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ental petrology and mineralogy ion and significance of s and their isotopes in the rocks.

Editor

Dr. J. Hoefs
Geologisches Institut der Universität
Göttingen, Platz der Göttinger
Universität 1, D-3400 Göttingen
Federal Republic of Germany

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The Petrology and Geochemistry of the Medicine Lake Volcano, California

S.A. Mertzman, Jr.

Department of Geology, Franklin and Marshall College, Lancaster, Pennsylvania 17604, USA

Abstract. The Medicine Lake shield volcano is part of the Oregon high alumina plateau basalt petrologic province, as defined by Waters (1962) and Higgins (1973). The early eruptions are basaltic andesites and they constitute a significant portion of the shield-forming lavas. These lavas are characterized by a mild iron enrichment trend produced by fractionation of plagioclase and olivine, together with lesser amounts of clinopyroxene. Siliceous andesites of less areal extent form the shield-capping lavas. Their formation is initiated by the appearance of titanomagnetite as a liquidus phase which prevents further iron enrichment. Additional fractionation of plagioclase, clinopyroxene, orthopyroxene, and minor olivine continued during this interval.

An origin for the basaltic andesites which involves the derivation of a liquid by partial melting of lithosphere composed of low Sr⁸⁷/Sr⁸⁶ material previously subducted along the continental margin is favored. This magma subsequently fractionated under low pressure conditions, a conclusion supported by least squares mixing calculations.

Introduction

The High Cascades are an array of composite volcanoes which extend from Mt. Lassen, the southern terminus, northward into southern British Columbia. The Medicine Lake Highland is part of a belt of shield volcanoes which lie essentially parallel to and east of the High Cascades. This Highland, together with Newberry volcano in central Oregon and Simcoe volcano in southcentral Washington as well as other lesser known volcanic centers, constitute the high-alumina plateau basalt petrographic province (Waters, 1962; Higgins, 1973). The earliest field-based regional studies in this area were undertaken by Peacock (1931), Powers (1932), and Anderson (1941). Later investigations, which were chiefly analytical and not based on extensive fieldwork include Taylor (1968), Smith and Carmichael (1968), Peterman and others (1970), Eichelberger (1974);

1975), Condie and Hayslip (1975), and Barsky (1975). Recent field-based investigations include Burnell (1974), Hackett (1974) and Walter (1975); all part of a systematic remapping project designed to cover the entire Highland. Efforts are also currently in progress to map the area between Mt. Shasta and Medicine Lake (Hughes, 1974; Hart, 1976; Weaver, 1976) so that regional petrologic variations can be described in detail.

Geological Observations

The Medicine Lake Highland is a shield volcano measuring 40 km in basal diameter and rising 1000 m above the surrounding Modoc Plateau (see Figure 1). A summit collapse caldera caps the shield and is 6×10 km in size. The lavas associated with this edifice overlie the volcanics of the Modoc Plateau. The oldest exposed Modoc lavas outcrop in N-S fault scarps to the north and northwest of the earliest Medicine Lake related lavas. For the most part the Modoc volcanics are thin flows (2-5 m thick) of low-K high alumina basalts.

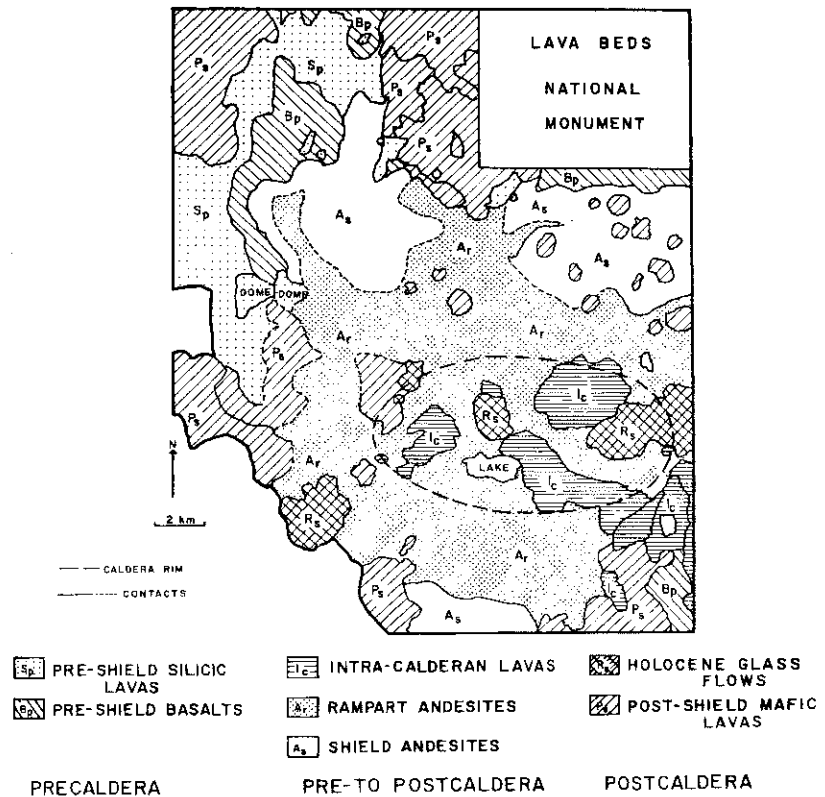


Fig. 1. A generalized reconnaissance geologic map of the Medicine Lake shield volcano. It is based in part on work reported in Burnell (1974), Hackett (1974), Hughes (1974), and Walter (1975)

5). Recent field-based investigations of Walter (1975); all part of the entire Highland. Efforts between Mt. Shasta and Medicine Lake so that regional petrologic

to measuring 40 km in basal Modoc Plateau (see Figure 1). The flows are 6 × 10 km in size. The lavas are typical of the Modoc Plateau. The lavas flow to the north and south. For the most part the flows are low-K high alumina basalts

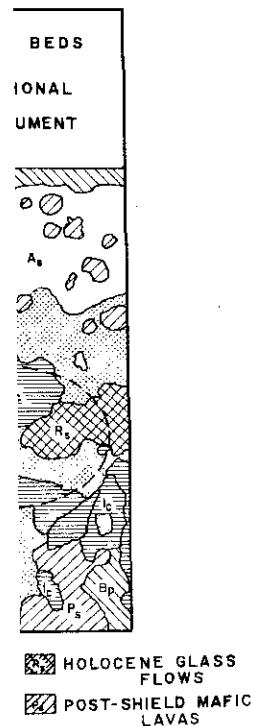


Table 1. Analytical results of K-Ar dating (R. Walter, analyst)^a

Sample	⁴⁰ Ar ^b /g	⁴⁰ Ar ^b / ⁴⁰ Ar × 100	% K ₂ O	K-Ar (my)
SM-75-69B ^c	0.00166	1.6	0.110	1.02 ± 0.55
SM-75-25 ^d	0.000906	0.69	0.85	0.07 ± 0.04

^a Constants used are: ⁴⁰K/Total K = 1.19 × 10⁻⁴; λ_b = 4.72 × 10⁻¹⁰ yr⁻¹; λ_e = 5.85 × 10⁻¹¹ yr⁻¹
^b Radiogenic argon, 10⁻¹⁰ mol.

^c Sample location: T.46N., R.4E., sec 31, NW1/4 NE1/4, Mt. Dome quadrangle, California; modal mineralogy: olivine 26.5%, clinopyroxene 21.5%, plagioclase 46.9%, groundmass 5.1%

^d Sample location: T.45N., R.3E., sec. 30, SE1/4 NE1/4, Medicine Lake quadrangle, California; modal mineralogy: see Table 2 'basaltic andesite'

(Mertzman, unpub. data; A.T. Anderson, personal communication). These basalts overlie rocks of the Cedarville Series of Miocene age (Anderson, 1941), which are very poorly exposed in this general area. At Gillem's Bluff, one of these N-S trending fault scarps, the lowest Modoc flow in the exposed sequence has been dated as Middle Pleistocene in age (Table 1, No. 1). This suggests most of the observable displacement along these N-S faults is quite young. It also substantiates a time-transgressive nature for this low-K high alumina basalt magma type as a significant number of flows with this chemistry are post-faulting and therefore latest Pleistocene to Recent in age. Overlying these basalts with no apparent angular discordance or large time hiatus is a tuff unit, originally referred to as the Andesite Tuff by Anderson (1941). The tuff definitely represents pre-shield volcanism; its age is between 0.7 and 1.0 my. as this unit has been found to have reversed polarity (Brown and Mertzman, unpub. data). Chemically it varies between 59–63% SiO₂ supporting its original classification as an andesite; yet, spatially and temporally, it appears to be related to a series of rhyolitic domes on the northern margin of the shield volcano. Younger lavas associated with the initial stages of development of the Medicine Lake shield volcano and the lack of erosional dissection preclude any definitive conclusions about the relationship between the tuff and the dome structures, as well as where the ultimate source of the tuff may be located.

On both the northern and northwestern flank of the Medicine Lake shield a stratigraphy can be outlined which documents the growth of the volcano from the earliest shield-forming lavas to those which are definitely post-calderan in age. A flow that rests directly on the eroded surface of the Andesite Tuff and appears to be stratigraphically-speaking the oldest shield-related lava has been dated at 0.07 ± 0.04 my (Table 1, No. 2). This date suggests the entire volume of lavas directly related to the development of the Medicine Lake volcano was erupted over a time span of approximately 100,000 yrs. This relatively short period of geologic time for the outpouring of nearly 2900 feet of lava (maximum thickness) is consistent with the data of McBirney and others (1974) concerning the Oregonian Cascades.

The actual flows from the Medicine Lake volcano vary in thickness between 6–20 m and in general possess very similar cross-sectional morphologies: an upper 2–3 m which is black, glassy, and finely vesicular, an interior of variable

Medicine Lake shield volcano. It is based on data of Hughes (1974), and Walter (1975)

thickness that is characteristically jointed with only 2–4 cm separating the joint planes, and a bottom rubble zone 1–2 m thick. Interbedded pyroclastics are virtually absent. Successively younger flows are generally of less areal extent and somewhat thicker. These younger flows are both syn- and post-calderan in age, and have emanated from a series of elliptically arranged volcanic sources which dot the caldera rim, whose boundary faults have acted as passageways for the upward migration of these youngest shield-related lavas. Anderson (1941) refers to these volcanics as rampart lavas.

The purpose of this paper is to examine major and trace element variations as a function of stratigraphy for the Medicine Lake volcano. Attention is restricted to the main volcano; younger cinder cones and their associated products are disregarded.

Petrography

The earliest lavas are basaltic andesites which are 15–25% crystalline and have a groundmass which varies from pilotaxitic to intergranular in texture. The modal mineralogy of representative lavas is found in Table 2. Plagioclase is the most abundant phenocryst found in these lavas, indicating its constant presence as a liquidus phase. Potassium feldspar was never observed, either as a phenocryst or as a groundmass constituent. The mafic minerals include olivine and augite, always less than 1.5 mm in diameter, with orthopyroxene only infrequently observed. Titanomagnetite is present only as a groundmass constituent within these early lavas. No reaction relationship was found between olivine and the groundmass.

