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Some quantitative aspects of orogenic volcanism in the Oregon Cascades

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ABSTRACT

Quantitative data on the rates of production and compositional variations of igneous rocks are needed before any of the various models for magmatic activity at convergent plate boundaries can be realistically evaluated. The Cascade Range provides an excellent opportunity to obtain this information, because it contains a record of igneous activity in various structural settings and through most of late Cenozoic time.

When analytical data are combined with volumetric estimates and are grouped according to the measured age relations of the principal eruptive episodes, they show significant compositional trends, both in space and time. The most notable changes since late Oligocene time have been a general decline in the volumes and average SiO_2 contents of erupted rocks. These changes have been accompanied by a marked drop in the degree of Fe enrichment, a steady increase in Na, Sr, and K/Rb and a simultaneous decrease in the Rb contents of rocks at the same stage of differentiation. Sr-isotope ratios remained essentially constant with time and show no relation to SiO_2 or Rb contents. The abundance of Rb in Quaternary rocks is inversely related to the volume of Tertiary rocks erupted the same region.

No single mechanism can account for all the observed variations. At least three distinct stages of crystal-liquid equilibration seem to be required, one in the mantle source region, another near the base of a steadily thickening lithosphere, and a third in the shallow reservoirs of mature volcanoes. There is no evidence that the magma is generated in a subducted plate.

INTRODUCTION

It is impossible to place quantitative constraints on the variety of competing models for magmatic activity at convergent plate boundaries without a better knowledge of the character, distribution, and rates of production of the principal rock units as a function of time and space. In an effort to alleviate the deficiency of such data, we have undertaken a study of the Cenozoic volcanic history of a section of the Cascade Range of central Oregon where an extensive series of Tertiary and Quaternary rocks can be mapped, sampled, and compared with similar rocks elsewhere.

We selected this area because it has an unusually complete Neogene section and has relatively clear stratigraphic and structural relations. Earlier workers, such as Thayer (1937), Williams (1957), and Peck and others (1964), established the basic geologic framework of the units, and more recent studies by the staff and students of the Center for Volcanology have provided a wealth of petrographic and geochemical data on individual groups of rocks and eruptive centers. Radiometric dating by John F. Sutter (Sutter, 1978) has provided essential chronologic control for stratigraphic correlations and estimates of the duration of magmatic events.

Using the results of these studies as a basis for additional sampling, we have attempted to fill the most conspicuous gaps in the stratigraphic and areal distribution of analyzed samples, so that better estimates can be made of the volumes and spatial relations of the principal rock types. A preliminary compilation of these data (McBirney and others, 1974) showed that late Cenozoic volcanism has been dominantly basaltic and that activity has been concentrated in four or five brief episodes that appear to have been synchronous with volcanism elsewhere in and around the Pacific Ocean (Kennett and others, 1977). Our purpose here is to present additional data on compositional trends that may reflect the mechanisms responsible for generation and differentiation of calc-alkalic magmas.

METHODS

Published analyses of Cascade rocks are strongly biased in favor of youthful differentiated lavas. The impression that andesites are the dominant rocks of the region is the result of the tendency for most workers to concentrate on large composite volcanoes and to pay less attention to flat-lying basaltic lavas. Although they are not topographically imposing, some individual basaltic flows have volumes greater than that of a large andesitic volcano. Our sampling has been designed to redress this imbalance by obtaining more data from flows beneath or between the major composite cones. In addition, we have attempted to carry out a more systematic sampling of stratigraphic sections through the Quaternary volcanoes and their underlying Tertiary basement.

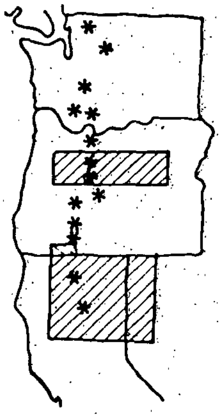


Figure 16-1. Areas for which proportions of upper Cenozoic rocks have been calculated (McBirney and others, 1974). The small area in Oregon near the California border has been studied by Naslund (1977) in order to provide a direct correlation between recent studies in central Oregon and older work in northern California. Asterisks show main Cascade axis.

Analyses have been compiled in a computer file from which the data can be selectively retrieved and statistically evaluated. All analyses from published sources, theses, and unpublished results from the Center for Volcanology are coded according to composition, age, location, and rock name. The file currently contains more than 1,000 analyses from the entire Cascade province; nearly half of these analyses are from the area of central Oregon where we have concentrated our main attention.

Rocks have been divided into three broad categories—basalt, andesite, and dacite-rhyolite—on the basis of SiO_2 content. Divisions have been placed at 53.5% and 63% SiO_2. A further subdivision has been made of Quaternary rocks by grouping rocks between 53.5% and 57% SiO_2 in a separate group of basaltic andesites and by dividing dacite from rhyolite at 68% SiO_2.

Averages for each compositional and age group have been calculated from available analyses of appropriate age and location. Overall averages of all rocks of a given area or magmatic episode have been weighted according to the volumetric proportions of the three main rock types. Volumetric proportions were calculated from the areal distribution, thickness, and probable original extent of each unit, as shown on geologic maps (McBirney and others, 1974).

Volumetric estimates have been made for two parts of the Cascade system, one in central Oregon and another in northern California (Fig. 16-1). Only three volcanic episodes are represented by enough data in northern California to justify volumetric calculations, but in central Oregon, where the section is deeper, four full units and the upper part of a fifth are exposed. One of these, the Elk Lake formation (about 9 to 10 m.y. old) is much less important than the others, and too few rocks, especially in the range of dacites and rhyolites, have been analyzed to provide a valid comparison with other groups. For this reason, the rocks have been included with those of the mid-Miocene Sardine Formation to which they have a close resemblance.

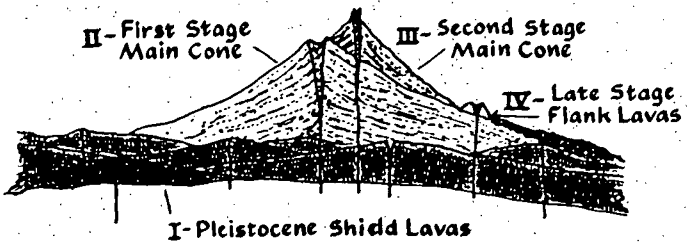
The numbers of major-element analyses from the four principal units in central Oregon are Oligocene–lower Miocene Little Butte Formation, 41; middle Miocene Sardine Formation and upper Miocene Elk Lake formation, 136; Pliocene Outerson Formation, 99; and Quaternary High Cascade rocks, 176.

RESULTS

Quaternary Rocks

Pleistocene and Holocene rocks of the High Cascade volcanoes have been examined in terms of their compositional relations in the chain as a whole and in the development of a single cone.

The largest Quaternary volcano in the central Oregon section that has been studied in detail is Mount Jefferson (Thayer, 1937; Condie and Swensen, 1974; Sutton, 1974; C. M. White, in progress). The rocks forming the base and main cone of Mount Jefferson were erupted during three stages, all of which took place within the present period of normal magnetic polarity (that is, less than 690,000 yr ago). The earliest-erupted lavas make up the glaciated Minto sequence, which formed scattered cones and shields covering an area nearly twice as broad as the basal diameter of Mount Jefferson. The composite cone of Mount Jefferson developed during two main stages, which were followed by minor postglacial flank eruptions (Forked Butte lavas). Sutton (1974) has shown that the volumes of these rocks tended to diminish with time as follows: Pleistocene shield lavas, 98 km^3; first stage of main cone,



