

## Quaternary Lavas from the Southern Cascades, Western U.S.A.

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Received June 24, 1968

*Abstract.* A series of basaltic and andesitic lavas from three centers in the Cascades (Lassen, Medicine Lake, Mt. Shasta) have been investigated. The lavas are weakly porphyritic, containing phenocrysts of plagioclase, augite, and olivine or orthopyroxene; these phases are also found in the groundmass. Titanomagnetite is a groundmass phase in most lavas but it appears to be absent in some. A sub-calcic augite is found in the groundmass in some of the basic lavas. Orthopyroxenes are present only in the salic lavas and show an increase in calcium with increasing iron. The range in composition shown by both phenocryst and groundmass plagioclase is very similar except that the phenocrysts extend to slightly more calcic compositions. The residual glasses in many of the lavas have a rhyolitic composition. However, only those from the Shasta andesites have normative salic constituents that plot near the ternary minimum in the Ab-Or-Qtz system at 500 bars. Both chemical and mineralogical data allow the lavas of the different centers to be distinguished from one another. The most likely origin for the orogenic lavas of the Cascades is by partial melting of the upper mantle.

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**A. Introduction**

The Cascade volcanic province, which extends from the Canadian border to just south of Lassen Peak in northern California (Fig. 1), may be subdivided into two parts; the Western Cascades composed of deeply eroded early Tertiary volcanic

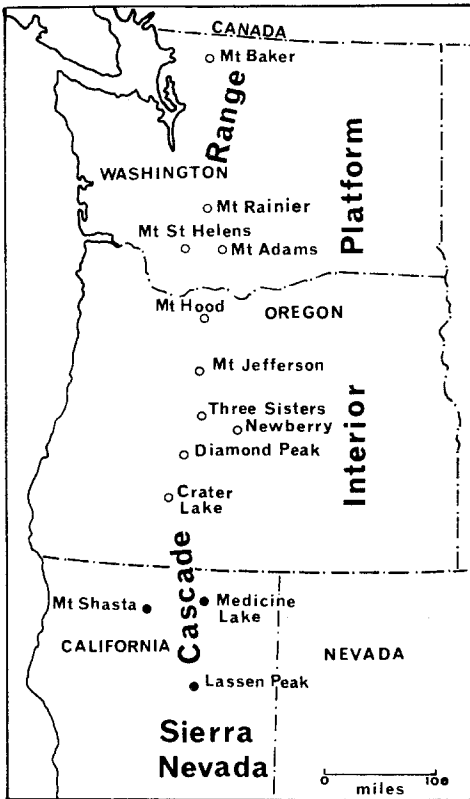


Fig. 1. Map of northwestern U.S.A. showing some of the major Cascade volcanoes. The three volcanic areas described in this paper are represented by filled circles

rocks, and the High Cascades, containing lavas of the orogenic basalt-rhyolite suite. Volcanic activity in the High Cascades began in the Pliocene (WATERS, 1962) and has continued intermittently until historic times. In the east, the Cascades pass into the relatively stable interior platform (Fig. 1) characterized by extensive outpourings of high-alumina basalt (WATERS, 1955, 1962).

Petrographically the volcanoes of the High Cascades belong to several distinct types. The majority of the large strato-volcanoes are composed mainly of pyroxene andesite; these appear to be dominant in the northern part (Mt. Rainier, Mt. Baker).

In contrast, some of the more southerly volcanoes are composed of lavas ranging in composition from basalt to dacite (Crater Lake, Lassen region). The volcanoes situated near the boundary between the High Cascades and the interior platform are characterized by eruption of basalt and rhyolite with little or no intermediate lava (Newberry, Medicine Lake). Interspersed among these larger cones are numerous basaltic shield volcanoes.

Quaternary lavas from three volcanoes, representing the major types mentioned above, have been studied with the object of describing the chemical and mineralogical variations between the different centers and to attempt to provide an explanation for the origin of these lavas.

The three volcanoes chosen were:

a) Mt. Shasta, the exposed part of which is predominantly andesite (WILLIAMS, 1932 a, 1934).

b) Medicine Lake, one of the bordering volcanoes, is composed mainly of basic andesites. However the latest lavas erupted range from basalt to obsidian with few intermediate lavas (POWERS, 1932; ANDERSON, 1941).

c) The Lassen group of volcanoes forming the southernmost extension of the Cascade chain, are characterized by a wide variety of rock types. This variation is reflected in the Quaternary lavas which range in composition from high-alumina basalt to dacite, many having been erupted almost simultaneously from separate volcanoes (DAY and ALLEN, 1925; ANDERSON, 1940; WILLIAMS, 1932 b).

## B. Petrography

The lavas studied range from olivine basalt to hornblende andesites (Table 1). CARMICHAEL (1967 a) has previously described the acid lavas of the province. Augite and plagioclase are present in nearly all of the lavas often both as phenocrysts and in the groundmass. Olivine is found only in the basic lavas, its place being taken by orthopyroxene in the more silicic representatives. Many of the lavas contain interstitial patches of dark brown residual glass with numerous granules of iron oxide. In some lavas an oxide phase is present as discrete groundmass grains, while in a few it is completely absent.

Table 1. *Modal analyses (volume percent)*

	Groundmass	Olivine	Clino- pyroxene	Ortho- pyroxene	Plagioclase	Other
1	93.6	6.4	tr	—	—	—
3	91.5	—	4.1	3.4	1.0	—
5	97.9	—	0.9	0.9	0.3	—
6	81.9	—	—	—	13.6	4.5 <sup>a</sup>
8	90.8	0.9	—	—	8.3	—
9	93.7	2.2	—	—	4.1	—
10	95.4	2.0	—	—	2.6	—
11	97.7	0.3	—	—	2.0	—
12	97.9	1.4	—	—	0.7	—
14	73.8	4.0	5.7	0.5	16.0	—
17	92.7	3.9	1.1	—	1.5	0.7 <sup>b</sup>
18	85.3	0.6	1.3	1.3	10.3	1.1 <sup>b</sup>

<sup>a</sup> Hornblende; <sup>b</sup> Quartz.

### C. Chemistry

Chemically the lavas studied vary from high-alumina basalts to andesitic dacites. Analyses (Table 2) reveal consistent differences between the three groups of rocks; those from Mt. Shasta are the most distinctive.

*a) Mt. Shasta.* Most of the latest lavas of Mt. Shasta are andesites with  $\text{SiO}_2$  between 61–65% and are relatively high in alumina and low in iron and alkalis. Compared with typical tholeiitic andesites (CARMICHAEL, 1964) they are relatively richer in calcium and magnesium; this is reflected in the compositions of their modal and normative pyroxenes.

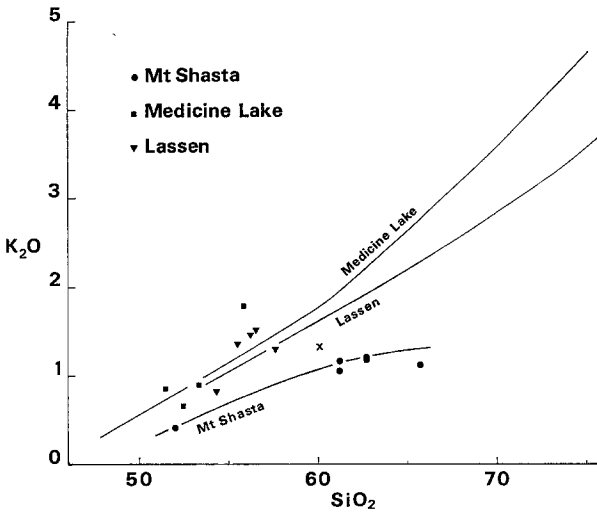


Fig. 2. A plot of potassium against silica for the lavas of Medicine Lake, Lassen, and Mt. Shasta. The X gives the position of the average orogenic andesite of TAYLOR and WHITE (1966); the other symbols represent the lavas studied in this paper (Table 2). The average trends (solid lines) are drawn using all available data

A single analysed basalt (Table 2, No. 1) is somewhat high in aluminum, magnesium and calcium and low in alkalis. The normative quartz probably reflects late oxidation, which is indicated petrographically by rims of iron-oxide granules around many olivine grains.

A striking feature especially in the andesites is the potassium content (Fig. 2) which is lower than has been recorded both for other Cascade andesites (MOORE, 1962) and for values considered by TAYLOR and WHITE (1966) as diagnostic of orogenic andesites in general. Preliminary determinations show these andesites are low in Rb, Ba and Zr and relatively high in Ni.

*b) Medicine Lake.* The Quaternary lavas of Medicine Lake can be divided into an acid and a basic group, the latter range in composition from high-alumina basalts (Nos. 8, 9 and 10) to basaltic andesite (No. 11). All are rich in alumina and show an increase of total alkalis and a decrease in magnesium and calcium with increasing silica (Table 2).