In successively younger lavas, a steady progression of mineralogic changes take place. The modal percentage of phenocrysts decreases, reaching a minimum of less than 1/2% in some of the youngest rampart lavas. Plagioclase remains the most important mineral modally but its average grain size becomes smaller. Olivine is gradually replaced as a significant constituent by orthopyroxene so that most of the younger rampart flows are two-pyroxene andesites. However, even in these lavas it is not unusual to see one or two olivine grains per thin section; each one always showing significant signs of resorption. Augite persists as a phenocryst mineral; however, the Cpx/Opx ratio varies over wide limits and either mineral can dominate the ferromagnesian mineralogy in a given flow. Titanomagnetite makes its initial appearance as a discrete phenocryst phase (0.2–0.4 mm in diameter) in the earliest rampart andesites. It is homogeneous with the exception of an occasional grain which has one or more exsolution lamellae of ilmenite. In addition to being found as separate grains, it is also encountered in clumps of small phenocrysts together with plagioclase, ortho- and clinopyroxene, and apatite. In the more siliceous andesites apatite becomes an ubiquitous trace constituent and is found in close association with titanomagnetite microphenocrysts and

Table 2. Modal mineralogy of representative specimens from the Medicine Lake volcano

	Early shield basaltic andesite	Early rampart andesite	Rampart andesite	Plagioclase- olivine cumulate
Groundmass	84.2	88.1	96.3	56.0
Olivine	0.8	0.6	—	11.7
Clinopyroxene	0.6	0.7	0.3	—
Orthopyroxene	—	0.2	0.2	—
Plagioclase	14.4	10.0	2.8	32.3
Opagues	—	0.3	0.3	—
Others	—	0.1	0.1	—

2-4 cm separating the joint interbedded pyroclastics are generally of less areal extent both syn- and post-calderan. Locally arranged volcanic sources have acted as passageways for later lavas. Anderson (1941)

and trace element variations at Medicine Lake volcano. Attention is given to these lavas and their associated pro-

ducts. The groundmass is crystalline and has a modal mineralogy of representative shield lavas. The only crystal found in these lavas, indicating that apatite was never observed, either as a phenocryst or as inclusions. Minerals include olivine and augite, always frequently observed. Titanomagnetite is common in the rhyolite lavas. No reaction relationships

are observed. The mineralogic changes that take place. The amount of less than 1/2 % in some of the most abundant mineral modally but its average is a significant constituent by orthopyroxene in the rhyolite andesites. However, even in these lavas in section; each one always showing a distinct mineral; however, the Cpx/Opx ratio is the ferromagnesian mineralogy in the rhyolite phenocryst phase (0.2-0.4 mm) as with the exception of an occasional titanomagnetite. In addition to being found as phenocrysts together with plagioclase, in the rhyolite andesites apatite becomes an ubiquitous titanomagnetite microphenocrysts and

at the Medicine Lake volcano

Rampart andesite	Plagioclase-olivine cumulate
66.3	56.0
—	11.7
0.3	—
0.2	—
2.8	32.3
0.3	—
0.1	—



Fig. 2. Apatite with numerous opaque rod-like inclusions; occurs as an inclusion within calcic plagioclase from a rampart andesite flow (length of grain is 0.21 mm)

as inclusions within the pyroxene phenocrysts. The apatite varies from typical small equant grains (0.1-0.2 mm in diameter) to infrequent acicular crystals up to 0.7 mm long. In many cases, however, the apatite is somewhat pleochroic in shades of pale violet or pink and contains numerous oriented opaque rod-like inclusions aligned parallel to the C-crystallographic axis of the apatite (see Figure 2). The inclusions are too small for optical identification.

Several lava flows have been found which contain glomeroporphyritic clumps of 1-2.5 mm plagioclase and olivine set in an intersertal groundmass, which range from being intercalated with shield-forming basaltic andesite flows to post-calderan in age. A representative mode of one of these flows is found in Table 2. Volumetrically this type of flow is minor in comparison to that of the total volume of the extrusives from the Medicine Lake volcano, certainly less than 10%. Textural evidence suggests that the plagioclase and olivine began crystallizing practically simultaneously and that they are cumulative in origin.

In summary, the observed phenocryst assemblage includes calcic plagioclase, olivine, orthopyroxene and clinopyroxene, titanomagnetite, and apatite. Only these phases can be utilized in any modeling calculations which might document the origin of the Medicine Lake shield lavas through crystal fractionation under low pressure conditions.

Mineral Chemistry

Microprobe analysis of the constituent mineral phases in the Medicine Lake lavas has been performed, with the exception of titanomagnetite which wasn't analyzed due to the lack of suitable standards. Representative chemical analyses are listed in Table 3 in terms of weight percent oxides.

Table 3. Microprobe analyses of olivine, clinopyroxene, orthopyroxene, and plagioclase. Total Fe is reported as FeO

Olivine										
ML-27			88-B-1		205-C-1		ML-57			
c	r	c	m	m	m					
SiO ₂	37.90	37.40	37.39	38.01	37.50	37.80				
FeO	21.10	22.75	22.91	21.24	22.65	22.25				
MgO	39.60	38.62	38.71	39.44	38.86	39.16				
MnO	0.27	0.30	0.29	0.25	0.30	0.29				
CaO	0.18	0.20	0.21	0.19	0.18	0.20				
Total	99.05	99.27	99.51	99.13	99.49	99.70				

Clinopyroxene										
88-B-1		205-C-1			ML-57		143-C-1			
m	m	c	r	g	c	c	m	m	g	
SiO ₂	49.36	51.34	52.08	53.19	52.56	52.57	52.09	51.56	53.01	52.28
Al ₂ O ₃	5.61	3.77	2.60	2.08	2.69	1.74	1.61	2.33	1.6	1.55
TiO ₂	1.60	1.05	0.67	0.60	0.72	0.66	0.70	0.91	0.71	0.63
FeO	11.15	10.38	8.80	8.98	8.87	10.66	10.19	10.08	10.78	10.68
CaO	19.09	18.27	19.63	19.87	20.18	18.95	19.99	19.66	19.81	19.86
MgO	13.46	15.68	15.98	16.17	15.80	15.23	14.91	14.84	14.58	14.51
Na ₂ O	0.52	0.47	0.42	0.41	0.41	0.46	0.44	0.47	0.46	0.44
Total	100.79	100.96	100.18	101.30	101.23	100.27	99.93	99.85	100.95	99.95

Orthopyroxene						
ML-57		143-C-1				
m	g	c	r	m	g	
SiO ₂	54.11	54.56	53.98	54.34	54.12	54.20
Al ₂ O ₃	1.01	0.72	0.92	0.77	0.54	0.68
TiO ₂	0.44	0.34	0.35	0.37	0.28	0.34
FeO	18.38	20.29	21.00	21.45	20.31	23.03
CaO	1.67	1.54	1.68	1.80	1.68	1.67
MgO	25.01	23.26	22.23	22.09	24.09	20.90
Total	100.62	100.71	100.16	100.82	101.02	100.82

Plagioclase										
ML-27			88-B-1			205-C-1				
c	r	m	c	r	g	c	r	m	g	
SiO ₂	49.8	51.8	50.2	49.4	50.9	52.4	49.5	48.0	50.5	52.5
Al ₂ O ₃	31.7	30.8	31.4	32.4	30.9	30.1	32.1	32.4	31.5	30.0
FeO	0.9	0.8	0.9	1.1	0.9	0.7	1.1	1.1	0.9	0.8
CaO	14.55	13.60	14.4	14.90	14.10	12.65	15.30	15.75	14.60	12.80
Na ₂ O	3.35	3.95	3.4	2.95	3.75	4.35	3.10	2.85	3.35	4.35
K ₂ O	0.13	0.14	0.13	0.12	0.13	0.15	0.10	0.10	0.13	0.13
Total	100.43	101.09	100.43	100.87	100.68	100.35	101.20	100.20	100.98	100.58

ML-57		143-C-1					
c	r	g	c	r	m	g	
SiO ₂	50.5	52.0	55.3	50.7	52.4	54.0	57.4
Al ₂ O ₃	31.0	29.7	28.2	30.7	29.6	28.8	26.9
FeO	1.1	0.8	0.7	1.0	0.7	0.6	0.6
CaO	14.30	12.85	10.85	14.25	12.35	11.80	9.10
Na ₂ O	3.60	4.30	5.35	3.45	4.70	5.05	6.25
K ₂ O	0.13	0.13	0.16	0.12	0.15	0.16	0.21
Total	100.63	99.78	100.56	100.22	99.90	100.41	100.46

c=phenocryst core, r=phenocryst rim, m=microphenocryst, g=groundmass

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pyroxene, and plagioclase. Total Fe

ML-57		143-C-1	
c	m	m	g
52.09	51.56	53.01	52.28
1.61	2.33	1.6	1.55
0.70	0.91	0.71	0.63
10.19	10.08	10.78	10.68
19.99	19.66	19.81	19.86
14.91	14.84	14.58	14.51
0.44	0.47	0.46	0.44
99.93	99.85	100.95	99.95

205-C-1			
c	r	m	g
49.5	48.0	50.5	52.5
32.1	32.4	31.5	30.0
1.1	1.1	0.9	0.8
15.30	15.75	14.60	12.80
3.10	2.85	3.35	4.35
0.10	0.10	0.13	0.13
101.20	100.20	100.98	100.58

g
57.4
26.9
0.6
9.10
6.25
0.21

100.46

g = groundmass

Plagioclase. The composition of the plagioclase varies systematically within the Medicine Lake shield volcanics. The basaltic andesite lavas contain plagioclase phenocrysts which range in composition from An₆₅ to An₈₀ and have normally zoned margins. However, some of these shield-forming flows do have plagioclase with a thin reverse zone (averaging 3–5 mole % more An-rich than the core composition) around a homogeneous core which in turn is surrounded by a normally zoned rim. This latter type of zoning pattern occurs in less than 10% of the basaltic andesite flows. Groundmass plagioclase compositions are nearly identical to that of the outermost phenocryst rim, independent of which type of zoning is present.

The more siliceous rampart-forming andesites contain plagioclase phenocrysts which range from An₅₅ to An₇₀ with normally zoned outer margins being essentially the only type of zoning pattern encountered in these flows. The rims are generally 5–10% more albitic than the core composition. The most sodic-rich plagioclase is found in the groundmass of these lavas, averaging An₄₅ in composition. Oscillatory zoning is only rarely observed in plagioclase from either group of lava flows.

Lastly within the plagioclase-olivine cumulates, the feldspar phenocrysts have very homogeneous unzoned cores that range in composition from An₇₀ to An₈₀, a range quite similar to that observed in the basaltic andesite lavas. The cores are surrounded by a thin normally zoned rim which averages 10% more albitic than the core compositions. No other zoning patterns were identified in flows of this type.

Olivine. Olivine is present throughout the lava series; as the dominant ferromagnesian mineral in the basaltic andesites (53–55% silica) and diminishes in importance becoming only an accessory phase in the most siliceous andesites (59–62% silica). Within the plagioclase-olivine cumulates, the phenocrystic olivines vary in composition from Fo₆₅ to Fo₇₀ and are only weakly zoned. They are chemically analogous to the olivines which occur in the shield and rampart lavas. The CaO concentration differences between phenocryst cores and rims are less than 0.1%, which suggests the dominance of decreasing temperature rather than significant pressure fluctuations (Stormer, 1973). Crystallization at shallow depths is indicated.

Clinopyroxene. Overall clinopyroxene shows little compositional variation with respect to Ca, Mg, and Fe through the entire sequence of Medicine Lake lavas, consistently being a magnesian augite averaging Ca₄₁Mg₄₃Fe₁₆ in composition. The clinopyroxenes found within the basaltic andesites have significant amounts of Al₂O₃ (2–5.6%), TiO₂ (0.6–1.6%), and Na₂O (0.4–0.52%) with little compositional distinction between phenocryst cores and rims as well as groundmass occurrences. The range of Al₂O₃ and Na₂O is nearly identical to the values in clinopyroxenes from Tongan (Ewart and others, 1973) and Aleutian andesites (Marsh, 1976). However, the TiO₂ is significantly higher in the Medicine Lake clinopyroxenes and probably reflects the much higher whole rock concentration of this element in these andesites. In the rampart andesites the Al₂O₃, TiO₂, and Na₂O values are slightly lower and once again little compositional variation exists between phenocryst cores, rims, and groundmass.