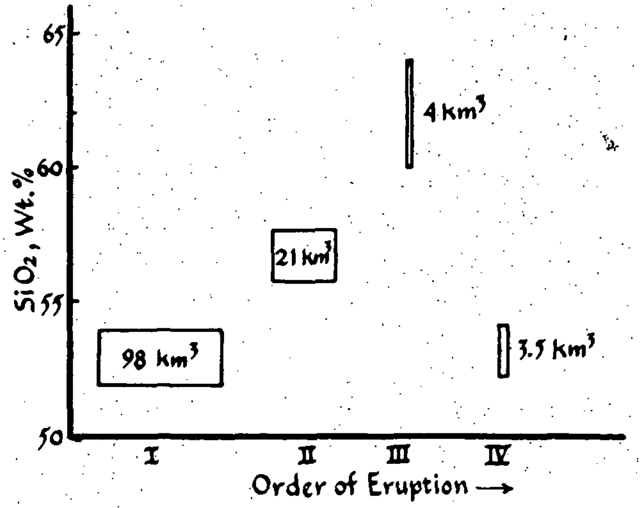
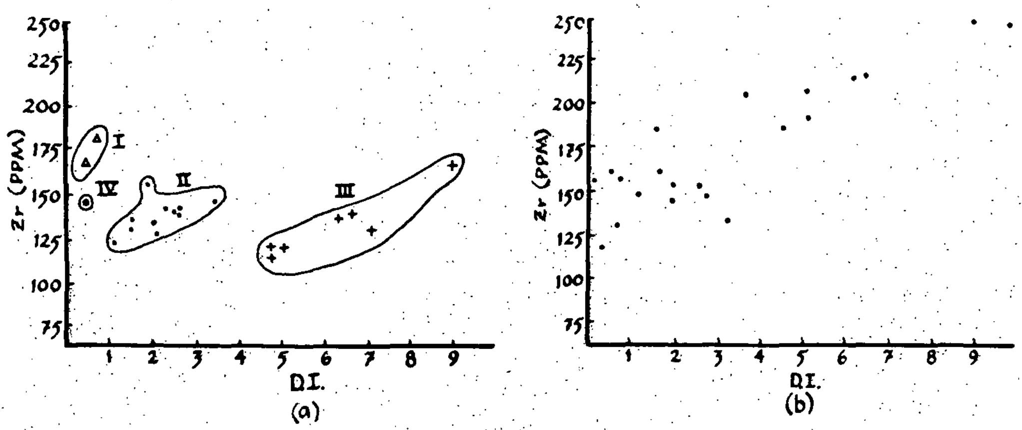


Figure 16-2. The Quaternary evolution of Mount Jefferson included four main stages, each of which was characterized by distinctive rocks. Volumes of rocks in each stage (measured by Sutton, 1974) are shown by the relative areas of rectangles in the lower diagram. The mid-point on the vertical dimension of the rectangles is placed at the mean value of SiO_2 for the rocks of that stage, and vertical length of the edge indicates one standard deviation from the mean SiO_2 value. Total range of SiO_2 for the four stages is I, 51.6% to 54.3%; II, 54.5% to 58.2%; III, 60.1% to 64.3%; and IV, 51.5% to 54.3% by weight.



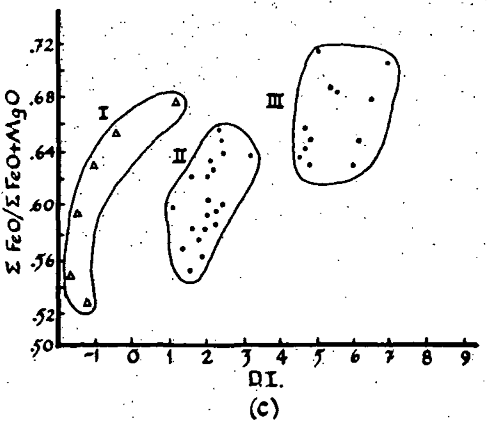


Figure 16-3. (a) Concentration of Zr in Quaternary volcanic rocks of Mount Jefferson plotted against a modified Larsen differentiation index (D.I. = $\frac{1}{3}$Si − Mg − Ca + K). Zr values determined by Sutton (1974). Stages of activity are the same as indicated in Figure 16-2. (b) Concentration of Zr in Miocene volcanic rocks of the central Oregon Cascade Range plotted against the same index as in Figure 16-3a. (c) $\Sigma FeO/(\Sigma FeO + MgO)$ of Quaternary volcanic rocks of the Mount Jefferson area plotted against the same index as in Figures 16-3a and 16-3b.

21 km^3; second stage of main cone, 4 km^3; and Forked Butte lavas, 3.5 km^3. If the entire Quaternary sequence for the central Oregon section of Figure 16-1 is considered, the three age groups show a similar decline of volumes with time: glaciated shield lavas, 1,282 km^3; main Cascade cones, 189 km^3; and Holocene cinder cones and lava, 55 km^3.

Each of the Quaternary age groups (stages) of Mount Jefferson is made up of rocks that appear to have been products of separate batches of magma with distinctive major- and trace-element compositions. There is, however, a general progression toward more-differentiated rocks through most of the evolution of the complex as a whole (Fig. 16-2). As the volume of eruptive rocks declined, the degree of differentiation increased, and although each group contains rocks that may not have appeared in any regular order of SiO_2 content, there is no overlap of the SiO_2 contents between the prinicipal groups.

In contrast to the behavior of SiO_2, factors such as the $FeO/(\Sigma FeO + MgO)$ ratio and Zr concentration do not increase linearly in successive suites (Fig. 16-3). The earliest lavas were slightly tholeiitic, whereas later rocks are strongly calc-alkalic. The initial Zr content of each sequence of lavas is lower than that of the previous group. The "resetting" of trace-element concentrations without a corresponding return to low SiO_2 suggests that a magma reservoir was replenished with magma that was strongly depleted in Zr but produced lavas that were differentiated to a pre-established level, which may have been controlled by some structural or thermal condition beneath the volcano. The Zr content of the Quaternary rocks as a whole does not differ significantly from that of the Miocene series in the same region (Fig. 16-3).

The very latest lavas are a conspicuous exception to the trend of increasing differentiation with time; they revert to more primitive compositions similar to those of the Pleistocene shield lavas. This feature of late-stage rocks is characteristic of most mature volcanoes of the Cascade Range of Oregon and California. Sequences of this type have been called "divergent" as distinguished from "coherent" suites in which the order of differentiation is continuous and unidirectional with time (McBirney, 1968). Divergent suites among the Quaternary rocks of the Oregon Cascades are characterized by late-stage eruptions of essentially contemporaneous basalt and dacite or rhyolite, mainly from satellite vents on the flanks of mature andesitic cones.

Average compositions of basalt, basaltic andesite, andesite, dacite, and rhyolite for the central Oregon Cascades are given in Table 16-1, and a volumetrically weighted average of these rocks is given in Table 16-2. Data on the section in northern California, though less complete, serve as a useful comparison to the central Oregon Cascades. The two areas differ markedly in crustal structure and prior tectonic history. The Quaternary volcanoes of northern California stand on thick continental crust, whereas those of central Oregon have been built on relatively thin crust consisting mainly of mafic lavas and volcanic sediments. The relative proportions of rocks in these two regions are shown in Figure 16-4, together with those of central Washington where the thickness of continental crust is also great, but the total volume of Cenozoic volcanic rocks is small. The proportion of andesite is greatest in the Washington Cascades, less in northern California, and least in central Oregon, and the relative abundance of andesite in the three areas varies inversely with the total volume of volcanic rocks. Where the volume is large, basalt is by far the dominant rock type; the absolute volumes of andesite in the three areas are essentially equal.

Too few analyses are available to estimate the overall compositions of rocks in central Washington, but average compositions weighted for the relative abundances of each rock type in northern California can be compared with the corresponding average for central Oregon (Table 16-2). When this is done, the resulting averages are more similar than the differences in relative volumes would indicate. The reason for this apparent inconsistency lies in the tendency for basalts of northern California to have lower SiO_2 and alkali contents and higher MgO and iron contents than those of central Oregon. These differences balance the effect of differing volumetric proportions.

