# Compositional Variation in Three Cascade Stratovolcanoes: Jefferson, Rainier, and Shasta

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## Abstract

Detailed major and trace element studies of volcanic rocks from Jefferson, Rainier, and Shasta stratovolcanoes in the Cascade Range indicate that each volcano has distinct geochemical distribution patterns. Silica variation diagrams are not smooth nor, in general, continuous for any volcano. Portions of stratigraphic sections within the volcanoes exhibit compositional coherency and are interpreted as eruptive groups which were extruded over time intervals which are short compared to the lifetimes of the volcanoes. The results of this investigation indicate the feasibility of geochemically mapping eruptive groups within stratovolcanoes. Systematic compositional trends are not observed within thick (500-1000 m) eruptive groups but may occur over thicknesses of < 200 m. Compositional variations within eruptive groups are commonly non-systematic and show ranges similar to the ranges observed in individual flows. Correlations between the amounts or kinds of phenocryst phases present and intra-group compositional variation is not observed. Inter-group compositional differences are sometimes accompanied by mineralogical differences. Late andesites and dacites at Rainier and Shasta are characterized by decreases in K and Rb while at Jefferson increases in these elements and other compositional changes occur in the late eruptives.

Progressive fractional crystallization models do not seem capable of explaining the element distributions observed in the three volcanoes. Existing data are consistent with a model involving varying degrees of melting of some combination of amphibolite, eclogite or peridotite in or above a subduction zone with varying water contents. Segregation and sequential eruption of small batches of magma may produce the eruptive groups characterizing the volcanoes. Late mafic magmas erupted at satellite vents appear to be produced in different (deeper?) mantle source areas.

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## Introduction

The stratovolcanoes of the high Cascades in the northwestern United States represent the most recent calc-alkaline volcanic activity in the conterminous United States. Paleomagnetic data suggest that most or all of these volcanoes were erupted during the present polarity epoch (McBirney, 1968). The purpose of the present investigation is to evaluate compositional variation within several Cascade stratovolcanoes in order to more fully understand the origin of the magmas which formed the volcanoes and the relationship of eruptional histories to magma evolution. Four stratovolcanoes were sampled and studied in detail: Mt. Jefferson in northwest Oregon, Mt. Rainier in southwest Washington, and Mt. Shasta and the Medicine Lake volcanic center both in northern California. Only results for the first three are herein reported.

Up to about 150 samples of flows were collected from each volcano, and many of these were analyzed for $K_2O$ and $SiO_2$ to identify gross geochemical features. Up to 30 samples from each volcano were then selected for more complete analyses. In order to evaluate compositional variations as a function of stratigraphic height (eruptive age), flows from several stratigraphic sections exposed on ridges and cleavers of the volcanoes were systematically sampled. Because of poor exposure or hazardous sampling conditions, however, only four sections were sampled where obvious age relationships were clear for more than a few volcanic units. The thickness of these sections, which are given in Table 1, range from 150 m to 1000 m. Sample locations and generalized geologic maps of each volcano are given in Figures 1-3.

## Analytical Methods

Twenty to thirty samples of lava from each volcano were analyzed for the major elements Si, Al, Ti, Fe, Mg, Ca, and K and the trace elements Rb, Sr, Zn, Cu, and Ni by non-destructive X-ray fluorescence methods previously described (Condie, 1967*a*, *b*) using standard rocks W-1, BCR-1, AGV-1, GSP-1, GR, T-1, G-2, and Sy-1 to construct major element calibration curves. Andesite AGV-1 was used as a standard for all trace element analyses. 8-10 samples from each volcano were analyzed for Na, Cs, Sb, Cr, Co, Ba, La, Ce, Sm, Eu, Tb, Yb, and La by non-destructive neutron activation analysis (Condie and Lo, 1971) using AGV-1 as a standard. Total analytical error is estimated $\leq 5$ percent for major elements, Rb, Sr, Cu, Zn, Co, Cr, La, and Ce; $\leq 10$ percent for Ni, Ba, Sb, Cs, Sm, Eu, Yb, and Lu; and $\leq 25$ percent for Tb. The Eu/Eu* ratio (defined by the chondrite-normalized Eu value divided by the value obtained by drawing a straight line from Sm to Tb and reading the Eu value) is reproducible to about 5 percent. Thin sections were examined of most samples and modal analyses were made of representative samples from each of the major stratigraphic successions.

## Mt. Jefferson

Mt. Jefferson is the most deeply dissected of the three strato-volcanoes studied and provided the most readily accessible stratigraphic sections. The general geology of the Mt. Jefferson Primitive Area has been described by WALKER, *et al.* (1966) and the petrology of the volcanic rocks is reported on by GREENE (1968). The volcano proper is composed of about equal amounts of interbedded flows and pyroclastics ranging from pyroxene andesite to pyroxene dacite

TABLE 1 - Accumulative thicknesses of stratigraphic sections sampled at Mt. Jefferson and Mt. Rainier.

| *Section* | *Thickness (m)* |
|---|---|
| Southwest Ridge, Jefferson | 1,000 |
| Success Cleaver, Rainier | 800 |
| Cowlitz Cleaver, Rainier | 400 |
| Ptarmigan Ridge, Rainier | 150 |

in composition. The nomenclature suggested by TAYLOR (1969) is assumed in this paper: *i.e.*, andesites range from 56-62 % $SiO_2$ and dacites from 62-68 % $SiO_2$. The lavas are remarkably uniform in mineralogy. They are porphyritic containing phenocrysts of plagioclase (30-35 percent), clinopyroxene (1-5 percent), and orthopyroxene (3-5 percent) with 0.5-3 percent of Fe-Ti oxides in the groundmass. Flows thin in average thickness towards the top of the volcano. The summit pinnacle is composed of a plug of pyroxene andesite emplaced during the final stages of activity. Major sampling traverses were made from the exposed base of the volcano to the summit pinnacle along the Northwest, West, and Southwest Ridges (Fig. 1). For comparative purposes some samples from nearby areas within a radial distance of 12 km of the peak were also collected and analyzed.

Major and trace element data from lavas of Mt. Jefferson are summarized in Table 2 and in Figures 4-7. The Jefferson rocks exhibit low K, Rb, and Cs concentrations and relatively high K/Rb ratios compared to volcanoes from most other high Cascade volcanoes for

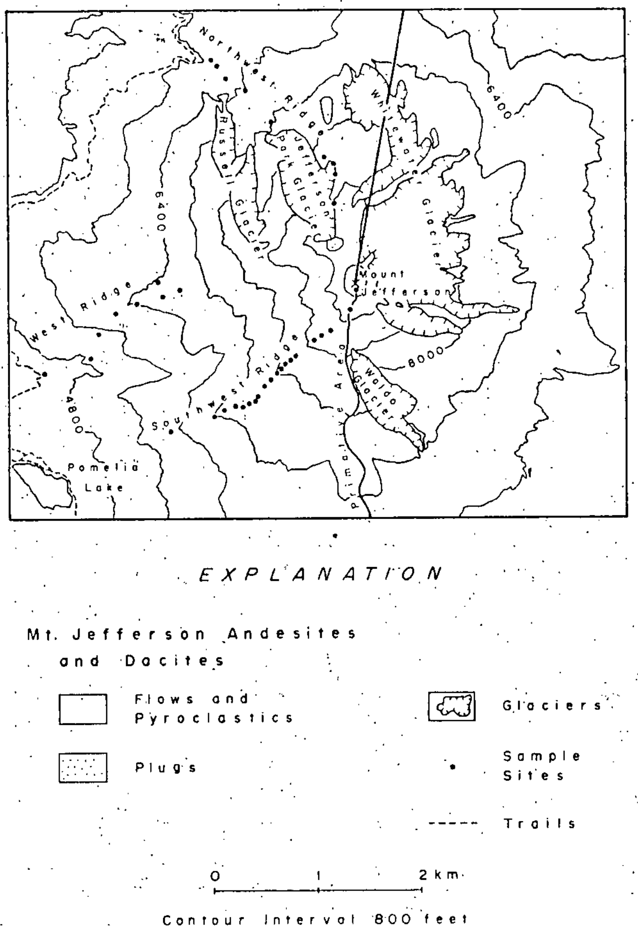


FIG. 1 - Generalized geologic map of Mt. Jefferson, Oregon, showing sample locations. Geology after WALKER, *et al.* (1966).

which data are available. In this respect they appear to be transitional between the calc-alkaline and arc-tholeiite series as defined by JAKES and WHITE (1972).