The decided lack of compositional variation as a function of grain size in this suite of andesitic lavas suggests they crystallized under quite similar physiochemical regimes; that is, under relatively near-surface conditions.

Orthopyroxene. This phase makes a significant appearance only in the more siliceous andesite lavas, ranging in composition from En₆₉ to En₅₉. Grain to grain zonation is miniscule, averaging only 1 to 2 mole %. The phenocrysts have slightly higher contents of Al₂O₃ and TiO₂ in comparison to groundmass orthopyroxene values. As in the clinopyroxenes, the TiO₂ is much higher in the Medicine Lake orthopyroxenes (0.28–0.40%) when compared to reported values from Aleutian and Tongan andesites (Marsh, 1976; Ewart and others, 1973). The lack of significant compositional differences between phenocryst and groundmass orthopyroxene is suggestive of nearly identical conditions of crystallization. This relationship together with the low Al₂O₃ values attest to a low pressure near surface site for the precipitation of the orthopyroxene.

Geochemistry of the Lavas

Chemical analyses of the lavas are listed in Table 4. The rationale for reporting data concerning only lava flow samples is that noticeably porphyritic

Table 4. Major element analyses (weight percent) and trace elements (ppm) of the Medicine Lake lavas

Sample	Cumulates			Shield andesites	
	ML-28 ^a	ML-27 ^a	ML-74-33A ^b	36-6W	319-D-1
SiO ₂	50.11	50.68	52.53	53.25	53.70
Al ₂ O ₃	19.33	19.29	16.47	17.24	18.25
Fe ₂ O ₃	7.56	6.60	4.34	2.32	2.98
FeO	1.13	1.86	6.45	6.31	5.10
TiO ₂	0.87	0.85	1.69	1.37	1.08
MnO	0.15	0.13	0.16	0.15	0.15
MgO	6.95	7.23	3.87	4.01	5.15
CaO	8.82	8.80	7.86	8.17	8.42
Na ₂ O	3.09	3.29	4.55	4.01	3.82
K ₂ O	0.42	0.53	0.94	0.85	0.88
P ₂ O ₅	0.14	0.10	0.38	0.19	0.16
L.O.I.	0.55	0.49	0.42	1.47	0.75
Total	99.12	99.85	99.66	99.34	100.44
FeO ^T	8.00	7.86	10.39	8.42	7.82

Trace elements (ppm)

Rb	3	4	—	11	10
Sr	756	760	521	657	699
Ni	136	119	9	12	30
Zr	137	144	200	192	148
Ba	330	315	560	595	365
Y	12	12	28	26	12
V	137	145	287	246	190
Rb/Sr	0.004	0.005	—	0.017	0.014
K/Rb	1167	1100	—	641	731

Sample	Shield andesites				
	SM-75-44	205-C-1	ML-56	ML-74-34A	SM-75-211
SiO ₂	55.42	55.57	55.68	55.92	57.05
Al ₂ O ₃	16.33	17.94	16.55	17.63	17.32
Fe ₂ O ₃	3.41	3.66	1.12	2.98	2.00
FeO	5.05	5.32	7.92	5.30	6.26
TiO ₂	1.26	1.53	1.44	1.61	1.19
MnO	0.15	0.16	0.15	0.15	0.15
MgO	4.38	3.41	3.93	2.64	2.98
CaO	7.49	6.79	7.09	6.08	6.41
Na ₂ O	3.94	4.36	4.49	4.70	4.20
K ₂ O	1.13	1.14	1.07	1.22	1.47
P ₂ O ₅	0.18	0.21	0.22	0.31	0.23
L.O.I.	0.48	0.88	0.33	0.73	0.38
Total	99.22	100.97	99.99	99.27	99.64
FeO ^T	8.96	8.65	8.94	8.02	8.09

^a ML-28 and ML-27 are plagioclase-olivine cumulates

^b ML-74-33A is a plagioclase, clinopyroxene, titanomagnetite cumulate

nts (ppm) of the Medicine Lake lavas

Shield andesites		
33A ^b	36-6W	319-D-1
	53.25	53.70
	17.24	18.25
	2.32	2.98
	6.31	5.10
	1.37	1.08
	0.15	0.15
	4.01	5.15
	8.17	8.42
	4.01	3.82
	0.85	0.88
	0.19	0.16
	1.47	0.75
	99.34	100.44
	8.42	7.82
	11	10
	657	699
	12	30
	192	148
	595	365
	26	12
	246	190
	0.017	0.014
	641	731

SM-75-25	SM-75-54	ML-74-35	SM-75-209	SM-75-52	88-B-1	ML-74-34C
53.78	53.85	54.32	54.78	54.91	55.00	55.24
18.21	18.39	17.45	17.80	17.98	18.10	17.58
2.00	3.32	5.69	2.75	2.09	4.62	2.67
5.97	4.92	2.87	5.40	5.97	4.02	5.59
1.09	1.01	1.31	1.25	1.11	1.43	1.23
0.15	0.16	0.16	0.16	0.15	0.15	0.16
4.77	4.67	3.85	3.47	4.45	3.62	3.87
8.38	8.23	7.35	7.12	7.99	6.98	7.51
3.92	4.01	4.40	4.35	4.10	4.83	4.97
0.85	0.77	0.93	1.07	0.87	1.15	0.97
0.16	0.16	0.20	0.18	0.18	0.24	0.21
0.35	0.84	0.79	0.87	0.73	0.40	0.52
99.63	100.33	99.32	99.20	100.53	100.54	100.51
7.98	7.94	8.05	7.91	7.88	8.23	8.03

12	8	16	21	20	13	20
678	685	612	644	656	629	588
31	31	6	7	17	7	2
155	158	179	175	166	172	181
335	405	510	460	395	540	515
15	13	14	25	15	21	14
196	171	207	218	195	238	217
0.018	0.012	0.026	0.033	0.030	0.021	0.034
588	799	483	423	361	734	403

Rampart andesites

ML-74-34A	SM-75-211	ML-43	26-16M	SM-75-248	22-2b	15-15-A2	ML-19	15-4-3
55.92	57.05	57.06	57.43	58.52	58.86	59.26	59.59	59.60
17.63	17.32	16.87	16.79	17.90	15.76	16.67	15.95	16.43
2.98	2.00	2.21	2.20	2.00	2.06	1.93	2.42	4.01
5.30	6.26	6.00	5.99	5.13	5.63	5.25	4.45	3.53
1.61	1.19	1.38	1.40	1.66	1.54	1.43	1.45	1.61
0.15	0.15	0.15	0.15	0.16	0.17	0.16	0.16	0.15
2.64	2.98	3.56	2.74	1.99	1.93	1.57	2.00	2.27
6.08	6.41	6.41	7.08	4.79	5.02	4.94	4.66	5.13
4.70	4.20	4.76	4.30	5.22	4.73	5.11	5.13	5.51
1.22	1.47	1.29	1.33	1.59	1.75	1.70	1.59	1.54
0.31	0.23	0.21	0.22	0.35	0.35	0.41	0.33	0.48
0.73	0.38	0.57	0.36	1.32	0.93	1.29	1.15	0.23
99.27	99.64	100.47	99.99	100.63	98.73	99.72	98.88	100.49
8.02	8.09	8.01	7.99	6.95	7.50	7.00	7.31	7.17

te cumulate

Table 4 (continued)

Sample	SM-75-44	205-C-1	ML-56	ML-74-34A	SM-75-211
Trace elements (ppm)					
Rb	23	27	20	18	40
Sr	615	603	638	582	553
Ni	10	—	11	1	6
Zr	178	186	190	206	207
Ba	475	575	515	600	450
Y	21	15	26	21	12
V	221	265	255	232	190
Rb/Sr	0.037	0.045	0.031	0.031	0.072
K/Rb	409	351	444	563	305
Rampart andesites					
Sample	ML-57	SM-75-31	22-7E	ML-74-16	ML-15
SiO ₂	59.85	59.91	59.93	60.19	60.19
Al ₂ O ₃	16.25	17.75	16.39	16.20	16.38
Fe ₂ O ₃	1.44	2.85	1.95	4.95	0.61
FeO	5.41	4.28	5.32	2.14	6.31
TiO ₂	1.47	1.55	1.53	1.41	1.50
MnO	0.16	0.17	0.16	0.15	0.15
MgO	2.64	2.08	1.92	1.96	2.34
CaO	4.27	4.69	4.87	4.52	4.77
Na ₂ O	5.21	4.96	4.93	5.22	5.30
K ₂ O	1.63	1.58	1.57	1.70	1.63
P ₂ O ₅	0.42	0.36	0.36	0.37	0.29
L.O.I.	0.90	0.22	0.79	0.65	0.68
Total	99.65	100.40	99.72	99.46	100.15
FeO ^T	6.72	6.88	7.09	6.64	6.86
Trace elements (ppm)					
Rb	34	32	34	37	26
Sr	465	493	493	473	484
Ni	3	—	6	5	7
Zr	254	256	262	272	250
Ba	899	768	820	882	877
Y	38	32	21	21	32
V	111	135	136	111	135
Rb/Sr	0.073	0.065	0.069	0.078	0.054
K/Rb	398	410	383	381	520

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ML-74-34A	SM-75-211
18	40
582	553
1	6
206	207
600	450
21	12
232	190
0.031	0.072
563	305

ML-43	26-16M	SM-75-248	22-2b	15-15-A2	ML-19	15-4-3
28	25	39	31	24	27	25
607	637	490	503	498	473	526
14	9	—	1	3	5	1
210	211	233	256	267	250	244
550	550	795	845	860	850	808
24	45	30	36	41	32	38
208	201	159	144	115	122	144
0.046	0.039	0.080	0.062	0.048	0.057	0.048
382	442	338	469	588	489	512

ML-74-16	ML-15
60.19	60.19
16.20	16.38
4.95	0.61
2.14	6.31
1.41	1.50
0.15	0.15
1.96	2.34
4.52	4.77
5.22	5.30
1.70	1.63
0.37	0.29
0.65	0.68
99.46	100.15
6.64	6.86
37	26
473	484
5	7
272	250
882	877
21	32
111	135
0.078	0.054
381	520

22-7d	8-9-B-1	6-10-D-7	22-12F	22-7C	143-C-1
60.53	60.78	60.84	60.88	60.90	62.21
16.63	16.61	16.43	16.61	16.33	17.07
1.93	1.89	2.01	1.95	1.92	1.43
5.26	5.61	4.48	5.32	5.21	4.25
1.53	1.46	1.31	1.53	1.50	1.15
0.16	0.16	0.12	0.16	0.16	0.15
2.09	2.07	1.91	2.17	2.00	1.38
4.87	4.50	4.49	4.93	4.80	3.65
5.49	5.67	5.96	5.38	4.72	5.70
1.58	1.75	1.78	1.63	1.68	1.81
0.32	0.39	0.35	0.35	0.42	0.24
0.49	0.59	0.65	0.51	1.18	0.32
100.88	101.48	100.33	101.42	100.82	99.36
7.02	7.30	6.31	7.10	6.95	5.55
36	39	43	23	32	38
495	474	451	506	497	399
6	5	10	4	5	—
263	283	264	262	263	263
835	922	810	870	895	953
11	41	29	46	35	33
145	123	132	140	138	69
0.073	0.082	0.095	0.045	0.064	0.095
364	373	344	588	436	413

