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# SOME GEOLOGIC CONSTRAINTS ON MODELS FOR MAGMA GENERATION IN OROGENIC ENVIRONMENTS

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## Abstract

It is impossible to choose between the many proposed models for magma generation at convergent plate boundaries without more information on the quantitative aspects of magma generation and the geochemical balance of the system as a whole. There is a clear need for more data on the relative abundances of rock types in different geologic settings and on the rates at which these rocks have been produced over extended periods of time.

Current concepts of the structural and magmatic processes associated with subduction are strongly biased toward present conditions that are not necessarily typical of the past. If one considers all of the Cenozoic, igneous activity has been episodic with long intervals of relative quiet between outbursts of volcanism. Some periods have been dominated by basaltic activity, others by rhyolite ignimbrite eruptions and others by plutonism. There is growing evidence that these episodes occur in unison over wide regions.

Preliminary estimates of the rate of eruption of volcanic rocks in the Oregon Cascades during the past 20 million years are of the order of $2.3 \times 10^{10}$ g/yr for each km of the volcanic chain. If such a rate is representative of the Circum-Pacific region as a whole, potassium is being returned to the continental crust by igneous activity at a rate that is less than, but of the same order as it is being removed from the continents in river water.

## Sommaire

Il est impossible de choisir parmi les différentes hypothèses visant à expliquer l'origine des magmas associés aux limites convergentes des plaques sans plus d'information sur les aspects quantitatifs de la formation des magmas et sur les équilibres géochimiques du système entier. Il faut plus de données sur l'abondance des diverses lithologies dans les contextes tectoniques différents, et sur les taux de production de ces roches à travers le temps. Les concepts actuellement en vogue supposent que les processus structuraux et magmatiques dans le passé ont été les mêmes qui sont actifs aujourd'hui. Si l'on considère l'activité ignée durant tout le cénozoïque, on la caractérise d'épisodique, avec de longues lacunes d'inactivité volcanique. Durant certaines périodes, le volcanisme basaltique prédomine, mais dans d'autres, les éruptions rhyolitiques et ignimbritiques ou encore le plutonisme sont dominants. L'évidence favorise de plus en plus l'hypothèse que ces épisodes s'appliquent uniformément à de vastes régions. Nos calculs des taux d'éruption de roches volcaniques dans la chaîne des Cascades, Oregon, durant les derniers 20 millions d'années indiquent $2.3 \times 10^{10}$ g/année pour chaque kilomètre de la chaîne volcanique. Si ce débit s'applique à toute la région circum-pacifique, le potassium ajouté à la croûte continentale par les phénomènes ignés est du même ordre que la quantité de potassium ajoutée aux bassins marins par les rivières.

(Traduit par le journal)

## Introduction

Recent discussions of the various processes associated with subduction have generated so many competing models that one finds it hard to summarize them, much less evaluate their merits. This dialectic free-for-all has been made possible by the small number of geologic constraints imposed on our speculations. It is quite easy to propose models for the dynamics of magma generation if there are no data on the rates at which such magmas have been produced over extended periods of time and if we have no idea what energy balance might be required to sustain a specific amount of melting. In the same way, anyone is free to advocate his favorite explanation for the supposed chemical features of orogenic igneous rocks if he has little information on the relative volumes of the different rock types in the series and does not have to account for an overall geochemical balance of the system as a whole.

Geologists seem to have agreed to accept a paradigm for convergent plate boundaries that is little more than a set of simplistic rules of thumb. They visualize a system in which volcanic activity is expressed in chains of large andesitic volcanoes at a constant distance of 150 to 250 km behind a trench and about the same distance above a dipping zone of earthquakes. Behind the main volcanic axis are scattered eruptions of lavas, the compositions of which are increasingly alkaline and potassic away from the trench. The generation of magma is in some way the result of underthrusting oceanic lithosphere descending at rates that can be deduced from the geometric patterns of magnetic anomalies.

Inasmuch as most theories of orogenic volcanism are likely to be based on such a picture, it is worth subjecting it to critical scrutiny.

## Time and Space Relations

There is no need to emphasize the variety of spatial relations seen in volcanic belts along the margins of the American continents. The recently active volcanoes form discontinuous segments that vary widely in the intensity of their activity. The most glaring anomaly is the Mexican belt, which diverges from the Pacific Coast and swings at an increasing angle away from the Acapulco Trench to the shores of the Gulf of Mexico. The Cascade Range has neither trench nor Benioff Zone. In fact, the central portion of the Cascade system has the lowest seismicity of any region west of the Rocky Mountains. The fact that it has also had little historic volcanism suggests that these two factors may be related, but the time scales of recorded seismic and volcanic activity are too short to be meaningful.

More important, perhaps, are the long-term fluctuations of volcanism that can be seen in the stratigraphic record. The presently active volcanoes are the products of only the latest of several episodes of Cenozoic activity. It has been suspected for some time that nearly all of the presently active chains of the Circum-Pacific region began their most recent activity at the end of the Pliocene, but the dramatic increase of ash layers found in deep-sea cores (Kennett & Thunell 1975) shows that the onset of Quaternary volcanism was not only sudden but that it was simultaneous on a global scale.