The data indicate that the Jefferson rocks fall into two rather distinct compositional groups. A discontinuity of varying magnitude



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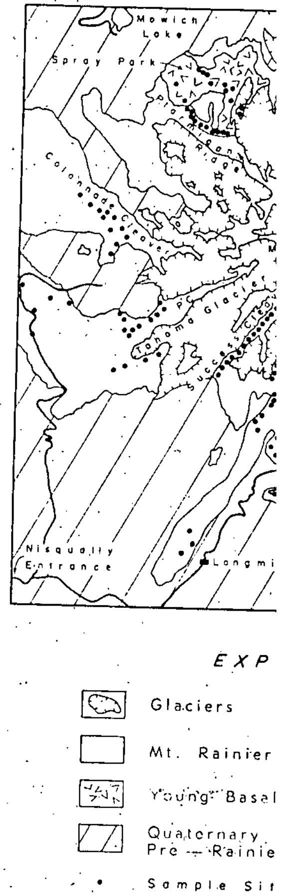


FIG. 2 - Generalized geologic map of M
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CCC = Columbia Crest Cone;
WC = Wapowety Cleaver.

lower two-thirds of Southwest
Mg, Ca, Cr, Sb, Cu, and Sr a
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in the concentration of most but not all elements separates the two groups and is observed both on $SiO_2$ variation diagrams (Figs. 4 and 5) and in the Southwest Ridge section (between samples 37 and 39, Fig. 6). The first group defined by samples from the West Ridge and

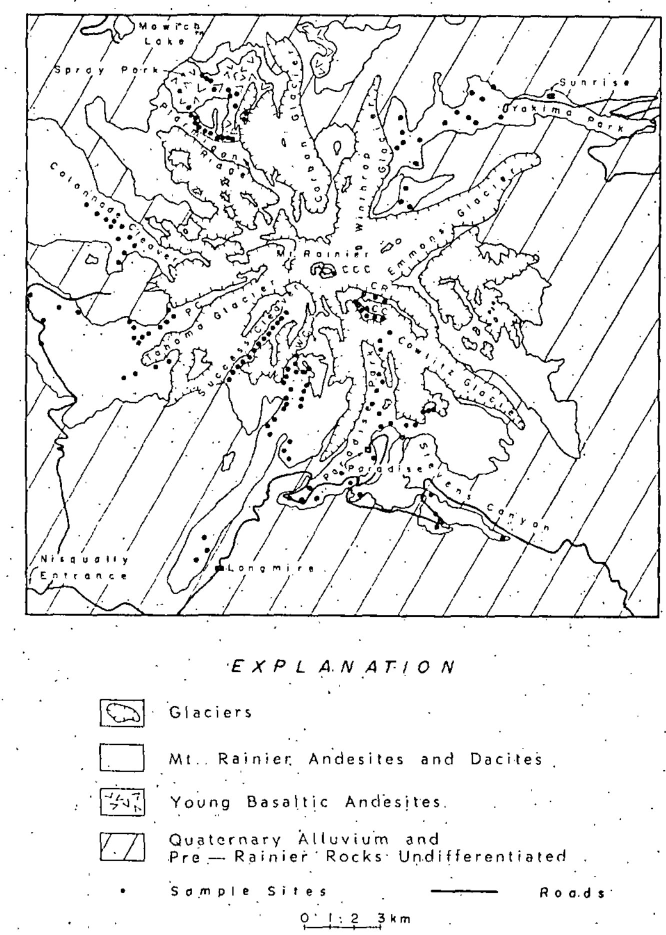


FIG. 2 - Generalized geologic map of Mt. Rainier, Washington, showing sample locations. Geology after FISKE, *et al.* (1963). Abbreviations: PC = Puyallup Cleaver; CCC = Columbia Crest Cone; CR = Cathedral Rocks; CC = Cowlitz Cleaver; WC = Wapowety Cleaver.

lower two-thirds of Southwest Ridge is relatively high in Fe, Ti, Al, Mg, Ca, Cr, Sb, Cu, and Sr and exhibits a $SiO_2$ range from 56-59 percent. Most element concentrations are rather constant over this

$SiO_2$ range (Figs. 4 and 5). Relative and absolute distributions of REE are similar to those reported for other young calc-alkaline volcanics (TAYLOR, 1969; GILL, 1970). The second group, defined by samples from the Northwest Ridge and Summit area (upper one-third of the

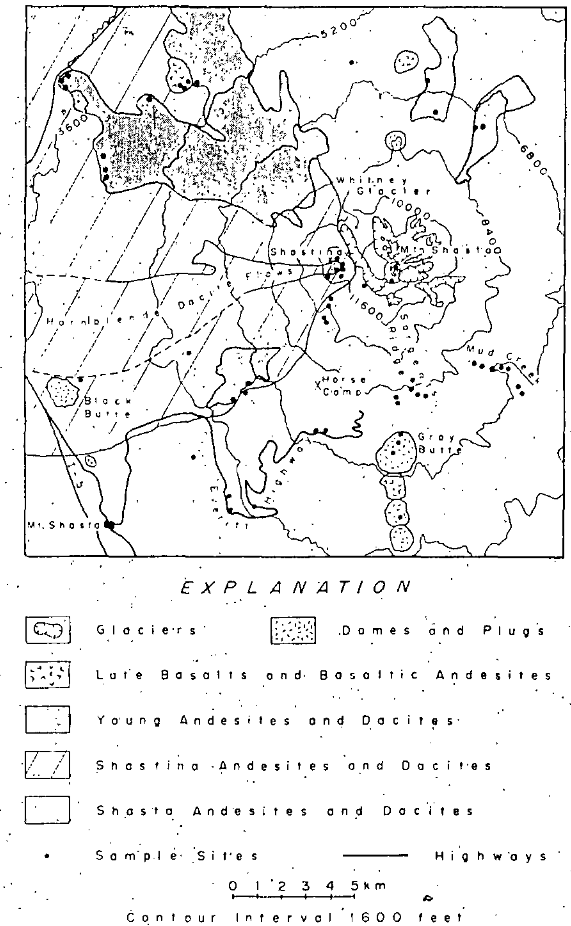


FIG. 3 - Generalized geologic map of Mt. Shasta, California, showing sample localities. Geology after WILLIAMS (1932; 1934).

Southwest Ridge section), ranges from 59-64 percent $SiO_2$, is enriched in Na, K, and to a lesser degree in Rb, and exhibits higher K/Rb, K/Cs, K/Ba, and Rb/Sr ratios than the first group (Table 2). In this group K slightly increases and Fe, Ti, and Ca decrease with $SiO_2$ (Fig. 4) and light REE are depleted relative to the first group (Fig. 7).



TABLE 2 - Average compositi

| | Southwest Ridge + |
|---|---|
| $SiO_2$ | 56.71 |
| $TiO_2$ | 1.02 |
| $Al_2O_3$ | 17.47 |
| $Fe_2O_3$ | 7.92 |
| MgO | 2.74 |
| CaO | 7.76 |
| $Na_2O$ | 3.97 |
| $K_2O$ | 0.91 |
| Ni | 18 |
| Co | 24 |
| Cr | 99 |
| Sb | 0.11 |
| Zn | 84 |
| Cu | 60 |
| Rb | 13 |
| Cs | 0.35 |
| Ba | 442 |
| Sr | 667 |
| La | 11 |
| Ce | 33 |
| Sm | 4.0 |
| Eu | 1.2 |
| Tb | 0.52 |
| Yb | 1.5 |
| Lu | 0.32 |
| Σ7REE | ~52 |
| K/Rb | 581 |
| Rb/Sr | 0.020 |
| K/Ba | 17 |
| K/Cs | $22 \times 10^3$ |
| Ba/Sr | 0.66 |
| Ni/Co | 0.75 |
| Zn/Cu | 1.4 |
| La/Yb | 7.3 |
| Eu/Eu * | 1.0 |

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* $Fe_2O_3$ = total Fe as $Fe_2O_3$
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Ca decrease with $SiO_2$
the first group (Fig. 7).