For comparable silica contents (Table 2) the lavas studied from Medicine Lake are relatively richer in potassium than those from Mt. Shasta and Lassen. However, when all the analyses from the different centers are compared (Fig. 2) there is little difference in potassium content between the basic lavas of Medicine Lake and Lassen. These two centers are also similar in trace element content but with

Table 2. Chemical analyses and CIPW norms of Quaternary Cascade lavas

	Mt. Shasta						Medicine Lake					Hat Creek		Lassen Region					
	(242)	(235)	(244)	(237)	(72)	(70)	(200)	(187)	(196)	(199)	(63)	(3)	(Cal 20)	(Cal 24)	(Cal 25)	(Cal 43)			
	1	2	3	4	5	6	8	9	10	11	12	14	15	16	17	18			
SiO <sub>2</sub>	52.03	61.17	61.20	62.74	62.74	65.67	51.46	52.46	53.34	55.80	48.46	54.31	55.46	56.19	55.48	57.64			
TiO <sub>2</sub>	0.66	0.69	0.71	0.58	0.56	0.42	1.00	0.84	0.97	1.28	1.07	0.90	0.80	0.80	0.79	0.85			
Al <sub>2</sub> O <sub>3</sub>	16.51	16.58	16.53	16.54	16.53	17.52	17.08	18.46	17.61	16.51	17.39	16.56	16.42	16.19	16.17	16.70			
Fe <sub>3</sub> O <sub>3</sub>	3.41	1.37	1.21	1.62	1.71	1.14	1.07	1.45	1.67	2.20	1.76	2.18	1.22	0.92	1.12	1.19			
FeO	4.51	3.18	3.43	2.35	2.14	2.05	7.53	5.93	6.29	5.12	7.97	4.44	5.23	5.40	5.35	5.05			
MnO	0.14	0.08	0.08	0.07	0.07	0.06	0.15	0.15	0.14	0.13	0.18	0.12	0.12	0.12	0.12	0.13			
MgO	9.59	4.03	3.65	3.32	3.24	1.96	7.40	6.88	6.17	4.75	8.64	7.23	7.23	7.28	7.19	5.01			
CaO	9.48	6.73	6.48	6.13	6.20	5.38	9.96	9.42	8.93	7.38	11.10	9.24	8.00	7.21	7.46	7.70			
Na <sub>2</sub> O	2.97	4.21	4.08	4.12	4.08	4.52	3.05	3.25	3.47	3.88	2.80	3.41	3.41	3.39	3.42	3.70			
K <sub>2</sub> O	0.41	1.05	1.16	1.20	1.18	1.12	0.85	0.66	0.89	1.78	0.22	0.82	1.36	1.46	1.52	1.30			
P <sub>2</sub> O <sub>5</sub>	0.12	0.21	0.24	0.17	0.16	0.11	0.16	0.18	0.17	0.56	0.12	0.29	0.16	0.17	0.18	0.19			
H <sub>2</sub> O <sup>+</sup>	0.30	0.49	1.01	0.67	1.02	0.00	0.12	0.32	0.21	0.56	0.07	0.40	0.47	0.28	0.30	0.43			
H <sub>2</sub> O <sup>-</sup>	0.09	0.14	0.15	0.26	0.29	0.03	0.13	0.12	0.19	0.18	0.08	0.07	0.14	0.08	0.09	0.11			
Total	100.22	99.93	99.93	99.77	99.92	99.98	99.96	100.12	100.05	100.13	99.86	99.97	99.96	100.05	100.19	100.00			
Qz	0.20	13.03	13.99	16.94	17.43	20.31	—	—	0.76	4.79	—	2.82	2.48	2.73	3.51	7.02			
Or	2.42	6.20	6.85	7.09	6.97	6.62	5.02	3.90	5.26	10.52	1.30	4.85	8.04	8.63	8.98	7.68			
Ab	25.13	35.62	34.52	34.86	34.52	38.25	25.81	27.50	29.36	32.83	23.69	28.85	28.69	29.19	28.94	31.31			
An	30.51	23.24	23.36	23.09	23.30	24.21	30.40	33.83	28.85	22.38	34.23	27.46	25.57	24.38	24.28	25.12			
Di-w	6.57	3.66	3.01	2.59	2.68	0.74	7.50	4.90	5.57	4.42	8.37	6.88	5.46	5.33	4.82	4.94			
Di-en	4.95	2.47	1.92	1.87	1.99	0.47	4.39	3.06	3.35	2.79	5.11	4.90	3.58	3.44	3.13	2.98			
Di-fs	0.96	0.91	0.90	0.49	0.42	0.22	2.75	1.53	1.93	1.35	2.79	1.38	1.49	1.53	1.37	1.70			
Hy-en	18.93	10.37	7.17	6.40	6.08	4.41	7.61	13.40	12.02	9.04	2.21	13.11	14.42	14.69	14.78	9.50			
Hy-fs	3.67	7.57	3.37	1.66	1.30	2.02	4.78	6.71	6.90	4.36	1.21	3.71	6.01	6.53	6.45	5.43			
Ol-fa	—	—	—	—	—	—	4.51	0.47	—	—	9.95	—	—	—	—	—			
Ol-fa	—	—	—	—	—	—	3.12	0.26	—	—	5.99	—	—	—	—	—			
Mt	4.94	1.99	1.75	2.35	2.48	1.65	1.55	2.10	2.42	3.19	2.85	3.16	1.77	1.33	1.62	1.73			
Il	1.25	1.31	1.35	1.10	1.06	0.80	1.90	1.60	1.84	2.43	2.03	1.71	1.52	1.52	1.50	1.61			
Ap	0.28	0.50	0.57	0.40	0.38	0.26	0.38	0.43	0.40	1.33	0.28	0.69	0.38	0.40	0.43	0.45			

Analyses by I. S. E. CARMICHAEL and J. HAMPEL.

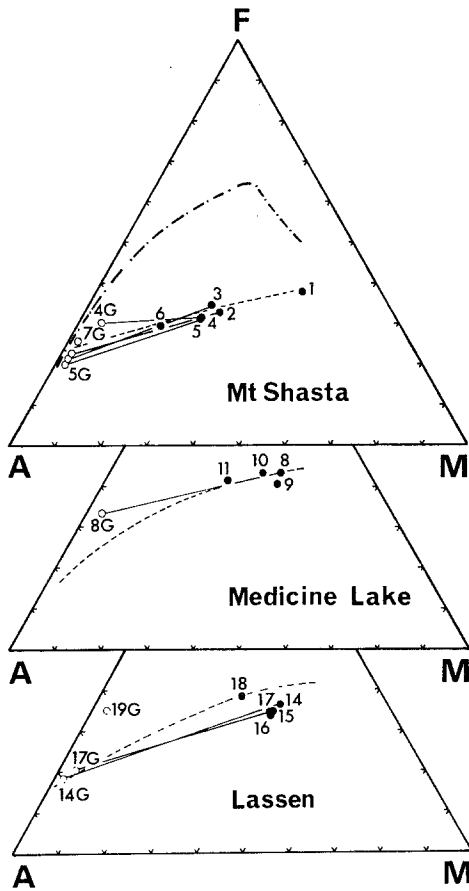


Fig. 3. A plot of the Cascade lavas (filled circles) with their residual glasses (open circles). --- represents the average trends for the three centers (drawn using all available analyses); the Thingmuli trend - · - is taken from CARMICHAEL (1964). *F* FeO + Fe<sub>2</sub>O<sub>3</sub>; *M* MgO; *A* Na<sub>2</sub>O + K<sub>2</sub>O (weight percent)

*Key to specimen localities*

a) Mt. Shasta

- |  |       |
|--|-------|
| 1. Olivine basalt, Cinder Cone                       | (242) |
| 2. Pyroxene andesite of Shastina, near Highway 97    | (235) |
| 3. Pyroxene andesite of Shastina, near Cinder Cone   | (244) |
| 4. Pyroxene andesite of Shastina, near Whitney Creek | (237) |
| 5. Pyroxene andesite, near McBride Springs           | (72)  |
| 6. Hornblende andesite, Black Butte                  | (70)  |
| 7. Pyroxene andesite, east of Inconstance Creek      | (73)  |

b) Medicine Lake

- |  |       |
|--|-------|
| 8. Olivine basalt, latest flow in Modoc Lava Beds      | (200) |
| 9. Olivine basalt, Paint Pot Crater flow               | (187) |
| 10. Olivine basalt, Callahan flow                      | (196) |
| 11. Basaltic andesite, Schonchin flow, Modoc Lava Beds | (199) |

c) Lassen Region

- |  |          |
|--|----------|
| 12. Olivine basalt, Hat Creek lava flow                                      | (63)     |
| 13. Olivine basalt, Hat Creek lava flow                                      | (81)     |
| 14. Basaltic andesite, Red Lake Mountain                                     | (3)      |
| 15. Quartz-basalt, near source vent of 1851 flow, Cinder Cone,               |          |
| Lassen National Park   | (Cal 20) |
| 16. Quartz-basalt, bomb, Cinder Cone, Lassen National Park                   | (Cal 24) |
| 17. Quartz-basalt, flow front of pre-1851 flow near Butte Lake, Cinder Cone, |          |
| Lassen National Park   | (Cal 25) |
| 18. Quartz-basalt, recent flow, West Prospect Peak, Lassen National Park     | (Cal 43) |
| 19. Pyroxene andesite, Crater Lake Mountain                                  | (117)    |
| 20. Olivine basalt, Cold Creek Butte, near Mineral                           | (175)    |

the Medicine Lake lavas being richer in Zr. The lavas from these two centers are distinguishable however on their iron contents; those of Medicine Lake being richer in iron (Figs. 3 and 9).