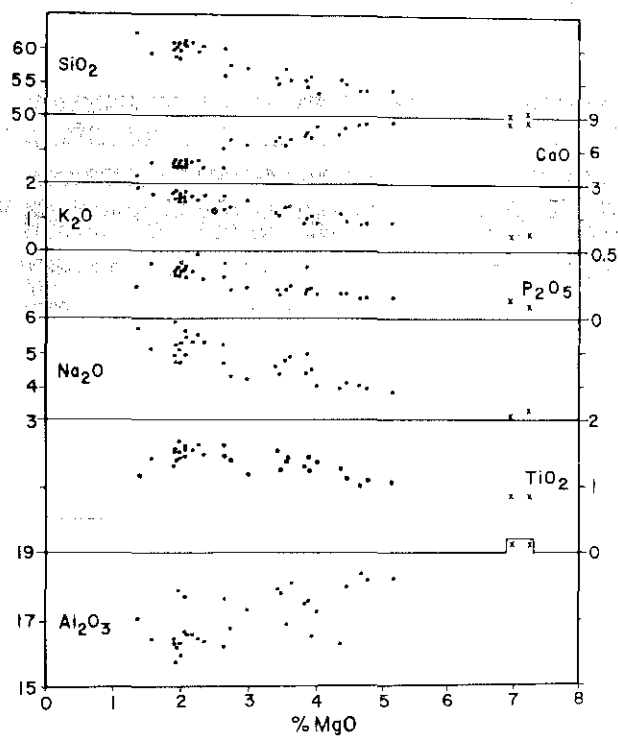


Fig. 3. SiO₂, CaO, K₂O, P₂O₅, Na₂O, TiO₂, and Al₂O₃ (weight percent) in the Medicine Lake lavas as a function of MgO. Symbols: ● = lava; × = plagioclase-olivine cumulates. All subsequent diagrams will utilize the same symbolism

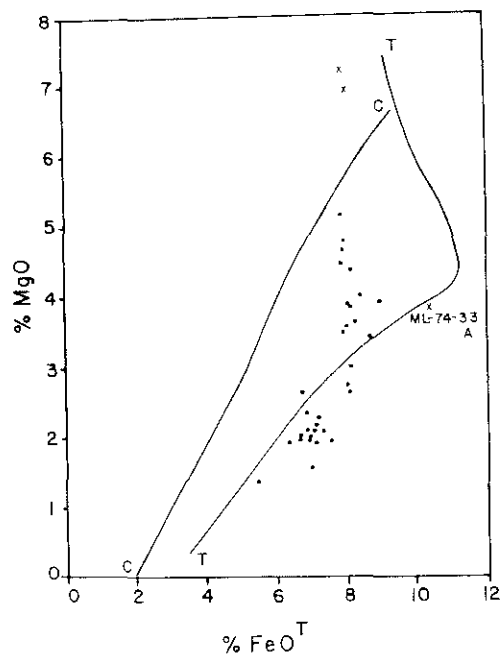


Fig. 4. FeO^T versus MgO diagram illustrating iron-enrichment. C-C represent the average High Cascade trend (Carmichael, 1964); T-T represents the Thingmuli trend (Lowder and Carmichael, 1970). ML-74-33A is a plagioclase, clinopyroxene, titanomagnetite cumulate

rocks, which are probably cumulative to some degree, can be excluded from variation diagrams enabling a liquid line of descent to be delineated.

For major element chemistry samples were fused with eight parts lithium tetraborate and one part lanthanum oxide to one part dried sample (Rose and others, 1963). The bead was crushed and one gram of it was mixed with 0.5 g of microcrystalline cellulose and pressed into a pellet using a coarse grade of cellulose as a backing. For trace element analysis one gram of dried whole rock powder was mixed with 0.5 g of microcrystalline cellulose and pressed into pellets, again using coarse cellulose as a backing. Trace element data reduction was achieved by the mass absorption correction method outlined by Hower (1959). A Diano 8300 automated X-ray spectrometer was used for all major and trace element determinations.

Major Element Chemistry. Major element MgO variations diagrams (Fig. 3) indicate three distinct elemental associations as a function of decreasing MgO: SiO_2 , Na_2O , K_2O and P_2O_5 increase in concentration; CaO and Al_2O_3 decrease in concentration; while FeO^T and TiO_2 depict a pattern of rising concentration which reaches a maximum and then declines. The last of these associations is of most interest as an iron enrichment trend is atypical of High Cascade volcanism (Carmichael, 1964). However, such a pattern has been identified at Newberry volcano (Higgins, 1973). MgO-FeO (Fig. 4) and AFM (Fig. 5) diagrams demonstrate this initial trend towards iron enrichment, which covers the silica interval of 53–57%. In comparison to the iron enrichment patterns which have been documented for Thingmuli (Carmichael, 1964) and Talasea (Lowder and Carmichael, 1970), the trend of the Medicine Lake lavas is considerably more mild. The FeO behavior (mirrored to a large extent by TiO_2) can be quantitatively related to the phenocryst mineral assemblage characteristic of the less siliceous andesitic lavas. The minerals crystallizing in the older shield-forming lavas are calcic plagioclase and olivine, with subordinate clinopyroxene and rare orthopyroxene; there is a decided lack of phenocrystic titanomagnetite

Fig. 3. SiO_2 , CaO , K_2O , P_2O_5 , Na_2O , TiO_2 , and Al_2O_3 (weight percent) in the Medicine Lake lavas as a function of MgO. Symbols: ● = lava; × = plagioclase-olivine cumulates. All subsequent diagrams will utilize the same symbolism

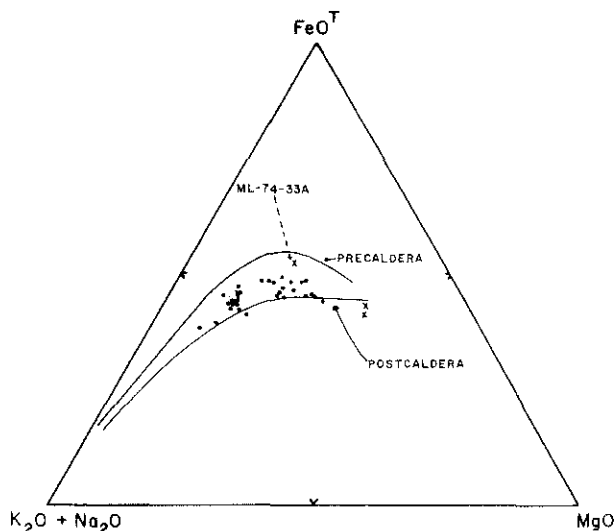


Fig. 5. AFM diagram for the Medicine Lake lavas. The dual trends reported by Higgins (1973) concerning Newberry volcano in Oregon are also depicted. All values are in weight percent

1. FeO^T versus MgO diagram rating iron-enrichment. represent the average High Cascade trend (Carmichael, 1964); T-T represents the Thingmuli trend (Lowder and Carmichael, 1970). ML-74-33A plagioclase, clinopyroxene, and titanomagnetite cumulate

Table 5. Least squares approximation of the average anhydrous basaltic andesite^a calculated as a linear combination of the most Fe-rich andesite (ML-56) together with plagioclase, olivine, and clinopyroxene from andesite (205-C-1)

	Observed	Calculated	Variable	Wt. fraction
SiO ₂	54.25	54.24	ML-56	0.7745
Al ₂ O ₃	18.22	18.21	Clinopyroxene	0.0242
FeO	8.13	8.11	Olivine	0.0331
MgO	4.70	4.71	Plagioclase	0.1682
CaO	8.39	8.40		
Na ₂ O	3.98	4.08	Σ of the square of residuals = 0.0106	
K ₂ O	0.85	0.86		
MnO	0.15	0.13		
TiO ₂	1.15	1.14		
P ₂ O ₅	0.17	0.17		

^a Average anhydrous basaltic andesite is based on analyses of samples 36-6W, 319-D-1, SM-75-25, and SM-75-54 recalculated to 100%.

Table 6. Least squares approximation of a cumulative basalt (ML-27) calculated as a linear combination of the average anhydrous basaltic andesite together with plagioclase and olivine from basaltic andesite (88-B-1)

	Observed	Calculated	Variable	Wt. fraction
SiO ₂	51.32	51.32	Basaltic andesite	0.6464
Al ₂ O ₃	19.53	19.49	Olivine	0.1102
FeO	7.95	7.95	Plagioclase	0.2433
MgO	7.32	7.32		
CaO	8.91	8.98	Σ of the square of residuals = 0.0234	
Na ₂ O	3.33	3.39		
K ₂ O	0.54	0.58		
MnO	0.13	0.13		
TiO ₂	0.85	0.74		
P ₂ O ₅	0.10	0.11		

in these flows. Utilizing a least squares linear mixing program (Bryan and others, 1969), calculations have been performed using the probe mineral data and the lava bulk compositions (recalculated to be anhydrous and total 100%) which clearly demonstrate that the initial iron enrichment trend depicted in Figures 4 and 5 is consistent with an origin through low pressure crystal fractionation of the observed phenocryst assemblage (see Table 5 for results of calculation). Analyzed lavas which represent cumulates of this early phase of crystallization are represented by samples ML-27 and ML-28. As previously indicated petrographic evidence suggests these basalts contain significant cumulitic plagioclase and olivine that result from a fractionating parental andesitic magma under low pressure conditions. Mixing calculations (see Table 6 for results) strongly support this supposition and are in reasonable agreement with available modal data (see Table 2 for mode).

rous basaltic andesite^a calculated as together with plagioclase, olivine, and

Variable	Wt. fraction
L-56	0.7745
Clinopyroxene	0.0242
Olivine	0.0331
Plagioclase	0.1682

of the square of residuals = 0.0106

of samples 36-6W, 319-D-1, SM-75-25,

basalt (ML-27) calculated as a linear trend with plagioclase and olivine from

Variable	Wt. fraction
Basaltic andesite	0.6464
Olivine	0.1102
Plagioclase	0.2433

of the square of residuals = 0.0234

mixing program (Bryan and using the probe mineral data of anhydrous and total 100%) enrichment trend depicted in Figure 5. Table 5 for results of calculation of this early phase of crystallization (L-28). As previously indicated in significant cumultic plagioclase parental andesitic magma compositions (see Table 6 for results) in good agreement with available

Table 7. Least squares approximation of the average anhydrous andesite^a calculated as a linear combination of the most siliceous andesite (143-C-1) together with orthopyroxene, clinopyroxene, olivine, and plagioclase from ML-57. The titanomagnetite analysis used is an average of 3 analyses from Medicine Lake lavas contained in Carmichael (1967), Table 3. The apatite composition used is stoichiometric $\text{Ca}_5(\text{PO}_4)_3$

	Observed	Calculated	Variable	Wt. fraction
SiO_2	56.10	56.10	143-C-1	0.6205
Al_2O_3	17.25	17.25	Orthopyroxene	0.0373
FeO	8.71	8.71	Olivine	0.0119
MgO	3.62	3.62	Clinopyroxene	0.0864
CaO	6.92	6.92	Plagioclase	0.2005
Na_2O	4.41	4.42	Titanomagnetite	0.0420
K_2O	1.15	1.15	Apatite	0.0014
MnO	0.15	0.11		
TiO_2	1.46	1.44		
P_2O_5	0.23	0.21		
				Σ of the square of residuals = 0.0021

^a Average anhydrous andesite is based on analyses of samples SM-75-44, 205-C-1, ML-56, and ML-74-34A recalculated to 100%.