TABLE 2 - Average compositions of lavas from Mt. Jefferson, Oregon.

| | *Southwest Ridge* + | *West Ridge* | *Northwest Ridge-Summit* |
|---|---|---|---|
| $SiO_2$ | 56.71 | 57.33 | 61.27 |
| $TiO_2$ | 1.02 | 1.02 | 0.78 |
| $Al_2O_3$ | 17.47 | 17.45 | 16.60 |
| $Fe_2O_3$* | 7.92 | 7.94 | 5.92 |
| MgO | 2.74 | 2.27 | 1.74 |
| CaO | 7.76 | 7.83 | 6.59 |
| $Na_2O$ | 3.97 | 4.02 | 4.44 |
| $K_2O$ | 0.91 | 0.94 | 1.16 |
| Ni | 18 | 19 | 16 |
| Co | 24 | — | 20 |
| Cr | 99 | — | 33 |
| Sb | 0.11 | — | 0.21 |
| Zn | 84 | 84 | 79 |
| Cu | 60 | 62 | 45 |
| Rb | 13 | 14 | 16 |
| Cs | 0.35 | — | 0.31 |
| Ba | 442 | — | 374 |
| Sr | 667 | 636 | 553 |
| La | 11 | — | 6.3 |
| Ce | 33 | — | 21 |
| Sm | 4.0 | — | 3.4 |
| Eu | 1.2 | — | 1.3 |
| Tb | 0.52 | — | 0.62 |
| Yb | 1.5 | — | 1.1 |
| Lu | 0.32 | — | 0.25 |
| $\Sigma$7REE | ~52 | — | ~34 |
| K/Rb | 581 | 557 | 602 |
| Rb/Sr | 0.020 | 0.022 | 0.029 |
| K/Ba | 17 | — | 26 |
| K/Cs | $22 \times 10^3$ | — | $31 \times 10^3$ |
| Ba/Sr | 0.66 | — | 0.68 |
| Ni/Co | 0.75 | — | 0.80 |
| Zn/Cu | 1.4 | — | 1.8 |
| La/Yb | 7.3 | — | 5.7 |
| Eu/Eu * | 1.0 | — | 1.1 |

Note: blank spaces indicate no determinations; complete data from all 3 volcanoes can be obtained from the authors upon request.

* $Fe_2O_3$ = total Fe as $Fe_2O_3$

+ older group of volcanics only.

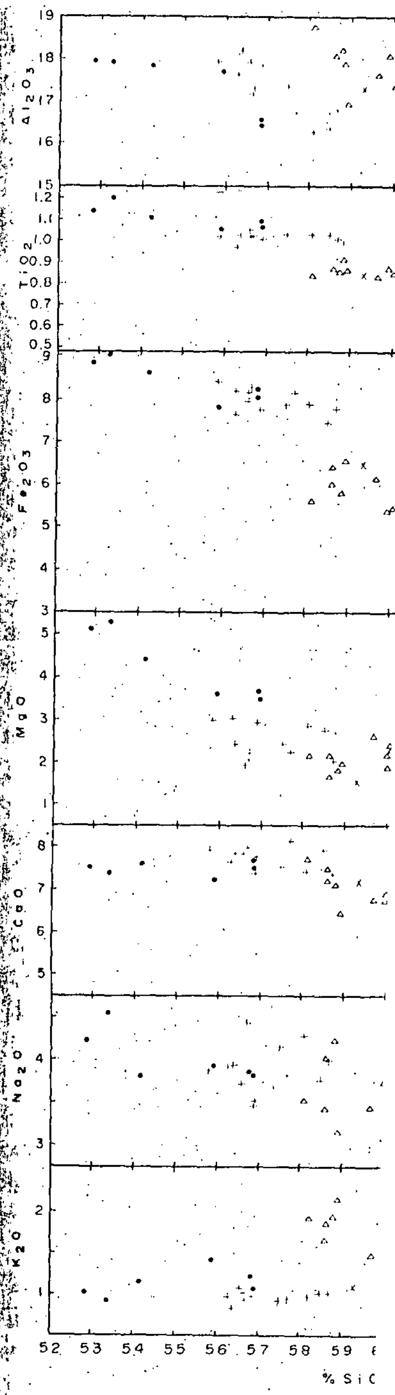
Eu anomalies are small to absent in both groups and in this respect are like other young calc-alkaline and arc-tholeiite volcanics (TAYLOR, 1969; JAKES and GILL, 1970).

Field relationships indicate that the first group is the older of the two groups and that it probably composes most of the volcano. The younger group found on the Northwest Ridge and Summit area today may have been removed by erosion from much or all of the western and southwestern parts of the volcano. Remarkably little variation in the concentration of most elements is observed within each group and especially the older group. The non-systematic variations observed with increasing stratigraphic height within the older group in the Southwest Ridge section (Fig. 6) are usually within the ranges observed in individual flows from other Cascade volcanoes (LAIDLEY and MCKAY, 1971; HAYSLIP and CONDIE, 1973, in prep.).

Rather smooth continuous $SiO_2$ variation diagrams covering a $SiO_2$ range from 52-74 percent have been reported from the Jefferson area (GREENE, 1968) and differ from those herein reported for the stratovolcano proper. The apparently smooth and continuous character of the variation diagrams described by GREENE (1968) results chiefly from inadequate sampling and the large $SiO_2$ range from the sampling of a large geographic area (up to 25 km from the volcano).

### Mt. Rainier

Mt. Rainier is the most voluminous of the Cascade volcanoes and was even larger prior to the removal of the summit region by collapse after a major eruption of by a series of smaller eruptions (FISKE, *et al.*, 1963). Most of the volcano is composed of rather uniform pyroxene andesites and dacites with flows dominating over pyroclastic rocks. Modal analyses indicate ranges of mineral abundances similar to those found at Mt. Jefferson. Olivine phenocrysts also occur in relatively young basaltic andesites of very minor volume erupted from two satellite cones on the northwest flank of the volcano (Fig. 2). Columbia Crest Cone resting on top of the decapitated volcano represents some of the most recent volcanic activity at Rainier and is composed of pyroxene andesites similar to those composing most of the volcano. Sampling at Rainier was concentrated along the cleavers between glaciers where the freshest, although often inaccessible, exposures occur. Detailed sampling was completed on Colon-