*c) Lassen.* The lavas of the Lassen region may be divided into two distinct groups. 1. Basaltic andesites similar to those already described from the Medicine Lake region. 2. Basic high-alumina basalts.

The Quaternary basaltic andesites of the Lassen region are distinctively rich in magnesium and sometimes calcium relative to their silica and alkali contents; this may be due to contamination of basaltic magma by sialic material (FINCH and ANDERSON, 1930). This is especially true of the so-called "quartz-basalts"

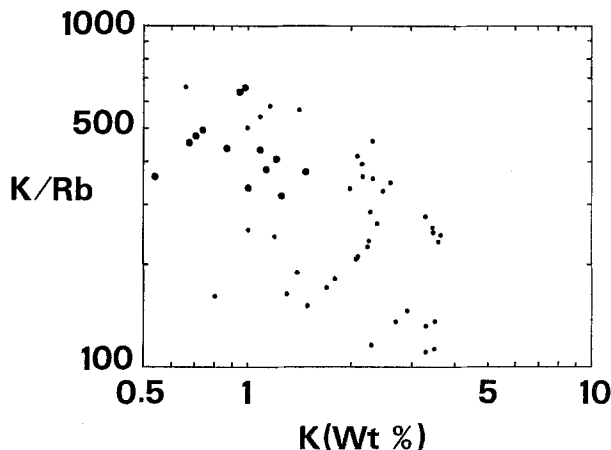


Fig. 4. The relationship between K and K/Rb in the lavas of the Cascades. The large circles represent the lavas described in this paper; the small circles are the other Cascade lavas for which data is available (NOCKOLDS and ALLEN, 1953; JACK and CARMICHAEL, unpublished data)

of Cinder Cone and West Prospect Peak which contain abundant xenocrysts of quartz. Trace element data indicate that the lavas from the Cinder Cone are rich in Cr and Ni and poor in Sr.

In striking contrast to the lavas just described is the high-alumina basalt of Hat Creek (Table 2, No. 12), which is characterized by relatively low silica and total alkalis and high iron, magnesium, calcium and alumina. Because of its distinctive character this lava will be discussed separately from the other Lassen lavas.

The only Cascade lava which is chemically similar to the Hat Creek flow is the Warner basalt (ANDERSON, 1941; YODER and TILLEY, 1962). This similarity is also shown by comparison of trace element data (SMITH, unpublished data).

*d) Discussion.* One of the most distinctive features of the lavas of the Cascades is that the more easterly volcanoes tended to extrude lavas richer in alkalis, especially potassium, than those further to the west (Figs. 1 and 2). An increase in potassium towards the continental side of orogenic volcanic belts has been previously noticed by KUNO (1966) and DICKINSON (1968). MOORE (1962) correlated this feature, by means of gravity anomalies, to an increase in the thickness of the underlying crust. Geophysical data by DEHLINGER *et al.* (1965) has shown that the crust under the western part of the Cascades is relatively thin (approximately 30 kms) and it thickens toward the east. In contrast, KUNO (1966) and

DICKINSON (1968) correlate the increasing potassium content of lavas with increasing depth of formation of the magmas. This seemingly systematic variation in potassium content will have to be accounted for in any explanation of the origin of the Cascade lavas.

With the exception of the hornblende andesite (No. 6) from Mt. Shasta, which has an anomalously low Rb content, the K/Rb ratios in the lavas from the Cascades decrease with increasing potassium content (Fig. 4). The ratios found for the lavas studied tend to be higher than those found by GUNN (1965) and TAYLOR and WHITE (1966) for New Zealand andesites but similar to those of the Japanese andesites (TAYLOR and WHITE, 1966).

## D. Mineralogy

### 1. Olivines

Olivines ( $\text{Fo}_{80-57}$ ) are found as phenocrysts in the basaltic andesites as well as in the basalts. They sometimes show skeletal outlines similar to those described by KUNO (1950) from the lavas of Hakone volcano, and invariably they contain inclusions of brown chrome spinel. The groundmass olivines have a more limited distribution. Apart from the lavas of Medicine Lake, orthopyroxene and groundmass olivines are not found in the same rock; this suggests a reaction relationship between the olivines and the enclosing liquid, which is supported by the fact that in two lavas (Nos. 14 and 17) containing both groundmass orthopyroxenes and phenocrystal olivines, the olivines are enclosed by rims of orthopyroxene. Both phenocrysts and groundmass olivines exhibit "normal" zoning (TOMKEIEFF, 1939) of a similar magnitude, the groundmass grains being richer in iron. The amount of zoning seems to be dependent, in part, on the rate of cooling. This is illustrated by two samples from the Hat Creek lava. The olivines of the more slowly cooled central portion of the flow (No. 12) have a much greater range in composition than those from the surface phase (No. 13). A similar situation has been described by MOORE and EVANS (1967) for the olivines of the Makaopuhi lava lake.

NiO, MnO and CaO are all found in values similar to olivines from tholeiitic (MOORE and EVANS, 1967; CARMICHAEL, 1967b) and alkali basalts (WILKINSON, 1956a; SMITH, unpublished data). NiO tends to be zoned in a similar way to magnesium and MnO and CaO become progressively enriched in the more iron-rich zones.

### 2. Pyroxenes

With the exception of the hornblende andesite (No. 6) from Mt. Shasta, a calcium-rich pyroxene is found in all the lavas studied. A co-existing orthopyroxene is found only in the more siliceous lavas, while pigeonite appears to be restricted to those lavas containing subcalcic augite. Analyses of the pyroxenes are given in Table 3<sup>1</sup>.

<sup>1</sup> Table 3 analyses of pyroxenes, and Table 4 analyses of feldspars, are not presented in the paper but can be obtained from the Department of Geology, University of California, Berkeley, Calif. 94720 upon request.



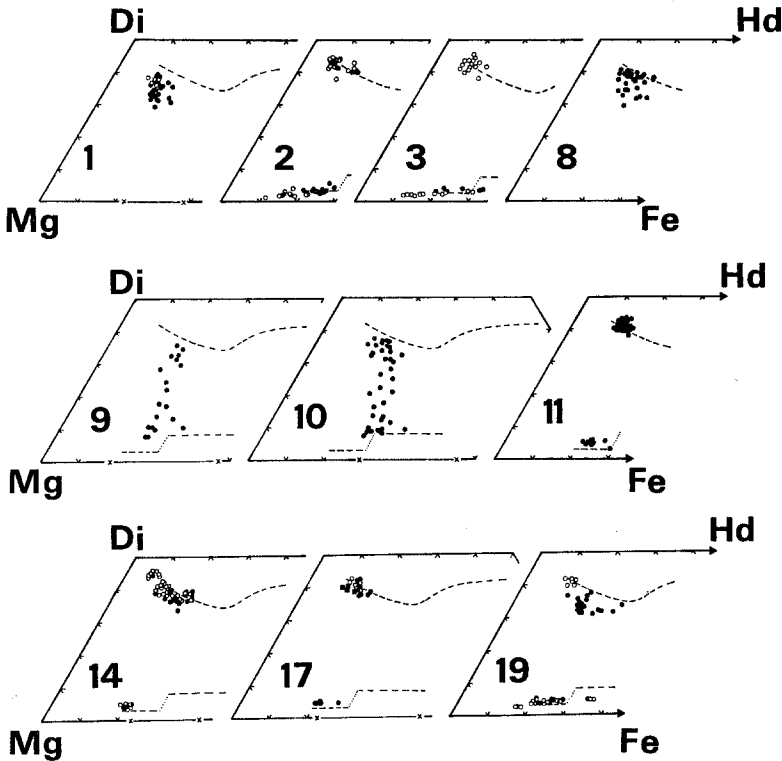


Fig. 5. Microprobe determinations of pyroxenes (Atom %). ○ phenocrysts; ● groundmass; ■ pyroxenes rimming xenocrysts of quartz (No. 17). Range in composition of phenocrystal olivines is given by ×—×. ----- represents pyroxene trends from the Skaergaard intrusion (BROWN and VINCENT, 1963). See p. 217 for key to specimens

*a) Mt. Shasta.* The single basalt specimen (No. 1) contains subcalcic augites with iron substituting for calcium (Figs. 5 and 6). All of the andesites contain both a calcium-rich pyroxene and an orthopyroxene. The calcium-rich phase, invariably present as phenocrysts, has a calcic composition near the magnesium end of the Skaergaard trend (BROWN, 1957). When also present in the groundmass it shows slightly increased Fe/Ca.

Orthopyroxene<sup>2</sup>, both as phenocrysts and in the groundmass, shows sympathetic increase in calcium with iron (Fig. 5). Only in the iron-rich types does calcium approach that of the Skaergaard orthopyroxenes (BROWN, 1957). Some phenocrysts are jacketed with an augite similar in composition to the outermost zones of the augite phenocrysts; such a texture is regarded by MUIR and LONG (1965) as parallel growth rather than a reaction texture.

Mt. Shasta pyroxenes, like the rocks in which they occur, are consistently more magnesian than those recorded from other orogenic andesites (KAWANO *et al.*, 1961) or from icelandites (CARMICHAEL, 1967b).