Wherever any of the volcanic sequences of island arcs or continental margins have been studied in detail, they have been found to fall into discrete age groups, each with its own com-

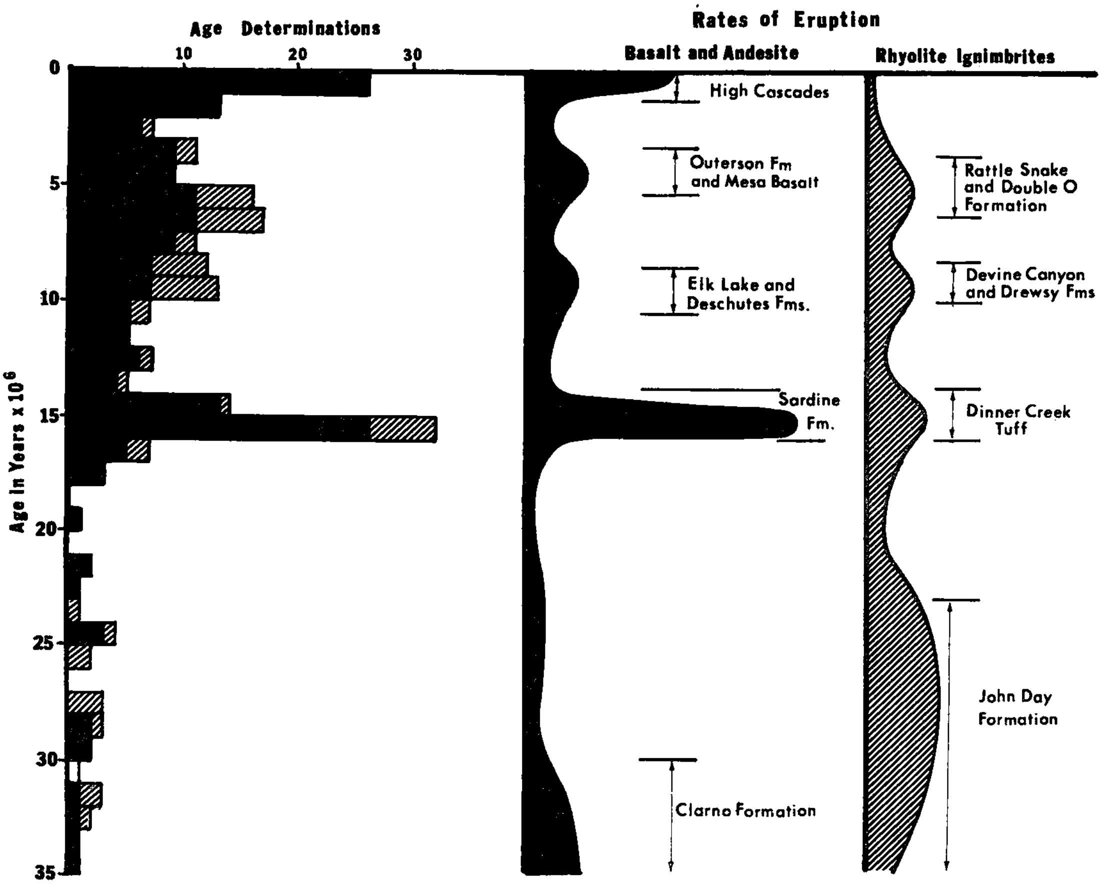


FIG. 1. Radiometric age determinations and estimated rates of eruptions of basalt and andesite (solid) and siliceous ignimbrites (diagonal ruling) in the Oregon Cascade Province during the Late Cenozoic. The scale for eruption rates is schematic and is based on volumetric data in Figure 6.