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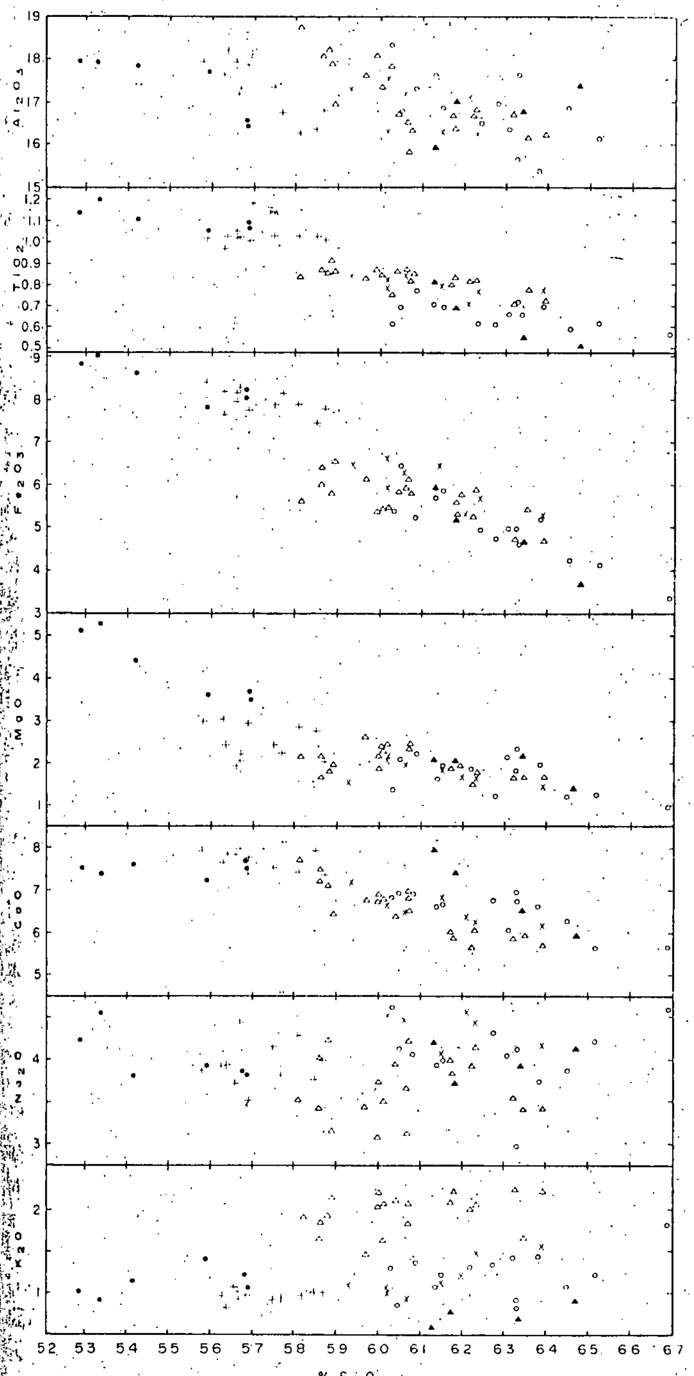


FIG. 4 - Major-element $SiO_2$ variation diagrams for volcanic rocks from Mounts Jefferson, Rainier, and Shasta. Symbols: Rainier, ● = young basaltic andesites; △ = andesites and dacites. Jefferson, + = older volcanic group; × = younger volcanic group. Shasta, ○ = older andesites and dacites; ▲ = Shastina and young flows. Oxides in weight %.

TABLE 3 - Average compositions of lavas from Mt. Rainier, Washington.

| | *Wapowety Cleaver* | *Success Cleaver* | *Paradise Area* | *Summit Area* | *Young Basaltic Andesites* |
|---|---|---|---|---|---|
| $SiO_2$ | 59.28 | 61.46 | 62.39 | 60.63 | 54.97 |
| $TiO_2$ | 0.87 | 0.84 | 0.77 | 0.81 | 1.11 |
| $Al_2O_3$ | 17.88 | 16.22 | 16.41 | 17.29 | 17.35 |
| $Fe_2O_3$ * | 5.84 | 5.69 | 5.17 | 5.83 | 8.42 |
| MgO | 1.97 | 2.00 | 1.95 | 2.08 | 4.23 |
| CaO | 7.08 | 6.30 | 6.20 | 6.64 | 7.49 |
| $Na_2O$ | 3.47 | 3.95 | 3.48 | 3.57 | 3.83 |
| $K_2O$ | 2.11 | 2.04 | 2.13 | 1.65 | 1.10 |
| Ni | 20 | 18 | 18 | 18 | 20 |
| Co | 22 | 21 | 20 | 20 | 34 |
| Cr | 80 | 104 | 73 | 79 | 196 |
| Sb | 0.25 | 0.24 | 0.07 | 0.22 | 0.70 |
| Zn | 71 | 120 | 51 | 94 | 104 |
| Cu | 40 | 36 | 41 | 39 | 41 |
| Rb | 50 | 49 | 52 | 42 | 25 |
| Cs | — | 1.9 | 1.5 | 1.9 | 0.92 |
| Ba | 200 | 448 | 288 | 430 | 226 |
| Sr | 516 | 524 | 439 | 496 | 501 |
| La | 15 | 21 | 21 | 17 | 17 |
| Ce | 49 | 55 | 48 | 43 | 42 |
| Sm | 4.8 | 5.2 | 4.7 | 4.1 | 4.8 |
| Eu | — | 1.6 | 1.3 | 1.3 | 1.6 |
| Tb | — | 0.87 | 0.62 | 0.46 | 0.86 |
| Yb | 1.2 | 1.3 | 1.7 | 1.4 | 1.9 |
| Lu | 0.24 | 0.26 | 0.21 | 0.21 | 0.41 |
| Σ7REE | ~71 | ~85 | ~73 | ~67 | ~69 |
| K/Rb | 350 | 345 | 340 | 326 | 365 |
| Rb/Sr | 0.097 | 0.094 | 0.12 | 0.085 | 0.050 |
| K/Ba | 88 | 38 | 62 | 32 | 40 |
| K/Cs | — | $8.9\times10^3$ | $12\times10^3$ | $7.2\times10^3$ | $9.9\times10^3$ |
| Ba/Sr | 0.39 | 0.86 | 0.66 | 0.87 | 0.45 |
| Ni/Co | 0.90 | 0.86 | 0.90 | 0.90 | 0.59 |
| Zn/Cu | 1.8 | 3.3 | 1.2 | 2.4 | 2.5 |
| La/Yb | 13 | 16 | 12 | 12 | 8.9 |
| Eu/Eu * | — | 0.9 | 1.0 | 1.1 | 1.0 |

Note: blank spaces indicate no determinations.
* $Fe_2O_3$ = total Fe as $Fe_2O_3$.



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nade, Lower Puyallup, Success, Wapowety, Cathedral Rocks and Cowlitz Cleavers, as well as in the Paradise, Yakima, and Spray Park areas (Fig. 2). Stratigraphic successions were sampled at Success and Cowlitz Cleavers in the main andesites and dacites and at Ptarmigan Ridge for the young basaltic andesites.

Compositional data from Rainier are given in Table 3 and Figs. 4, 5, 7 and 8. Both major and trace element distributions in Rainier rocks indicate that they are typical of the calc-alkaline association with dacites being only slightly less abundant than andesites in the majority of the volcano. The young basaltic andesites form a minor, but distinct geochemical group. Rainier pyroxene andesites and dacites are significantly enriched in K, Rb, Cs, and light REE compared to similar rocks from Jefferson and Shasta (Tables 2-4; Figs. 4-7). Alkali element ratios exhibit rather limited ranges and are in general similar in both the pyroxene andesites and dacites and in the young basaltic andesites: K/Rb = 300-400; K/Cs = 5,000-15,000; K/Ba = = 30-90. Most elements in the pyroxene andesites and dacites do not seem to define a trend on $SiO_2$ variation diagrams although the data are suggestive of a rough decrease in Ca, Ti, Fe, Al, and Sr with increasing $SiO_2$ (Figs. 4 and 5). Both absolute and relative REE distributions are rather similar in all Rainier rocks including the basaltic andesites (Fig. 7). The Eu/Eu* ratio is also rather constant ranging only from 0.9-1.1.

The young basaltic andesites define a distinct compositional group separated on $SiO_2$ variation diagrams by a discontinuity in many element concentrations. They are significantly enriched in Fe, Ti, Mg, Sb, Cr, Co, Ni, and Cu and depleted in K, Rb, and Cs compared to the voluminous pyroxene andesites and dacites. In some respects they are similar to the older Jefferson volcanic group (Figs. 4 and 5). The relatively high contents of Mg and transition metals in these rocks is probably controlled by the presence of olivine and the relatively large amount of Fe-Ti oxides in the groundmass.