<sup>2</sup> In the hornblende andesite (No. 6) the orthopyroxene is too small to be analysed with the electron probe.

b) *Medicine Lake*. The majority of the lavas from Medicine Lake are characterized by subcalcic augites (Fig. 5) whose composition (in two of the lavas) covers the complete range from augite to magnesian pigeonite. Although subcalcic augites are found in other Cascade lavas (Fig. 5) the compositional range is never as great as in these lavas. The most basic lava (No. 8) is distinctive in that it precipitated pyroxenes with only a limited substitution of magnesium for calcium. In contrast, the most silicic lava (No. 11) contains both a calcium-rich pyroxene and an orthopyroxene (Wo content 4.5%) (Fig. 5). The orthopyroxene is rather rare and only a partial analysis is given in Table 3. The precipitation of two pyroxenes in this latter lava could be due to lower temperature of crystallization, slower cooling of the lava or to some compositional difference.

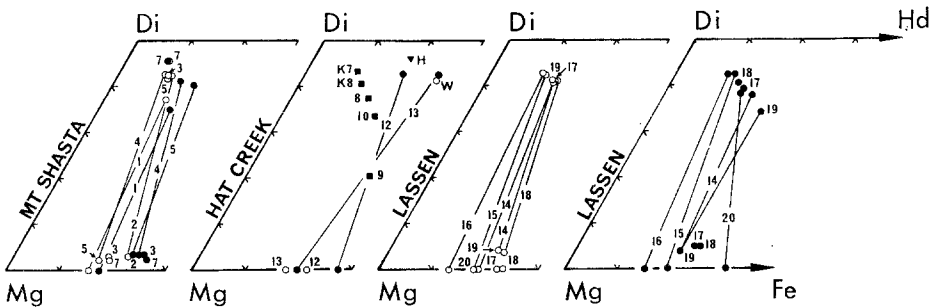


Fig. 6. Average analyses of pyroxenes and olivines (Atom %). ○ phenocrysts; ● groundmass. In the diagram for Hat Creek the following symbols are used: ▼ *H* average pyroxene from high-alumina basalt of Hawaii (Muir and Tilley, Table 9, Anal. 4, 1961); ■ pyroxenes from high-alumina basalts of the second type (K 7 and K 8 from Kuno, Table 3, Anal. 7 and 8; 8, 9, and 10 from Medicine Lake, Table 3); ○ average pyroxene from the Warner basalt (Yoder and Tilley, 1962, Table 3, Anal. 16)

c) *Hat Creek*. From Fig. 6 it can be seen that this lava contains only one pyroxene which is rich in both calcium and iron<sup>3</sup>. Tie-lines between co-existing pyroxenes and olivines indicate an approach to equilibrium for the more slowly cooled central part of the flow (No. 12) but a disequilibrium trend for a specimen (No. 13) from the upper part of the flow.

Comparison of the composition of the pyroxenes in the Hat Creek lava with those from other high-alumina basalts (Fig. 6) indicate a close similarity to the pyroxenes of the Warner basalt, thus confirming their similarity noted above on the basis of chemical composition.

d) *Lassen*. The majority of the Quaternary lavas from the Lassen region contain two pyroxenes, an orthopyroxene and an augite. The augites are relatively magnesian in composition. In two of the lavas (Nos. 19 and 20) the calcium-rich pyroxenes exhibit a subcalcic trend. However, the andesite from Crater Lake Mountain (No. 19) also contains an orthopyroxene (Wo content 4%).

<sup>3</sup> ANDERSON (1940) reported that the characteristic pyroxene in the Hat Creek lava was pigeonitic. In this study no trace of a pyroxene of this composition could be found. This discrepancy may be the result of the relatively high content of titanium and alumina found in these pyroxenes (Table 3), since WILKINSON (1956b) has suggested that pyroxenes rich in these constituents have optical properties which "indicate a higher iron and lower calcium content than revealed by analysis".

The "quartz-basalts" of the Cinder Cone (FINCH and ANDERSON, 1930) and West Prospect Peak are characterized by xenocrysts of quartz. These xenocrysts are surrounded by a reaction rim of augite and sometimes glass. The augite rims are of a more magnesian composition than the co-existing groundmass pyroxenes. Although the groundmass pyroxenes show a slight enrichment in iron compared to the phenocrysts (Fig. 6) many of the individual grains exhibit an increase of magnesium from core to margin. It is suggested that this reversal of zoning is associated with the contamination of these lavas since BOWEN (1928, p. 206) noted that the addition of silica to a basic magma tends to decrease the amount of olivine and to increase the magnesian content of the pyroxene.

Although WILLIAMS (1932b) reported the presence of orthopyroxene in many of the Cinder Cone lavas, orthopyroxene was found in only one of the pre-1851 flows (No. 17) where it occurs both as a groundmass constituent, and as rims around phenocrystal olivines. The orthopyroxenes in this lava show only a restricted range in composition (Fig. 5) and are thus similar to the orthopyroxenes of the basaltic andesite of Red Lake Mountain (No. 14).

*e) Minor Elements in the Pyroxenes.* The distribution of minor elements between co-existing pyroxenes from all of the lavas studies is similar to that described by BROWN (1957). The augites are always enriched in Al, Ti and Na and impoverished in Mn with respect to their co-existing orthopyroxenes. Although somewhat variable, Al and Ti generally tend to increase with increasing iron content (Table 3), rather than decrease as in the pyroxenes of the Thingmuli tholeiitic lavas (CARMICHAEL, 1967b).

On comparison of the minor element content of the pyroxenes from the different centers it can be seen that the calcium-rich pyroxenes from Mt. Shasta tend to be poor in Al and Ti, while those from Hat Creek are the richest in these elements. The pyroxenes from Hat Creek are also rich in alumina in tetrahedral coordination as are the "quartz-basalts" from the Lassen region. There generally seems to be less difference between the orthopyroxenes of the different areas than between the calcium-rich pyroxenes.

### 3. Feldspars

The Quaternary lavas of the Cascades are characterized by only one feldspar, a plagioclase, which is found as scattered phenocrysts in most of the lavas, and as a groundmass constituent in all. There is generally a complete gradation in size between phenocrysts and groundmass crystals. The phenocrysts, which sometimes form clots of smaller crystals, usually possess subhedral outlines. Some crystals however, exhibit a subrounded shape suggestive of resorption.

All of the feldspars are zoned (Table 4). Some crystals exhibit zoning of an irregular nature; in other feldspars a large number of zones are discernable and the zoning is commonly oscillatory. A third type of zonation is one in which the feldspars display a wide, approximately homogeneous core, surrounded by a narrow, more sodic margin. Often within a single thin section (especially of the andesites) crystals may be found exhibiting the different types of zoning.

Many of the feldspar phenocrysts within the lavas of Medicine Lake and Lassen contain inclusions, some of which appear as interstitial areas in glomerocrysts

and were probably formed by the trapping of the liquid between the coalescing grains. In other phenocrysts the inclusions occur either in the cores or in definite zones. In most of the inclusion-rich crystals the outermost zone is generally clear. Sometimes this clear zone reflects the shape of the inclusion-rich area but more often, the outer zone has a subhedral shape in contrast to the rounded outline of the inclusion-rich area. Satisfactory analysis of the inclusion-rich areas was not possible in the majority of cases due to the closeness of the inclusions. Where analyses were obtained the anorthite content was higher in these zones than in the surrounding areas. The compositions of the outer clear zones are similar to those of the margins of inclusion-free crystals, while the average composition of those feldspars which contained inclusions was not significantly different from those of inclusion-free feldspars.

One explanation for the formation of these inclusions is that during the growth of the feldspar the concentration of iron and magnesium increased at the boundary layer until co-precipitation of plagioclase and ferromagnesian phases occurred (BOTTINGA *et al.*, 1966). Another explanation is that these inclusion-rich feldspars are xenocrysts which have been partly resorbed by the enclosing magma (KUNO, 1950) breaking down into a more calcic feldspar and glass (MACDONALD and KATSURA, 1965).

Of the minor elements in the feldspars only barium and iron are present in significant amounts. Barium is rather low (0.1% BaO); iron, on the other hand, ranges between 0.4 and 1.2% Fe<sub>2</sub>O<sub>3</sub> and is zoned in a similar manner to calcium.

*a) Mt. Shasta.* The feldspars of the lavas from Mt. Shasta are relatively free of inclusions, but are strongly zoned. It can be seen from Table 4 that although the andesites of Mt. Shasta are the most silicic lavas studied, their feldspars, especially the centers of grains, are relatively calcic. There is also a considerable overlap in composition between phenocrysts and groundmass feldspars. The most calcic composition found in the phenocrysts is generally about 3 to 15% more anorthitic than the most calcic groundmass composition. On the other hand, the most albite rich composition found in both phenocrysts and groundmass is approximately the same (Fig. 7).

When the modal and normative feldspars are plotted in the system Ab-An-Or (Fig. 8) the low potassium content of the Shasta suite of lavas is evident. The trend exhibited by the normative feldspars lies wholly within the one feldspar field and is similar to the trends reported for the Skaergaard and Icelandic tholeiitic sequences (WAGER, 1960; CARMICHAEL, 1963).

*b) Medicine Lake.* The lavas of Medicine Lake contain only a few plagioclase phenocrysts (Table 1), many of which contain inclusions. Some of the more basic lavas contain some very calcium-rich feldspars (An<sub>88-83</sub>) (Fig. 7). These are found in the cores of large phenocrysts and there is generally a slight compositional gap between them and the generality of phenocryst compositions. Again it can be seen that there is a large compositional overlap between phenocrysts and groundmass (Fig. 7). In contrast to the relatively large range shown by the feldspars in the basalts, the basaltic andesite (No. 11) contains relatively albite-rich feldspars which are rather restricted in composition (An<sub>66-56</sub>).