All samples with silica greater than approximately 57%, have discernible microphenocrysts of titanomagnetite. With the appearance of titanomagnetite as a liquidus phase, the potential exists for its incorporation into a fractionated mineral assemblage thereby causing a considerable change in the path of the liquid line of descent. Mixing calculations once again demonstrate that major element changes which occur between the most Fe-rich lava to the most siliceous andesite can be accurately modeled via a crystal fractionation scheme involving only the phenocryst-forming minerals that are characteristic of the rampart lavas. The results illustrated in Table 7 are completely reasonable in light of the modal mineralogy previously described.

An AFM diagram (Figure 5) permits a direct comparison to be made with the trends reported by Higgins (1973) for Newberry Volcano. Two trends were observed at Newberry which Higgins related to the presence or absence of a lake within the summit caldera. Higgins suggested this lake would exert significant influence over the oxygen fugacity of magma differentiating in very shallow chambers, so that when the lake was in existence an alkali enrichment trend would be produced and when it was not, more of an iron enrichment trend would occur. The Medicine Lake andesites do not depict two trends, even though a summit caldera lake of considerable volume has been present for a significant period of the volcano's geologic history. Assuming Higgins' interpretation is valid, the lack of a dual trend at Medicine Lake suggests fractionation was occurring under slightly deeper conditions, thereby negating lake water access to the magma chamber. However, no $\text{O}^{18}/\text{O}^{16}$ analyses have been performed to verify this suggestion.

In an $\text{SiO}_2 - \text{K}_2\text{O}$ diagram (Figure 6) the Medicine Lake data produce a relatively coherent linear relationship. Smith and Carmichael (1968) also determined a $\text{SiO}_2 - \text{K}_2\text{O}$ relationship for Medicine Lake and, interestingly enough,

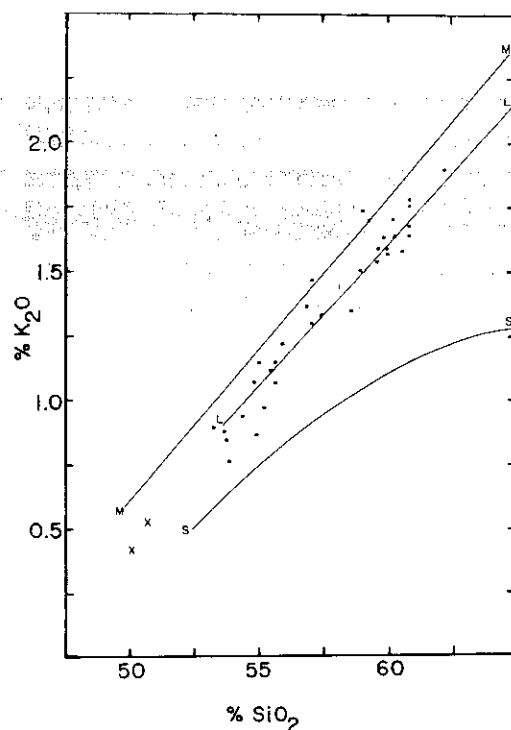


Fig. 6. K_2O versus SiO_2 for the Medicine Lake lavas. The solid lines (M-M, Medicine Lake; S-S, Mt. Shasta; L-L, Mt. Lassen) are the average trends reported by Smith and Carmichael (1968), which were based on all available data

the two lines do not coincide. However, most of their data were from postcaldera basalts and basaltic andesites that are younger than the rampart andesites and which may not have originated under the same physical conditions as those lavas directly related to the Medicine Lake volcano. Comparison of available K_2O-SiO_2 data from other nearby Cascade volcanoes indicates that Mt. Lassen and Newberry are similar to Medicine Lake, while Crater Lake and Mts. Jefferson and Shasta have progressively lower K_2O values at a given percent of SiO_2 (Smith and Carmichael, 1968; Condie and Swenson, 1973). In light of the ideas of Dickinson and Hatherton (1967), Dickinson (1968), and Hatherton and Dickinson (1968, 1969) concerning increasing K content in andesitic lavas as a function of depth to the Benioff zone, qualitative agreement exists between the locations of these volcanoes and the dominant trend of the Cascade Mountains; that is, a pattern of increasing K_2O away from the trench is apparent.

Trace Element Chemistry. Whole-rock trace element contents are listed in Table 4. With respect to the steadily declining MgO content of the Medicine Lake lavas (Fig. 7), Rb , Zr , Y , and Ba steadily increase in concentration; Ni and Sr continually decrease; while V initially rises and then sharply declines. The last of these associations is of interest as V behavior faithfully mirrors that of Fe and Ti . Since V exists in the +3 oxidation state, its geochemical behavior will be strongly controlled by the availability of a cation site which

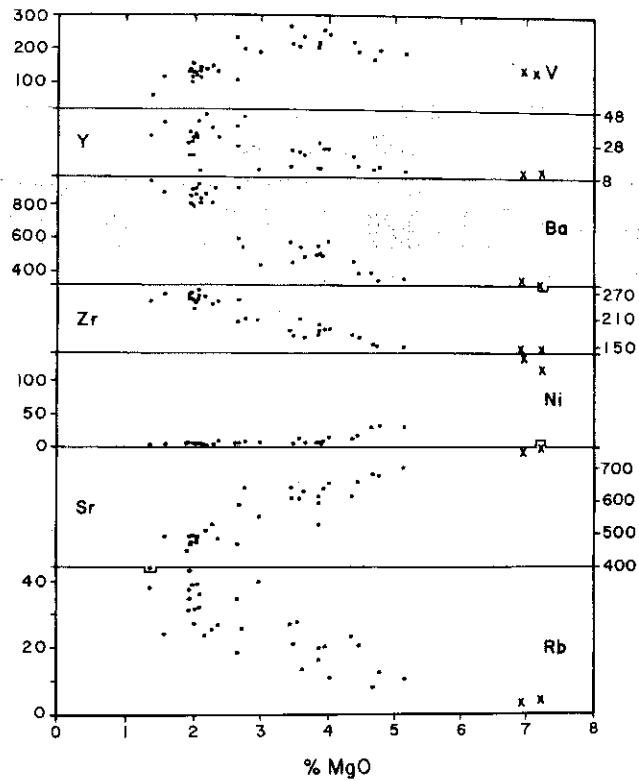


Fig. 7. V, Y, Ba, Zr, Ni, Sr, and Rb (ppm) in the Medicine Lake Lavas as a function of MgO (weight percent)

can accommodate this ion in terms of its size and charge. Mineralogically, titanomagnetite has a readily available Fe^{+3} site in which V^{+3} will be preferentially substituted in terms of crystal field effects (Burns, 1970). The titanomagnetite typical of orogenic andesites contains from 0.4–1.8% V_2O_5 (Smith and Carmichael, 1968; Duncan and Taylor, 1969; Ewart and others, 1973) with a partition coefficient between 30 and 40. In light of the mixing calculations illustrated in Table 7 fractionation of 4% titanomagnetite is required to produce the major element chemistry of the most siliceous andesite. An average of 0.5% V in the fractionated titanomagnetite, a value well within the limits outlined above, produces the measured changes in V concentration between the projected parent liquid and the fractionated product. The calculated value based on a 0.5% V figure is 43 ppm and the actual measured value is 69 ppm. The mixing calculations are in agreement with the conclusion that the Fe, Ti, and V trends characteristic of the Medicine Lake lavas are largely controlled by the presence or absence of titanomagnetite as a phenocryst-forming mineral.

The appearance of titanomagnetite as a liquidus phase can also be demonstrated in a Ti/V vs. MgO diagram (Fig. 8). Between approximately 5.15 and 3% MgO, the Ti/V ratio is nearly constant, and between 3 and 2.5% the ratio begins to rise due to the advent of titanomagnetite precipitation. This interval of MgO values also corresponds with a change in slope of the SiO_2 –MgO relationship and a gap in the SiO_2 – K_2O diagram, indicating a significantly

K_2O versus SiO_2 for the Medicine Lake lavas. The solid (M-M, Medicine Lake; Mt. Shasta; L-L, Mt. Lassen) are the average trends established by Smith and Carmichael (1968), which were based on all available data

data were from postcaldera the rampart andesites and typical conditions as those of Mt. Lassen. Comparison of available data indicates that Mt. Lassen is at a given percent of SiO_2 on Mt. Shasta (1973). In light of the work of Smith (1968), and Hatherton (1973), the agreement exists between the trends of the Cascade Mountain trench is apparent.

contents are listed in Table 7. The content of the Medicine Lake lavas increases in concentration; Ni and then sharply declines. This behavior faithfully mirrors the behavior of a cation site which

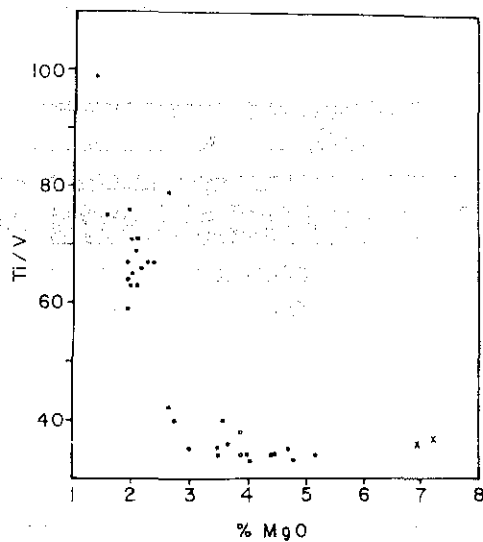


Fig. 8. The Ti/V ratio as a function of MgO (weight percent) for the Medicine Lake lavas

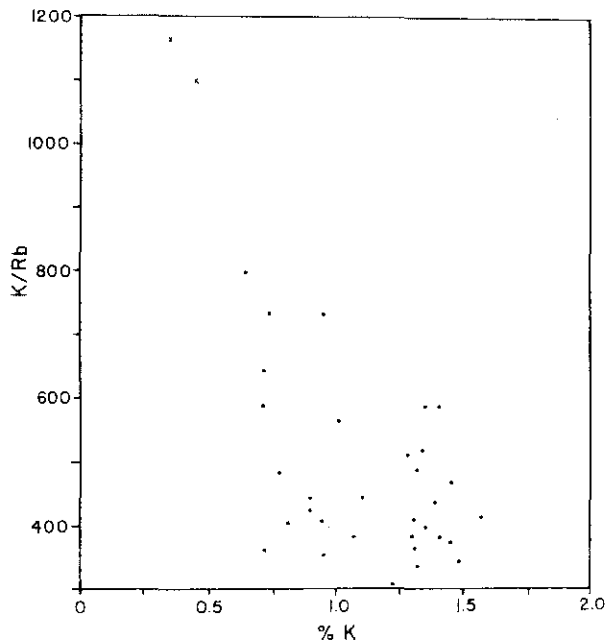


Fig. 9. A plot of K/Rb versus % K for the Medicine Lake lavas

greater rate of silica enrichment after titanomagnetite becomes available as a cumulative phase. This effect has been previously documented by certain experimental studies (Eggler and Burnham, 1973; Eggler, 1974) and appears to be confirmed by trends documented to exist within the Medicine Lake volcanics.