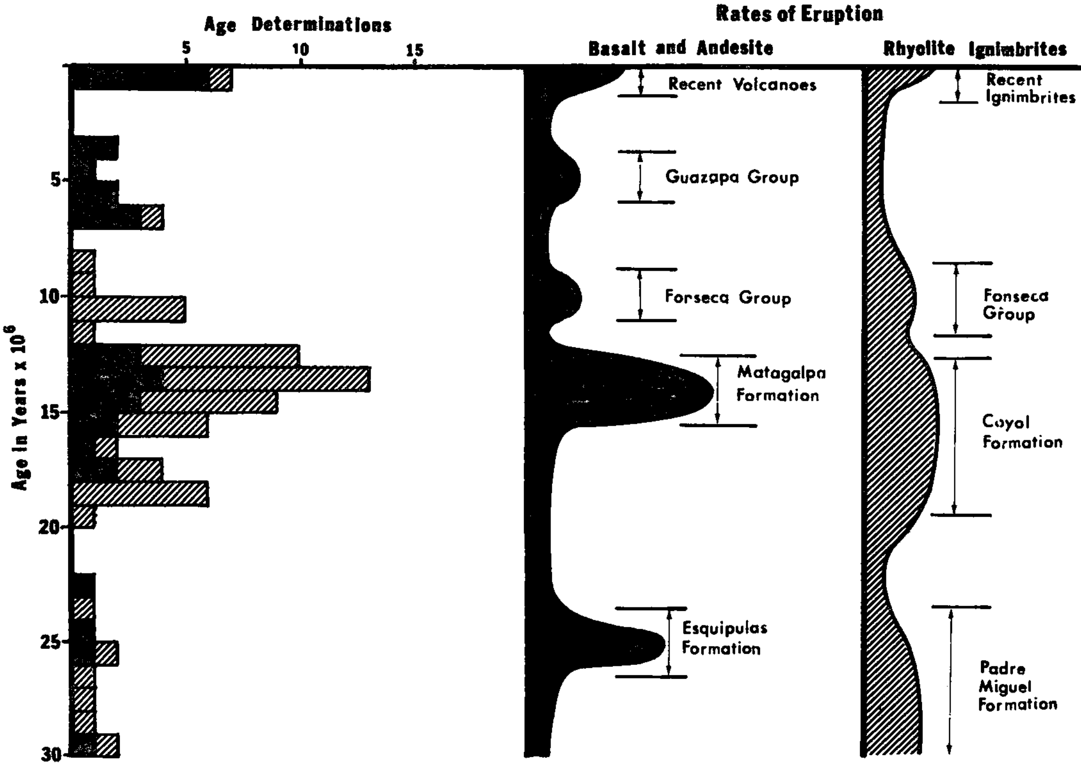


FIG. 2. Age determinations and estimated rates of volcanic eruptions in the Central American volcanic province during the Late Cenozoic. Rates of eruption are based on relative proportions and distribution of exposed rocks and are subject to large uncertainties. Symbols the same as Figure 1.

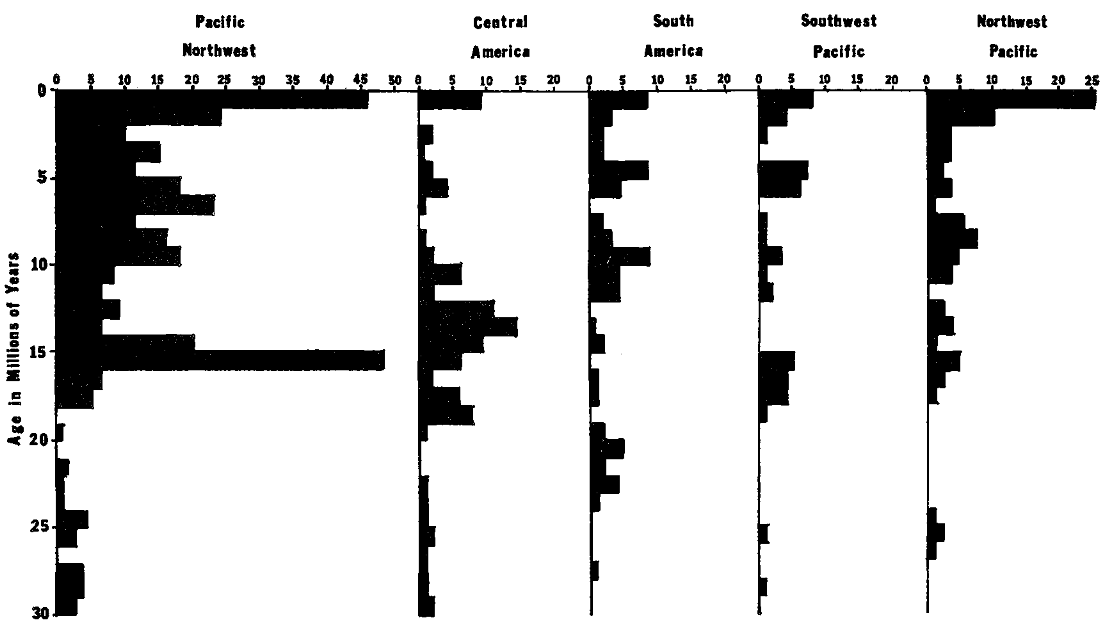


FIG. 3. Histograms of published radiometric age determinations for the major segments of the Circum-Pacific volcanic chains.

positional and structural relations. As more radiometric dating steadily refines the age relations of these rocks, the definition of the age span of each group has become sharper.

These relations have been brought out very well by the stratigraphic studies that John F. Sutter and I have been carrying out in the volcanic belts of Oregon and Central America. In the Cascade Province, our attention has been concentrated on a 300km-long belt normal to the modern volcanic chain and on a few selected areas in different structural settings within the High Cascade Range. In Central America, the section that shows the most complete Tertiary volcanic section is parallel to the present axis in Honduras and adjacent parts of Guatemala, Salvador and Nicaragua. Summaries of the Late Cenozoic volcanism in these two sections are shown in Figures 1 and 2, together with frequency diagrams of age determinations on the principal stratigraphic units. For comparison, histograms for published radiometric ages from other parts of the Circum-Pacific region are

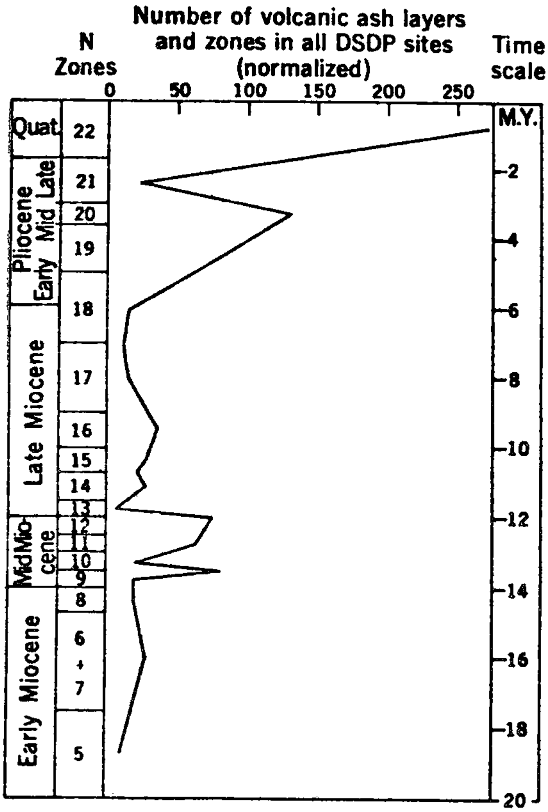


FIG. 4. Summary of world-wide data on numbers of ash layers in deep-sea cores as a function of age (after Kennett & Thunell 1975).