Andesites in the northern and southern High Cascade volcanoes are slightly more potassic than those of the central part of the range. The average K_2O contents (normalized to 60% SiO_2) of andesites from volcanoes in the three regions are Rainier (10 analyses), 1.66% K_2O; Hood and Jefferson (41 analyses), 1.43% K_2O; and Lassen and Shasta (10 analyses), 1.59% K_2O. K_2O content appears to vary directly with the proportion of andesite in these three parts of the chain. There is an even greater variation in Rb contents, which, as we shall

TABLE 16-1. AVERAGE COMPOSITION OF QUATERNARY ROCKS, CENTRAL OREGON CASCADES

	Basalt 43 analyses (<53.5% SiO_2)		Basaltic andesite 57 analyses (53.5%–57% SiO_2)		Andesite 56 analyses (57%–63% SiO_2)		Dacite 16 analyses (63%–68% SiO_2)		Rhyolite 15 analyses (>68% SiO_2)	
	(wt %)	(S.D.)	(wt %)	(S.D.)	(wt %)	(S.D.)	(wt %)	(S.D.)	(wt %)	(S.D.)
SiO_2	51.1	1.84	55.4	0.91	60.0	1.72	64.9	1.78	71.6	2.47
TiO_2	1.4	0.33	1.0	0.17	0.9	0.16	0.7	0.22	0.3	0.13
Al_2O_3	17.3	0.99	17.9	0.72	17.4	0.64	16.2	0.42	13.9	0.65
ΣFeO	9.4	2.40	7.6	0.79	6.4	0.79	4.7	0.83	2.4	0.57
MnO	0.2	0.02	0.1	0.1	0.1	0.03	0.1	0.03	0.1	0.02
MgO	6.1	2.03	4.6	0.92	2.8	0.73	1.7	0.56	0.5	0.34
CaO	8.9	0.78	7.5	0.78	6.1	0.75	4.4	0.99	1.7	0.36
Na_2O	3.6	0.56	3.9	0.29	4.3	0.34	4.5	0.56	4.5	0.43
K_2O	0.8	0.24	0.9	0.22	1.2	0.33	1.6	0.33	3.0	0.35
P_2O_5	0.3	0.12	0.2	0.07	0.2	0.06	0.2	0.08	0.1	0.05

TABLE 16-2. WEIGHTED AVERAGE COMPOSITIONS OF CASCADE VOLCANIC ROCKS

	Quaternary rocks	Quaternary rocks	Pliocene rocks	Middle and upper Miocene rocks	Oligocene-Miocene rocks
	Northern California	Central Oregon			
	Average composition (in wt %)				
SiO_2	52.2	52.7	52.7	57.3	62.4
TiO_2	1.2	1.4	1.3	1.1	0.9
Al_2O_3	18.0	17.4	17.3	16.6	15.7
ΣFeO	9.6	9.1	8.6	7.4	6.1
MnO	0.1	0.1	0.1	0.1	0.1
MgO	5.5	5.3	5.6	3.7	2.3
CaO	9.1	8.4	8.7	6.7	5.3
Na_2O	3.2	3.8	3.5	3.5	3.4
K_2O	0.9	0.9	0.9	1.3	1.7
P_2O_5	0.2	0.3	0.2	0.3	0.2
Total	100.0	99.4	98.9	98.0	98.1
	No. of analyses and percentage of rock type by volume (in parentheses)				
Basalt	7 (69)	33 (85)	17 (90)	20 (39)	6 (10)
Andesite	22 (29)	112 (13)	76 (9)	99 (41)	25 (45)
Dacite-rhyolite	35 (2)	31 (2)	6 (1)	17 (20)	10 (45)
	Total volume of rocks (in km^3)				
	3,095	4,600	2,150	24,850	10,000

ave. ~919 km³ per segment, non-basalt
Oregon is ~93% of ave.
Calif. is 105% of ave
basalt is ~32% of volcanics in Wash. Cascades
basalt is ~81% of volcanics in C. Oreg.

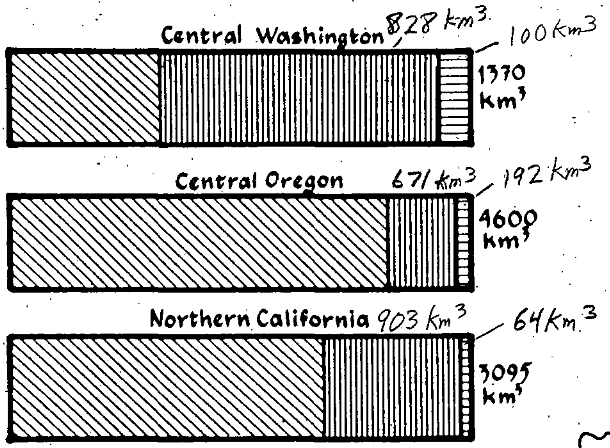


Figure 16-4. Proportions of Quaternary volcanic rocks in central Washington, central Oregon, and northern California. North-south dimensions of the three areas are approximately equal. Diagonal pattern indicates basalt; vertical, andesite; horizontal, dacite and rhyolite.

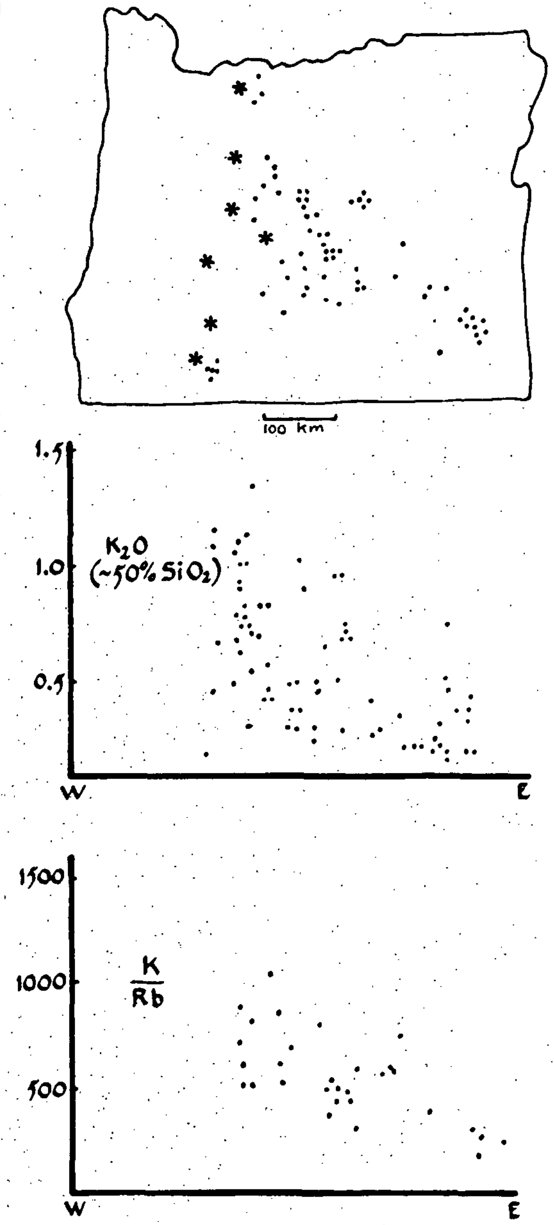


Figure 16-5. Distribution of analyzed samples of Pliocene basalts. K_2O and K/Rb values are shown as a function of longitude and distance behind the main Cascade axis (shown by asterisks). Some points on the location map may have more than one analyzed sample, and some samples have not been analyzed for Rb.

TABLE 16-3. AVERAGE COMPOSITION OF 33 PLIOCENE BASALTS FROM CENTRAL OREGON

	Wt %	S.D.
SiO_2	48.5	1.92
TiO_2	1.4	0.46
Al_2O_3	17.1	1.03
Fe_2O_3	2.9	1.98
FeO	7.4	
MnO	0.2	0.03
MgO	8.0	1.36
CaO	9.9	1.12
Na_2O	3.0	0.46
K_2O	0.5	0.33
P_2O_5	0.3	0.20

note, appear to be related to the volume of Tertiary volcanic rocks erupted in the same parts of the chain.

Pliocene Rocks

Pliocene rocks have been considered in two groups, one near the Cascade axis and another extending eastward across central Oregon.

The Pliocene rocks of central Oregon consist mainly of a distinctive group of thin but widespread basaltic lava flows and much smaller volumes of rhyolitic pumice and obsidian. Most basaltic eruptions occurred during a period between 3 and 6 m.y. ago and were scattered in seemingly random fashion over a broad region between the Cascade axis and eastern Oregon. Rhyolites are restricted to two linear belts in which eruptions appear to have migrated westward over a period of at least 10 m.y. (MacLeod and others, 1977).