Systematic compositional changes were not observed in the Success or Cowlitz Cleaver sections. A discontinuity occurs about midway in the Cowlitz Cleaver section with the upper group depleted in K and Rb. This same discontinuity, although not as precisely defined because of inadequate sampling, occurs on Cathedral Rocks north of Cowlitz Cleaver (Fig. 3). The variations above and below this discontinuity and throughout the Success Cleaver section are non-systematic and of about the same magnitude as those found in the Southwest

Ridge section of Jefferson (Fig. 6). Unlike these two sections, the thin stratigraphic section in the basaltic andesites at Ptarmigan Ridge showed systematic variations in many elements as a function of stratigraphic height. These can be seen in Figures 4 and 5 since $SiO_2$

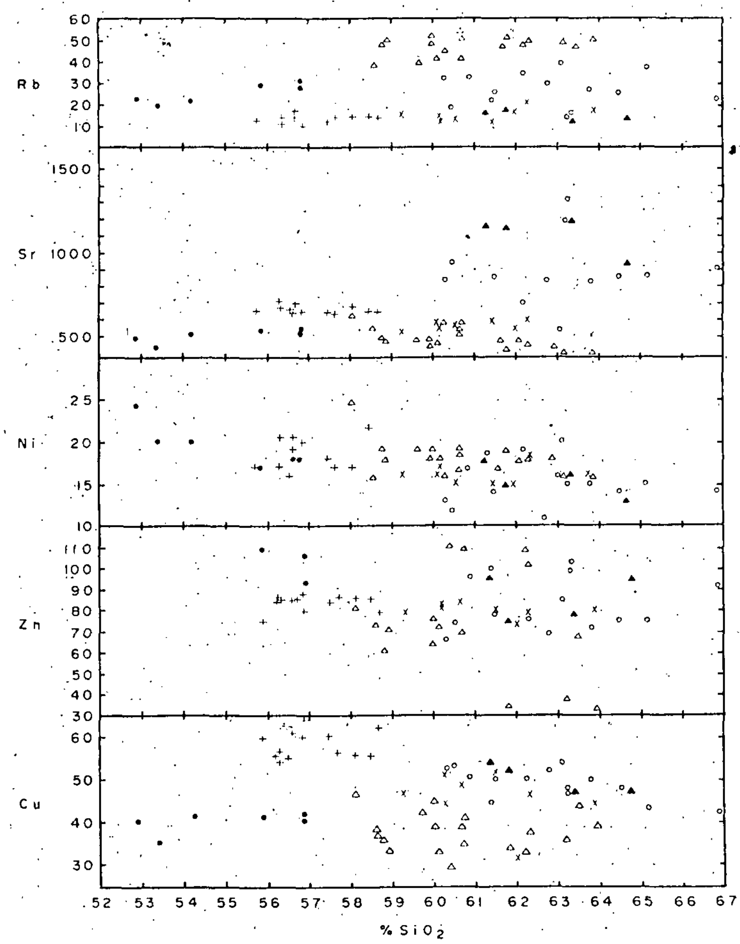


FIG. 5 - Trace-element $SiO_2$ variation diagrams for volcanic rocks from Mounts Jefferson, Rainier and Shasta. Symbols as given in Fig. 4. Concentrations in ppm.

increases from about 53 to 57 percent with increasing stratigraphic height. Mg, Ti, Fe, Cr, Co and Ni decrease and K, Rb, Cs, and La (with some suggestion of Na and Al) increase with stratigraphic height. Modal analyses indicate the absence of a relation-ship between the abundances of phenocrysts or groundmass minerals and the

TABLE 4 - Average compo

| | *Mud Creek* |
|---|---|
| $SiO_2$ | 62.20 |
| $TiO_2$ | 0.71 |
| $Al_2O_3$ | 17.02 |
| $Fe_2O_3$ * | 5.09 |
| MgO | 1.96 |
| CaO | 6.77 |
| $Na_2O$ | 3.75 |
| $K_2O$ | 1.00 |
| Ni | 17 |
| Co | 18 |
| Cr | 66 |
| Sb | 0.21 |
| Zn | 99 |
| Cu | 47 |
| Rb | 21 |
| Sr | 1205 |
| Ba | 545 |
| Cs | 0.89 |
| La | 12 |
| Ce | 35 |
| Sm | 3.3 |
| Eu | 1.12 |
| Tb | 0.48 |
| Yb | 1.2 |
| Lu | 0.20 |
| Σ7REE | ∼53 |
| K/Rb | 387 |
| Rb/Sr | 0.017 |
| K/Ba | 15 |
| K/Cs | $9.1 \times 10^3$ |
| Ba/Sr | 0.45 |
| Ni/Co | 0.94 |
| Zn/Cu | 2.1 |
| La/Yb | 10 |
| Eu/Eu * | 1.1 |

Note: blank spaces indicate no de
* $Fe_2O_3$ = total Fe as $Fe_2O_3$.

TABLE 4 - Average composition of lavas from Mt. Shasta, California.

| | *Mud Creek* | *Sargents Ridge* | *Cascade Gulch-Summit area* | *Shastina and Young Flows* |
|---|---|---|---|---|
| $SiO_2$ | 62.20 | 61.79 | 64.16 | 62.81 |
| $TiO_2$ | 0.71 | 0.65 | 0.60 | 0.64 |
| $Al_2O_3$ | 17.02 | 16.82 | 16.38 | 16.75 |
| $Fe_2O_3$ * | 5.09 | 5.50 | 4.27 | 4.81 |
| MgO | 1.96 | 1.67 | 1.45 | 1.90 |
| CaO | 6.77 | 6.75 | 6.04 | 6.94 |
| $Na_2O$ | 3.75 | 4.14 | 4.25 | 3.98 |
| $K_2O$ | 1.00 | 1.18 | 1.35 | 0.73 |
| Ni | 17 | 13 | 16 | 16 |
| Co | 18 | 15 | 18 | 16 |
| Cr | 66 | — | 13 | 80 |
| Sb | 0.21 | — | 0.22 | 0.19 |
| Zn | 99 | 72 | 81 | 87 |
| Cu | 47 | 52 | 48 | 52 |
| Rb | 21 | 27 | 30 | 16 |
| Sr | 1205 | 867 | 785 | 1120 |
| Ba | 545 | — | 314 | 290 |
| Cs | 0.89 | — | 0.93 | 0.93 |
| La | 12 | — | 11 | 7.9 |
| Ce | 35 | — | 24 | 26 |
| Sm | 3.3 | — | 2.7 | 2.7 |
| Eu | 1.12 | — | 0.70 | 1.01 |
| Tb | 0.48 | — | 0.24 | 0.29 |
| Yb | 1.2 | — | 0.74 | 0.71 |
| Lu | 0.20 | — | 0.17 | 0.17 |
| Σ7REE | ∼53 | — | ∼40 | ∼39 |
| K/Rb | 387 | 355 | 367 | 369 |
| Rb/Sr | 0.017 | 0.031 | 0.038 | 0.014 |
| K/Ba | 15 | — | 35 | 20 |
| K/Cs | $9.1\times10^3$ | — | $12\times10^3$ | $6.0\times10^3$ |
| Ba/Sr | 0.45 | — | 0.40 | 0.26 |
| Ni/Co | 0.94 | 0.87 | 0.90 | 1.0 |
| Zn/Cu | 2.1 | 1.4 | 1.7 | 1.7 |
| La/Yb | 10 | — | 15 | 11 |
| Eu/Eu * | 1.1 | — | 1.0 | 1.3 |

Note: blank spaces indicate no determinations.
* $Fe_2O_3$ = total Fe as $Fe_2O_3$.

compositional variation observed within any of the stratigraphic sections.