shown in Figure 3. The similar distribution of ages of dated volcanic rocks from these regions is readily apparent.

In many provinces the evidence of past volcanism is better preserved by the ash interlayered with marine sediments than it is in surface exposures on land. A summary of data from deep-sea cores compiled by Kennett & Thunell (1975) is shown in Figure 4. Its broad similarity to the age distributions in Figure 3 is apparent. There are differences in the scales that probably reflect the fact that the marine record is tied to paleontological ages whereas the land record is based on radiometric dating. Nevertheless, it is probably safe to conclude that the concentrations of marine ash layers correspond to maxima in the intensity of nearby volcanoes. Dr. Peter Vail and his co-workers (pers. comm.) have found that the stratigraphic record shows major marine transgressions throughout the world during the Middle Miocene. Other periods when there was strong volcanism also coincide with high stands of the sea, whereas intervals of reduced volcanism correspond to marine regressions. The changes of sea level may result from rise of the oceanic ridges during periods of strong igneous activity at the spreading axes. If so, two facts seem to emerge from these records: volcanism is strongly episodic, and it tends to be syncronous over broad regions of the Earth.

## Compositions and Rates of Eruptions

The proportions of the various rock types erupted during any particular period vary widely. Moreover, the timing of activity seems to differ for magmas of different compositions. The records for the American continental margins show that siliceous rocks, particularly ignimbrites but possibly plutonic intrusions as well, tend to appear over widely spaced time intervals. Andesitic activity is more concentrated in time with more frequent eruptions of small volumes, while basaltic volcanism is often brief but of high intensity. The most striking example of the latter is the great outpouring of Columbia River basalts over a period of 1 or 2 m.y. (Watkins & Baski 1974).

The detailed histories of individual regions differ, but taken as a whole, the record of Cenozoic volcanism shows that some periods were characterized by frequent eruptions of widespread plateau lavas or flood basalts, others by composite cones of andesite, and still others by voluminous outpourings of siliceous ignimbrites. The intervening periods, including long intervals of the early Cenozoic, were quiet and almost devoid of volcanism. During these long periods there was far less activity than we witness today, and over the long term, there has been more time when there was little or no volcanism than when there was activity of the kind we consider typical of the convergent-plate environment.

These broad generalizations are only tentative, of course, because there are too few detailed studies of enough regions around the Pacific margins to permit more than a crude evaluation of their comparative records. The dangers of interpreting histograms of age determinations in terms of volumes of igneous rocks are known well (Gilluly 1973). One need only look to Japan, where the single most voluminous volcanic unit is the highly altered "Green Tuff" of Honshu, for which there are not