Because the basalts are restricted to a narrow time range but have a wide areal distribution (Fig. 16-5), they are well suited for comparing compositional features at differing distances from the Cascade axis. Although the range of their SiO_2 contents is rather narrow and their average composition is that of high-alumina basalt (Table 16-3), they cover a spectrum between nepheline-normative and quartz-normative compositions. The compositional range is greatest in the west and becomes narrower toward the east. The K contents, for example, have the highest average values and greatest spread in the west and diminish eastward (Fig. 16-5).

Too few Pliocene rocks have been analyzed within the Cascade province to say whether they have regional variations along the axis. Our data are most complete for the rocks of central Oregon and somewhat less so for northern California. The total volumes and proportions of Pliocene rocks are similar to those of the Quaternary group in both areas, but the proportions of differentiated rocks are slightly lower in the Pliocene group. The weighted average composition for central Oregon (Table 16-2) reflects this difference in its lower Na_2O and higher MgO and CaO content.

Most of the Pliocene rocks of the Cascade region were erupted from small central-vent volcanoes scattered over a zone about twice as wide as that of the Quaternary High Cascade chain. We have found no large composite volcanoes in this age group in the area we have studied.

Middle and Upper Miocene Rocks

Two series of rocks have been combined in this age group, one a minor sequence (the Elk Lake formation) produced during a short episode between 9 and 10 m.y. ago and a much more voluminous series (the Sardine Formation) erupted between about 13.5 and 16 m.y. ago. The present status of mapping and dating is inadequate to separate these rocks in most areas. Our data on volumes and proportions of rock types are confined to the section in central Oregon.

The combined volumes of volcanic rocks in this age group exceed that of all younger calc-alkalic rocks combined. The locus of this episode of intense volcanism was concentrated in a chain of large composite volcanoes similar to but probably larger than those of the Quaternary High Cascade Range and displaced a few tens of kilometres to the west. The axis of Miocene centers trended slightly east of north at an angle of about 15° to the younger Cascade chain, which the Miocene axis intersects near the Oregon-Washington border. Despite its great thickness on the west side of the High Cascades, the Sardine Formation has not been found on the east side of the range in central Oregon, where minor amounts of coarse sedimentary debris are the only materials derived from the huge western Cascades volcanic pile. For this reason the volume of mid-Miocene rocks beneath the High Cascades is uncertain, and the calculations are subject to a large possible error.

Most mid-Miocene volcanic centers coincide crudely with shallow stocks and associated aureoles of low-grade metamorphism. The intrusions are only slightly younger than the lavas they intrude. Their compositions are similar to those of their volcanic counterparts, but too few rocks have been analyzed to date to permit an accurate comparison.

The proportions of rock types in the middle and upper Miocene groups differ from those of the younger episodes (Table 16-2). Andesite makes up a larger fraction and is approximately equal in volume to basalt. Much of the andesite was erupted as lahars and other types of clastic rocks. Tephra and shallow-marine volcanic sediments make up a major fraction of the Miocene section, especially around the lower flanks of the large cones.

Upper Oligocene and Lower Miocene Rocks

An extensive sequence of siliceous pyroclastic rocks and subordinate andesitic and basaltic lavas underlies the Sardine Formation in most of the central and southern parts of the western Cascades Range (Peck and others, 1964). The rocks of this group belong to the Little Butte Formation and include minor members, such as the Breitenbush Tuff of Thayer (1937). The boundary between the Little Butte and Sardine Formations has previously been taken to coincide with a thin but widespread basaltic unit that is part of the Columbia River Group, but radiometric dating has shown that the major time break is somewhat lower in the section (Sutter, 1978), and the proportion of Miocene rocks we have included with the Sardine Formation is greater than that of earlier workers, whereas the proportion in the Little Butte is correspondingly less.

The main feature of the Little Butte Formation is its high proportion of differentiated rocks. Tephra beds, including air-fall tuffs, ignimbrites, and water-laid pyroclastic deposits of dacitic and rhyolitic compositions, are by far the most abundant rocks. Elsewhere in the western Cascades, however, basaltic and andesitic lavas are common, especially in the lower part of the formation. It is difficult to determine the eruptive centers that were active during this period. The few that have been identified tend to follow close to the line of mid-Miocene centers, and there seems to have been no major shift in the axis of volcanism between the early and middle Miocene episodes.

Geochemical Variations

In addition to these changes in the absolute and relative volumes of rock types, the various age groups show systematic spatial and temporal variations of their major- and trace-element compositions, most notably in Fe, Na, and Rb. Comparisons of these elements are given in Table 16-4 and Figure 16-7. The differences are best seen in rocks of basaltic composition in which the effects of differentiation have not been superimposed on the more primitive character of the mafic magmas.

Fe versus SiO_2. Oligocene and lower Miocene basalts in the Little Butte Formation near the base of the exposed section in central Oregon differ markedly from younger basalts of the Cascades in that they are distinctly more Fe-rich and tholeiitic. Because their compositions resemble those of quartz-normative tholeiites of the Columbia River Group, they have been correlated with that group of basalts and have been said to have originated outside the main Cascades system. Work by Nathan and Fruchter (1974) has shown that the rocks differ from

Columbia River basalts in their trace-element compositions, and our own radiometric dating indicates that the Cascade tholeiites predate the Columbia River basalts by as much as 10 m.y. A few Columbia River basalts have been identified within the Sardine Formation well above the Little Butte tholeiites, but the relationship, if any, between the Cascade basalts and those of the Columbia River Group remains unclear.

The Fe enrichment of Little Butte rocks (Fig. 16-6) is greater than that of any younger lavas in the Cascade series. The general trend with time is from a distinctly tholeiitic suite to one that is strongly calc-alkalic. Baker (1968), Jakeš and Gill (1970), and others have recognized the tholeiitic nature of early volcanic series in island arcs, where tholeiites are common near the base of the volcanic sequence and tend to give way to more calc-alkalic rocks as the crust thickens with time (Miyashiro, 1974). It may be significant that we have only found strongly tholeiitic rocks in the central part of the Cascade province where there is no evidence for thick pre-Tertiary continental crust. The abrupt change from tholeiitic to calc-alkalic rocks in the same region after the Oligocene–early Miocene episode is one of the most conspicuous features of the temporal evolution of the Cenozoic Cascade system.

In other respects, however, the change in the compositions of rocks with time differs from the pattern that Miyashiro (1974) considered typical of the evolution of island arcs and continental margins. Miyashiro indicated that the change to more calc-alkalic compositions is accompanied by an increase in average SiO_2 content, but our data show the reverse; SiO_2-rich rocks are most abundantly formed in the older episodes, and the average SiO_2 content declines sharply thereafter (Table 16-2). In these respects, it appears that the trend of SiO_2 and Fe contents differs from what is thought to be the rule elsewhere, but we suspect that the difference is due to the fact that plots of analytical data in variation diagrams that ignore relative volumes can be misleading, at least in terms of the overall character of igneous rock series.

Osborn and Watson (1977) have pointed out that a change from tholeiitic to calc-alkalic compositions can result from an expansion of the spinel stability field with an increase of either f_{O_2} (O_2 fugacity) or dry load pressure. Eggler and Burnham (1973) have found that magnetite is not a liquidus phase in a melted Mount Hood andesite at elevated water pressures and any geologically reasonable f_{O_2}, but experimental studies of basalt and basaltic andesite from the Oregon Cascades by Osborn and Watson (1977) indicate that dry pressures of 10 kb and modest values of f_{O_2} result in an Fe-rich spinel phase at near-liquidus temperatures.

