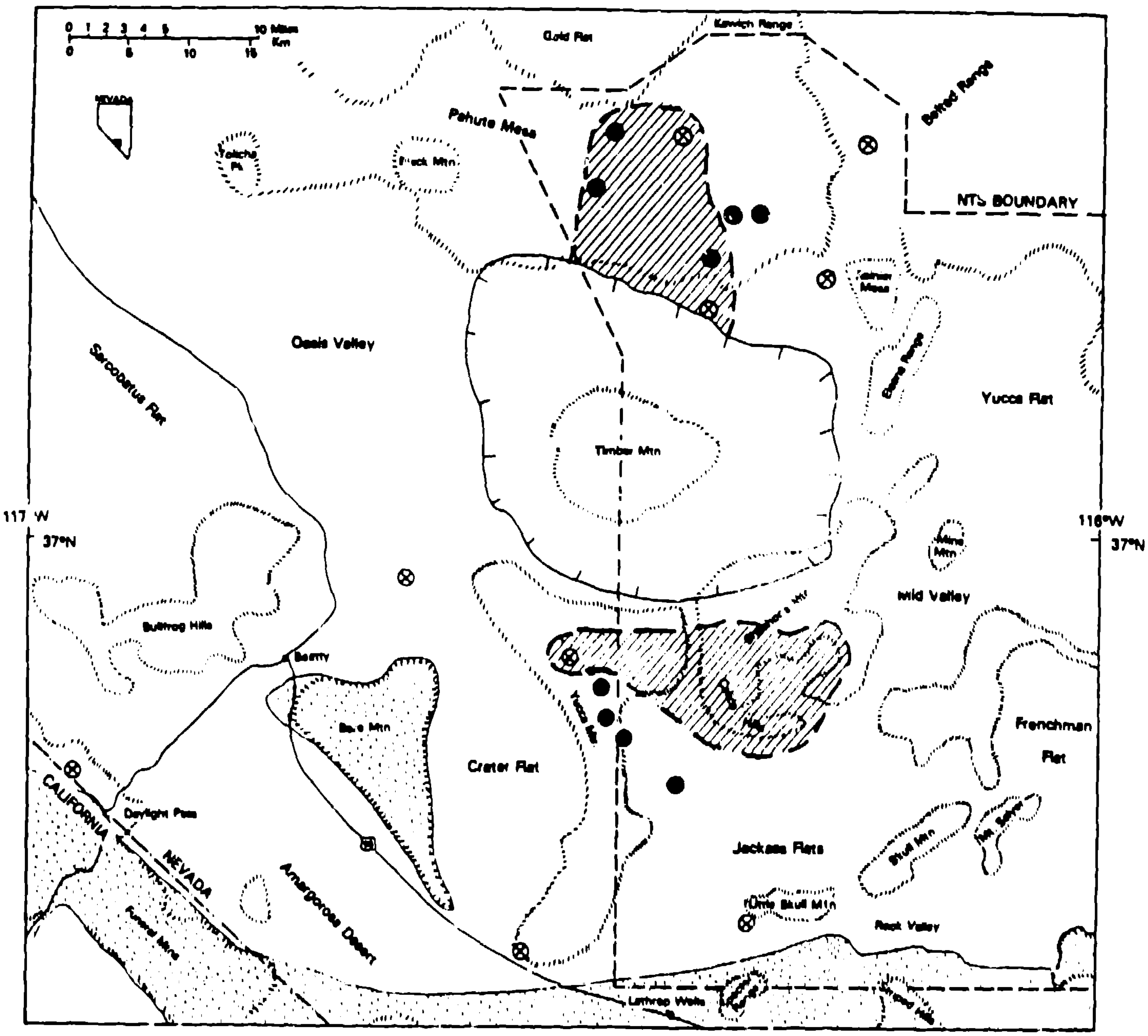


Fig. 5
Location of lavas of the TRA(u) unit (diagonal pattern north of Timber Mountain) and of the TH unit (same pattern south of Timber Mountain). Non-welded tuff shows a wider distribution for both units. The single magma chamber inferred to be the source of both lavas is centered beneath Timber Mountain; the distribution of the lavas may approximate the location of the outer portion of a magma chamber.

solidified to form a large pluton beneath Timber Mountain. If the size and shape of the magma chamber did not change substantially through time, then the distribution of lavas shown in Figure 5 may also approximate the subsurface location of such a pluton, which presumably would be a granitic body.

The nearly identical mineral chemistry for units erupted from opposite sides of this hypothetical magma chamber indicates that chemical equilibrium between phenocrysts and liquid is closely maintained throughout an extraordinarily large volume of magma. This is true even where substantial variations of phenocryst concentrations occur within a unit. This indicates that the magma has an inhomogeneous distribution of phenocrysts, and the concentration observed within a unit depends upon the precise position that the sample occupied as a liquid in the magma chamber. Probable causes for variations in phenocryst content throughout a magma chamber are temperature and water pressure variations. Such factors might also affect the mineral chemistry, but the data at hand indicate that for many units they do not. There is good evidence (Warren, in preparation) that mixing of magmas occurs at the margins of the magma system. This is not an equilibrium process and non-equilibrium conditions are evident in units affected by magma mixing.