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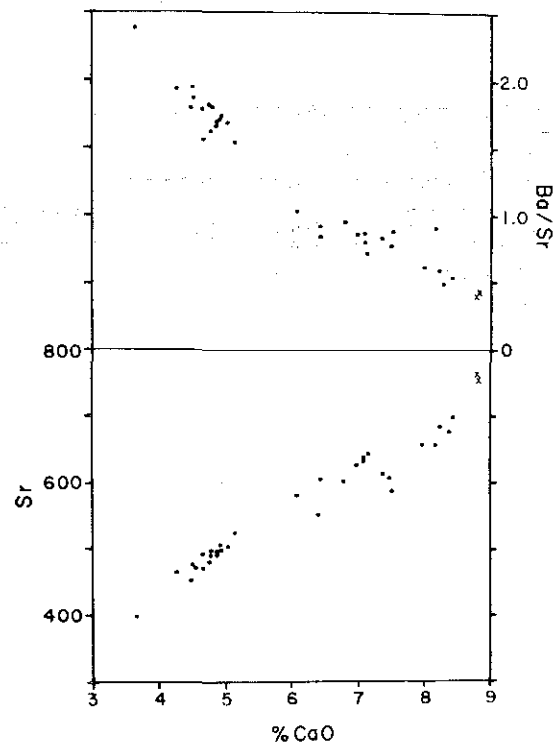


Fig. 10. Ba/Sr and Sr (ppm) as a function of CaO (weight percent) in the Medicine Lake lavas

The K/Rb-% K relationship (Fig. 9) indicates a generally declining pattern as K increases, although a fair amount of scatter is present. Presumably plagioclase is the mineral phase responsible for the decrease of the K/Rb ratio during liquid-crystal fractionation (Philpotts and Schnetzler, 1970; Gill and Murthy, 1970). This conclusion is supported by the high (K/Rb) values of the early cumulates (> 1000), a direct result of the accumulated plagioclase in the specimens). Ni-MgO (Fig. 7) demonstrates a sharply declining trend as MgO decreases, a result of a distribution coefficient for Ni in olivine of 10–15 (Hakli and Wright, 1967; Gunn, 1971). The early cumulates plot at high Ni values, reflecting the substantial amount (8–13%) of cumulative olivine. Zr and Y have consistently increasing abundance patterns. Apparently zircon was not a liquidus phase at any time during the crystallization of the Medicine Lake andesites. Y has a strong geochemical coherence with Ca; as Ca decreases, Y increases with significant scatter. This trend probably results from plagioclase fractionation, as it has a very high Ca/Y ratio and its inclusion into a cumulate would lead to an increasing Y concentration in the residual magma (Lambert and Holland, 1974).

Strontium decreases in concentration from the oldest least siliceous lavas to the youngest, most fractionated lavas. Removal of calcic plagioclase would produce the sympathetically declining CaO-Sr pattern depicted in Figure 10, and is in complete accord with the mixing calculations presented in Tables 5–7.

the Ti/V ratio as a function of MgO (weight percent) in the Medicine Lake lavas

Fig. 9. A plot of K/Rb versus % K for the Medicine Lake lavas

etite becomes available as is documented by certain (Eggler, 1974) and appears in the Medicine Lake volca-

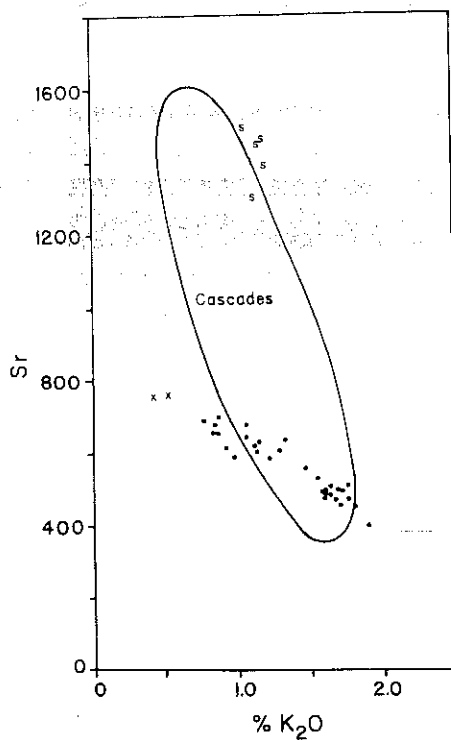


Fig. 11. A plot of Sr (ppm) versus K_2O (weight percent) for the Medicine Lake lavas. The large field-labeled "Cascades" is from Gunn (1973) and represents a summary of available whole-rock Sr data. Data points "S" are from Peterman and others (1970) and Condie and Swenson (1973)

Clinopyroxene fractionation is not capable of producing this pattern; it would result in strong CaO depletion with a constant to rising Sr concentration (Philpotts and Schnetzler, 1970; Jensen, 1973). Gunn (1974) reported that Cascade andesites have some of the highest whole-rock Sr values ever determined for subduction zone related andesites. Portions of his data have been reproduced in Figure 11 (Field labeled "Cascades") with Medicine Lake values plotted for direct comparison. The Medicine Lake data does not totally fall within the "Cascades" field. Almost all of the highest Sr values are from Mt. Shasta and its associated volcanics in northcentral California (Peterman and others, 1970; Condie and Swenson, 1973), which is located approximately 60 km southwest of the Medicine Lake Highland. It appears that traversing eastward from the vicinity of Mt. Shasta the whole rock K_2O increases and the Sr decreases, a relationship which has to be considered in any petrogenetic model suggested for the entire area.

Ba increases in concentration as the lavas become more siliceous, however, the data plot in two discrete groups (Fig. 7). Ba/Sr as a function of CaO (Fig. 10) further emphasizes the dichotomy. Both the gap in CaO values and the change in slope of the Ba/Sr ratio probably result from the advent of significant clinopyroxene fractionation, an interpretation that is strongly supported by the mixing calculations contained in Tables 5 and 7. Its accumulation in a fractionating mineral assemblage together with omnipresent plagioclase would result in a

much more rapid CaO depletion of the residual liquid and also cause a change in the Ba/Sr ratio due to its significantly lower Ba distribution coefficient (Onuma and others, 1968; Jensen, 1973).

Rare earth element (REE) data concerning shield and rampart andesites have been determined by Barsky (1975). They show a fractionated pattern in favor of the light rare earth elements (LREE) and a total abundance of less than 100 ppm. The general shape of the chondrite-normalized-REE pattern is essentially identical for samples of low silica andesite and for the most fractionated rampart andesites. However, the total concentration of REE increases as the silica content rises. The low silica andesite lavas have only a very slight negative europium anomaly that becomes more accentuated in the rampart andesites. The increasing negative Eu anomaly suggests plagioclase fractionation is involved in differentiating from low silica basaltic andesite to the more siliceous rampart andesite, a conclusion strongly supported by detailed mixing calculations, whole-rock Sr data, and petrographic evidence.

Strontium isotope data (Mertzman, unpublished data; Mueller, unpublished data) from the Medicine Lake shield-forming volcanics vary between 0.703–0.704, a range of values quite typical of orogenic andesites (Peterman and others, 1970; Dickinson, 1970; Hedge and Lewis, 1971; Carmichael and others, 1974). Ratios within this range can be produced by an origin within the upper mantle or lower crust from a low Sr^{87}/Sr^{86} source. However, strontium isotopes alone cannot be more precise in delineating the source region of these volcanics.

Petrogenesis

Following the very lucid petrogenetic exposition by Marsh (1976) probe mineral data has been collected so that the physiochemical conditions of crystallization of the Medicine Lake andesites can be delineated. The pressure under which the phenocryst-forming minerals crystallized is interpreted as being relatively low. The negligible difference in Na_2O content between clinopyroxene core and rim as well as phenocryst-groundmass values is indicative of low pressure crystallization (Thompson, 1974). The calcium zoning pattern in olivine and the small differences in Al_2O_3 content between microphenocryst and groundmass orthopyroxene are also suggestive of crystallization under low pressure conditions. In light of the experimental work of Green (1969) which demonstrated that plagioclase becomes more Na-rich in andesitic liquids as pressure is increased under isothermal conditions, the calcic nature of the phenocrystic plagioclase in these andesites would be symptomatic of low pressure crystallization.

The lack of discrete grains of ilmenite preclude the direct estimation of the oxygen fugacity in these lavas. Extensive mineralogic and chemical evidence exists, however, which strongly indicates titanomagnetite was *not* a liquidus phase initially, rather it crystallized only after plagioclase, olivine, and clinopyroxene had made their debuts on the liquidus. Some petrographic evidence is suggestive of orthopyroxene and titanomagnetite becoming liquidus phases nearly concurrently. As no hydrous phases are present in these lavas and olivine

of Sr (ppm) versus percent) for the lavas. The large "S" represents a available whole-rock Sr data "S" are from others (1970) and Jensen (1973)

g this pattern; it would Sr concentration (Phil- reported that Cascade ies ever determined for i have been reproduced e Lake values plotted ot totally fall within es are from Mt. Shasta (Peterman and others, oproximately 60 km south-aversing eastward from es and the Sr decreases, enetic model suggested

more siliceous, however, nction of CaO (Fig. 10)) values and the change nt of significant clinopy- supported by the mixing ation in a fractionating ase would result in a

is present in many of them, the oxygen fugacity most likely ranged somewhere between the Ni-NiO and QFM buffers (Carmichael, 1967, Fig. 2 and Eggler and Burnham, 1973, Fig. 5).

The lack of precise crystallization temperature information precludes any quantitative estimation of the P_{H_2O} during the solidification of these particular andesites. However, the paragenetic sequence (early plagioclase and olivine followed by clinopyroxene, with orthopyroxene and titanomagnetite appearing somewhat later) can be used to interpret a possible range of P_{H_2O} values by comparison with available experimental evidence concerning the phase relationships in andesitic liquids. The presence of olivine as the most important ferromagnesian phase in the basaltic andesites probably reflects lower silica activity values in these lavas. The silica activity rises during the course of the observed fractionation trends leading to the eventual replacement of olivine by orthopyroxene in the more siliceous lavas. However, the presence of olivine in andesites can also result under conditions where $P_{H_2O} = P_{Total}$ (Eggler, 1972). In light of plagioclase being the initial liquidus phase in most of these lavas, the possibility of H_2O -saturation can be eliminated since Eggler (1972, Fig. 3) has convincingly demonstrated that plagioclase crystallizes before olivine and orthopyroxene only for water contents less than 2 to 3 weight %. This limitation of P_{H_2O} values is also consistent with the dominant normal zoning sequence observed in the plagioclase feldspars. Pringle and others (1974) have suggested that when crystallization is controlled by relatively rapid heat removal which leads to some degree of supercooling, a normally zoned plagioclase will result under conditions which vary from anhydrous to P_{H_2O} -undersaturated. The presence of a zoning sequence calcic core followed by a thin more calcic (3-5 mole % An) zone with a more albitic outer margin which occurs in a minority of the basaltic andesite flows, suggests nearly anhydrous conditions (Pringle and others, 1974). The reverse zoning jump of 3-5 mole % An would reflect a maximum pressure drop of 3 to 5 kb.

Summarizing, crystallization of the observed phenocryst assemblage took place under a low pressure regime (upper maximum of 5 kb) characterized by water-undersaturated to nearly anhydrous conditions (upper maximum approximately 3% H_2O) with the oxygen fugacity fixed somewhere between the Ni-NiO and QFM buffers.

Using various chemical parameters does permit the identification of potential types of source materials which would give rise to the major and trace element abundances found in these particular andesites. The least fractionated low silica andesites of the Shield have $Mg/(Mg+Fe^{+2})$ ratios which range between 0.5-0.55 and Ni values of 30-35. Liquids generated in equilibrium with upper mantle pyrolite or some type of residual peridotite, whose $Mg/(Mg+Fe^{+2})$ is 0.88-0.92 and Ni content is approximately 3000 ppm (Ringwood, 1975), should have a $Mg/(Mg+Fe^{+2})$ of 0.68-0.72 and a Ni content of 250-400 (Green, 1970; Green and others, 1974). The disparity between the measured $Mg/(Mg+Fe^{+2})$ and Ni in the least silicic shield andesites and those reported above indicate these andesites cannot be primary partial melts which were in equilibrium with upper mantle pyrolite or magnesian peridotite. The high LIL element concentrations of these andesites also support this conclusion.