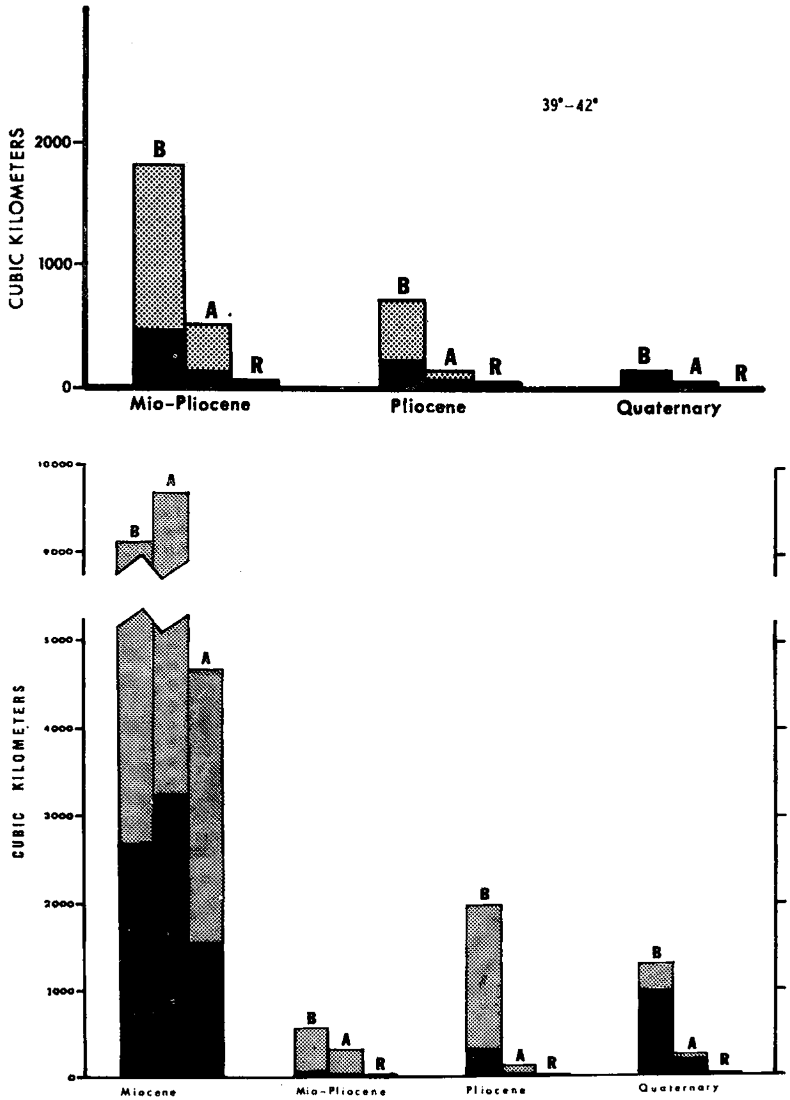


FIG. 5. Calculated volumes of the principal rock types in two portions of the Cascade Province. Upper diagram (a) is for central Oregon and the lower diagram (b) shows the corresponding data for southern Oregon and northern California. Basalts of the Columbia River Group have not been included. Solid portions of the bars correspond to measured volumes of rock preserved today; the stippled pattern shows the inferred amount of rock that occupied areas between the remaining outcrops but has since been removed by erosion.

more than two or three reliable K/Ar age determinations, to see how careful one must be to consider the geological basis of such data.

The same problem arises in dealing with chemical analyses. A histogram of analyzed Quaternary rocks from almost any part of the Circum-Pacific volcanic system shows a strong dominance of andesite. The only thing this shows is that geologists have a preference for scenic field areas; a large andesitic cone is more likely to have been studied than a monotonous pile of flat-lying basaltic lavas. There are more than 150 analyses of lavas from Mount Hood, for example, but a single lava in the Columbia River Group, the Rosa flow, has a volume seven times that of Mount Hood and is represented by two analyses.

There is an obvious reason why there are so few data on volumes of volcanic rocks. Measurements are very difficult, and even when they are made with great care, one has little assurance that they are accurate. There are two areas in the Cascade system where exposures are good enough to permit detailed mapping, dating, and correlation of large units laid down in the Late Cenozoic. One is the section across central Oregon that has already been mentioned, and the other is a strip across northern California and southern Oregon. The calculated volumes of rocks of various compositions and ages in these two areas are shown in Figure 5.

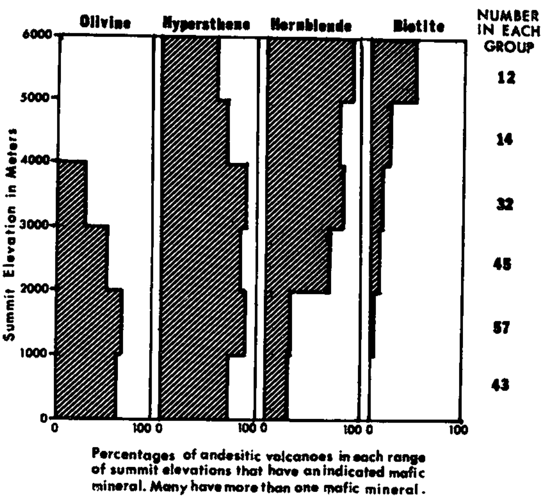


FIG. 6. Mafic phenocrysts in andesites erupted from volcanoes of different heights. Hornblende and biotite are much more common in volcanoes with high summit elevations than they are in lavas of comparable composition but from low elevations. Augite has been omitted because it is ubiquitous in andesites from all localities. Since most of the very high volcanoes are in the Andes and other regions of thick sialic crust, the abundance of hornblende and biotite in their lavas may indicate the influence of thick continental crust on the crystallization of rising calc-alkaline magmas. Data have been compiled from analyzed rocks described in the Catalogues of Active Volcanoes and from unpublished petrographic and chemical data on rocks of the Pacific Northwest, Central America, and Ecuador.

Although corrections were made for the effects of post-depositional erosion, there is no way of estimating what proportion of the erupted material was carried away by wind and water at the time of eruption. Consequently, the estimates are probably low, perhaps by a factor of as much as two or three. The exposed sequence in central Oregon is deeper and more closely dated. In that section, rates of eruption for the four most recent episodes ranged from 0.6 to $5 \times 10^{-5} km^3/y$ for each km of length of the chain. Averaged over the entire time period of 20 million years, the rate of production was about $0.9 \times 10^{-5} km^3$ or $2.3 \times 10^{10}$ grams/yr/km. Eighty percent of the volume was produced between 17 and 14 million years ago or in about fifteen percent of the time. If the Columbia River lavas which were also erupted during the same episode of the mid-Miocene were included in the total, the discrepancy would be more than twice as great.

Unfortunately, there is so little information on other regions that it is difficult to judge how representative these values are for the Circum-Pacific region as a whole. Sugimura and his co-workers (1963) calculated volumes of volcanic rocks in the Japanese arc, and their data indicate an average rate of about $0.4 \times 10^{-5} km^3$/yr/km for the last 25 million years. This rate is about half of that obtained for the Cascade system, possibly because most of the rocks in the Izu arc are submerged and were not included in the calculation.