One of the most striking results of the Rainier study is the compositional grouping of rocks from all or portions of specific

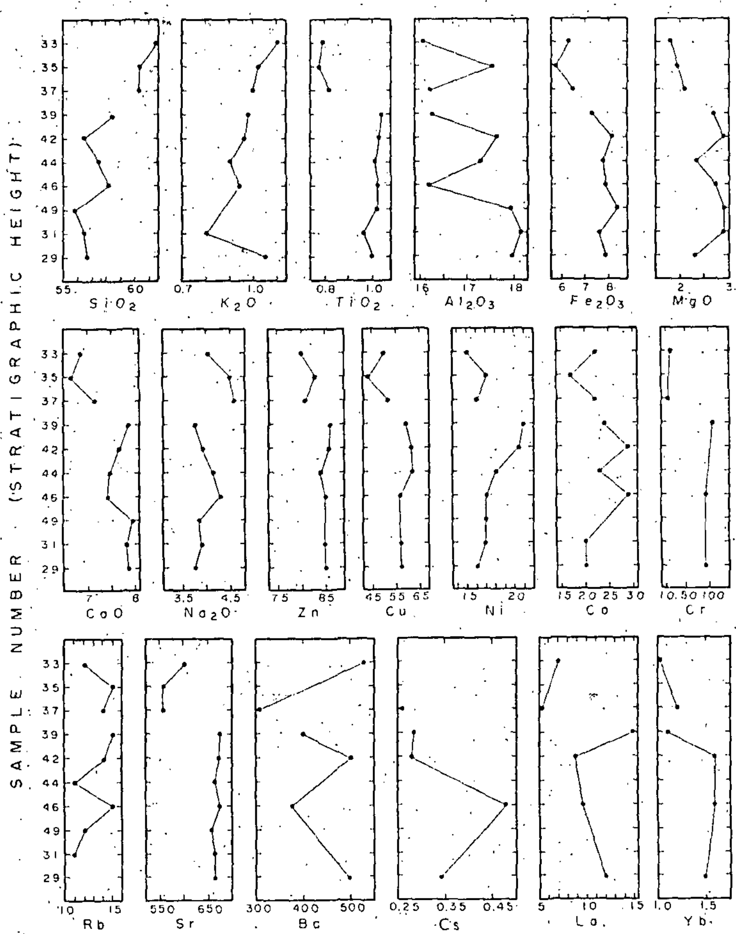


FIG. 6 - Compositional variations along the Southwest Ridge stratigraphic section of Mt. Jefferson, Oregon. Major element oxides in weight percent; trace elements in ppm; vertical axes in arbitrary units.

ridge and cleaver sections. This is best illustrated with the extensive $K_2O$ and $SiO_2$ data which are summarized in Figure 8. Samples from Wapowety and Success cleavers define rather narrow and distinct



distributions. Samples from
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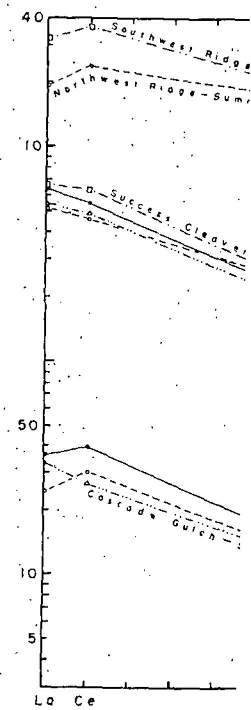

FIG. 7 - Average chondrite-normali
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define a very low-K, low-Si
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generally fall within or on
Success Groups (Fig. 8).
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distributions. Samples from the Paradise area (including those from below the compositional discontinuity previously referred to on Cowlitz Cleaver and Cathedral Rocks) define a much larger region, in part overlapping the Success Cleaver section. More detailed sampling will probably allow this group to be subdivided. Samples from upper Cowlitz Cleaver, upper Cathedral Rocks, Columbia Crest Cone, and

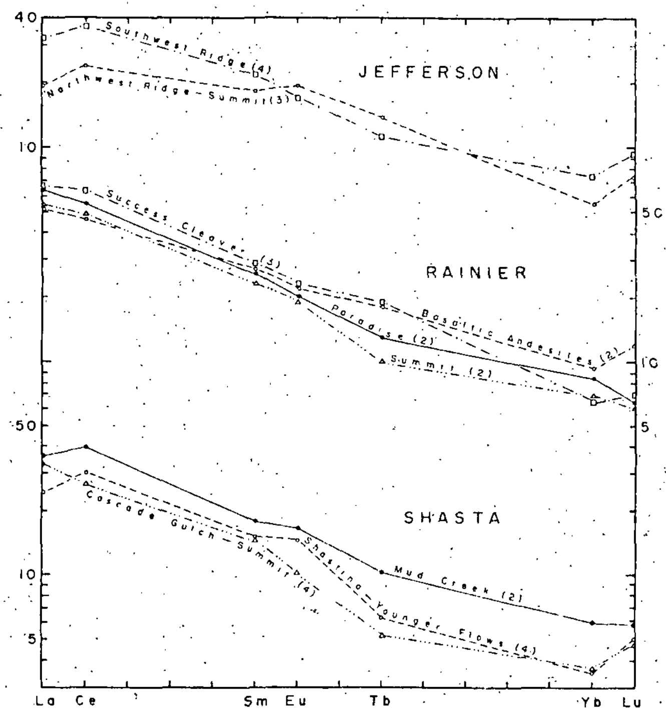


FIG. 7 - Average chondrite-normalized REE distributions in volcanic rocks from Mounts Jefferson, Rainier and Shasta. Number in parenthesis refers to number of samples included in average.

some samples from the northwest side of Rainier define a low-K group-herein called the Summit Group. The young basaltic andesites define a very low-K, low-$SiO_2$ group. Scattered samples from the other cleavers on the west side of Rainier and from the Yakima Park area generally fall within or on the extension of the Wapowety-Paradise-Success Groups (Fig. 8). Existing data for many other elements, although not as numerous, tend to substantiate the groups defined on the $K_2O$-$SiO_2$ diagram. These data suggest that it may be possible with extensive sampling to make a « geochemical map » of a strato-volcano like Rainier by defining specific compositional groups. These groups are herein defined as *eruptive groups* and are tentatively interpreted as individual batches of magma that are erupted over time intervals that are small compared to the total age of the volcano.

Most of the Rainier volcanics appear to have rather constant $K_2O$ contents between 1.8 and 2,4 percent (Fig. 8). The Summit Group, however, which represents some of the youngest activity of the strato-volcano proper, exhibits distinctly lower values (1.4-1.8

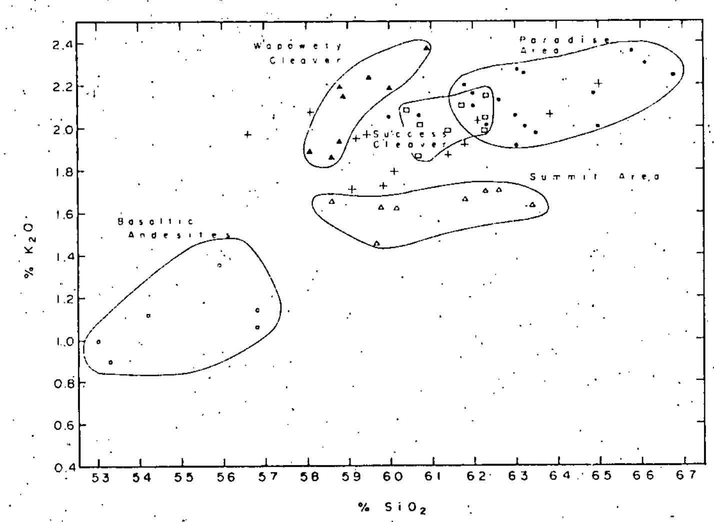


FIG. 8 - $K_2O$-$SiO_2$ distribution diagram for samples from Mt. Rainier. + = Miscellaneous samples.

percent). Although Columbia Crest Cone is probably younger than the basaltic andesites, most of the Summit Group was probably erupted before the basaltic andesites as evidenced by compositional data from pyroxene andesites and dacites beneath the basaltic andesites suggesting that the former belong to the Summit Group. A Rb-$SiO_2$ diagram shows essentially the same groupings as the $K_2O$ diagram but no other element clearly distinguishes the Summit Group from the older andesites and dacites. The data clearly indicate that the final stages of Rainier's eruptive history were characterized by

K and Rb-poor magmas exhibiting a $SiO_2$ range that broadly overlaps the older rocks (except for the minor basaltic andesites). This contrasts to Jefferson, which shows terminal increases in K and Rb and a distinct increase in $SiO_2$.