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SiO₂
Al₂O₃
Fe₂O₃
FeO
TiO₂
MnO
MgO
CaO
Na₂O
K₂O
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Table 8. Representative chemical analyses of the major magma types from the Medicine Lake Highland (Mertzman, unpublished data). Analyses of lavas typical of the earliest shield-forming stage and the late rampart-building stage of the Medicine Lake volcano are included for comparison

	Warner basalt type magma	Fractionated Warner basalt magma	Mammoth- Modoc type magma	Fractionated Mammoth- Modoc magma	Holocene glass flow	Early shield basaltic andesite	Rampart andesite
SiO ₂	47.83	48.78	50.80	59.65	73.15	53.78	60.19
Al ₂ O ₃	17.38	17.58	17.14	16.01	13.68	18.21	16.38
Fe ₂ O ₃	1.29	1.57	2.92	1.12	0.88	2.00	0.61
FeO	7.44	9.37	5.65	4.41	1.22	5.97	6.31
TiO ₂	0.77	1.33	0.77	0.72	0.28	1.03	1.50
MnO	0.18	0.19	0.15	0.10	0.03	0.15	0.15
MgO	9.96	7.49	8.47	3.87	0.34	4.77	2.34
CaO	10.94	10.25	10.01	5.87	1.26	8.38	4.77
Na ₂ O	3.19	3.47	2.87	4.28	3.96	3.92	5.30
K ₂ O	0.19	0.21	0.61	2.25	4.21	0.85	1.63
P ₂ O ₅	0.08	0.13	0.07	0.08	0.02	0.16	0.29
L.O.I.	0.47	0.18	0.17	1.17	0.45	0.35	0.68
Total	99.72	100.54	99.63	99.53	99.48	99.57	100.15
FeO ^T	8.62	10.80	8.30	5.43	2.02	7.98	6.86
Rb	<1	1	18	74	168	12	36
Sr	264	392	272	225	121	678	484
Ni	190	71	143	57	6	31	7
Zr	70	128	113	229	232	155	250
Ba	141	126	200	508	916	335	875
V	153	221	149	95	8	196	135

The Ni contents of the Medicine Lake andesites are very similar to the low Si andesite average Ni value reported in Taylor and others (1969a, b). Also, the V/Ni ratios are comparable, being greater than 6 in all the shield-forming lavas excepting the plagioclase-olivine cumulative rocks. The major and trace element similarities between Medicine Lake andesites and the average low Si calc-alkaline andesite suggest the possibility of an analogous origin involving anatexis of subducted lithosphere composed of low Sr⁸⁷/Sr⁸⁶ material along continental margins.

Eichelberger (1975) has hypothesized an origin of intermediate volcanic rocks by contamination of basaltic magma with rhyolite and vice versa within a volcanic pile. His theory is based on the Quaternary-Holocene basalt-rhyolite association that is superimposed on the Medicine Lake andesitic volcano. Two major categories of basalt characterize the flanks of the Medicine Lake Highland: a Mammoth Crater magma-type and its differentiates (Mertzman, in preparation; Condie and Hayslip, 1975) (See Table 8 for respective compositions). The former magma-type is volumetrically important and underlies 1/2 to 2/3 of Lava Beds National Monument. The latter magma-type is a LIL element depleted basalt that is remarkably time-transgressive in nature, having

likely ranged somewhere 1967, Fig. 2 and Eggler

formation precludes any variation of these particular plagioclase and olivine foliation. The appearance of anomalous magnetite, appearing in the range of P_{H_2O} values by changing the phase relationships. The most important ferro-magnesian effects lower silica activity in the course of the observed crystallization of olivine by orthopyroxene. The crystallization of olivine in andesites (Eggler, 1972). In light of these lavas, the possibility (Eggler, 1972, Fig. 3) has convinced us that olivine and orthopyroxene crystallization. This limitation of P_{H_2O} during the crystallization sequence observed have suggested that when olivine removal which leads to plagioclase will result under saturated conditions. The presence of more calcic (3-5 mole % Ca) occurs in a minority of these conditions (Pringle, 1972). The % An would reflect

the first assemblage took place characterized by water-saturated conditions approximately between the Ni-NiO and

identification of potential major and trace element in a fractionated low silica magma which range between equilibrium with upper mantle whose Mg/(Mg+Fe²⁺) ratio (Ringwood, 1975), should be in the range of 250-400 (Green, 1975). When the measured Mg/Fe ratios and those reported for mantle melts which were in equilibrium with peridotite. The high LIL element depletion in his conclusion.

been erupted from Latest Miocene to Recent (Macdonald, 1966). Its differentiates follow an iron-enrichment trend similar to that reported by Kuno (1965) in his investigation of segregation veins found within one of these basalt flows. A composition representative of Recent glass flow eruptions together with average analyses of least and most fractionated Medicine Lake lavas are listed in Table 8. With regard to TiO_2 , Na_2O , P_2O_5 , Zr, and Sr conceivable mixtures of these compositions with the rhyolite do not closely match the andesite chemistry. This hybrid origin of andesite suggested by Eichelberger (1975) is applicable in certain localized instances. However, the voluminous Medicine Lake andesite does not appear to be one of them.

Regional Geochemical Implications

Jakeš and White (1972) have summarized the chemical characteristics of island-arc and active continental margin calc-alkaline volcanic associations. Table 9 provides a comparison between their data and that concerning Medicine Lake, indicating the latter rocks to be more closely aligned to island-arc volcanism. This overall classification is also appropriate with regard to volume, as 30–40% of the Medicine Lake lavas have silica values of less than 56%. However, a degree of overlap with continental margin characteristics exists and should not be simply dismissed. One interpretation of this mingling of characteristics is that it arises from the complex regional tectonic setting of the Medicine Lake volcano; i.e., near the intersection of the Cascade Range, the Modoc Plateau, and the Basin and Range provinces (Macdonald, 1966; Higgins, 1973; Lawrence, 1976). With the interpretation of the Basin and Range physiographic province as an ensialic interarc basin by Scholz and others (1971), it becomes apparent that evaluating the petrogenetic behavior of the Medicine Lake volcano in particular and the southern Cascades in general within the framework of a classic arc-trench system may not be valid. It is suggested that the elemental characteristics of the Medicine Lake shield andesite may result as a combination of both subduction and interarc spreading processes. Elucidation of a reasonably complete regional history of petrogenesis awaits a detailed outlining and meshing of the volcanic chronology of both the Medicine Lake Highlands

Table 9. Generalized major and trace element characteristics of the Medicine Lake volcano. The island-arc and continental margin data are from Jakeš and White (1972)

	Medicine lake	Island-arc	Continental margin
SiO_2 range in %	50–63	50–66	56–75
$\text{FeO} + \text{Fe}_2\text{O}_3/\text{MgO}$	1.2–4.6	<2.0	>2.0
Iron enrichment	Yes	Sometimes	No
$\text{K}_2\text{O}/\text{Na}_2\text{O}$	0.14–0.35	<0.8	0.6–1.1
K_2O at 60% SiO_2	1.55–1.65	1.3–2.7	>2.0
Trace element content at 58% SiO_2	Rb island-arc; Ba, Sr, Zr continental margin; K/Rb 300–550	lower Rb, Ba, Sr, Zr; K/Rb 400	higher Rb, Ba, Sr, Zr; K/Rb 230
Mafic phenocrysts	clinopyroxene, orthopyroxene, olivine (no hornblende or biotite)	clinopyroxene, orthopyroxene, hornblende (rare biotite)	biotite, hornblende, clinopyroxene, orthopyroxene

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1966). Its differentiates by Kuno (1965) in these basalt flows, together with average lavas are listed conceivable mixtures with the andesite chemistry (1975) is applicable to Medicine Lake andesite

and the surrounding Modoc Plateau. Examination of major and trace element data, REE, lead and strontium isotopic evidence in light of this regional chronologic framework would permit the separation of magmatic characteristics arising from oceanic plate subduction versus those from ensialic interarc spreading, in a manner similar to Gill (1976).

Conclusions

The Medicine Lake andesite volcano has the following characteristics which delineate its geochemical nature: 1. an early stage of iron enrichment in the basaltic andesites that is produced by fractionation of plagioclase, olivine, and clinopyroxene. 2. a later stage of fractionation initiated by the appearance of titanomagnetite as a significant liquidus phase, preventing further iron enrichment. Continued fractionation of plagioclase, clinopyroxene, orthopyroxene, and minor olivine occur during this stage. Least squares linear mixing calculations are in agreement with this interpretation.

An origin for the basaltic andesite involving partial melting of lithosphere composed of low $\text{Sr}^{87}/\text{Sr}^{86}$ material that was subducted along the continental margin and which subsequently fractionated under low pressure conditions in line with the model outlined above is favored.

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References

- Anderson, C.A.: Volcanoes of the Medicine Lake Highland, Calif. Univ. Publ. Geol. Sci. Bull. **25**, 347-422 (1941)
- Barsky, C.K.: Geochemistry of basalts and andesites from the Medicine Lake Highland. Unpub. Ph.D. thesis, Washington Univ. (1975)
- Bryan, W.B., Finger, L.W., Chayes, F.: Estimating proportions in petrographic mixing equations by least-squares approximation. *Science* **163**, 926-927 (1969)
- Burnell, J.R.: Geology and petrology of the southeast portion of the Medicine Lake Highland, California. Unpub. B.A. thesis, Franklin and Marshall College (1974)
- Burns, R.G.: Mineralogical applications of crystal field theory. 224 pp. Cambridge: University Press 1970
- Carmichael, I.S.E.: The petrology of Thingmuli, a Tertiary volcano in eastern Iceland. *J. Petrol.* **5**, 435-460 (1964)
- Carmichael, I.S.E.: The iron-titanium oxides of salic volcanic rocks and their associated ferromagnesian silicates. *Contrib. Mineral. Petrol.* **14**, 36-64 (1967)
- Carmichael, I.S.E., Turner, F.J., Verhoogen, J.: *Igneous petrology*. 739 pp. New York: McGraw Hill 1974
- Condie, K.C., Hayslip, D.L.: Young bimodal volcanism at Medicine Lake volcanic center, northern California. *Geochim. Cosmochim. Acta* **39**, 1165-1178 (1975)