*c) Hat Creek.* In some respects the feldspars from the Hat Creek lava are similar to those described from Mt. Shasta, in that they have a low orthoclase content

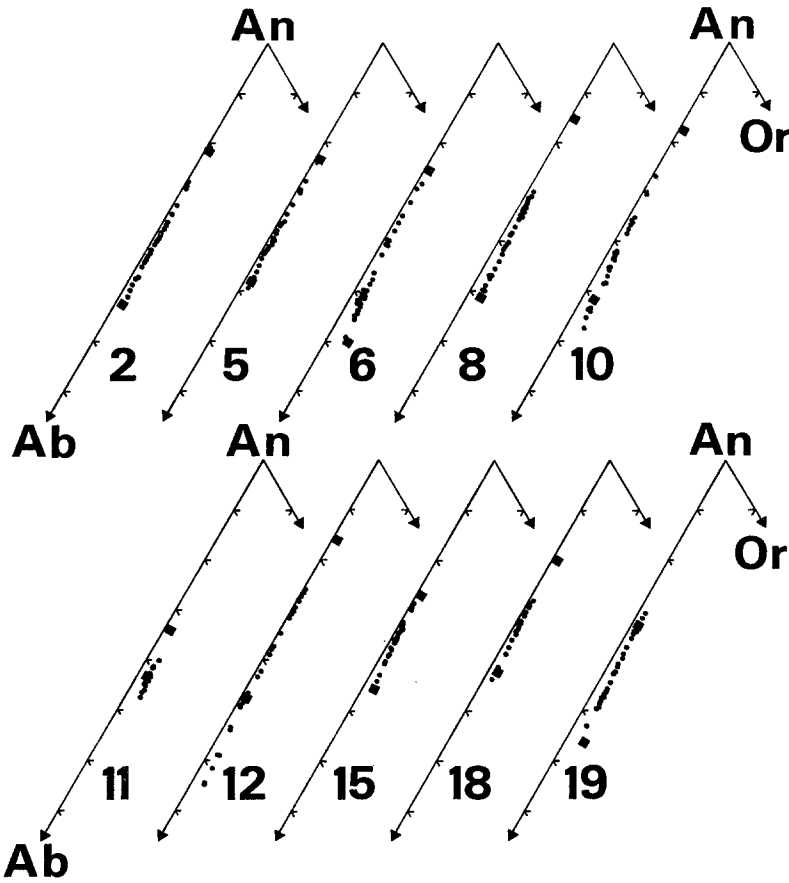


Fig. 7. Microprobe analyses of feldspars (Wt. %). ■ the most anorthitic and albitic phenocryst compositions; ● groundmass feldspars. See p. 217 for key to specimens

and inclusion-rich feldspars are lacking. The phenocrysts in this lava range in composition from bytownite ( $An_{80-84}$ ) to labradorite ( $An_{53}$ ). The groundmass feldspars in the two samples studied have the same maximum anorthite content ( $An_{74}$ ) while their most sodic composition is andesine ( $An_{35-42}$ ).

Comparison of the normative and modal feldspars from a number of high alumina basalts (Fig. 8) indicates that the normative feldspars in the Warner and Hat Creek basalts are poorer in potassium than the other high alumina basalts with the exception of that studied by NICHOLLS (1965) from the Atlantic Ocean. Of all the high-alumina basalts plotted in Fig. 8, the Hawaiian example (MUIR and TILLEY, 1961) has by far the most sodic composition of both its modal and normative feldspar.

*d) Lassen.* Inclusion-rich feldspars are common in the Quaternary lavas described from the Lassen region, especially in the "quartz-basalts" of Cinder Cone and West Prospect Peak. MACDONALD and KATSURA (1965) have also reported similar feldspars from the Recent dacites of Lassen Peak.

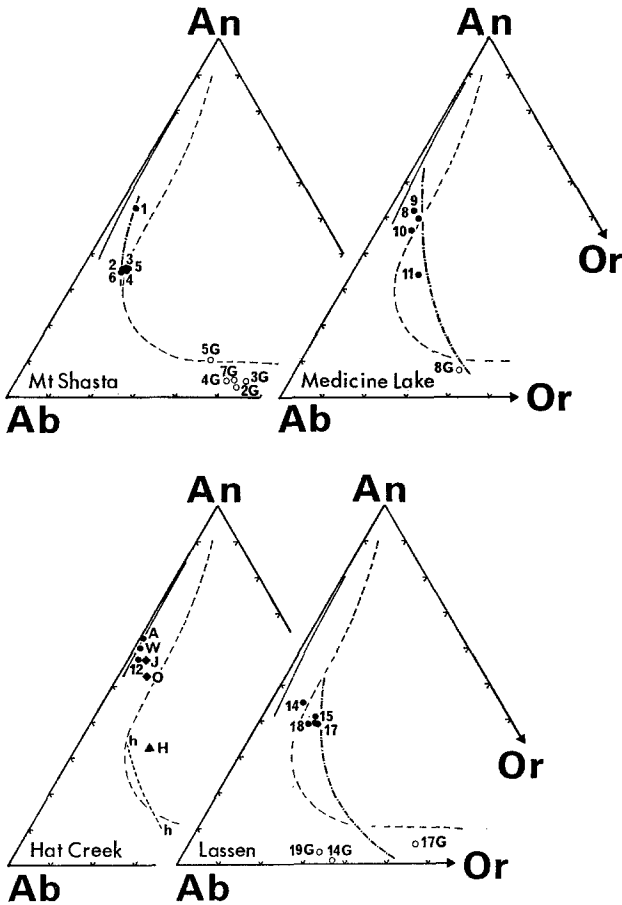


Fig. 8. Normative feldspar of rocks (●) and residual glasses (○) (Tables 2 and 6); - - - trend of normative feldspars for the lavas of the different centers; ——— compositional range of feldspar phenocrysts (only No. 12 in Hat Creek diagram). In the figure representing Hat Creek the following symbols are used: ▲ *H* normative feldspar of alkali high-alumina basalt (Muir and Tilley, 1961, Table 4, Anal. 4); *h*-----*h* range in composition of modal feldspar in above lava (Muir and Tilley, 1961, Table 11, Anal. 4); ◆ normative feldspar components of second type of high-alumina basalt (Kuno, 1960, Table 6); *O* average high-alumina basalt of Oregon (Waters, 1962, Table 5); ● normative feldspars of third type of high-alumina basalt; *A* high-alumina basalt from N. Atlantic (Nicholls, 1965, Table II, Anal. 1); *W* Warner basalt (Yoder and Tilley, 1962, Table 2, Anal. 16); *12* Hat Creek (Table 2). The dashed line represents the limit of ternary solid solution in natural feldspars (Smith and MacKenzie, 1958)

As in all the other lavas described, the composition of the phenocryst and groundmass feldspars show a considerable overlap. The phenocrysts with one exception (No. 19), are more calcic than the groundmass feldspars while at the more sodic end they have approximately the same composition (Fig. 7).

A plot of the normative feldspars of the lavas studied in the system An-Ab-Or (Fig. 8) does not show the systematic trend exhibited by the Quaternary lavas

of Medicine Lake, but all the points do fall in or near the two feldspar field. When the normative feldspars of all the Lassen lavas reported in the literature are plotted, a pronounced trend across the two feldspar field becomes evident.

*e) Discussion.* Perhaps the most striking feature to come out of the study of these feldspars is the large overlap in composition between phenocrysts and groundmass feldspars. Such an overlap was not found by the second author in his study of the Thingmuli tholeiitic lavas (CARMICHAEL, 1967 b). From Table 7 it can be seen that there is still a compositional gap between the *average* phenocryst and the *average* groundmass feldspars, although in general this is rather small, and it is not until individual analyses are plotted that this overlap becomes evident (Fig. 7).

One possible explanation for such a feature is that the phenocrysts had only a very restricted range in composition on eruption and that the compositional overlap is due to the crystallization of the feldspars on eruption both as individual groundmass grains and as rims around the phenocrysts. Another explanation is that the groundmass feldspars are metastable and that their composition is the result of rapid quenching of the lava. In order to evaluate these and other explanations, and to determine the frequency of occurrence of this overlap more work is being undertaken.

#### 4. Iron-Titanium Oxides

In nearly all of the lavas studied the precipitation of an oxide phase has been restricted to a late stage in the crystallization history of the lava, or it has been suppressed almost entirely. Of the Quaternary lavas studied it is generally the more basic which exhibit this lack of oxides but some of the older andesites of Medicine Lake also show this feature (SMITH, unpublished data). The possible reasons for the absence of an oxide phase in basaltic lavas will not be discussed here as they have been considered recently in a paper by CARMICHAEL and NICHOLLS (1967, pp. 4682—4684) to which the reader is referred.

*a) Mt. Shasta.* Of the lavas described from Mt. Shasta it is only the basalt (No. 1) which lacks an oxide phase. This lack of oxides in the more basic lavas, in contrast to their presence in the more silicic ones may only reflect a decrease in solubility of the oxide minerals as the lavas become more siliceous (CARMICHAEL and NICHOLLS, 1967).