The crystallization sequence is preserved, however, by variations in the barium contents of sanidine. Sanidine has a marked tendency to concentrate barium (Leeman and Phelps, 1981; Hanson, 1978), which readily substitutes for potassium because these elements are very large ions of similar size. As crystallization proceeds, changing physiochemical conditions require the equilibrium composition of sanidine to change. The primary change usually requires progressive replacement of orthoclase component ($KAlSi_3O_8$) by albite component ($NaAlSi_3O_8$) as temperature decreases. This is rapidly accomplished under magmatic conditions simply by exchange of Na with K. Early crystallized sanidine contains relatively high Ba concentrations compared to sanidine formed later. However, equilibrium for Ba between early and late sanidines requires an exchange of celsian component ($BaAl_2Si_2O_8$) with albite. This equilibrium cannot be attained simply by exchange of Ba with Na, because it also requires a coupled substitution of Al with Si. The latter elements are present in a much more tightly bound (tetrahedral) structural site within sanidine, and require considerably greater energies for exchange. Consequently, although the Na and K exchange is rapid and complete up to the time of eruption and reflects equilibrium, Ba exchange is limited or does not occur. This process is here termed "limited equilibrium." Thus, portions of the magma that began to crystallize sanidine earliest will have the highest Ba contents, and those that formed sanidine latest will have the lowest. Thus, the differing Ba contents for sanidine between paired Petrologic Units of Yucca Mountain and Pahute Mesa simply relate to the crystallization history of the magma, and not to inherent compositional differences between the units.

The distribution and concentration of volatiles (primarily water) within the magma chamber is very important, because they certainly provide the driving force of the eruption. The higher their concentration, the more violent an eruption might be expected. The element cesium concentrates strongly in the upper portion of the magma that produced the Bishop Tuff (Hildreth, 1979); this element shows an extremely strong association with volatiles. Cesium concentrations in the TRA(lr) unit are extraordinarily high, generally more than an order of magnitude higher than those of other NTS units, including the TCB unit (Warren, in prep.). The cesium contents suggest that volatiles concentrated strongly in the portion of the magma chamber that erupted the TRA(lr) unit, but not in the portion of this same magma chamber that erupted the TCB unit. These volatiles drove an unusually violent eruption of the TRA(lr) unit that resulted in the incorporation of remarkably large and poorly sorted lithic fragments within the TRA(lr) unit.

CONCLUSIONS AND FUTURE RESEARCH

A very striking geochemical similarity, based on chemistry of primary mineral phases, has been demonstrated between volcanic groups that flank the Timber Mountain Caldera. It is concluded that paired units within the two locations were derived from the same magma. Lithologic and petrographic differences between units flanking Timber Mountain that have similar mineral chemistries are attributable to an inhomogeneous distribution of phenocrysts and volatiles within the magma. The distribution of paired units that contain thick lavas indicates that the magma body was very large and centered on Timber Mountain. The similarities in mafic mineral compositions among an entire group of units suggest that each successive unit represents the evolution of a single, large magma system.

It is the author's belief that the hypothesized magma system centered at Timber Mountain was also associated with the eruption of the oldest known NTS volcanic rocks. The mineral chemistry is presently being investigated for such units of Pahute Mesa for comparison with well-characterized units of Yucca Mountain (Warren et al., in prep.). The Petrologic Unit introduced here serves as a valuable correlative tool for bedded tuffs, and is particularly valuable for drill holes that do not penetrate the ash-flow cooling units used as marker beds. Volcanic units in other areas of the NTS (e.g., Yucca Flat) can probably be related to those of Pahute Mesa and Yucca Mountain by utilizing the Petrologic Unit. Such use is required to correlate older, poorly exposed units effectively over a large region such as the NTS due to marked lithologic differences that may occur among such units at different locations.

ACKNOWLEDGMENTS

This work has built on 20 years of geologic mapping and study, largely by geologists of the U.S. Geological Survey but also geologists of several other organizations. Many of their names are found among the references cited. The correlations described herein could not have been accomplished without the basic stratigraphic framework developed by previous NTS workers.

David E. Broxton, Frank M. Byers, Jr., and B. W. Smith provided very timely and thoughtful reviews. The advice and counsel of Frank M. Byers, Jr., has been very helpful. Roland C. Hagan and Lois F. Gritzo have greatly aided in the microprobe analyses. The ability of Marcia A. Jones to produce complex tables without error and with remarkable speed is simply astounding. Similarly, the ability of David A. Mann and Tino Lucero to create wonderful probe sections from rocks that fall apart in one's hands is remarkable. This research has been vigorously supported by Thomas A. Weaver and Wayne A. Morris, past and present group leaders of the ESS-2 (Geochemistry) group, and by Jack W. House, program leader for containment. I am very grateful to all for their generous contribution.

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