Medicine Lake volcano. The

Continental margin

56-75

> 2.0

No

0.6-1.1

> 2.0

higher Rb, Ba,
Sr, Zr; K/Rb 230

biotite, hornblende
clinopyroxene,
orthopyroxene

- Condie, K.C., Swenson, D.H.: Compositional variation in three Cascade stratovolcanoes: Jefferson, Ruiter, and Shasta. *Bull. Volcanol.* **37**, 205-230 (1973)
- Dickinson, W.R.: Circum-Pacific andesite types. *J. Geophys. Res.* **73**, 2261-2269 (1968)
- Dickinson, W.R.: Relations of andesitic volcanic chains, granitic batholiths, and derivative graywacke-arkose facies to the tectonic framework of arc-trench systems. *Rev. Geophys.* **8**, 813-839 (1970)
- Dickinson, W.R., Hatherton, T.: Andesitic volcanism and seismicity around the Pacific. *Science* **157**, 801-803 (1967)
- Duncan, A.R., Taylor, S.R.: Trace element analyses of magnetites from andesitic and dacite lavas from the Bay of Plenty, New Zealand. *Contrib. Mineral. Petrol.* **20**, 30-33 (1969)
- Eggler, D.H.: Water-saturated and undersaturated melting relations in a Parícutin andesite and an estimate of water content in the natural magma. *Contrib. Mineral. Petrol.* **34**, 261-271 (1972)
- Eggler, D.H., Burnham, C.W.: Crystallization and fractionation trends in the system andesite-H₂O-CO₂-O₂ at pressures to 10 kb. *Geol. Soc. Am. Bull.* **84**, 2517-2532 (1973)
- Eichelberger, J.C.: Magma contamination within the volcanic pile: origin of andesite and dacite. *Geology* **2**, 29-33 (1974)
- Eichelberger, J.C.: Origin of andesite and dacite: Evidence of mixing at Glass Mountain in California and at other circum-Pacific volcanoes. *Bull. Geol. Soc. Am.* **86**, 1381-1391 (1975)
- Ewart, A., Bryan, W.B., Gill, J.B.: Mineralogy and geochemistry of the younger volcanic islands of Tonga. *S.W. Pacific. J. Petrol.* **14**, 429-465 (1973)
- Gast, P.W.: Trace element fractionation and the origin of tholeiitic and alkaline magma types. *Geochim. Cosmochim. Acta* **32**, 1057-1086 (1968)
- Gill, J.B.: From island arc to oceanic islands: Fiji, southwestern Pacific. *Geology* **4**, 123-126 (1976)
- Gill, J.B., Murthy, V.R.: Distribution of K, Rb, Sr and Ba in Nain anorthosite plagioclase. *Geochim. Cosmochim. Acta* **34**, 401-408 (1970)
- Green, D.H.: The origin of basaltic and nephelinitic magmas. *Trans. Leicester Lit. Philos. Soc.* **64**, 28-54 (1970)
- Green, D.H., Edgar, A.D., Beasley, P., Kiss, E., Ware, N.G.: Upper mantle source for some hawaiites, mugearites and benmoreites. *Contrib. Mineral. Petrol.* **48**, 33-43 (1974)
- Green, T.H.: High-pressure experimental studies on the origin of anorthosite. *Canad. J. Earth Sci.* **6**, 427-440 (1969)
- Green, T.H., Ringwood, A.E.: Genesis of the calc-alkaline igneous rock suite. *Contrib. Mineral. Petrol.* **18**, 103-190 (1968)
- Gunn, B.M.: Trace element partition during olivine fractionation of Hawaiian basalts. *Chem. Geol.* **8**, 1-13 (1971)
- Gunn, B.M.: Systematic petrochemical difference in andesite suites. *Bull. Volcanol.* **38**, 481-490 (1974)
- Hackett, W.R.: Geology and petrology of a portion of the Medicine Lake Highland, northern California: Unpub. B.A. thesis, Franklin and Marshall College (1974)
- Hakli, T.A., Wright, T.L.: The fractionation of nickel between olivine and augite as a geothermometer. *Geochim. Cosmochim. Acta* **31**, 877-884 (1967)
- Hart, W.K.: Geology and petrology of the northern one-half of the Bray Quadrangle, northeastern California. Unpubl. B.A. thesis, Franklin and Marshall College (1976)
- Hatherton, T., Dickinson, W.R.: Andesitic volcanism and seismicity in New Zealand. *J. Geophys. Res.* **73**, 4615-4619 (1968)
- Hatherton, T., Dickinson, W.R.: The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs. *J. Geophys. Res.* **74**, 5301-5310 (1969)
- Hedge, C.E., Lewis, J.F.: Isotopic composition of strontium in three basalt-andesite centers along the Lesser Antilles arc. *Contrib. Mineral. Petrol.* **32**, 39-47 (1971)
- Higgins, M.W.: Petrology of Newberry volcano, central Oregon. *Bull. Geol. Soc. Am.* **84**, 455-488 (1973)
- Hoyer, J.: Matrix corrections in the X-ray spectrographic trace element analysis of rocks and minerals. *Am. Mineralogist* **44**, 19-32 (1959)
- Hughes, J.M.: Geology and petrology of the western Medicine Lake Highlands and Garner Mountain area, northern California. Unpubl. B.A. thesis, Franklin and Marshall College (1974)

- scade stratovolcanoes: Jefferson, *73*, 2261-2269 (1968)
- batholith belts, and derivative trench systems. *Rev. Geophys.* **8**, 1-10 (1970)
- icity around the Pacific. *Science* **170**, 115-117 (1970)
- s from andesitic and dacite lavas. *Mineral. Petrol.* **20**, 30-33 (1969)
- ons in a Paracutin andesite and dacite. *Mineral. Petrol.* **34**, 261-271 (1979)
- trends in the system andesite and dacite. *Mineral. Petrol.* **84**, 2517-2532 (1973)
- le: origin of andesite and dacite. *Mineral. Petrol.* **84**, 2517-2532 (1973)
- g at Glass Mountain in California. *Geology* **5**, 1381-1391 (1975)
- y of the younger volcanic islands. *Geology* **4**, 123-126 (1976)
- ciitic and alkaline magma types. *Geology* **4**, 123-126 (1976)
- ern Pacific. *Geology* **4**, 123-126 (1976)
- anorthosite plagioclase. *Geochim. Cosmochim. Acta* **34**, 307-322 (1970)
- rans. Leicester Lit. Philos. Soc. **17**, 253-294 (1932)
- Upper mantle source for some rocks. *Canad. J. Earth Planet. Sci.* **48**, 33-43 (1974)
- of anorthosite. *Canad. J. Earth Planet. Sci.* **48**, 33-43 (1974)
- ous rock suite. *Contrib. Mineral. Petrol.* **19**, 1-71 (1968)
- ion of Hawaiian basalts. *Chem. Geol.* **38**, 481-490 (1982)
- ites. *Bull. Volcanol.* **38**, 481-490 (1976)
- edicine Lake Highland, northern California. *Geology* **4**, 123-126 (1976)
- vine and augite as a geothermometer. *Contrib. Mineral. Petrol.* **19**, 1-71 (1968)
- the Bray Quadrangle, northeastern California. *Geology* **4**, 123-126 (1976)
- icity in New Zealand. *J. Geophys. Res.* **74**, 5301-5310 (1969)
- lesitic volcanism and seismicity in the Pacific Northwest. *J. Geophys. Res.* **74**, 5301-5310 (1969)
- three basalt-andesite centers along the Cascade Range. *Bull. Geol. Soc. Am.* **84**, 455-488 (1973)
- ice element analysis of rocks and minerals. *Geochim. Cosmochim. Acta* **37**, 1815-1821 (1973)
- lake Highlands and Garner Mountain. *Unpub. B.A. thesis, Franklin and Marshall College* (1974)
- Hughes, J.M., Mertzman, S.A.: Geology and petrology of the Garner Mountain area, northern California. *Northwest Geol.* **5**, 10-20 (1976)
- Jakes, P., White, A.J.R.: Major and trace element abundances in volcanic rocks of orogenic areas. *Bull. Geol. Soc. Am.* **83**, 29-40 (1972)
- Jensen, B.B.: Patterns of trace element partitioning. *Geochim. Cosmochim. Acta* **37**, 2227-2242 (1973)
- Kuno, H.: Fractionation trends of basalt magmas in lava flows. *J. Petrol.* **6**, 302-321 (1965)
- Lambert, R.S.L., Holland, J.G.: Yttrium geochemistry applied to petrogenesis utilizing calcium-yttrium relationships in minerals and rocks. *Geochim. Cosmochim. Acta* **38**, 1393-1414 (1974)
- Lawrence, R.D.: Strike-slip faulting terminates the Basin and Range province in Oregon. *Bull. Geol. Soc. Am.* **87**, 846-850 (1976)
- Lowder, G.G., Carmichael, I.S.E.: The volcanoes and caldera of Talasea, New Britain: geology and petrology. *Bull. Geol. Soc. Am.* **81**, 17-38 (1970)
- Macdonald, G.A.: Geology of the Cascade Range and the Modoc Plateau. *Calif. Div. Mines. Geol.* **190**, 65-96 (1966)
- Marsh, B.D.: Some Aleutian andesites: their nature and source. *J. Geol.* **84**, 27-45 (1976)
- McBirney, A.R., Sutter, J.F., Naslund, H.R., Sutton, K.G., White, C.M.: Episodic volcanism in the central Oregon Cascade Range. *Geol.* **2**, No. 12, 585-589 (1974)
- Onuma, N., Higuchi, H., Wakita, H., Nagasawa, H.: Trace element partition between two pyroxenes and the host lava. *Earth Planet. Sci. Lett.* **5**, 47-51 (1968)
- Peacock, M.A.: The Modoc lava field, northern California. *Geogr. Rev.* **21**, 259-275 (1931)
- Peterman, A.E., Carmichael, I.S.E., Smith, A.L.: Sr⁸⁷/Sr⁸⁶ ratios of Quaternary lavas of the Cascade Range, northern California. *Bull. Geol. Soc. Am.* **81**, 311-318 (1970)
- Philpotts, J.A., Schnetzler, C.C.: Phenocryst-matrix partition coefficients for K, Rb, Sr, and Ba, with applications to anorthosite and basalt genesis. *Geochim. Cosmochim. Acta* **34**, 307-322 (1970)
- Powers, H.A.: The lavas of the Modoc lava bed quadrangle, California. *Am. Mineralogist* **17**, 253-294 (1932)
- Pringle, G.J., Trembath, L.T., Pajari, Jr., G.E.: Crystallization history of a zoned plagioclase. *Mineral. Mag.* **39**, 867-877 (1974)
- Rose, H.J., Adler, I., Flanagan, F.J.: X-ray fluorescence analysis of the light elements in rocks and minerals. *Appl. Spectr.* **17**, 81-85 (1963)
- Schoiz, C.H., Barazangi, M., Sbar, M.L.: Late Cenozoic evolution of the Great Basin, western United States, as an ensialic interarc basin. *Bull. Geol. Soc. Am.* **82**, 2979-2990 (1971)
- Smith, A.L., Carmichael, I.S.E.: Quaternary lavas from the southern Cascades, western U.S.A. *Contrib. Mineral. Petrol.* **19**, 212-238 (1968)
- Smith, J.V.: X-ray emission microanalysis of rock-forming minerals II. Olivines. *J. Geol.* **74**, 1-16 (1966)
- Stormer, J.C., Jr.: Calcium zoning in olivine and its relationship to silica activity and pressure. *Geochim. Cosmochim. Acta* **37**, 1815-1821 (1973)
- Taylor, H.P.: The oxygen isotope geochemistry of igneous rocks. *Contrib. Mineral. Petrol.* **19**, 1-71 (1968)
- Taylor, S.R., Capp, A.C., Graham, A.L., Blake, D.H.: Trace element abundances in andesites. *Contrib. Mineral. Petrol.* **23**, 1-26 (1969b)
- Taylor, S.R., Kaye, M., White, A.J.R., Duncan, A.R., Ewart, A.: Genetic significance of Co, Cr, Ni, Sc and V content of andesites. *Geochim. Cosmochim. Acta* **33**, 275-286 (1969a)
- Thompson, R.B.: Some high-pressure pyroxenes. *Mineral. Mag.* **39**, 768-787 (1974)
- Walter, R.C.: Geology and petrology of the northwest portion of the Medicine Lake Highland, California. *Unpub. B.A. thesis, Franklin and Marshall College* (1975)
- Waters, A.C.: Basalt magma types and their tectonic associations: Pacific Northwest of the United States. *Am. Geophys. Union Mono.* **6**, 158-170 (1962)
- Weaver, S.G.: Geology and petrology of the southeast portion of the Bray Quadrangle, northern California. *Unpub. B.A. thesis, Franklin and Marshall College* (1976)

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