A titaniferous magnetite is found as a groundmass phase in all of the andesites studied and as microphenocrysts in one. The relationship between the phenocrystal and groundmass  $\beta$ -phases in this one lava (No. 7) is similar to that described by CARMICHAEL and NICHOLLS (1967), in that the phenocryst is enriched in Mg, Al and ulvospinel when compared to its co-existing groundmass phase.

One of the lavas, the hornblende andesite (No. 6) contains a  $\beta$ -phase of two distinct compositions. One has been precipitated by the lava, while the other formed by the breakdown of the amphibole. The latter  $\beta$ -phase can be seen to be poor in titanium but rich in silica, magnesium and alumina (Table 5).

*b) Medicine Lake.* A titaniferous magnetite is found of two of the lavas studied (Nos. 9 and 10) while the other two lavas (Nos. 8 and 11) appear to be lacking in oxides entirely. In comparison to the oxides from the other Quaternary lavas,

Table 5. Analyses of iron-titanium oxides (A = magnetite; B = ilmenite)

	(235)	(244)	(237)	(72)	(70)	(73)	(187)	(196)	(63)	(81)	(3)	(Cal 25)	
	2A	3A	4A	5A	6A	7A	9A	10A	12A	12B	13A	14A	17A
	ground-	ground-	ground-	ground-	ground-	pheno-	ground-	ground-	ground-	ground-	ground-	ground-	ground-
	mass	mass	mass	mass	mass	crysts	mass	mass	mass	mass	mass	mass	mass
	mass	mass	mass	mass	mass	rim	mass	mass	mass	mass	mass	mass	mass
SiO <sub>2</sub>	0.26	0.24	0.23	0.18	0.17	0.41	0.26	0.16	0.14	0.14	0.29	0.16	0.25
TiO <sub>2</sub>	13.4	15.9	12.0	13.3	14.0	9.8	13.0	23.4	26.1	49.5	25.3	17.8	22.0
MnO	0.30	0.28	0.28	0.48	0.43	0.36	0.41	0.39	0.67	0.70	0.64	0.47	0.35
MgO	1.47	1.09	1.65	1.99	1.18	5.75	1.14	2.00	0.87	0.69	0.26	0.23	2.01
CaO	0.17	0.22	0.24	0.19	0.06	0.24	0.10	0.35	0.10	0.20	0.23	0.11	0.24
ZnO	*	*	*	0.06	0.12	0.03	0.10	0.06	0.09	*	0.18	0.10	0.07
Al <sub>2</sub> O <sub>3</sub>	1.50	1.54	1.88	1.29	2.12	4.24	1.37	1.89	0.41	0.05	1.03	0.88	1.09
Cr <sub>2</sub> O <sub>3</sub>	0.04	0.05	0.04	0.04	0.02	0.02	0.02	0.44	0.02	*	0.07	0.03	*
V <sub>2</sub> O <sub>3</sub>	1.05	1.36	1.08	1.23	0.56	0.72	1.09	0.91	0.55	0.21	0.37	1.14	1.24
FeO	77.5	75.6	78.6	77.1	77.9	73.7	78.3	71.4	68.8	47.7	69.7	76.4	68.6
Sum	95.7	96.3	96.0	95.9	96.6	95.3	95.8	96.6	97.8	99.2	98.1	97.3	95.9
Ilmenite basis													
FeO	33.0	34.4	32.5	32.0	33.8	—	33.3	33.8	37.5	42.6	38.2	36.4	32.8
Fe <sub>2</sub> O <sub>3</sub>	49.4	45.8	51.2	50.1	49.0	—	50.0	41.9	34.8	5.7	35.0	44.5	38.1
Total	100.6	100.9	101.1	100.9	101.5	—	100.8	100.9	101.3	99.8	101.6	101.8	98.2
Ulvo-spinel basis													
FeO	41.3	44.1	39.9	40.0	42.4	29.4	41.3	45.3	53.2	—	53.6	47.2	47.7
Fe <sub>2</sub> O <sub>3</sub>	40.2	35.0	43.0	41.2	39.5	49.3	41.1	29.0	17.3	—	18.0	32.5	23.2
Total	99.7	99.8	100.3	100.0	100.6	100.3	99.9	99.5	99.5	—	100.0	100.6	98.2
Mol% Usp	38.6	45.5	34.3	37.8	39.6	26.8	39.9	47.3	73.9	—	71.9	50.6	63.0
Mol% Fe <sub>2</sub> O <sub>3</sub>	—	—	—	—	—	—	—	—	—	5.7	—	—	—
Temp°C	—	—	—	—	—	—	—	—	—	1050	—	—	—
fO <sub>2</sub>	—	—	—	—	—	—	—	—	—	10 <sup>-10.6</sup>	—	—	—



that from the Paint Pot Crater flow (No. 9) is seen to be relatively enriched in chromium. It was previously noted that many of the olivines in the more basic lavas contain inclusions of chrome spinel. The fact that such inclusions are lacking in the phenocryst olivines in the Paint Pot Crater flow may account for the relative richness of the groundmass oxides in chromium.

*c) Hat Creek.* The high alumina basalt of Hat Creek is characterized by the presence in the groundmass of a titaniferous magnetite which only co-exists with an ilmenite in the more slowly cooled central parts of the flow (No. 12). The temperature and fugacity of oxygen of the equilibration of these oxides have been determined using the curves of BUDDINGTON and LINDSLEY (1964). Comparison of this equilibration data (Table 5) with that given by CARMICHAEL (1967b) for a series of tholeiitic lavas from Iceland indicates that the conditions under which the oxides equilibrated in both types of basalts were very similar.

*d) Lassen.* Of the three areas studied it is the lavas from Lassen which are the most characterized by a lack of oxides. Only two (Nos. 14 and 17) of the six samples contain an oxide phase (excluding the chrome-spinels) of sufficient size for analysis. In the other lavas an oxide phase appears either to be lacking entirely (No. 19) or it only occurs as small granules confined to the residual glass.

*e) Discussion.* When  $\beta$ -phases which co-exist with similar ferromagnesian species, such as orthopyroxenes (see Tables 1 and 5), are compared, their ulvospinel contents are found to vary only within restricted limits. For example, the  $\beta$ -phases associated with olivine and augite exhibit a range from 74 to 65 molecular percent ulvospinel. Those  $\beta$ -phases associated with both phenocryst and groundmass orthopyroxenes also show a restricted range in composition (34–45% Usp); however, those  $\beta$ -phases which co-exist with both olivine and orthopyroxene have values overlapping the two ranges mentioned above. The only oxide phase which falls outside these limits is that from the Paint Pot Crater flow (No. 9) but as has already been noted the composition of this spinel is unusual in that it is rather rich in minor elements, particularly Cr. Similar restrictions in ulvospinel content were found for  $\beta$ -phases co-existing with orthopyroxenes, iron-rich olivines and amphiboles from salic lavas (CARMICHAEL, 1967a). This similarity between the ulvospinel contents of  $\beta$ -phases from obsidians and the lavas described here is not altogether surprising if it is remembered that in many of these lavas the groundmass oxides are associated with residual glasses of rhyolitic composition. On the assumption that if  $\alpha$ -phases had been present in the residual liquids of the basalts and andesites from the Cascades they would have had  $R_2O_3$  contents similar to those found in obsidians (CARMICHAEL, 1967a) then oxide equilibration data can be calculated for these lavas. Temperatures of between 800 and 980° C were indicated from the curves of BUDDINGTON and LINDSLEY (1964) for those oxides co-existing with orthopyroxene. These temperatures are within the range of what the authors would expect for co-existing groundmass oxides in salic andesites and suggest that the temperature (and perhaps oxygen fugacity) during the final stages of crystallization of these andesites were similar to those shown by the obsidians (CARMICHAEL, 1967a).

OSBORN (1959, 1962) noted that differentiation of basalt followed either of two trends, one involving silica enrichment, the other iron enrichment. From his study of the system  $MgO-FeO-Fe_2O_3-SiO_2$  he proposed that these two trends

were dependent upon the oxygen conditions under which the magma fractionated. Recently, ROEDER and OSBORN (1966) found that the general course of crystallization described for the above system was not changed by the addition of anorthite. PRESNALL (1966) from his study of the join Fo-Di-Iron oxide concluded that during the *early* stages of crystallization regardless of whether the system was "internally" or "externally" buffered<sup>4</sup> the trend of enrichment depended on the initial composition; only during the late stages of fractional crystallization was control of oxygen fugacity important. The main conclusion of this experimental work is that in order for a basaltic magma to undergo silica enrichment with restricted iron enrichment it must be externally buffered at moderate to high fugacities of oxygen; and, as a consequence of this, magnetite must precipitate in significant amounts during the early and middle stages of crystallization. Petrographically, lavas which have crystallized under these conditions should therefore show some evidence of early separation of a  $\beta$ -phase.

The orogenic suite of lavas are probably the best known examples of silica enrichment with little or no iron-enrichment. The Cascades are perhaps more suited than most orogenic areas to test the hypothesis noted above as they were the original examples cited by OSBORN (1959, 1962) of crystallization under conditions of constant fugacity of oxygen (externally buffered).