TABLE 16-4. MEAN Rb, Sr, Na_2O, AND K_2O VALUES FOR ROCKS OF CENTRAL OREGON CASCADES

Age group	Rock type	Rb (ppm)	Sr (ppm)	Na_2O (wt %)	K_2O (wt %)	Rb/Sr	K/Rb
Quaternary	Basalt (14)	10	761	3.6	0.8	0.013	808
	Andesite (14)	13	621	4.1	1.0	0.022	765
	Rhyolite (3)	23	558	4.5	1.8	0.037	775
Pliocene	Basalt (3)	12	538	3.5	1.0	0.020	807
	Andesite (1)	18	539	3.9	1.1	0.033	594
	Rhyolite (1)	25	349	4.7	1.9	0.072	756
Late and Middle Miocene	Basalt (5)	17	611	3.1	1.0	0.028	602
	Andesite (7)	31	397	3.7	1.5	0.081	491
	Rhyolite (6)	64	225	3.9	3.1	0.373	480
Early Miocene	Basalt (6)	25	365	2.9	0.9	0.068	369
	Andesite (3)	52	400	3.5	2.1	0.133	396
	Rhyolite (5)	66	264	3.4	2.3	0.287	353

Note: Numbers in parentheses after rock names are numbers of analyses used in calculating averages for Rb and Sr. Rock-type divisions have been placed at 53.5% and 63.0% SiO_2.

Their results, though preliminary, indicate that basic tholeiitic liquids would result from equilibration of magmas under thin lithosphere and that the liquids would change to a more calc-alkalic trend with an increasing depth of equilibration under a thickening lithosphere.

Subsequent differentiation at higher levels in the crust should follow trends that are essentially similar, regardless of the degree of Fe enrichment of the mafic parental magma. The trends of andesites, dacites, and rhyolites in both tholeiitic and calc-alkalic series should converge on end members that are very similar, as they do in the Cascade rocks, in which there is little difference in the rhyolitic differentiates of the tholeiitic and calc-alkalic series.

Na and K. If only rocks at the same stage of differentiation are considered, we observe a slight decrease in the K_2O contents of rocks from the oldest to the youngest series (Table 16-4), but taken as a whole, the weighted average K_2O content of the rocks declines markedly with time (Table 16-2). Miyashiro (1974) indicated that K_2O should increase with time as the rocks become more calc-alkalic, but we find no evidence that this is so. Miyashiro (1974) and Sugisaki (1976) thought that alkalic rocks are abundant where rates of plate convergence are low, but the subduction rate off the coast of the Pacific Northwest is one of the lowest known, and we have found no alkalic rocks in the main Cascade system. And finally, it is often said that the average K_2O contents at a constant SiO_2 value increase toward the continental side of a volcanic front, but our data on Pliocene rocks behind the Cascade axis show the opposite to be true (Fig. 16-5).

Na, unlike K, shows an almost perfect linear relationship to the mean age of the units we have sampled (Fig. 16-7). The increase of sodium with time is less pronounced in more differentiated rocks that have probably evolved through high-level fractionation of plagioclase. The tendency for andesites of various ages to be more uniform than basalts may indicate that they have equilibrated at shallow depths and in so doing, have lost the contrasting Na contents that characterized their parental basaltic liquids. The temporal increase of Na in basalts is consistent with two possible relations, one resulting from increasing depths of melting and the other from increasing depths of differentiation.

The increase is the opposite of what one would expect from progressive melting of a solid-solution series in which the sodic end member is enriched in early liquids. It is, however,

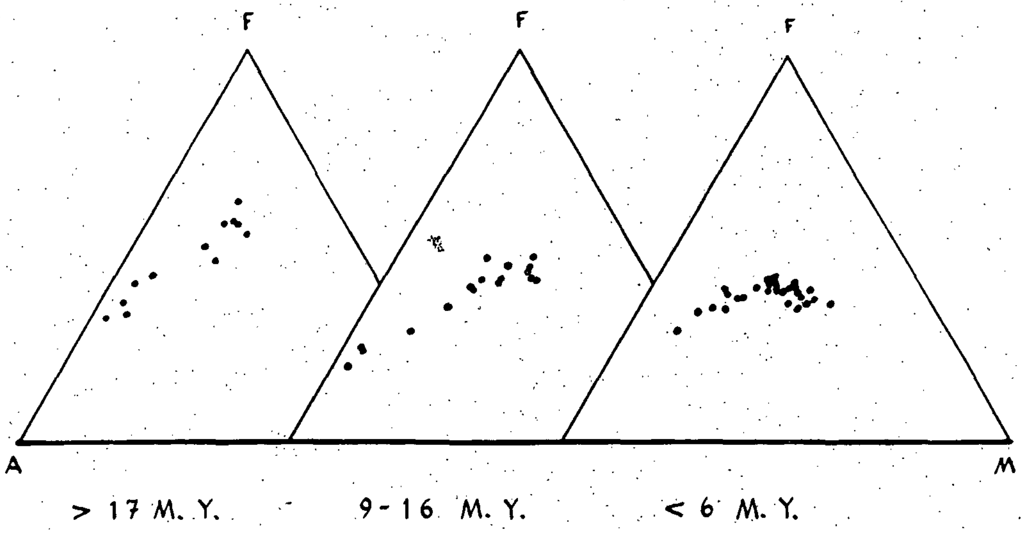


Figure 16-6. AMF [$(Na_2O + K_2O)$:MgO:ΣFeO] relations for rocks in three major age groups in the central Oregon Cascade Range.

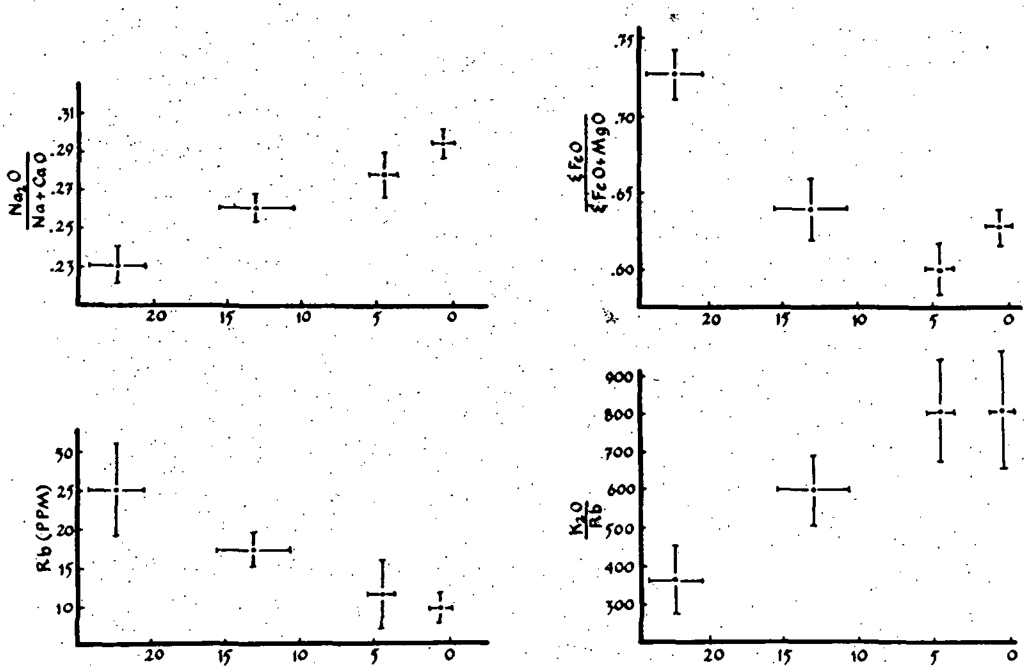


Figure 16-7. Variations of Fe, Na, Rb, and K/Rb with time (millions of years) in basaltic rocks of the central Oregon Cascade Range. Error bars show 1 standard deviation in chemical data and range in radiometric dates.

consistent with either of two melting relations at pressures where plagioclase is not a stable mineral. Kushiro (1973) observed that the Na content of partial melts of garnet lherzolite increased with pressure, while Mysen (1974) found that increasing f_{O_2} caused a similar increase in partial melts of a spinel lherzolite. The relations we have already noted in the Fe contents of the same rocks are consistent with both of these possibilities, but it seems less likely that the variations in basaltic liquids of the Cascade system are the result of increasing f_{O_2}; the geologic relations are consistent with thickening of the lithosphere with time but suggest no apparent mechanism by which f_{O_2} might increase concurrently.