Baker (1968) presented volumetric data on Quaternary rocks of the Antilles and South Sandwich Islands and illustrated the marked differences in the proportions of andesite in different island arcs. He suggested that andesite becomes proportionately more important as the arc evolves with time.

The relative proportions of rock types in volcanic chains seem to be connected in some way with the history and structural environment of orogenic belts. We see this on a wide range of scales. For example, there is a marked tendency for the andesites of volcanoes that stand on thick continental crust and reach high elevations to contain hornblende and biotite, whereas these minerals are rare in rocks of similar bulk composition erupted at lower elevations, especially in island arcs where the crust is presumably thin (Fig. 6). There must be a simple reason why basalts are so rare in some regions, such as the Andes and the northern Cascades, and so common elsewhere. The limited amount of data we have indicates that basalts become progressively less important with increasing thicknesses of the crust.

Figure 7 shows the relative proportions of basalt, andesite, and dacite or rhyolite in the three segments of the Cascade Range where it has been possible to calculate volumes of Quaternary and Late Tertiary rock. The proportion of andesite in the northern and southern Cascades where the volcanoes are built on thick sialic crust is much greater than it is in central Oregon where the crust is thin and composed of mafic volcanic rocks and sediments. Perhaps, as Kuno suggested some years ago (1962), there is some structural or thermal feature of thick sialic crust that inhibits basalt from reaching the surface.

The fact that andesite is dominant only when the total volume of volcanic rocks is low would be in accord with Kuno's interpretation. Wherever large volumes of calc-alkaline rocks are erupted on a well-defined volcanic front, basalt is by far the dominant rock type, and the conspicuous andesitic cones that we associate so instinctively with such systems are volumetrically trivial. This fact argues strongly against a primary andesitic magma.

Figure 8 is a plot of analyzed post-Miocene lavas from the section we have studied in central Oregon. It illustrates the compositional continuity among the various rock types found in the youngest sequences of lavas. Viewed as a whole, the suite has all the features of a series of differentiates derived from a basaltic parent. The rocks display smooth compositional variations that are consistent with fractional crystallization, and they diminish in volume both in time and with increasing degrees of differentiation. The most primitive basalts in the series have high Mg and Ni and are low in alkalis and Zr.

We can gain an insight into the mechanisms responsible for these compositional relations by examining the spatial distribution of the rocks across the volcanic chain and into the continental interior. This approach has been applied to many other regions and has led to recognition of what appear to be systematic relations between the composition of lavas and their distance behind a volcanic front.

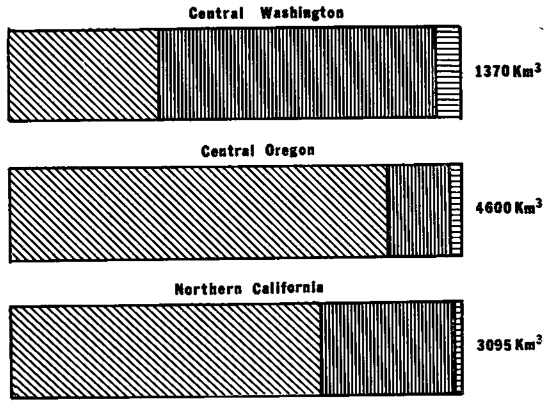


FIG. 7. Relative proportion of rock types (basalt, andesite, and dacite or rhyolite in order from left to right) in the two areas represented by Figure 6 and a third area in the Cascade Range of Washington. Only rocks younger than 12 m.y. are included. Note that the total volumes of rocks, shown to the right of each bar, are different for the three areas.

## *K*

In all the dogma of convergent plate boundaries, there is nothing dearer to the hearts of geochemists than the "*K*/*d* ratio". The popularity of this simple device is well deserved, for it enables one to plot Benioff zones where there are no earthquakes and to find trenches where there is no deep water.

It has been known for many years that the potassium contents of igneous rocks tend to increase toward the interior of continents; this fact has been pointed out repeatedly for more than half a century. The important question for plate tectonics is whether this increase results from (a) the thickness of sialic crust through which the magma rises, as argued by Waters (1955), Moore (1962), Condie & Potts (1969), Best (1975) *et al.;* (b) the degree of differentiation of magmas that rise through cool lithosphere, as proposed by O'Hara (1973); (c) the depth of segregation of magma from its source rocks (e.g. Kuno 1968; Schilling 1973); (d) the depth to a Benioff zone where melting presumably takes place along the top of the descending slab (Dickinson & Hatherton 1967; Lipman & Christiansen 1972; and many others); or (e) some other effect that we have not yet suspected.

The first question to be resolved is whether the reputed patterns are in all cases real. If one examines the basic data on which the alleged relation is founded, it is clear that much depends on the distribution of analyzed rocks more than a few tens of km behind a volcanic front. More often than not, the data are from samples that are widely scattered and have differing ages and silica contents.