## Mt. Shasta

Like Rainier and Jefferson, Mt. Shasta is composed chiefly of rather uniform pyroxene andesites and dacites. It differs from Rainier and Jefferson in that, 1) it is composed of a proportionally larger amount of dacites, 2) pyroclastic rocks are more abundant than flows, and 3) hornblende phenocrysts occur in 5-10 percent of the rocks. The geology of Mt. Shasta is described by WILLIAMS (1932; 1934) and general features of the major element geochemistry of whole-rock and phenocryst samples are discussed by Smith and CARMICHAEL (1968). WILLIAMS (1932) suggests that a north-south fissure system developed during the late stages of activity and controlled the locations of several andesite domes (including the summit plug) and at least two basaltic cinder cones (Fig. 3). Shastina, a large parasitic cone west of Shasta's summit also formed during the late stages of activity perhaps along an east-west fissure system. The final activity at Shastina is marked by the eruption of hornblende dacite and emplacement of a hornblende dacite plug in the throat of Shastina. Very young pyroxene andesite and dacite flows were erupted from the flanks of the volcano particularly on the northwest side. Hornblende occurs in andesites and dacites of all eruptive ages and does not exhibit an obvious time-dependent relationship. Minor basalt and basaltic andesite eruptions occurred at satellite cones low on the flanks of the volcano during and after the final phases of the major activity of Shasta and Shastina.

Shasta was the most difficult of the three volcanoes to sample due to relatively poor outcrops, inaccessible outcrops, and snow cover. The deepest canyon (Mud Creek) cuts only about 500 m into the southeast slope and stratigraphic relationships in the canyon are not clearly exposed. Unambiguous stratigraphic sections at Shasta were not readily accessible for sampling. Representative samples were collected, however, from lavas ranging in age from the oldest exposed parts of the volcano (in Mud Creek) to the youngest flank and satellite eruptions (Fig. 3).

Element distributions in the andesites and dacites indicate that Shasta is also a calc-alkaline volcano (Table 4; Figs. 4, 5, and 8). It differs from both Rainier and Jefferson in that, with exception of the minor basaltic rocks found in satellite cones, it contains principally dacites (60-67 percent $SiO_2$) and the rocks exhibit more scatter on $SiO_2$ variation diagrams (Figs. 4 and 5). Representative samples of the satellite basalts and basaltic andesites (which show a $SiO_2$ range of 49-52 percent) are not shown in the figures because complete analyses are not available. Shasta andesites and dacites also differ from those at Rainier and Jefferson in their much higher Sr contents and in their slightly higher Ca and slightly lower Ti contents. They tend to have K, Rb, and Cs contents intermediate between Rainier and Jefferson samples. Most other elements broadly overlap with samples from one or both of these volcanoes. Except for the younger volcanic group at Jefferson, REE distribution patterns are similar for samples from all three volcanoes (Fig. 7) although the absolute concentration of REE (especially light REE) is lower in Jefferson and Shasta rocks than in Rainier rocks (Tables 2-4). $Eu/Eu^*$ ratios in andesites and dacites from Shasta are also similar to those ratios observed in andesites and dacites from Jefferson and Rainier except for Shastina and young flows which exhibit anomalously high ratios (1.2-1.5). Shasta Rocks are more like Rainier rocks with their relatively low K/Rb, K/Cs, and high La/Yb ratios and more like Jefferson rocks with their low K/Ba and Rb/Sr ratios.

Two discontinuities in composition occur at Shasta. The largest one is between the andesites and dacites of Shasta-Shastina and the late, small satellite basaltic eruptions. The Shastina eruptions and the young andesite-dacite flows from the flanks of the stratovolcano also tend to define an eruptive group. These rocks have lower K and Rb contents and higher Cr, Sr, and $Eu/Eu^*$ ratios than the andesite-dacites which compose most of Shasta. No obvious mineralogical changes accompany these chemical changes. A correlation of high Sr with high $Eu/Eu^*$ values probably results from plagioclase accumulation during the late stages of eruption since Sr and Eu are preferentially encorporated in plagioclase (PHILPOTTS, 1970).

Shasta is very similar to Rainier in that during its final stages of activity, magmas being erupted from the main vent region (in this case, Shastina) and from some associated flank eruptions decreased in K and Rb yet roughly maintained the same $SiO_2$ range while other less numerous satellite eruptions exhibited a significant decrease in



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## Summary and Discussion

Geochemical studies of Mounts Jefferson, Rainier, and Shasta in the northwestern United States result in the following major conclusions which bear on stratovolcano origin and evolution in general.

1) Each volcano has distinct major and trace element distribution patterns. Silica variation diagrams are not, as previous studies have reported for these and other calc-alkaline volcanic centers, smooth nor are they, in general, continuous.

2) Portions of stratigraphic volcanic sections within the stratovolcanoes often exhibit compositional coherency and are interpreted as eruptive groups. Eruptive groups probably represent batches of magma that are erupted over intervals of time which are short compared to the lifetime of a stratovolcano. Differences of varying magnitude in the concentrations of a few to many elements occur between these groups. Within-group coherency may be developed to such a degree as to allow geochemical « mapping » of a stratovolcano.

3) Systematic compositional trends in lavas as a function of stratigraphic height within an eruptive group are not observed over volcanic thicknesses of 500-1000 m. Rarely, systematic trends may occur in part of an eruptive group ($\leq$ 200 m thick) or within eruptive groups of small total volume.

4) Compositional variations within most eruptive groups are typically non-systematic and exhibit variational ranges similar to those ranges observed in individual lava flows from calc-alkaline volcanoes.

5) Except for mafic satellite eruptions which compose an insignificant volume of the volcanoes studied, no inter-group correlation is observed between the amounts of kinds of phenocryst phases present

in the lavas and corresponding compositional differences. Intra-group compositional variations are not accompanied by parellel mineralogical variations.

6) Decreases in K and Rb concentration occur in the late andesites and dacites erupted from Rainier and Shasta. Also minor satellite eruptions of K- and Rb-poor mafic lavas characterize the final stages of activity at these volcanoes. Jefferson andesites and dacites, on the other hand, exhibit increases in K and Rb (as well as other compositional changes) during the late stages of activity.

Rainier and Shasta are commonly cited as exhibiting coherent geochemical trends (McBirney, 1968). From the extensive data for these volcanoes and Mt. Shasta herein summarized, however, it appears that a simple two-fold classification into divergent and coherent types for Cascade volcanoes is an oversimplification. It critically depends on the extent of the area sampled around the volcano and the number of samples analyzed. At Jefferson, for instance, if a region within a 25 km radius of the peak is included, rocks ranging from 52 to 74 percent $SiO_2$ occur (Greene, 1968), whereas if only samples from the stratovolcano proper are included the observed $SiO_2$ range is only 56 to 64 percent. At Rainier and Shasta, on the other hand, rocks ranging from basalt or basaltic andesite (49-52 percent $SiO_2$) to siliceous dacite (64-67 percent $SiO_2$) occur in or on the immediate flanks of the volcanoes. As previously discussed for Jefferson, inadequate sampling can produce apparently smooth and continuous variation diagrams for a stratovolcano. The results of this study indicate that a large number of samples ($> 20$) are needed to identify discontinuities on variation diagrams. Such discontinuities characterize the three stratovolcanoes studied. Interpretations of variation diagrams of calc-alkaline volcanic centers based on only a few samples or samples from a widely scattered area should be considered questionable.

Eruption accompanying progressive fractional crystallization of high-alumina basalt or andesite is one mechanism to be considered by which stratovolcanoes may grow. For instance, the element trends, observed at Paricutin in Mexico during its approximately 10-year lifetime, can be most easily interpreted in terms of approximately concurrent eruption and fractional crystallization ($\pm$ minor crustal contaminations; Wilcox, 1954). The absence, however, of long-term



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systematic compositional changes in the stratigraphic sections at Rainier and Jefferson does not favor such a mechanism for larger volcanoes. Local, short-term systematic trends within a volcano may be consistent with such a mechanism. As an example, the progressive decreases in Fe, Ti, Cr, Ni, Mg, and related elements and corresponding increases in alkali and related elements as a function of decreasing age in the Ptarmigan Ridge section at Rainier can be readily interpreted in terms of periodic eruption of basaltic andesite magma from a shallow (< 35 km) magma chamber undergoing progressive fractional crystallization involving principally the removal of olivine, pyroxene, and plagioclase in the ratios that phenocrysts are observed to occur in the rocks.