The increase of Na with time could also be caused by an increase in the depth of differentiation. At shallow depths, plagioclase should have a large field of stability, and crystallization of this mineral in place of another aluminous phase such as spinel or garnet would inhibit the enrichment of Na. Such a relation is consistent with an increasing depth of segregation of liquids at the base of the lithosphere and could be independent of the original depth of melting.

Rb and Sr. With the exception of the Pliocene units for which we have little data, Sr contents of basalts have increased regularly with time in a manner similar to Na, but Rb varies inversely with Na and Sr and declines with time (Table 16-4, Fig. 16-8). The fact that Sr, which should be fractionated into plagioclase, behaves in a manner similar to Na lends support to the second of the two interpretations considered in the preceding section. As the thickness of the lithosphere increased with time, the pressure at which basalt last equilibrated in the mantle became higher, and the stability field of plagioclase must have been reduced.

The trend of Rb is emphasized in differentiated rocks (Fig. 16-8), owing, no doubt, to the incompatible nature of the large Rb ion. Because basalts of all ages have nearly constant K contents, their K/Rb ratios increase with time.

Rb contents of lavas from seven Quaternary Cascade volcanoes are shown in Figure 16-9. Despite a certain amount of scatter, at least part of which results from the varied sources of the analytical data, it is apparent that the Rb contents of lavas from the central part of the Cascade Range are lower than those of volcanoes at the northern and southern ends. A comparison of the Rb contents at the same stage of differentiation is given in Figure 16-10, together with measured thicknesses of the Tertiary volcanic sections in corresponding segments of the chain. There appears to be a crude inverse correlation between the amount of Tertiary volcanism in a given region and the Rb contents of Quaternary lavas in the same part of the chain. Where there was a large amount of Tertiary volcanism, Quaternary lavas are poor in Rb, and where there was little Tertiary volcanism, Rb contents are high.

Systematic variations in Rb contents have been cited from a variety of tectonic settings (Kesson, 1973; Baxter, 1976), and several explanations for these variations have been proposed: (1) continued melting of a given source rock would result in large amounts of Rb entering the first liquid. If melting continues without separation of this liquid, the Rb content should decline as it is diluted in a larger volume, but if the first liquid is removed and melting continues, a sharp decrease will be seen in successive melts from the same source. (2) If Rb is concentrated in phlogopite and the mineral persists through a wide range of melting, there could be a steady decline of both Rb and K at a rate that depends on the distribution coefficient between phlogopite and basaltic liquids rather than on the frequency of separation of liquids. (3) Rb may be introduced in varying amounts by subduction of sedimentary material

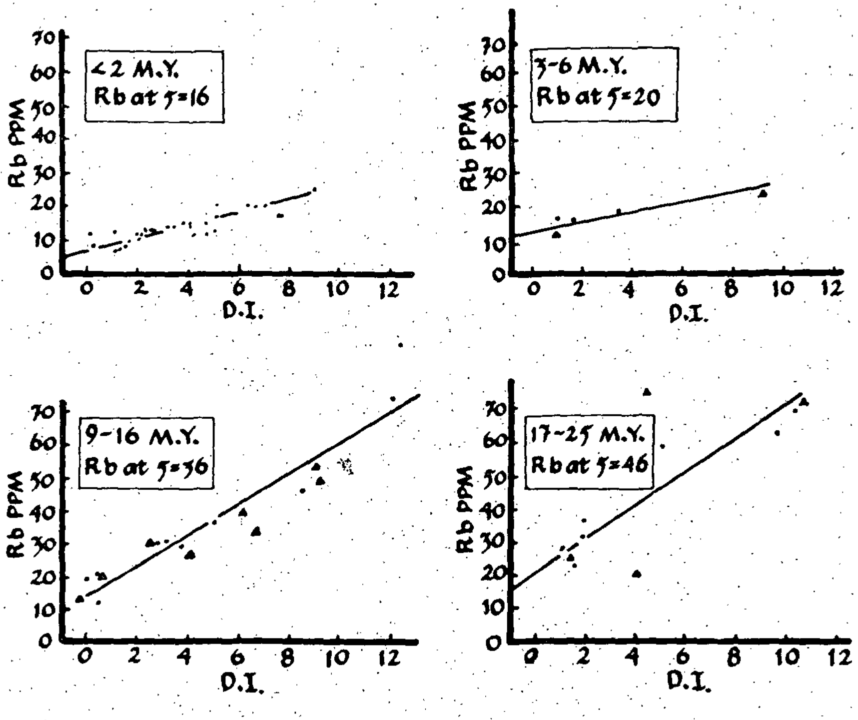


Figure 16-8. Concentrations of Rb in volcanic rocks of four age groups in the central Oregon Cascades plotted against a modified Larsen differentiation index (D.I. = $\frac{1}{3}\text{Si} - \text{Mg} - \text{Ca} + \text{K}$). Solid triangles represent chemically analyzed splits of radiometrically dated samples; dots represent rocks for which the age is inferred from stratigraphic relations. The Rb content at an intercept of the least-squares line at a D.I. of 5 (andesite) is given for each group.

and by transfer of Na and K along with H_2O and other mobile components into a melt generated in or above the zone of subduction. (4) Rising magma may scavenge Rb from the rocks through which it passes and gradually deplete them as successive magmas follow similar paths toward the surface. And (5), the mantle may be compositionally zoned with decreasing amounts of Rb with depth; melting may migrate downward through these zones with time. Below, we examine the Rb relations we observe in the light of these various possibilities.