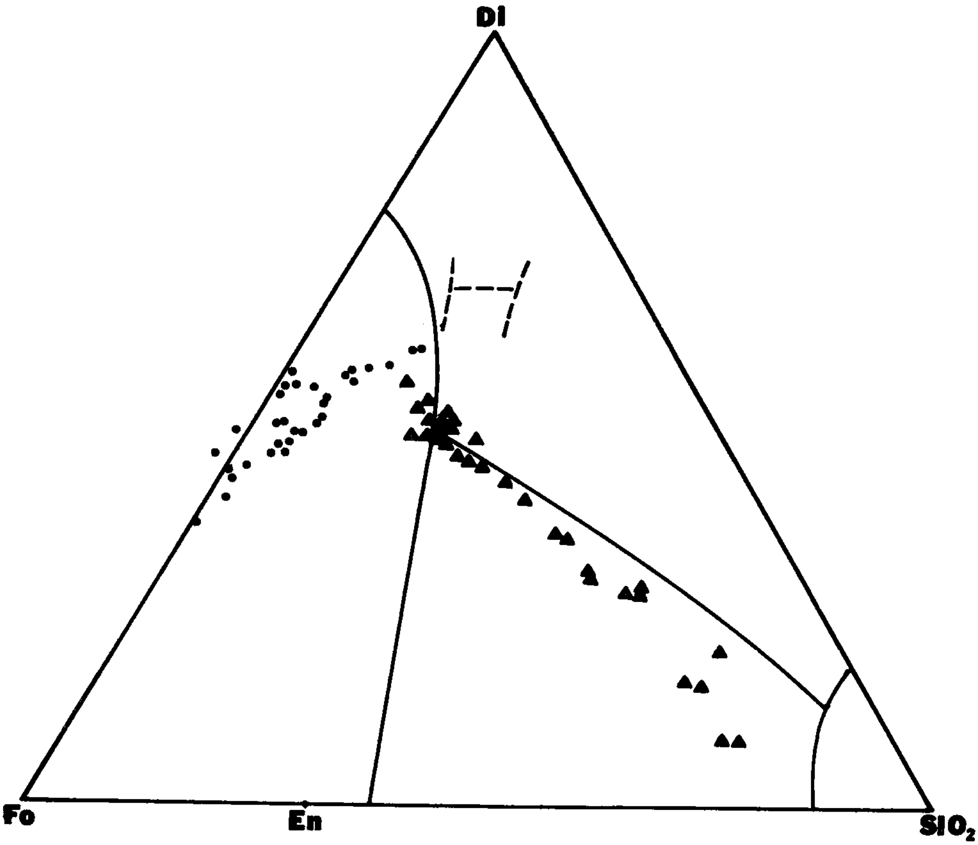


FIG. 8. Compositions of Pliocene and Holocene lavas of central Oregon plotted on the diagram for forsterite-diopsite-silica. Pliocene basalts are indicated by solid points, and lavas of the High Cascade volcanoes are shown by open triangles. The invariant points for the system at 20 km are shown by broken lines. The fact that the two series trend toward or away from slightly different points near the invariant points may indicate differing depths of equilibration. The trend of basalts is consistent with fractionation of an amphibole with a composition lying somewhere outside the left margin of the diagram. The trend of High Cascade lavas, however, implies fractionation of large amounts of augite and lesser amounts of hypersthene. Diagram is in weight percent.

What is sorely needed are data on a statistically significant number of volcanic rocks having comparable silica contents, closely equivalent ages, and a linear distribution over a broad distance behind a volcanic axis. The high-alumina basalts of central Oregon are admirably suited for this purpose; they were erupted during the Pliocene from a swarm of small cones that stretch nearly 300 km from the western edge of the Cascade Range to within a hundred km of the Idaho boundary. The rocks are almost indistinguishable in outcrop or hand-specimen. They form the uppermost volcanic unit over much of central Oregon and underlie most of the High Cascade Range. Radiometric age determinations at six localities fall between 3.6 and 5.7 m.y. None of the analyzed specimens used in the plots comes from a vent more than 20 km from the axis of the nearly east-west section to which the data have been projected.

The minor and trace-element patterns displayed by this suite are illustrated in Figures 9 and 10. They show a decreasing spread in the range of values inland and away from the volcanic axis. Unfortunately, there are too few basaltic rocks of this age exposed on the western side of the Cascade Range to show whether or not the decline might be symmetrical to the west. It is clear, however, that if the relative proportions of $K_2O$ to total alkalis are a reflection of the depths to a subducted plate, the latter must be rising toward the east. This possibility offers a novel explanation for the rise of the Rocky Mountains; they are being elevated by an emerging slab of oceanic lithosphere which should be surfacing shortly somewhere in Idaho.