Another, perhaps more realistic, fractional crystallization model for stratovolcano growth involves several magma chambers and does not necessitate synchronous eruption and fractionation. The magma chambers may receive fresh magma from the same mantle source, yet they are tapped sporadically and at different stages in their fractionation history thus not producing systematic compositional trends with stratigraphic height in the volcanoes. Such a mechanism is consistent with the eruptive group interpretation previously discussed, in that such groups could be produced by eruptions from the different magma chambers at various fractionation stages. However, the same geochemical problems discussed by TAYLOR (1969) for andesitic magmas in general, specifically limit the role of fractional crystallization in producing the diversity of rock types found in the Cascade volcanoes. Transition elements such as Ni and Co should be rapidly removed from an andesite magma from which pyroxenes are being removed, yet in the Cascade volcanoes where both orthopyroxene and clinopyroxene are important phenocryst phases, the concentrations of these elements are rather constant (or scatter in the case of Shasta) over a broad $SiO_2$ range (Fig. 5). Also such ratios as K/Rb and K/Cs, which should decrease rapidly with fractional crystallization (TAYLOR, 1969), are high and rather constant over a broad $SiO_2$ range. Finally, the absence of major Eu anomalies (except in the Shastina and young flows at Shasta), either positive or negative, severely restricts the amount of plagioclase removal or accumulation in fractionating liquids.

The possibility that the diversity of rock compositions at each Cascade volcano was produced by varying degrees of crustal contamination of basalt or basaltic andesite magma also seems unlikely in terms of the low $Sr^{87}/Sr^{86}$ ratios (0.703-0.704) reported from Cascade volcanoes (HEDGE, *et al.*, 1970; PETERMAN, *et al.*, 1970; CHURCH and TILTON, 1973). The exceptionally high Sr contents yet very low $Sr^{87}/Sr^{86}$ ratios in Shasta lavas indicate that they could not have been produced by mixing of ridge tholeiite magma and graywacke or by partial fusion of older graywackes or sialic crust (PETERMAN, *et al.*, 1970). Uniformity of $Sr^{87}/Sr^{86}$ ratios in Cascade volcanics, in general, irrespective of Sr concentration argues against any magma origin model involving mixing of ridge tholeiite magma with eugeosynclinal sedimentary rocks, Pacific ocean deep sea sediments, or crystalline basement rocks upon which some Cascade volcanoes rest (CHURCH and TILTON, 1973).

Seismic data suggest that calc-alkaline magmas move from mantle segregation chambers at 100-200 km depth in or above subduction zones to their sites of eruption over periods of several months (SHEINMAN, 1971) with probably little or no time spent in shallow fractionation chambers prior to eruption. Experimental data also provide boundary conditions for magma origin. Most data indicate that andesites and dacites (which compose most of Cascade volcanoes) can be produced in or above subduction zones (80-200 km deep) by varying degrees of partial melting of amphibolite ($\leq$ 80 km), eclogite, or peridotite under conditions ranging from dry to wet (GREEN and RINGWOOD, 1968; YODER, 1969; GREEN, 1972; KUSHIRO, 1972). Recent experimental daat of NICHOLLS and RINGWOOD (1972), however, do not favor an origin for calc-alkaline andesites and dacites by hydrous partial melting of peridotite. The trace-element results herein reported together with existing isotope data support a model for the origin of Cascade magmas involving production from partially depleted upper mantle, segregation into sub-crustal reservoirs, and periodic tapping of these reservoirs. At each tapping, a relatively small volume of magma moves upward over several months and is erupted forming an eruptive group. Most of the time, little or no shallow fractional crystallization occurs during eruption of these batches of magma. It is possible that the composition of an eruptive group, and in particular the $SiO_2$ range, is controlled by one or some combination of, *a*) varying degrees of melting of appropriate mantle source materials, or *b*) changes in the water content at the source. The importance of water is illustrated by the experimental data of GREEN and RINGWOOD (1968) which indicate that andesite magma is produced by partially melting dry eclogite at depths of about 100 km whereas dacite magma is produced at the same depths under hydrous conditions. Varying amounts of water in the source area could result in a spectrum of magma compositions ranging from andesite to dacite. Such variations in water content could be produced by variations in the rate of eruption, in which water is lost, and in the rate at which water migrates into the source area from surrounding mantle.

The overall differences in composition between the three volcanoes are more difficult to explain with existing data but probably reflect differences in element concentrations but not in Sr isotope composition of mantle source materials. An explanation for the changes in composition of magmas erupted during the final stages of activity, involving enrichment in K and Rb at Jefferson and depletion in these elements at Rainier and Shasta, appears to be more complex. The decrease in these elements at Rainier and Shasta is not accompanied by a change in $SiO_2$ range and may simply reflect depletion of these elements in the mantle source area, and because subduction is decreasing or terminating they are not replenished. It is puzzling, however, if this is the correct explanation why Cs and light REE do not also exhibit decreases since distribution coefficient data (PHILPOTTS and SCHNETZLER, 1970; SCHNETZLER and PHILPOTTS, 1970) would suggest that they should be depleted in the source as rapidly or more rapidly than K and Rb.

At Jefferson, as previously discussed, not only do K and Rb increase in the late lavas, but many transition elements and light REE decrease and $SiO_2$ contents increase. A possible explanation for these changes may involve changing of mantle source materials. For instance, most of the volcanics at Jefferson may have formed by hydrous melting of peridotite or/and eclogite above a subduction zone. Such melting may have resulted from the upward escape of water from the subduction zone. Equilibration of melts with residual garnet or/and orthopyroxene could account for the relatively enriched REE patterns observed in the older Jefferson volcanics. As water is used up, melting in this region would come to an end and the melting geotherms may move down-wards with melting eventually continuing in the upper part of the subducted plate. If the plate were $\leq$ 100 km deep, amphibolite or hornblende eclogite may be the dominant constituent. Melting of this material with amphibole as a major solidus phase could produce liquids with less enriched REE patterns, higher contents of K, and Rb and higher K/Rb ratios as are observed in the younger Jefferson volcanic group. A smaller degree of melting could account for the higher $SiO_2$ range.

Still another problem in stratovolcano evolution is the origin of the late mafic satellite eruptions observed at Rainier and Shasta and at other Cascade volcanoes. Somehow these magmas avoid mixing or at least completely mixing with the more voluminous andesites and dacites. In this regard they seem to have two features in common: 1) they form during the final stages of activity of the stratovolcano and 2) they erupt from satellite cones low on the flanks of the stratovolcano. Although the present data are not sufficient to fully discuss the origin of these eruptions, it appears that they are derived from different, perhaps deeper, source regions than the andesites and dacites and that they have or produce their own plumbing systems which are, at least in part, not interconnected with the main conduit systems of the stratovolcanoes.

The data herein presented indicate that calc-alkaline stratovolcanoes have undergone complex developmental histories and that extensive sampling programs and field studies are necessary to unravel these histories. After individual eruptive groups are defined, mapped and dated (by fission track or other methods) in a volcano like Mt. Rainier, it should be possible to reconstruct time-dependent, quantitative models of stratovolcano evolution.

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# Textural Analysis
# of the Donzurubo Subaq

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The Donzurubo subaqueous p
aqueous environments maintaining
Each flow unit of these pyrocla
size distributions in its stratigraph
the top clearly defines the top faci
and the averages of the largest te
starting from both the top and th
points of Md Ø and the averages
are usually found in the middle zon
points are generally in a lower posi
show that the deposits consist of
whole, an asymmetrical distribution,
coarser fractions of the main popu
and the C-M pattern of the deposit
flow deposits were not originated b
but by incandescent turbulent flows

## Geologic Setti
## Characteristics of

The Nijo group is one of
Cenozoic volcanic deposits in
which lies in the middle zone
volcanic activity in the Nijo-s

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