1. Gast (1968) pointed out that differing degrees of partial melting of the same source

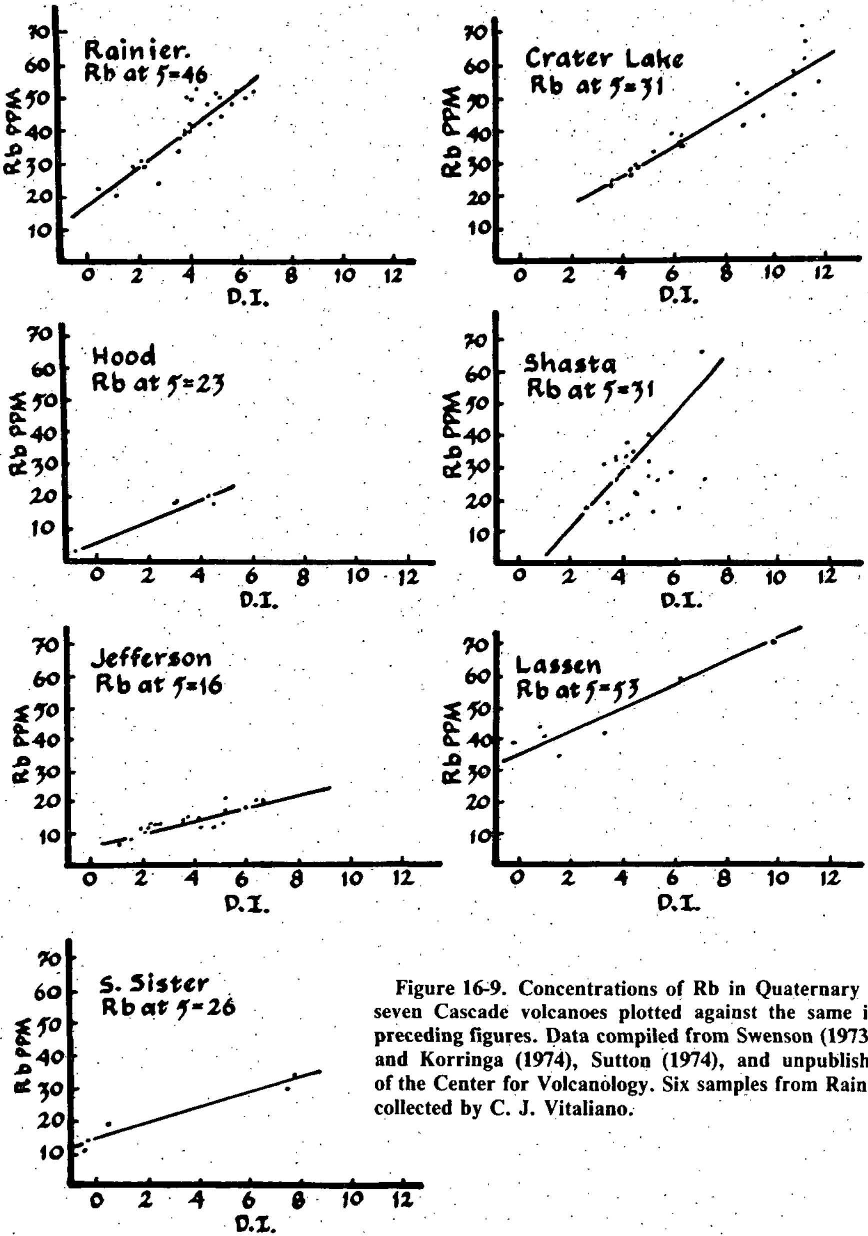


Figure 16-9. Concentrations of Rb in Quaternary lavas of seven Cascade volcanoes plotted against the same index as preceding figures. Data compiled from Swenson (1973), Noble and Korringa (1974), Sutton (1974), and unpublished data of the Center for Volcanology. Six samples from Rainier were collected by C. J. Vitaliano.

should result in either a steady or step-wise decline of the abundances of strongly excluded elements, depending on the frequency of extraction of successive melts. Our estimates of volumes indicate that post-Miocene rocks comprise only 15% of the total volume of the central Oregon Cascades and could represent only a small volume compared to earlier episodes. Such a relation argues against dilution as an explanation of the low Rb contents of young basalts, because the rate of decline is far from proportional to the volumes of erupted magma. Similarly, we can rule out different degrees of melting of different source rocks, because the volumetric relations are the reverse of what such a model predicts. These conclusions depend, of course, on the assumption that the volumes of eruptive rocks are roughly proportional to the amount of magma generated at depth.

2. The fact that the decline in Rb is steady and crudely proportional to the amount of volcanism may be consistent with progressive melting of a source in which phlogopite persists through a wide range of melting, but the amount of phlogopite necessary to satisfy this condition seems too large for the observed heat-flow from the mantle (Yoder and Kushiro, 1969). Beswick (1976) predicted that progressive melting of phlogopite should cause K/Rb ratios of basalts to decline with time; the fact that we find the opposite trend also argues against this mineral remaining through long melting intervals.

3. Fyfe and McBirney (1975) have considered the problem of the stability of hydrous minerals during subduction and their possible roles in magma generation. They concluded that, because phlogopite is the only hydrous mineral that is likely to persist to depths where melting can take place below a volcanic front, there should be a relation between the amount of H_2O, K, and other components released when this mineral breaks down and the volumes and compositions of magma produced by flux melting. If Rb was supplied from a descending slab of lithosphere, its abundance and ratio to K should be a function of the rate of subduction and composition of sedimentary material and independent of the earlier history of the region. Hence, the model is not supported by our data. It cannot be ruled out, however, because other factors may intervene between the locus of melting and final equilibration of the magma and may influence the compositional relations.

4. Best (1975) has proposed that alkalies may be scavenged from the lithosphere as magma rises from deeper sources. Presumably other components would be added to the magma at the same time. The decline of Rb with time and the fact that it is more depleted where

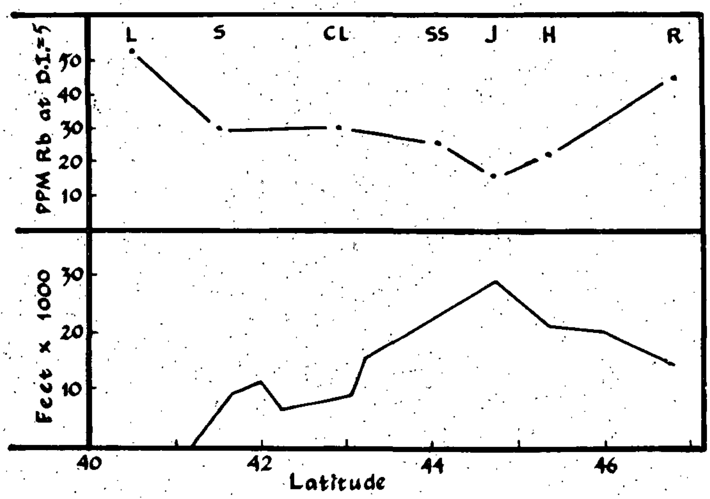


Figure 16-10. Relations of Rb contents of Quaternary volcanoes in Figure 16-9 to measured stratigraphic thicknesses of Tertiary volcanic rocks in the same area. Volcanoes are shown in order from south to north: L, Lassen: S, Shasta; CL, Crater Lake; SS, South Sister; J, Jefferson; H, Hood; R, Rainier (stratigraphic thicknesses from Fiske and others, 1963; Kays, 1970; Maynard, 1974; Wells, 1956; Wise, 1969, 1970).

TABLE 16-5. Sr-ISOTOPE DATA FOR ROCKS OF CENTRAL OREGON

No. in Figure 11	Field no.[*]	Rock type	K/Ar age (m.y.)	Rb (ppm)	Sr (ppm)	$^{87}Sr/^{86}Sr$
1	BX-99	Basalt	24.2	21	325	0.7029[§]
2	DMS-77	Granodiorite	15.9	97	161	0.7029
3	DMS-24	Basalt	15.4	18	516	0.7027
4	SJ-201	Basalt	<0.7[†]	7	658	0.7026[#]
5	SJ-70	Andesite	<0.7[†]	19	522	0.7031
6	DMS-23	Basalt	15.8	32	340	0.7054

Note: Rb and Sr concentration determined by X-ray fluorescence analysis. Samples 1 and 6 were analyzed in duplicate. All ratios have been corrected for isotope fractionation to a standard value of $^{86}Sr/^{88}Sr = 0.1194$. The average $^{87}Sr/^{86}Sr$ ratio for seven analyses of the Eimer and Amend Sr-isotope standard was 0.70807 ± 0.0002 (1σ). The initial Sr-isotope ratios of the Tertiary samples were calculated by correcting the measured values for the decay of ^{87}Rb since the rocks crystallized.

[*] Sample localities and analytical data are on file in the computer data bank of the Center for Volcanology, University of Oregon.

[†] Normally polarized flows from the main cone of Mount Jefferson, not dated by K/Ar method.

[§] Split analyzed by R. L. Armstrong at the University of British Columbia yielded a value of 0.7035.

[#] Split analyzed by R. L. Armstrong at the University of British Columbia yielded a value of 0.7030.

there has been the greatest amount of previous volcanism is consistent with this interpretation. K shows a similar but less-pronounced relation, but we find no systematic decline in Zr (Fig. 16-3) or in other lithophile elements that should be affected more strongly than Rb.

In an effort to clarify this question, we have measured the Sr-isotope compositions of samples of various ages and compositions (Table 16-5 and Fig. 16-11). The values we obtained are remarkably uniform (0.70283 ± 0.00014 at one standard deviation) and unusually low. In fact, they are among the lowest yet reported from the Cascade Range and are considerably lower than that of a Columbia River basalt in the same section (no. 6, Table 16-5). The older lavas do not have higher ratios than younger ones, and rocks that are more differentiated and richer in Na and K are not more radiogenic than basalts. If Rb were scavenged from the crust, the process would have to have operated in such a way that the radiogenic Sr formed by decay of Rb was not assimilated, at least in measurable amounts. Scavenging from deeper levels in the lithosphere is not ruled out by the Sr-isotope data.

5. The uniformity of Sr-isotope ratios also argues strongly against derivation from a compositionally inhomogeneous mantle. If source regions differed in their original Rb contents, their Sr-isotope ratios must also have differed, and we have found no correlation between these two factors.