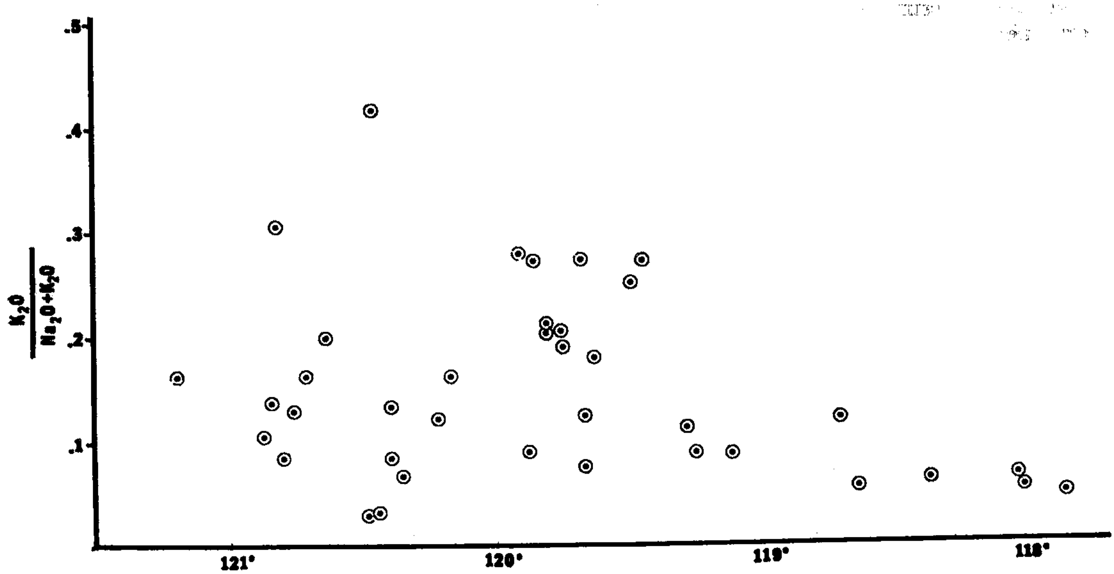


FIG. 9. $K_2O/Na_2O+K_2O$ for Pliocene basalts of central Oregon. The axis of the High Cascades is near the left edge of the diagram. All points are for analyzed rocks with 47 to 51 percent $SiO_2$.

The question that has been of most concern to petrologists and geochemists is where the potassium is coming from, but a better question might be "where is all the potassium going?". If we consider the system as a whole, there should be a balance between the input to the oceans and what is removed by subduction and returned to the continents. Potassium does not seem to be accumulating in the seas (Goldberg & Arrhenius 1958); it is absorbed in abyssal sediments and eventually subducted. But if the potassium were "underplating" one edge of the continental crust, prolonged subduction would have produced an asymmetrical distribution of heat flow between active and inactive margins, and there would be a steady change in the composition of the continental crust with time. Since there seems to be little evidence for either of these effects, the potassium must be returned to shallow levels in calc-alkaline rocks, as already suggested by Barth (1961) and Gilluly (1971).

If we ignore the contribution of sediments dumped directly into trenches from the continents and if we also neglect wind-blown dust of continental origin and consider only the input of river water, it is a simple matter to calculate an approximate value for the minimum amount of potassium that must be recycled. The potassium content of river water, exclusive of that which is recycled by rain, is about $2.3 \times 10^{-3}$ grams per liter, and mean annual river flow is about $3.6 \times 10^{16}$ liters per year; so the input from this source alone is roughly $8.3 \times 10^{13}$ grams per year.

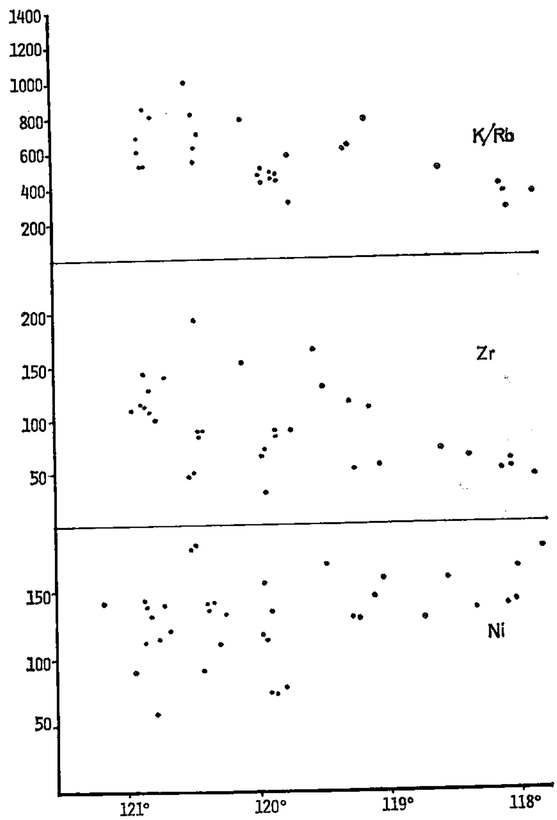


FIG. 10. Concentrations of trace elements in the same rocks as Figure 9.

If we take the estimated average rate of $2.3 \times 10^{10}$ grams per year per km for the igneous rocks produced in the Oregon Cascades over the last 20 million years as representatives of the 40,000 km of volcanic chains for all the time that oceanic lithosphere has been subducted and assume an average potassium content of 2.5 percent, the output would be about $2.3 \times 10^{13}$ grams of potassium per year or a third of the input of rivers alone.

Considering all the uncertainties in calculations of this kind, it is surprising that the two numbers are even of the same order of magnitude.

## Summary

No real advance in our understanding of subduction can be expected until more quantitative data are obtained on the kinds of magmas being produced and the rates at which magmas are generated, both as a function of time and of space. The widely accepted model of convergent plate boundaries is heavily biased toward present conditions, which are by no means typical of the geologic past. The synchronous nature of episodic volcanism over wide regions of the Earth implies a global mechanism that has yet to be identified, but the overall geochemical balance of the system requires that the long-term production of calc-alkaline magmas be related to the rate of subduction of oceanic sediments.

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