From the data present in Table 5 and discussed on p. 226—228 it appears that the Quaternary lavas studied do not support the experimental evidence. In nearly all of the lavas examined a  $\beta$ -phase is not an early crystallizing phase; indeed in some lavas a  $\beta$ -phase was not a primary phase at all. It could be argued perhaps that this is the result of fractionation of  $\beta$ -phase at depth; if such was the case then it would seem reasonable to expect some evidence of this in the derived lavas. As was pointed out by CARMICHAEL and NICHOLLS (1967), the absence of oxide phenocrysts indicates a more complete fractionation than is evident from the other early crystallizing phases.

Thus, it would appear that the conditions which give rise to silica enrichment in rocks are not the same as those found experimentally. The oxide equilibration data for the more basic and acid lavas from *both* orogenic and non-orogenic environments are similar (Table 5, No. 12; CARMICHAEL, 1967 a, 1967 b) indicating that orogenic and non-orogenic lavas have crystallized under similar oxygen fugacity conditions, this does not mean however, that they necessarily originated under similar conditions.

### 5. Amphibole

An amphibole is only found in one of the lavas investigated (No. 6). It occurs only as elongate phenocrysts which are characterized by a deep red to yellow-brown pleochroism. Some of the phenocrysts are completely replaced by iron-oxide while all are surrounded by oxide rims. The amphibole which is a Ti-rich hornblende, is relatively rich in alumina (12%) and magnesium (16%) but poor in potassium (0.19%).

<sup>4</sup> These terms are after CARMICHAEL and NICHOLLS (1967); internally buffered meaning a system in which the crystal liquid assemblage has an oxygen buffer capacity; while an externally buffered system is one in which the environment or the volatile phase is the controlling factor.

### E. Residual Glass

Residual glass appears in many of the lavas described, however in some, due to the presence of microlites, the glasses are too variable to be satisfactorily analyzed with the electron probe. The composition of the glasses (Table 6) ranges from dacitic to rhyolitic; however, only the residual glasses from Mt. Shasta form a closely related group.

Table 6. *Chemical analyses and CIPW norms of residual glasses*

	Mt. Shasta					Medicine Lake	Lassen Region		
	(235) -2G-	(244) -3G-	(237) -4G-	(72) -5G-	(73) -7G-	(200) -8G-	(3) -14G-	(Cal 25) -17G-	(117) -19G-
SiO <sub>2</sub>	75.9	75.8	73.7	73.2	75.7	66.2	72.1	72.2	71.3
TiO <sub>2</sub>	1.00	1.00	1.00	1.00	0.68	2.70	1.20	1.30	1.30
Al <sub>2</sub> O <sub>3</sub>	11.2	11.4	11.0	11.3	11.1	13.8	13.8	12.4	12.2
FeO <sup>a</sup>	2.5	2.3	3.6	1.8	2.8	4.6	2.3	2.4	4.7
MnO	0.02	0.02	0.05	0.40	0.02	0.16	0.03	0.03	0.08
MgO	0.26	0.24	0.59	0.22	0.23	0.46	0.21	0.40	0.40
CaO	0.75	0.58	1.40	0.60	0.70	2.40	0.43	0.86	1.40
Na <sub>2</sub> O	3.0	2.8	3.0	3.0	2.9	4.3	5.3	3.0	4.7
K <sub>2</sub> O	5.2	5.4	4.7	4.0	4.9	4.5	4.5	5.8	3.4
Total	99.83	99.54	99.04	96.52	99.03	99.12	99.87	98.38	99.48
Qz	35.6	36.1	33.0	36.1	36.5	17.7	22.1	29.3	25.4
Or	30.7	31.9	27.8	23.6	29.0	26.6	26.6	34.3	20.1
Ab	25.4	23.7	25.4	25.4	24.5	36.4	44.9	25.4	39.8
An	1.7	2.6	2.7	5.6	2.8	5.1	0.6	3.2	2.2
Di-wo	0.8	0.1	1.8	1.0	0.3	2.9	0.7	0.4	2.0
Di-en	0.2	0.0	0.4	0.2	0.1	0.6	0.1	0.1	0.3
Di-fs	0.7	0.1	1.5	0.9	0.3	2.4	0.6	0.3	1.9
Hy-en	0.5	0.6	1.0	0.4	0.5	0.5	0.4	0.9	0.7
Hy-fs	2.3	2.5	3.6	1.5	3.8	1.9	1.7	2.0	4.7
Il	1.9	1.9	1.9	1.9	1.3	5.1	2.3	2.5	2.5

<sup>a</sup> All iron calculated as FeO.

In contrast to the relatively large depletion in iron shown by tholeiitic residual glasses (VINCENT, 1950; WALKER *et al.*, 1952; ELLIOT, 1956) those from the basalts and andesites of the Cascades exhibit less impoverishment in iron. This perhaps is due to the late crystallization (if at all) of an oxide phase in the Cascade lavas. Trend-lines between lavas and their residual glasses tend to cut across the average trends of the lavas from the different centers when plotted in an A-F-M diagram (Fig. 3). This difference in trend may indicate that the more salic lavas of the Cascades and the residual glasses are not related to the basalts in the same way.

In a recent paper BROWN and SCHAIRER (1967) have shown that a series of orogenic lavas from the West Indies exhibit a distinctive trend towards low magnesia and total iron oxides. Trend-lines between rocks and associated ground-masses (BROWN and SCHAIRER, 1967, Fig. 65) when plotted in terms of MgO

and  $\text{FeO} + \text{Fe}_2\text{O}_3$  exhibit a progressive flattening of slope from basalts to rhyodacites. When the lavas and their residual glasses from the Cascades are plotted in such a diagram the trend-lines between rock and glass are steep (i.e., similar to the trend-line for the basalt given by BROWN and SCHAIRER) and show no tendency to flatten out as the lavas become more silicic (Fig. 9).

The feldspar components of the glasses have been plotted in Fig. 8. All of the glasses co-exist with only a plagioclase feldspar. The glasses from Mt. Shasta form a compact group with only (No. 5 G) plotting outside. The glass from one

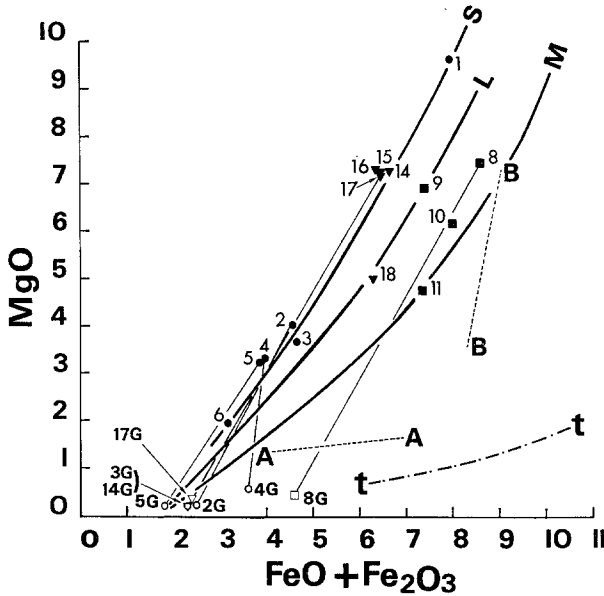


Fig. 9. Relationship of total iron oxide to magnesia for the lavas of Medicine Lake (*M*), Lassen (*L*), and Mt. Shasta (*S*). Closed symbols represent rocks studied in this paper; open symbols residual glasses; ● Mt. Shasta; ▼ Lassen; ■ Medicine Lake; *B*-.....*B* and *A*-.....*A* represent trends shown by olivine basalt and andesite from the West Indies (BROWN and SCHAIRER, 1967); *t*-...-*t* part of Thingmuli trend (CARMICHAEL, 1964), for complete trend see BROWN and SCHAIRER (1967, Fig. 64)

of the Medicine Lake basalts (No. 8 G), as far as its feldspathic components are concerned, is similar in composition to the two recent Medicine Lake obsidians (CARMICHAEL, 1967 a).

The relationship of the lavas to their residual glasses in terms of their normative salic constituents (less anorthite) is shown in Fig. 10. As in most of the other diagrams the residual glasses from Lassen and Medicine Lake are more variable in composition than those from Mt. Shasta, which plot near the ternary minimum at 500 bars (TUTTLE and BOWEN, 1958). As (No. 5 G) has not precipitated quartz, its position above the quartz-feldspar boundary curve is seemingly anomalous. However, since this glass is richer in anorthite than the others, its projection from the Qtz-Ab-Or-An tetrahedron onto the Ab-Or-Qtz plane may be responsible for its position.

Unfortunately, no residual glass has been found in the samples of the Hat Creek lava studied. As this lava is similar both chemically and mineralogically to the Warner basalt, perhaps the late stage crystallization trend described for this lava may also apply to the Hat Creek flow as well. KUNO (1965) has shown that late stage segregation veins in the Warner basalt show a trend towards

iron enrichment. This is in contrast to the trend exhibited by other high alumina basalts (KUNO, 1965, Nos. 5 and 7) and the Medicine Lake high alumina basalts (p. 230) for which similar information is available. If this iron-enrichment is typical of the Warner-Hat Creek high alumina basalts, then it would appear that these lavas may be distinguished from other high alumina basalts not only on their chemistry but also on their late stage fractionation trends.