Rare-Earth Elements. All rare-earth elements (REE) for which we have data show a progressive decline in abundance from older to younger units (Fig. 16-12). This trend is especially apparent in the light REE and is analogous to the general trends in Rb discussed above. The similarity in the configurations of the chondrite-normalized REE plots suggests that the lavas of each age group were derived from mineralogically similar source regions.

SUMMARY AND CONCLUSIONS

The principal observations that can be made from these data are as follows: (1) The volumes of volcanic rocks erupted since late Oligocene time have declined with time in an irregular fashion. (2) At the same time, the proportions of basaltic rocks have increased. The greatest

However the volume of non-basalt rock is uniform per length between Calif, Oregon, Wash,

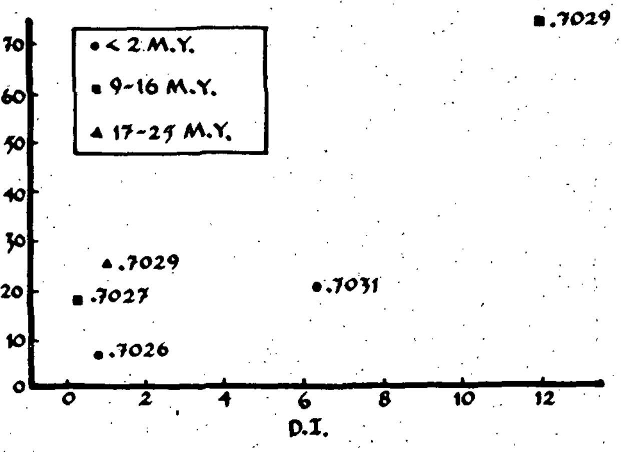
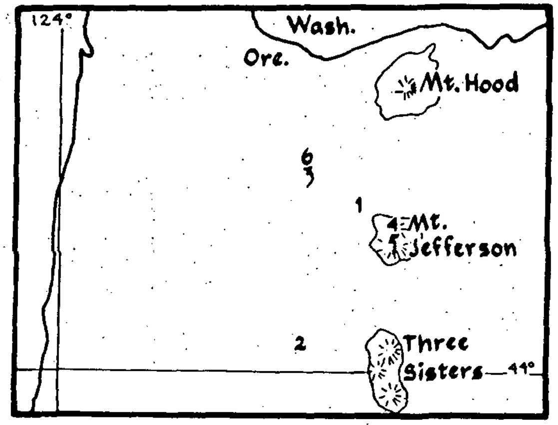


Figure 16-11. Distribution of Sr-isotope ratios listed in Table 16-5 according to their Rb content, age, and differentiation index (above). Locations of samples are shown in the sketch map to right.



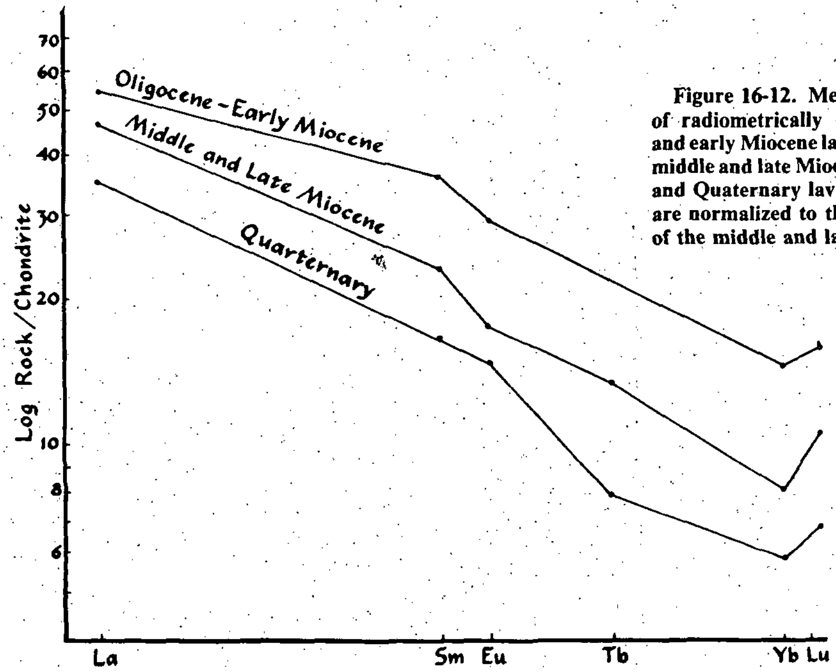


Figure 16-12. Mean REE abundances of radiometrically dated late Oligocene and early Miocene lavas (4 samples), dated middle and late Miocene lavas (6 samples), and Quaternary lavas (22 samples). Data are normalized to the mean SiO_2 content of the middle and late Miocene group.

increase followed the large Miocene event, and since that time, basalt has outweighed all other rocks in the central part of the Cascade Range. Andesite is relatively more important in the northern and southern parts of the chain where there was less Tertiary volcanism and the thickness of continental crustal rocks is greater. (3) When basaltic rocks of each episode are compared, they show a decrease in Fe, Rb, REE, and to a minor extent, K, with time. Simultaneously, Na, Sr, and K/Rb increase, and Sr-isotope ratios remain essentially constant. (4) The abundance of Rb in Quaternary rocks is highest at the extremities of the chain. Its abundance varies inversely with the volume of Tertiary volcanism in the same segment of the chain. (5) The variations of K in basalts erupted at differing distances behind the volcanic front differ from the conventionally accepted pattern. Both the range and mean abundances of K are highest near the main axis and become lower toward the east. (6) Quaternary volcanism responsible for construction of Mount Jefferson was fed by distinct batches of magma, which became more calc-alkalic and poorer in Zr with time, even though SiO_2 contents increased steadily throughout all but the last stage of activity.

See p. 375
comparisons

No single mechanism of partial melting or differentiation is adequate to explain all these variations. The only process for which we find no supporting evidence is one that requires a steady input of components from a subducted slab; temporal variations we observe would require improbable changes in the rates of subduction or the compositions of subducted material on a short scale of Cenozoic time. A more complex multi-stage process seems to be required. The combination that best fits our present knowledge is a three-stage sequence that includes (1) progressive depletion of a source region in the mantle, (2) re-equilibration of each large batch of magma at a greater depth than the preceding one, possibly near the base of the lithosphere, and (3) subsequent differentiation at a high level in the crust.

The evidence for these three stages has been considered in the discussions of individual components and can be briefly summarized. Progressive melting of a single source in the mantle is consistent with the decline of volumes, Fe/Mg ratios, SiO_2, K, Rb, and REE with time, but these same variations are also consistent with successive batches of magma passing through the same rocks overlying the source and depleting them in components that would be fractionated into the liquid. We have no way of making a distinction between these two possibilities, but we can rule out significant contamination by old continental crust.

The change from a tholeiitic to a more calc-alkalic trend of differentiation with time can be explained as the result of equilibration of the rising liquid with its co-existing mineral phases and segregation of the liquid at a level that has become deeper with time, possibly as a result of accumulation of crustal rocks and underplating of the lithosphere with the dense residue of earlier batches of rising magma.

The increasing Na and Sr contents of basalts also lend support to this interpretation and indicate that plagioclase was fractionated from the earlier magmas but with time became less important than an Fe-rich spinel.

Most of the final differentiation from basaltic to more SiO_2-rich compositions seems to have taken place at shallow depths, possibly immediately below the volcanic superstructure. Crustal contamination does not appear to have played an important role in this process. At least three separate batches of magma rose beneath Mount Jefferson, but they were drawn from a source that was progressively depleted in Fe and Zr until the latest stage, which appears to have come from a small but separate pulse of magma similar to that of the earliest stage. Studies of subvolcanic stocks may clarify these processes.

We have not attempted to relate our observations to possible changes in the tectonic regime of the Pacific Northwest. Changes of the structure and stress distribution in the crust must affect the manner in which magmas rise through the lithosphere and could also influence the depth and degree of differentiation. If so, they may have altered the compositions and proportions of rock types we find at the surface. We consider the most important conclusion to be drawn from the data we have presented to be that volcanic rocks can only be seen in their true perspective when they are considered in relation to the compositions, volumes, and structural settings of the volcanic series as a whole.

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