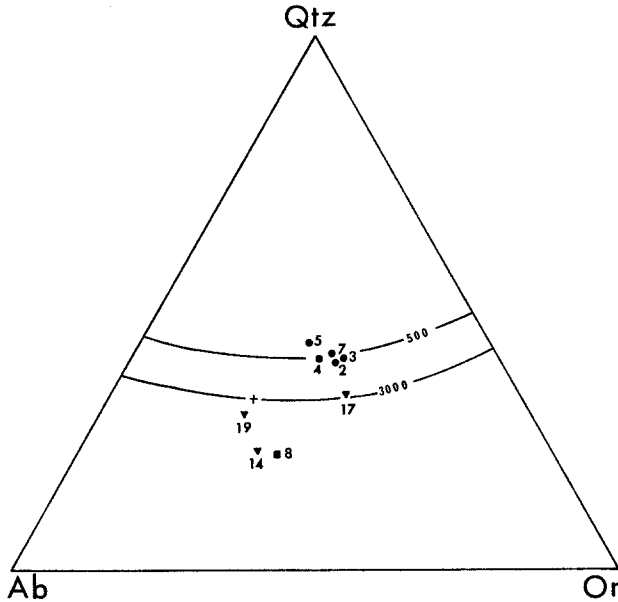


Fig. 10. The salic normative constituents of the residual glasses are plotted in the system Ab-Or-Qtz; ● Mt. Shasta; ▼ Lassen; ■ Medicine Lake. The boundary curves at 500 and 3,000 bars are taken from TUTTLE and BOWEN (1958)

## F. Petrology

*a) High-Alumina Basalts.* In the preceding pages the high alumina basalt of Hat Creek has been compared with other high-alumina basalts. From the evidence presented it would appear that the term high-alumina basalt has been applied to a wide variety of lavas whose only common denominator is that they are aphyric and contain alumina in excess of 17%. It would appear (Table 7; Figs. 6 and 8) that there are at least three types of high-alumina basalt: 1. Alkali high-alumina basalts; 2. KUNO'S high-alumina type basalt; 3. Warner-Hat Creek high-alumina basalt.

The first type is similar mineralogically to other alkaline lavas and their chemical composition can most easily be explained by separation of olivine and pyroxene from a normal alkali olivine basalt. Lavas belonging to the second type seem to be related in many of their mineralogical and chemical features to their associated lavas. It is these high-alumina basalts which appear to be characteristic of orogenic regions. Any theory regarding the origin of this type of high-alumina basalt must account for the association of these lavas with other members (andesite, rhyolite, etc.) of the orogenic volcanic suite. Lastly, lavas of the third type, namely the Warner-Hat Creek high-alumina basalts, have a distinctive mineralogy and chemical composition noted above and show no gradational features to their

Table 7. Comparison of high-alumina basalt compositions

	1	2	3	4	5
SiO <sub>2</sub>	48.27	49.15	50.19	49.77	48.13
TiO <sub>2</sub>	0.89	1.52	0.75	2.46	0.72
Al <sub>2</sub> O <sub>3</sub>	18.28	17.73	17.58	18.37	17.07
Fe <sub>2</sub> O <sub>3</sub>	1.04	2.76	2.84	4.28	1.17
FeO	8.31	7.20	7.19	6.55	8.65
MnO	0.17	0.14	0.25	0.21	0.13
MgO	8.96	6.91	7.39	3.86	10.29
CaO	11.32	9.91	10.50	7.19	11.26
Na <sub>2</sub> O	2.80	2.88	2.75	5.08	2.39
K <sub>2</sub> O	0.14	0.72	0.40	1.98	0.09
P <sub>2</sub> O <sub>5</sub>	0.07	0.26	0.14	0.36	0.10
Total	100.25	99.18	99.98	100.11	100.00
Or	0.56	4.25	2.36	11.70	0.53
Ab	23.58	24.37	23.27	33.29	20.22
An	36.97	33.32	34.44	21.47	35.58
Ne	—	—	—	5.25	—
Di	15.23	11.45	13.58	9.59	15.93
Hy	—	12.86	16.65	—	4.77
Ol	20.55	5.43	3.80	7.09	19.67
Mt	1.39	4.00	4.12	6.21	1.70
Il	1.67	2.89	1.42	4.67	1.37
Ap	0.17	0.62	0.33	0.85	0.24

1 Warner basalt (YODER and TILLEY, 1962, Anal. 16, p. 362).

2 Average high-alumina basalt, Oregon plateau (WATERS, 1962, p. 165).

3 Average high-alumina basalt, Japan (KUNO, 1960, p. 141).

4 Hawaiite, Mauna Kea, Hawaii, (MUIR and TILLEY, p. 190).

5 Glass rim of dredged basalt fragment, N. Atlantic, (NICHOLLS, 1965, p. 378).

associated volcanics (unlike types 1 and 2). Lavas of the third type have also been described both from non-orogenic continental areas (WAGER and DEER, 1939) and from oceanic environments (NICHOLLS, 1965).

### G. Petrogenesis

The rocks of the Cascade Quaternary volcanic province range from high-alumina basalts to rhyolites. As in other orogenic areas andesite greatly predominates over basalt, in contrast to non-orogenic provinces such as Iceland (WALKER, 1958; CARMICHAEL, 1964), where basalts are more abundant than their andesitic and rhyolitic differentiates.

Some of the petrogenetic theories that have been proposed for the origin of orogenic andesites and their associated lavas are:

1. Fractional crystallization of a *parental* basaltic magma as suggested by BOWEN (1928, pp. 92—132) or OSBORN (1959, 1962) who indicated the controlling role of oxygen.

2. Fractional crystallization of basaltic magma modified by sialic contamination as proposed by TILLEY (1950), KUNO (1950) and WATERS (1955).

3. Mixing of basaltic and more siliceous magmas as suggested by LARSEN *et al.* (1938) for the San Juan region and by HOLMES (1932) who invoked melting of the lower crust to give primary granitic magma which then mixed with basaltic magma.

4. Melting of the lower crust to give andesitic magmas (TURNER and VERHOOGEN, 1960, p. 287).

5. Partial melting of the mantle (or subsequent fractional crystallization of the derived liquid in the mantle) to give primary andesitic magma as proposed by O'HARA (1965), GREEN and RINGWOOD (1966, 1968), HAMILTON (1966).

Among the pertinent features of the Cascade volcanic series which should be considered by any theory of petrogenesis are the following:

1. Presence of andesite in great abundance at all eruptive centers. The inference is that andesite has the status of a primary magma<sup>5</sup>.

2. Presence of aphyric high-alumina basalts which are unlikely to be differentiates of a parent andesite magma.

3. Presence of both basalt and rhyolite, without intermediate andesite, in Recent eruptive cycles of some volcanoes (Newberry, Medicine Lake).

4. Absence under Mt. Shasta of a large mass of basic material (LAFEBER, 1965) such as must be invoked to account for the predominance of andesites by fractionation according to the models of BOWEN (1928) and OSBORN (1959, 1962).

5. Evidence of magmatic mixing as shown by the Recent dacites of Medicine Lake (ANDERSON, 1941, p. 395).

6. Increase in the potassium content of the andesites towards the interior platform (p. 218).

7. Low initial strontium isotope ratios of some of the Cascade acid lavas (HEDGE and WALTHALL, 1963) and of orogenic lavas (especially andesites) in general (COMPSTON, unpublished data quoted by TAYLOR and WHITE, 1966; TILLEY *et al.*, 1967; PUSHKAR, 1968).

8. Presence of relatively thin crust under the Cascades (DEHLINGER *et al.*, 1965) beneath which is found an upper mantle of low density material. Other orogenic areas are also characterized by a thin crust (or no crust at all) underlain by an anomalous mantle. THOMPSON and TALWANI (1964) and DEHLINGER *et al.* (1965) suggest that the upper mantle in these regions is composed of either hydrated peridotite or feldspathic peridotite.

These facts, taking into consideration also GREEN and RINGWOOD'S (1966, 1968) experimental data on the melting of hydrated peridotite and feldspathic peridotite<sup>6</sup> at high pressure, are consistent with the following model of petrogenesis. Partial melting of an upper mantle of feldspathic peridotite under either wet or dry conditions over an appropriate range of pressure and temperature. This would give rise to basaltic, andesitic or rhyolitic magma with andesite predominant.

<sup>5</sup> Although andesite predominates among the lavas of Pleistocene age it should be emphasized that during the Pliocene, basalt (particularly high-alumina basalt) was erupted in great abundance; in fact, Pliocene andesites are exceptional (H. WILLIAMS, written communication).

<sup>6</sup> Although GREEN and RINGWOOD (1966) concluded that andesites formed the low melting fraction of quartz-eclogite at depths of 100—140 kms, their evidence indicates that liquids of andesitic composition will also be the low melting fraction of feldspathic peridotite at much shallower depths (35—60 kms).

The magmas so formed may be subsequently modified by high level fractional crystallization and/or contamination. However, modification at high levels is not in any way essential for the formation of the Cascade orogenic lavas.

*Acknowledgements.* The authors are indebted to the National Science Foundation for materially assisting (GA-338 and GA-480) this study. The National Park Service kindly allowed the collection of specimens. We would also like to thank Dr. B. W. EVANS and L. BURNS for their help and advice in the techniques and use of the electron probe and Dr. H. WILLIAMS, W. JOHNSON and J. NICHOLLS for their advice in preparing this paper.

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